wbcsd

New energy solutions for 1.5°C

Pathways and technologies to achieve the Paris Agreement

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Executive summary

Limiting global warming to 1.5°C compared to 2°C reduces the severity of climate change impacts on our natural and human systems. As highlighted by the Intergovernmental Panel on Climate Change's (IPCC) *Global Warming of 1.5°C* special report, several hundred million people would be less exposed to climate-related risks to health, livelihoods, food security and water supply. For our natural systems, the IPCC projects that coral reefs will be virtually eliminated at 2°C, while under 1.5°C of warming, they will decline by 70-90%.[1]

Human activities have already caused global warming of about 1.0°C and global warming is likely to reach 1.5°C around 2040 if it continues to increase at the current rate.[2] While a 1.5°C world is still possible, we need to urgently and radically transform all systems at an unprecedented scale. Transforming the energy system will be crucial as unabated fossil fuels are currently responsible for over 80% of primary energy demand. We must move swiftly toward an increase in all available zero-carbon energy sources across all sectors.

As the global temperature increase is linked to cumulative net CO_2 emissions, it is imperative that emissions remain within the carbon budget. This means that in parallel to aiming for net-zero emissions as early as possible in the second half of the century, we need to also achieve emissions reductions in the near-term to limit cumulative emissions. According to the IPCC, we need to reduce CO_2 emissions by about 1.4 $GtCO_2$ per year to limit warming to 1.5°C (Figure 1).[3] **It is therefore crucial that the transition to a zero-carbon energy system is accelerated now, using technologies already existing today.**

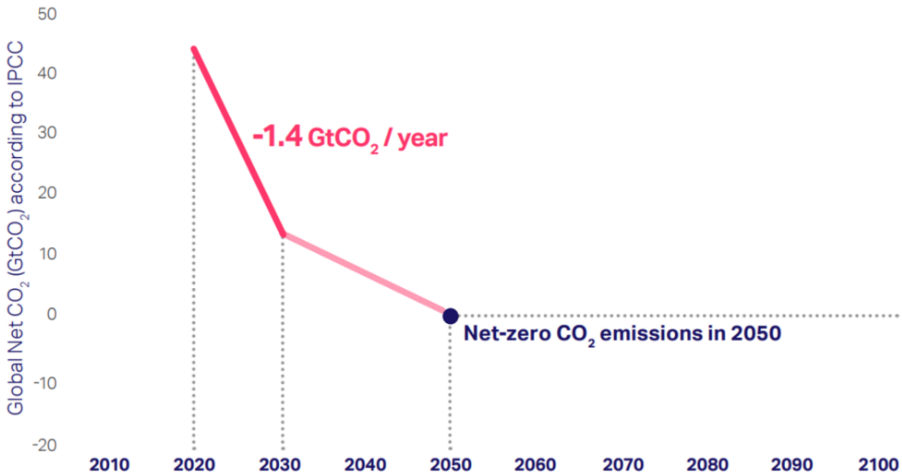

Figure 1 Deduced from median absolute annual change in CO_2 emissions compatible with limiting warming to 1.5°C (average of high and low overshoot scenarios).[4]

We can make significant headway in decarbonizing the power, transport, buildings and industry[5] sectors with existing technologies at the same time as research and development (R&D) efforts tackle the technologies needed for the full, long-term decarbonization of the energy system. Companies and individuals can act today by assessing the carbon footprint from their energy use and choosing low-carbon alternatives where possible. The range of low-carbon solutions available is summarized in Figure 2. Long-term policy signals, new financing mechanisms, demand for low-carbon goods and services and maximum benefits to society are important enablers to the uptake of these solutions.

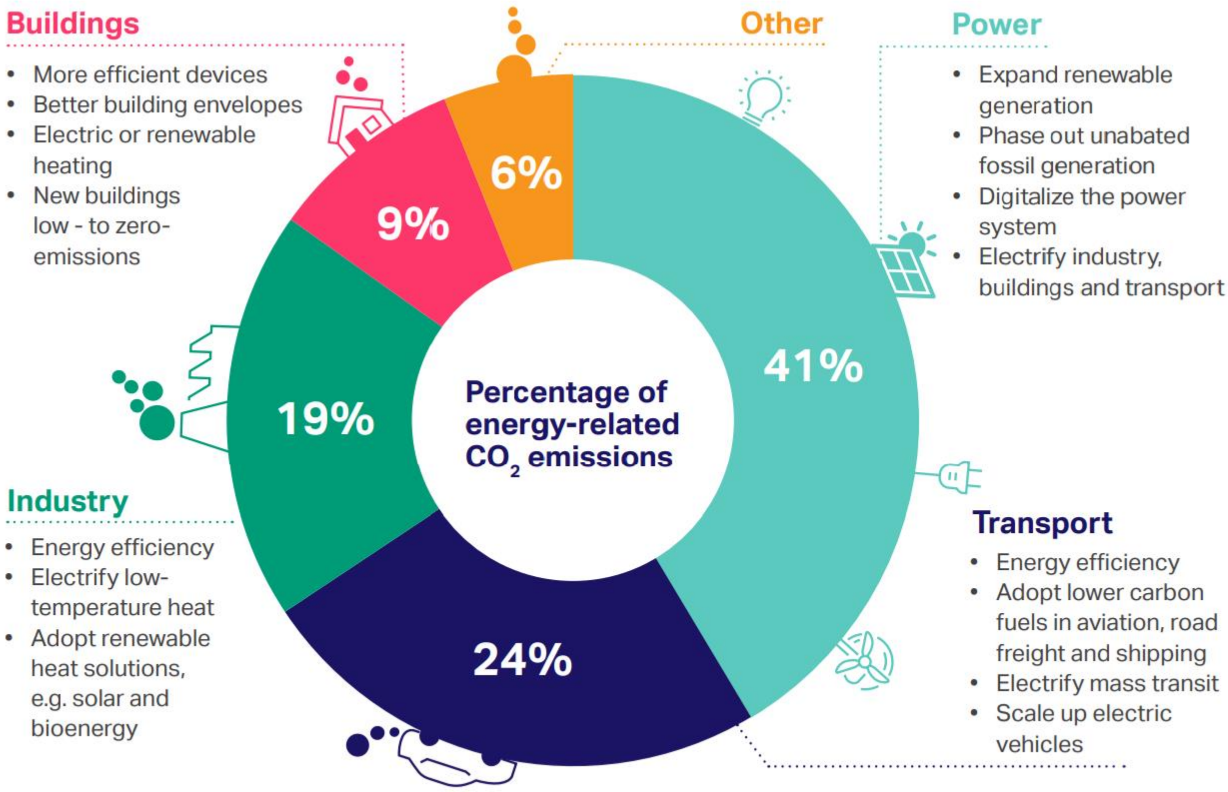

Figure 2 Low-carbon solutions available today in the power, transport, industry and buildings sectors

The transition to a decarbonized energy system that is smart, digitized, interconnected and distributed will both require and drive change across the entire energy value chain. Collaboration across value chains and sector initiatives are a key enabler of coordinated decarbonization actions throughout the energy system. While the transition will be highly disruptive for existing business models, it offers the potential to develop innovative technologies, access new markets and create new business models to deliver energy services.

Energy plays an important role in meeting almost all Sustainable Development Goals (SDGs). It is therefore important that the ongoing transition results in an energy system that is not only sustainable and modern, but also affordable and reliable.

The primary levers to decarbonizing the power sector are expanding zero-carbon generation and phasing out unabated fossil fuel-based generation. Scaling up renewable-based electricity (RE) is crucial, especially related to generation from solar and wind technologies. The costs of solar and wind technologies have fallen substantially, making them competitive with fossil fuel-based generation in several regions. In addition to RE, some countries may opt for nuclear power or carbon capture and storage or use in their energy transition. The transformation of the power sector will also contribute substantially to the decarbonization of transport, buildings and industry as energy end uses become increasingly electrified.

Alongside changing the power generation mix, we need to accelerate the evolution of electricity grids and markets. In particular, digitalization of the power sector, including the deployment of smart grid technologies, will improve supply and demand side efficiency and be crucial to network management and monitoring. At the same time, power systems will need greater flexibility to integrate increasing shares of variable RE. Traditional forms of flexibility such as thermal generation and hydropower are increasingly complemented by, for example, utility scale batteries for short-term storage. Smart grid technologies enable the provision of flexibility services to the grid from distributed energy resources (DERs). Examples of DERs include behind-the-meter battery storage, distributed renewable generation and electric technologies – in particular in the passenger transport and buildings sectors – which can provide demand response, and thermal or electric storage. Virtual power plants (VPPs), which aggregate DERs, will be important to facilitating participation in electricity and balancing markets.

Energy efficiency is a key lever in reducing CO_2 emissions in all energy-demand sectors – transport, buildings and industry. It is a particularly important near-term action in energy uses where fuels and technologies for full decarbonization are not yet commercially available. These include aviation, shipping, trucking, and medium- to high-temperature heat in industry. Due to the higher efficiency of electric technologies such as heat pumps and battery electric vehicles compared to their fossil fuel-based counterparts, electrification can also help to improve energy efficiency. Further improvements in energy efficiency are nonetheless important for electric technologies, to reduce emissions from a power sector which is gradually decarbonizing and to reduce the volume of additional investments in electricity capacity needed to meet demand.

Transport

Electrification will play an important role in decarbonizing transport. In addition to decarbonization targets, the electrification of passenger mobility in urban settings is driven by air quality concerns. The two main elements of the transport decarbonization pathway are the increasing deployment of battery electric vehicles (BEVs) and maximizing use of electrified mass transit systems. Technologies for the latter are likely to include both battery and fuel cell electric buses and the electrification of rail. We need to develop low-carbon value chains and parallel investments in charging or hydrogen fueling infrastructure to scale up battery and fuel cell technologies. Pricing measures that make mass transit more attractive than private transport and policies that restrict the use of private vehicles are important to incentivizing a modal shift from private transport to mass transit. In addition, urban planning policies can encourage active mobility (walking and cycling), and improve the business case for mass transit services.

In addition to efficiency improvements, switching to lower-carbon fuels is a key short-term option to reduce emissions from aviation, road freight and shipping. Opportunities include biofuels in aviation and road freight, and liquefied natural gas (LNG) or shore-to-ship power for shipping. In the long-term, electric drivetrain technologies, including both battery and fuel cell technologies, will be important to decarbonizing road freight. For aviation and shipping, the long-term pathway to full decarbonization is less clear. In aviation, this will require new zero-carbon motor technologies or a considerable scaling up of sustainable 'drop-in' aviation fuels used in existing engine and fueling infrastructure. Similarly, for zero-emissions shipping, electric motors or zero-emissions fuels in internal combustion engines should power vessels. In the shipping and aviation sectors, where activity is predominantly international, sector initiatives driven by international organizations are essential to coordinated sector-wide decarbonization and to reducing competitive distortions.

Buildings

In the long-term, all buildings must be net-zero emissions; the technologies we need to achieve this goal are available today. We need to decarbonize space and water heating, which are currently responsible for three-quarters of direct CO_2 emissions from the sector, via electric or renewable technologies such as heat pumps or solar thermal heating. Electricity demand from the buildings sector will grow as result of increasing electrification rates and economic and population growth. To minimize load on the grid, electric devices across all end uses (heating, cooling, cooking, appliances and lighting) must be highly energy efficient. In addition to technology choices, the energy required for space heating and cooling is strongly influenced by the performance of the building envelope. The key challenge to decarbonizing the sector is accelerating the renovation rate of existing buildings and ensuring that all new buildings and electric products are highly efficient.

Industry

Technologies available today can go some way towards decarbonizing industry. These include electrification via the integration of heat pumps for low-temperature heat and solar heat for low- to medium-temperature heat. In addition, energy-efficiency measures and a transition to more circular business models reduce CO_2 emissions. For long-term decarbonization, particularly of medium- to high-temperature heat, the pathway is less defined. Options include electrofuels, fuel switching to bioenergy, and the integration of carbon capture and storage or use. The way forward will depend on several factors, including investment costs and price differentials between conventional and alternative fuels.

Key enablers to accelerate the development of low-carbon energy value chains are: long-term policy signals, new financing mechanisms, demand for low-carbon goods and services and benefits to society.

Long-term national climate strategies consistent with the Paris Agreement's goals and the SDGs are crucial. The private sector needs credible and clear long-term policy signals from governments to provide investment certainty. Economy-wide carbon pricing is one of the most efficient means of levelling the playing field between incumbent fossil fuel technologies and low-carbon alternatives. Governments need to phase out fossil fuel subsidies to avoid distortions to the carbon price signal. Other policies needed include efficiency standards and time-limited support for R&D and pilot project deployment to help technologies reach commercial scale. We also need government support for infrastructure development, e.g. partnerships between the public and private sectors.

New financing mechanisms and business models help overcome the cost barrier. In the power sector, these include renewable power purchase agreements and green bonds for RE. We can also use green bonds to finance other decarbonization measures, such as energy efficiency in buildings and industrial decarbonization projects. In addition, product-as-a-service and energy service company (ESCO) business models help overcome the barrier of high upfront costs in energy-use sectors. Also, business models are emerging to provide owners of electric technologies, such as BEVs and heat pumps, with revenue from flexibility services provided to the grid, strengthening the business case for electrification.

Business plays a crucial role in helping people make more sustainable consumption choices. Peoples' aspirations of a 'good life' are today largely focused on ever-increasing levels of consumption; this is not compatible with a trajectory to a net-zero emissions economy. Traditional solutions to this challenge encourage people to change their consumption patterns and sacrifice key lifestyle aspects that contribute to their perceived quality of life. This approach has had limited success. An alternative approach is to shift middle-class aspirations, complemented by goods and services that offer a better quality of life with a fraction of the environmental impacts. Business has a crucial role to play in advancing technologies that will support sustainable lifestyles and in promoting a shift in aspirations.

Maximizing the benefits to society and minimizing negative impacts are important for public acceptance and the political feasibility of the energy transition. Energy access plays an important role in sustainable development; it is crucial that the energy transition delivers universal access to modern energy services. Companies have a significant impact on accelerating energy access by investing in infrastructure, low-carbon technologies, and developing innovative business and financing models to ensure that clean energy is affordable. The energy transition will also have profound impacts on employment, including job losses in carbon-intensive industries and development of new jobs in the low-carbon economy. We need to effectively navigate the transition in this challenging context by involving all stakeholders, investing in re-training for workers and promoting site repurposing. Companies are establishing new supply chains to decarbonize the energy system and, like with other supply chains, they will need to manage the risks including those associated with human rights infringements. Companies must manage their human rights risks by conducting due diligence of their supply chains to identify and mitigate risks throughout the life of projects/products.

1 Introduction

To achieve the principal goal of the Paris Agreement of limiting the global average temperature increase to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C above pre-industrial levels, CO_2 emissions need to be net-zero as early as possible in the second half of this century.

Limiting global warming to 1.5°C compared to 2°C reduces the severity of climate change impacts on our natural and human systems. As highlighted by the Intergovernmental Panel on Climate Change's (IPCC) *Global Warming of 1.5°C* special report, several hundred million fewer people would be exposed to climate-related risks to health, livelihoods, food security and water supply. Within our natural systems, the IPCC projects that coral reefs will be virtually eliminated at 2°C, while under 1.5°C of warming, they will decline by 70-90%.[6]

Human activities have already caused global warming of 1.0°C and global warming is likely to reach 1.5°C around 2040 if it continues to increase at the current rate.[7] While a 1.5°C world is still possible, it will require the radical and urgent transformation of all systems at an unprecedented scale. In pursuit of this target, the energy system must transition away from unabated fossil fuels – currently responsible for over 80% of primary energy demand (Figure 3) – and toward an increase in zero-carbon energy in all sectors. Figure 3 shows that the power sector has the largest amount of direct emissions to abate; but it also highlights the importance of decarbonizing the energy end-use sectors: transport, buildings and industry. It is a challenge faced by Organisation for Economic Co-operation and Development (OECD) and non-OECD countries alike, with non-OECD countries currently responsible for about two-thirds of CO_2 emissions.

The transition to a decarbonized energy system that is smart, digital, interconnected and distributed will both require and drive change across the entire energy value chain. This shift will affect a wide range of stakeholders, including fossil fuel extraction companies, electricity generators, transmission and distribution operators, investors and energy end users – at both company and household level. While the transition will be highly disruptive for existing business models, it also offers the potential for the development of innovative technologies, access to new markets and the creation of new business models to deliver energy services for evolving customer needs.

One of the biggest disruptions will take place in the power system and electricity end users. The current linear value chain of power being transmitted from a centralized generation plant to the end user is giving way to a system of increasing shares of distributed energy resources (DERs) – including distributed generation, behind the meter storage and battery electric vehicles (BEVs). This emerging ecosystem is characterized by two-way power flows where traditional energy end users across all sectors also provide power or flexibility services to the grid. The new energy ecosystem will also see increasing cross-sectoral links. For example, for the up-take of green hydrogen (produced using renewable-based electricity) as an energy carrier, or as feedstock for synthetic fuels or chemicals, players across an entirely new value chain need to collaborate and co-create new business and user models.

Figure 3: Total primary energy demand, final energy consumption per sector, and direct CO_2 emissions per sector in 2016.[8] Direct emissions are from sources that are owned or controlled by the reporting entity. For example, in an industrial facility, direct emissions include those related to fossil fuel combustion; it does not include emissions related to the generation of purchased electricity.

Energy plays an important role in sustainable development and that demand for energy will grow. This is because energy is crucial to achieving almost all Sustainable Development Goals (SDGs) – from its role in the eradication of poverty through advancements in health, education, water supply and industrialization, to combatting climate change. It is therefore important that the ongoing transition results in an energy system that is not only sustainable and modern, but also affordable and reliable. These objectives are also reflected in the targets of SDG 7, which should be achieved by 2030:[9]

- Ensure universal access to affordable, reliable and modern energy services;
- Increase substantially the share of renewable energy in the global energy mix;

- Double the global rate of improvement in energy efficiency;
- Enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil fuel technology, and promote investment in energy infrastructure and clean energy technology;
- Expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, Small Island Developing States, and land-locked developing countries, in accordance with their respective programs of support.

This publication presents the collective viewpoints of World Business Council for Sustainable Development (WBCSD) member companies – comprising technology and energy providers, energy users, and engineering consultants and contractors – on the necessary components of an energy transition compatible with the Paris Agreement and the developments and actions needed to move onto this pathway. This includes technology and policy developments, as well as the societal, behavioral and infrastructure changes that will enable the energy transition. While many technical and academic studies exist on this topic, this publication is unique as it presents the views of leading companies committed to the energy transition – the entities who will be at the forefront of implementation efforts.

Section 2 of this publication presents the key components of the energy transition – technical solutions, finance, long-term and consistent climate and energy policies, sustainable consumer choices and consideration of the societal impacts of the energy transition. Sections 3, 4, 5, 6, expand on this by explaining the decarbonization pathways to net-zero emissions in the power, transport, buildings and industry sectors, respectively. These sections also explain the required actions and developments for a net-zero emissions trajectory, including policy support, technology and infrastructure developments, new financing mechanisms and innovative business models.

As the global temperature increase is linked to cumulative net CO_2 emissions, it is imperative that emissions remain within the carbon budget. This means that in parallel to aiming for net-zero emissions in the second half of the century, emission reductions must also be achieved in the near-term to limit cumulative emissions. It is therefore crucial that the transition to a zero-carbon energy system starts now, using technologies that exist today. This publication therefore focuses on pursuing existing low-carbon solutions that can be scaled up in the short- to medium-term (from now to 2030), and highlights long-term solutions (beyond 2050) that need to be developed to fully decarbonize the energy system.

This publication steers the future work of the WBCSD New Energy Solutions project by identifying the current barriers and potential solutions to decarbonizing the power, transport, buildings and industry sectors. The project's ambition is to increase the implementation of low-carbon energy solutions through cross-sectoral collaboration. To scale markets and increase speed, the project specifically helps energy users in creating and implementing integrated energy strategies, decarbonizing power, heating, cooling and transport end-uses. It produces a guideline for energy procurement professionals to develop their energy strategy and a portfolio of business cases to rapidly assess technology options. Several business cases are highlighted in boxes throughout this publication.

2 Enabling the energy transition

This section provides an overview of the key enablers to the unfolding energy transition. Section 2.1 describes the technical solutions to decarbonizing the energy system. Section 2.2 explains how climate and energy policies support the implementation of these solutions and Section 2.3 provides an overview of the potential challenges and solutions to financing. Beyond that, the adoption of more sustainable consumer choices (Section 2.4) also supports the decarbonization of the energy system. With the rapid transformations required for an energy transition compatible with the Paris Agreement, it is important to build and maintain public support. Section 2.5 highlights some of the key societal impacts of the energy transition that need to be managed.

2.1 Technical solutions to decarbonize the energy system

Two interlinked elements are needed to decarbonize the energy system: increasing energy efficiency and the move to CO_2-free energy mixes and processes. Energy producers and users must consider combinations of both strategies to maximize their decarbonization achievements. The optimal decarbonization solution for each sector and in each country will differ depending on factors such as the evolution of costs (technology, fuel and infrastructure), economic development levels and the ability to finance decarbonization technologies, energy security, political will and social acceptance. In addition, technical feasibility will differ across countries, for example, due to varying renewable energy potentials, differences in energy consumption patterns, suitable storage sites for CO_2, and existing infrastructure. For sectors where technologies for deep decarbonization are not yet viable at scale, investments in natural climate solutions is an approach that companies in these sectors could use as a bridge solution to meeting ambitious GHG reduction targets quickly and in the short-term.

Energy efficiency

Energy efficiency is a key lever to reduce CO_2 emissions in all energy-demand sectors – transport, buildings and industry. It is a particularly important near-term action in energy uses where fuels and technologies for full decarbonization are not yet commercially available. These include aviation, shipping, trucking, and medium- to high-temperature heat in industry. Due to the higher efficiency of electric technologies such as heat pumps and battery electric vehicles compared to their fossil fuel-based counterparts, electrification can also help to improve energy efficiency. Further improvements in energy efficiency are nonetheless important for electric technologies, to reduce emissions from a power sector which is only gradually decarbonizing and to reduce the volume of additional investments in electricity capacity needed to meet demand. Potential solutions to these barriers are highlighted for each energy-demand sector in Sections 4 to 6.

There is potential for an even wider reduction in energy consumption through shifts to a more circular economy. As circular economy business models reduce demand for resources, materials and parts – most of which currently rely on fossil fuel-based energy sources for extraction and/or manufacture – they can also contribute to decarbonizing the economy. For example, product-as-a-service solutions help increase the productivity of assets such as buildings and cars and reduce their carbon intensity.

Shifting to lower CO_2 intensity energy mixes and processes

The second lever to decarbonize the energy sector is the shift from emission-intensive, fossil fuel-based energy sources to zero-emission sources of energy. The options are: direct or indirect electrification of final energy consumption coupled with a decarbonized electricity grid, switching to zero-carbon energy sources or the implementation of carbon capture and storage or use (CCS/U) technologies.

Electrification

A key strategy to reduce CO_2 emissions from end-use sectors is sector coupling, which exploits synergies between the decarbonization of the power sector and the electrification of energy demand in the transport, buildings and industry sectors. Electric technologies can also support the integration of variable renewable generation by providing flexibility services to the grid. Many electric technologies exist today, e.g. heat pumps and BEVs in passenger transport. While these technologies are commercially available, high upfront costs and a relatively high electricity price compared to fossil fuel-based alternatives are some of the key barriers holding back deployment. In addition, in many markets, such technologies are not allowed to participate in the flexibility services market; overcoming this issue will provide an additional revenue stream that supports the business case for electrification technologies.

Indirect electrification via the electrolysis of water using zero-carbon electricity to produce green hydrogen will also play a role in the energy transition.[10] While electrolysers need to operate at a relatively high load factor, they can be partly operated as a flexible load on the power system, providing balancing services to the grid. Numerous energy carriers or 'electrofuels' can be developed through this process. For instance, hydrogen can be used directly as an energy carrier or in processes to create other energy carriers, such as jet fuel, methanol, ammonia and methane. For the latter, carbon capture will also be needed to provide carbon feedstock. An alternative route to low-carbon hydrogen is the steam methane reforming process (currently the main process route for hydrogen production) combined with CCS.

There are many potential electrofuel applications, including industrial processes requiring medium- and high-temperature heat, fuel cell passenger vehicles, road freight, shipping and aviation. In addition, electrofuels may play an important role in providing long-term seasonal storage for the electricity grid and could be injected into a gas grid to help meet seasonal heating demand peaks in the buildings sector.

While hydrogen will play a role in the energy transition, large-scale solutions are not yet commercially available. Electrofuels are currently not cost-competitive with fossil fuels and direct electrification solutions, and the evolution of electrofuel costs compared to those of other energy carriers will strongly shape the role of electrofuels in the energy system. A carbon price will be important to leveling the playing field between electrofuels and fossil fuels. The key factors influencing electrofuel costs are electrolyser capital expenditure (capex) costs and the price for renewable electricity. Substantial infrastructure investments will also be needed to support market scale up.

For both direct and indirect electrification, the emissions reduction impact is strongly dependent on the power generation mix. Due to conversion and transmission inefficiencies in power generation, electrification of energy end-uses before sufficient decarbonization of the electricity grid might result in CO_2 emissions increases. Also, the conversion efficiency of electrolysers (currently up to about 65%)[11] suggests that indirect electrification should only be used when direct electrification options are not feasible. Life cycle emissions and energy-efficiency assessments are important considerations in evaluating the role of electrification in decarbonizing the energy system.

Lower carbon energy sources

Switching to lower carbon energy sources is another technical solution to decarbonization. An intermediate step toward decarbonizing the power and industry sectors could be to switch from coal to natural gas, provided that fossil fuel technology lock-in is avoided in order to reach net-zero CO_2 emissions as early as possible in the second half of this century. However, fuel switching only leads to full decarbonization of direct emissions when fossil fuels are displaced by zero-carbon energy sources. While the largest potential for scaling up zero-carbon energy sources lies with renewable energy, some countries may opt for nuclear as part of their zero-carbon energy mix in the power sector.

Of the renewable energy options, bioenergy (including biofuels, biogases and biomass) is the most versatile as it can be used in the power, transport, buildings and industry sectors. The carbon intensity of bioenergy is still a matter of debate, and dependent on factors such as direct and indirect land use change emissions and feedstock. Nonetheless, it is generally considered that bioenergy use results in lower lifecycle CO_2 emissions per unit of useful energy delivered compared to fossil fuels if sourced and used sustainably.[12] The role of bioenergy in each sector will depend on the evolution of costs compared to other decarbonization options, as well as the supply of sustainable feedstock. Given the potentially constrained supply of sustainable feedstocks compared to demand, bioenergy should be prioritized for sectors with limited alternative decarbonization options, such as international aviation and medium- to high-temperature heat in industry. Bioenergy can also be combined with CCS for carbon dioxide removal. In the future, bioenergy is likely to be produced from a broader variety of feedstocks and diverse processing routes; assessments of life cycle CO_2 emissions and the broader impacts (for instance on air pollution, water supplies, biodiversity and labor rights) of bioenergy will be needed to ensure supply chain sustainability.[13]

Carbon capture storage or use (CCS/U)

Where direct or indirect electrification or shifting to zero-carbon fuels or feedstock is not feasible, CCS/U can be a possible route to mitigating CO_2 emissions. The application of CCS/U technology is likely to reduce CO_2 emissions by about 90%. CCS/U can be used in industry sectors where emissions are difficult to abate, such as steel, cement, and chemicals. Also, CCS/U may play a role in the power sector, capturing emissions from fossil fuel plants. Captured emissions could be used, for instance, as feedstock in the chemicals sector or to produce electrofuels.

While technically feasible, there has been limited progress in deploying CCS/U at scale.[14] As of 2017, 17 large-scale CCS facilities were operating globally, capturing 37 million metric tons of carbon dioxide ($MtCO_2$) per annum.[15] Issues include limited cost reductions for the technology over the past decade[16] and the absence of a long-term, stable policy and regulatory framework.

Natural climate solutions

For sectors where technologies for deep decarbonization are not yet viable at scale, natural climate solutions are an approach that companies in these sectors could use as a bridge solution to meeting ambitious GHG reduction targets quickly and in the short-term. Natural climate solutions are an established way of capturing and storing emissions through natural carbon sinks such as forests and peatlands and they play a role alongside technical mitigation strategies under all IPCC pathways for 1.5°C. A recent study showed that natural climate solutions can provide 37% of the emissions mitigation needed between now and 2030 to stabilize warming to below 2°C at a cost of less than US$100/$tCO_2$.[17]

2.2 Climate and energy policy principles

The adoption and implementation of long-term national climate strategies consistent with the Paris Agreement's goals and the SDGs will be crucial to meeting the global climate challenge. The private sector needs stability and a long-term commitment from governments that provides credibility and certainty to investors. These strategies should aim to achieve carbon-neutral economies as early as possible in the second half of the century, in line with Paris Agreement objectives. Developed economies should aim to achieve this by 2050.[18]

Long-term national climate strategies should include policies that target all elements of the decarbonization challenge. A key focus is levelling the playing field between fossil fuel technologies and low-carbon alternatives. Governments should design policies such that they drive emissions reductions following a least-cost pathway for society. One way to do this is to implement market-based instruments, such as carbon pricing or renewable energy auctions. They trigger businesses to respond to a market price and select the most profitable and lowest cost measures for decarbonization. To enable such decisions, technology-neutral policies are important as they empower businesses to choose their own preferred path forward.

Economy-wide carbon pricing that is market-based and technology neutral should be central to governments' long-term climate strategies. As explained further in Box 1, carbon pricing is one of the most efficient means of driving the transition to a low-carbon world.

Business may also need additional policies beyond carbon pricing to overcome barriers that inhibit them from responding to carbon price signals.[19] For example, companies may not be implementing energy-efficiency measures that are cost-effective even with a carbon price, due to high upfront costs or lack of awareness. Standards – as discussed in sections 4 and 5 for transport and buildings, respectively – are important to driving the implementation of energy-efficiency measures. On the other hand, high-cost mitigation options will likely not be stimulated by current levels of carbon pricing. To support the scaling up of these technologies and to reduce their costs, businesses need policies such as time-limited support for research and development (R&D) and pilot project deployment to foster the move to commercial-scale development.

Governments should carefully consider the interplay of climate and energy policies to ensure alignment and limit unintended consequences.[20] For example, policies supporting energy efficiency and renewable energy that coexist with a carbon pricing instrument can result in interactions that jeopardize the achievement of policy goals if they are not properly coordinated. They may provide businesses with an additional financial incentive (on top of the carbon price), meaning that businesses will be encouraged to take up less cost-effective measures. Another example of misaligned policy is the implementation of a carbon pricing instrument alongside fossil fuel subsidies. The latter is effectively a negative carbon price, which reduces the impact of the carbon price signal. Policy-makers need to intervene and adjust policies when interactions between them cause undesired effects. At the same time, governments also need to consider the broader impact of climate and energy policies – such as air quality, energy security and international competitiveness – and understand the related policy interactions.

Box 1: Carbon pricing[21]

Carbon pricing is one of the most efficient means of driving the transition to a net-zero emissions economy. A carbon price is a monetary cost put on carbon dioxide emissions into the atmosphere. A carbon price steers companies away from investments in emissions-intensive technologies and toward investments in low-carbon alternatives. As it is technology neutral, an economy-wide carbon price encourages businesses to implement the lowest cost ways of reducing emissions. Provided that the carbon price is fully passed through in energy prices, it is also fuel neutral and helps to level the playing field between fossil fuel and zero-carbon technologies. Carbon pricing also provides businesses with compliance flexibility; businesses have the option of paying for the direct cost of emitting CO_2 to avoid making capital investments to reduce emissions.

Common types of carbon pricing approaches such as cap-and-trade systems, baseline and credit approaches, and carbon taxes are often mandatory for certain sectors. In 2018, a total of 51 mandatory carbon pricing initiatives had been implemented or were scheduled for implementation, covering about 20% of global greenhouse gas (GHG) emissions. Voluntary carbon pricing approaches via project-based crediting also exist in various forms.

However, existing carbon prices are well below the levels needed to accelerate the energy transition and trigger the CO_2 emissions reductions needed to meet the temperature goal of the Paris Agreement. Carbon prices vary from US$ 1 to US$ 139 per metric ton of carbon dioxide equivalent (tCO_2e), with almost half of emissions covered by carbon pricing initiatives priced at less than US$ 10/tCO_2e.[22] In comparison, according to the High-Level Commission on Carbon Prices, a carbon price corridor of between US$ 40 and US$ 80/tCO_2e is necessary in 2020 to stimulate the emissions reduction effort level required.[23] Similarly, the Carbon Pricing Corridors initiative found that carbon prices in 2020 should be in the range of US$ 24 to US$ 36/tCO_2e in the power sector, and US$ 30 to US$ 50/tCO_2e in the chemical sector in order to be on an emissions reduction pathway consistent with the Paris Agreement.[24]

With a diverse range and approaches of carbon prices in place, as well as the still limited implementation of carbon pricing around the world, measures must be taken to minimize the impact of the cost of carbon on international, competitive, emissions-intensive and trade-exposed industries. Approaches taken or proposed include the distribution of free allowances or tax exemptions or rebates based on benchmarking, and border tax adjustments for carbon-intensive imports.

Many carbon pricing policies raise revenue – for instance via the auction of allowances or carbon tax receipts. In 2017, governments raised US$ 33 billion in carbon pricing revenues.[25] Revenues from carbon pricing should be adequately recycled back to the economy, creating a virtuous cycle to finance the decarbonization process and mitigate the social impacts of carbon pricing. Such measures include government-supported technology development and compensating measures for low-income households to prevent economic disparity caused by the pass through of carbon prices to consumers, including higher electricity and heating costs.

2.3 Finance

Access to finance is crucial to the implementation of the decarbonization options described in Section 2.1. For wind and solar RE technologies, access to private finance is on the rise, as technologies are mature and cost competitive with fossil fuel-based generation in several regions. Project have also become more standardized and replicable, increasing the attractiveness of such projects to investors. On the other hand, financing other types of decarbonization projects can be complicated by various factors: they can be small and have relatively high upfront capital costs, making private-sector financing relatively expensive. They can also contain risks that are unfamiliar to financial institutions due to the use of innovative technologies or business models. Or they can have limited potential for replication and standardization that would support the type of market scale of interest to private investors.

As discussed in Section 2.2, the long-term commitment of governments to decarbonization and a coherent and predictable climate and energy policy environment are important to providing long-term visibility on the business case for low-carbon technologies and to reducing investment risks. In addition, specific policy measures can be targeted at supporting deployment. Educating investors on the underlying risks of projects is also important as this enables the development of innovative financial mechanisms to overcome barriers to investment.

New financial mechanisms and business models continue to emerge. In the power sector, these include renewable power purchase agreements (PPAs), off-balance-sheet financing, and the issuance of green bonds for RE. Green bonds can also be used to finance other decarbonization measures, such as energy efficiency in buildings and industrial decarbonization projects. In addition, product-as-a-service and energy service company (ESCO) business models can help overcome the barrier of high upfront costs in energy-use sectors. In addition, business models are emerging to provide owners of electric technologies such as BEVs and heat pumps with revenue from the flexibility services provided to the grid, which strengthens the business case for investments.

2.4 The role of sustainable lifestyles

Recent research indicates that household energy consumption and the energy associated with the production and use of products and services consumed by households contribute over 60% of global GHG emissions.[26] This implies that the transition to a decarbonized energy system must also involve a transformation of the way in which people consume goods and services, as well as the infrastructure that enables ways of life around the world.

This is a challenge for developed and developing economies alike. In developed economies, almost everyone uses resources in excess of what the planet can support; in developing economies, many aspire to developed-world lifestyles. As incomes rise, the new entrants to the middle class expect to improve their quality of life through a range of consumption increases (such as personal mobility, larger homes, and electrical appliances). This reflects people's aspirations of a 'good life', which, today, is largely focused on things being bigger or faster, and ever-increasing levels of material consumption. Such aspirations are not compatible with a trajectory to a net-zero emissions economy.

Traditional solutions to sustainable consumption challenges encourage people to change their consumption patterns and sacrifice key lifestyle aspects – such as eating meat and driving– that contribute to their perceived quality of life. Such tactics have had limited success in bringing about more sustainable behaviors and reducing the lifestyle impacts among the global middle class.

An alternative approach is to shift people's aspirations from a focus on bigger to better lifestyles, complemented by goods and services that offer a better quality of life with a fraction of the environmental impacts. Businesses have a crucial role to play in advancing technologies that will support more sustainable lifestyles at the same time as promoting aspirations that support the uptake of new technologies and linked behaviors at scale. Companies can explore what it means for their customers to live well and how they can help them to aspire to lifestyles that are neither about less nor excess, but that are smarter, cleaner and healthier.[27]

2.5 Societal impacts of the energy transition

Maximizing the benefits to society and minimizing negative impacts of the energy transition are important for public acceptance and the political feasibility of decarbonization actions. This section highlights three key topics: energy access, employment and human rights.

Energy access

Energy access plays an important role in sustainable development as energy is crucial to achieving almost all SDGs – from its role in the eradication of poverty through advancements in health, education, water supply and industrialization, to combatting climate change. It is therefore important that the energy transition delivers universal access to affordable, reliable and modern energy services. Key issues to address include access to electricity and clean fuels and technologies for cooking: 1.1 billion people do not have access to electricity and 3 billion people use polluting, inefficient fuels and technologies for cooking.[28]

Companies can have a significant impact on accelerating energy access. This includes investments in electricity grid extensions and the development and production of clean energy technologies such as off-grid renewables, low-carbon microgrids, advanced biomass and modern cookstoves, and energy-efficient technologies such as LED lighting. Companies also play a key role in developing innovative business and financing models to ensure that clean energy is affordable and accessible to low-income households. Governments should support private sector actions by implementing policies that encourage a wide range of solutions and business models and by creating suitable conditions for investment.[29] Consistent investment frameworks and political stability are particularly important as the business cases for off-grid renewables and renewable-based microgrids often have tight margins.

Employment

Employment is the engine at the center of our economies. It is crucial to enable individuals, businesses and societies across the world to thrive. The energy transition will have profound impacts on employment, including job losses in carbon-intensive industries and the development of new jobs in the low-carbon economy. Effectively navigating the transition in this challenging context is an imperative to avoid jobless growth, income inequality and social instability. The International Labour Organization (ILO) estimates that the transition to a low-carbon energy system will lead to a net addition of 18 million direct and indirect jobs by 2030. This consists of 6 million job losses by 2030, with fossil fuel extraction and refinery industries set to experience the strongest decline, and the creation of 24 million jobs over the same period, particularly in the renewables sector.[30]

While the energy transition will result in a global net addition of jobs, any development that results in job losses must nonetheless be accompanied by public and private measures to deliver a just transition. Governments' long-term climate strategies should appropriately consider employment planning, national skills and education policy, and social protection planning. For specific regions and sectors that will undergo a major transition, governments can collaborate with business to define responsible approaches to the implementation of new technologies, building foundations for fair and meaningful work based on respect, transparency and trust. In addition, governments should invest in training and skills provision for workers who will need to transition jobs and to work with businesses to create tools and strategies that contribute to building resilience in the workforce, in businesses, in labor markets and in social support mechanisms. Finally, it is important that governments address concerns related to climate policies, so that climate action is seen as an opportunity by all.

Human rights

All forms of business activity can affect human rights in a positive or negative way. Corporate respect for human rights is one of the most significant opportunities for business to contribute to the SDGs. But where companies don't pay enough attention to the risks of negative impacts, business activities can cause human rights infringements. Human rights infringements most commonly identified in the energy system supply chain include child labor, land rights violations, lack of consultation with affected communities, and the resettlement of entire communities with resulting impacts on their livelihoods. For example, Section 4.1 highlights the human rights risks related to rapidly expanding BEV deployment. Human rights breaches could result in significant public and stakeholder opposition, litigation and disruption of business operations, all of which affect the profitability and sustainability of a project.

The numerous new supply chains that will be created to enable the transition to a low-carbon energy system will come with the risk of other human rights infringements. Downstream companies must manage their human rights risks by conducting due diligence to identify and mitigate potential infringements across their upstream supply chains throughout the life of the projects/products.[31] In addition, project developers must minimize such infringements via stakeholder engagement and consultation to understand concerns and identify actions to avoid or mitigate human rights risks. Such consultation can identify areas for community investment that project developers implement for positive impacts, such as providing access to energy, water and sanitation and the promotion of economic and social development.[32]

3 Powering the energy transition

The transformation of the power sector is at the core of the energy transition. The power sector is currently responsible for about 13.2 gigatons of carbon dioxide ($GtCO_2$) or 41% of global energy-related CO_2 emissions.[33] A Paris Agreement-compatible pathway sees the power sector virtually fully decarbonized around mid-century. This transformation of the power sector will also contribute substantially to the decarbonization of transport, buildings and industry as energy end uses become increasingly electrified.

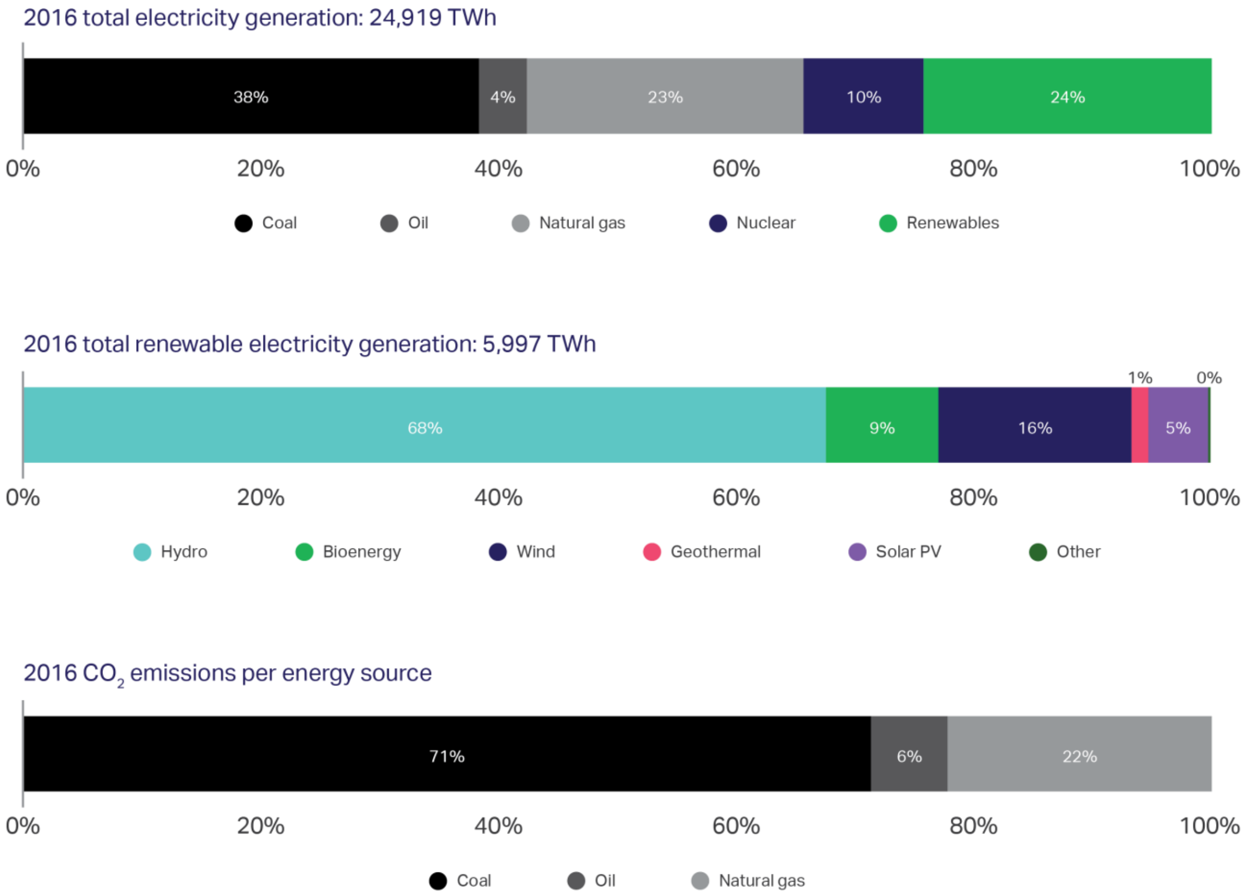

Figure 4: Electricity generation per technology and emissions from the power sector in 2016.[34]
CO_2 emissions from power generation refers to fuel use in electricity plants, heat plants and cogeneration plants. This includes both main activity producer plants and so-called auto-producer plants that produce electricity or heat for their own use.

The shift toward low-carbon electricity generation takes place in two systems: in markets where centralized fossil fuel assets exist, they are being replaced with low-carbon alternatives; in markets where people and small businesses do not have access to electricity, the leap to low-carbon technologies is an important component of sustainable development. Therefore, the decarbonization of the power sector will also take place in the context of expanding the installed capacity of power generation technologies to accommodate growth in electricity demand, particularly in non-OECD countries.

Expanding zero-carbon generation, particularly the scale up of renewable technologies (at 24% of total electricity generation in 2016, Figure 4) is one of the primary drivers of the mid- to long-term decarbonization of the power sector, as discussed in Section 3.1. Solar and wind technology costs have fallen substantially, making these technologies competitive with fossil fuel-based generation in several regions and hence carrying the biggest growth expectations. In addition to RE, some countries may opt for nuclear power or carbon capture and storage or use in their energy transition. As explained in section 3.2, while near-term actions are concentrated on extending the lifetime of existing nuclear reactors, some countries are also expected to bring new nuclear capacity online. In addition, as discussed in section 3.3, unabated fossil fuel-based generation will need to be phased out in the transition to a decarbonized power sector.

In parallel with the changing power generation mix, electricity grids and markets – which have been designed around large generation plants delivering electricity on a centralized basis – will also need to evolve. In particular, the digitalization of the energy system, including the deployment of smart grid technologies – which facilitates a bidirectional flow of both electricity and data – will be crucial to network management and monitoring. Power systems will need greater flexibility to integrate increasing shares of variable RE. Traditional forms of flexibility such as thermal generation and hydropower are increasingly complemented by utility scale batteries for short-term storage. Smart grid technologies also enable the provision of flexibility services to the grid from DERs. Examples of DERs include behind-the-meter battery storage, distributed renewable generation and electric technologies – in particular in the passenger transport and buildings sectors – which can provide demand response, or thermal or electric storage. Virtual power plants (VPPs), which aggregate DERs, will be important to facilitating participation in electricity and balancing markets.

Each country's pathway to power sector decarbonization – including both the technology choices and the rate of change – is unique and its evolution depends on many factors. These include technology and fuel costs, renewable resource potential, energy security and natural resource endowment (including fossil fuels and suitable CO_2 storage sites). In addition, political and societal support and a country's investment climate – linked to its governance and economic performance – will also shape the power transformation pathway.

3.1 Renewable electricity

Decarbonization pathway

The deployment of renewable-based electricity (RE) technologies, and in particular the rapid acceleration of this deployment, is the primary driver of the mid- to long-term decarbonization of the power sector. RE generation accounted for about one-quarter of total power generation in 2016 (8% excluding hydro)[35]; and the share will grow as the energy transition accelerates. The installed capacity of RE continues to increase; in 2017, RE accounted for about 70% of net additions to global power capacity.

This growth is mainly attributed to continued improvements and cost reductions in variable renewable technologies. The reduction in the global average levelized cost of electricity (LCOE) of utility-scale solar photovoltaic (PV) has been particularly significant, with a 73% reduction from 2010 to 2017. Over the same period, the LCOE for onshore wind has fallen by 23%. While deployed in lower quantities, offshore wind power also saw a global average cost reductions of 13% over 2010 to 2017, although larger cost reductions have been seen in certain countries. For example, in Germany, the LCOE of offshore wind has more than halved over 2011 to 2017.[36] In addition, concentrated solar power (CSP) technologies also saw cost reductions of 33% over the same period. Based on recent RE auction results and project-level cost data, further cost reductions in solar and wind technologies are set to continue to 2020 and beyond,[37] strengthening their role in the transition to a net-zero emissions energy system.

Non-variable RE technologies such as hydropower and bioenergy also play a role in the power sector transition. Hydropower is a mature and reliable technology; it is currently responsible for around two-thirds of RE generation.[38] With the growing share of variable RE, reservoir storage and pumped storage hydropower schemes will continue to be needed to provide flexibility services to the grid.[39] New hydropower sites must be selected carefully, considering potential environmental and social issues, as well as the risks of variable climate conditions.[40] Bioenergy generation currently accounts for about 10% of RE generation. This includes the co-firing of biomass in coal power plants - with a 50% share of biomass, the emission intensity of co-firing is approximately equivalent to that of a combined cycle natural gas plant. Future expansion of bioenergy will depend on the availability of sustainable, long-term supplies of biomass feedstock. Bioenergy plants equipped with CCS can also be a long-term option for carbon dioxide removal.

RE deployment will also increase in the form of off-grid and microgrid solutions. Microgrids, which are characterized by their ability to function in island mode, have traditionally been based on diesel generation and used in off-grid areas or areas with unsatisfactory and intermittent grids. However, with the declining costs of renewable generation and battery storage, renewable-based microgrids are emerging as a solution to provide a stable supply of electricity in such areas.

Required actions and developments

The four crucial factors in expanding RE deployment are cost reductions, supportive policy frameworks, financial mechanisms, and evolution of the electricity grid and market rules to accommodate RE.

Cost reductions

The costs of solar and wind technologies have fallen substantially and are already competitive with fossil fuel-based generation in several regions. **Cost decreases must be maintained for renewables to be deployed at the scale needed under a pathway compatible with the Paris Agreement.** With growth in both production volumes and unit sizes, economies of scale are leading to cost reductions. In addition, technology improvements are a key driver of the cost decline, including innovations that unlock efficiencies in manufacturing, reduce installation costs and improve the performance of power generation equipment. Supply chain efficiencies and competition are also driving cost reductions through, for example, standardized sourcing methods and competitive auctions. Predictive maintenance, advanced weather forecasting, optimal dispatch and other factors are reducing operation and maintenance costs. At the same time, financiers now see these technologies as mature, which reduces a project’s risk and lowers the cost of capital. Also, project developers are expanding their operations internationally and bringing with them project experience and access to international capital markets – all of which have been conducive to further cost reductions.[41]

Policy

As described in section 2.1, **a stable climate and energy policy framework that levels the playing field for RE is a cornerstone of expanding RE deployment.** Of particular importance in this framework is a robust carbon price with a long-term price signal and phasing out of fossil fuel subsidies. However, even with such policies, private investors may not find RE technologies sufficiently attractive due to their high capital costs and an uncertain return on investment. The latter is linked to the decrease in revenues experienced during periods of high renewable resource availability. To address merchant market risk and to scale up initial deployment, policies should include mechanisms to provide direct financial support or revenue stabilization measures, such as contracts for difference. However, as RE technologies become increasingly competitive, direct financial mechanisms should be phased out and replaced by competitive procurement approaches, such as auctioning.

Financial mechanisms

Access to finance is crucial to the implementation of the decarbonization options. For wind and solar RE technologies, access to private finance is on the rise, as technologies are mature and cost competitive with fossil fuel-based generation in several regions. Projects have also become more standardized and replicable, increasing the attractiveness of such projects to investors. On the other hand, certain other types of RE projects may not lend themselves easily to conventional financing approaches. They can be small and have relatively high upfront capital costs, making private sector financing comparatively expensive. They can also contain risks that are unfamiliar to financial institutions due to the use of innovative technologies or business models. Or they can have limited potential for replication and standardization that would support the type of market scale of interest to private investors. Saying that, **private-sector finance for RE can be scaled up through innovation and diversification in financing mechanisms, which attracts a broader range of investors to renewable markets.**[42]

RE projects can be financed off-balance sheet, meaning that the company is not the owner or legally responsible for the assets or liabilities. The most common form of off-balance-sheet financing is an operating lease in which the company makes a small down payment upfront and then monthly lease payments. Off-balance-sheet financing allows a company to maintain a healthier balance sheet through a lower debt-to-equity ratio. Another benefit is increased liquidity. By selling an asset the company owns, such as a RE project, and immediately leasing it back from the buying entity, capital is released for investment in other projects. This is a mechanism through which RE project owners can leverage non-traditional investors, including institutional investors, to reduce the load on their balance sheet.

The development of liquid instruments such as green bonds and asset-backed securities are likely to be key to facilitating access to a wider pool of capital as they provide investors with access to renewable energy projects via familiar, tradable instruments. Corporate renewable power purchase agreements (PPAs) - direct contracts between corporate customers and suppliers - have also emerged as a solution to manage offtake risk.[43] Investors working with multinational development banks to access emerging markets and the development of local/regional aggregators to facilitate cost-effective financing for smaller projects can also contribute to scaling up finance for RE. Ongoing two-way education between the renewables industry and the investment community will be a key factor in facilitating such developments.

Companies, individuals and national / local governments are increasingly using RE projects as a means to convert capital investment into long-term revenue streams. Investment in RE enables communities to use energy as a source of income and can help to address socio-economic issues such as fuel poverty and social inclusion. This is demonstrated by the prevalence of international community-led schemes and local authority-led (municipal) schemes, such as the Paris urban heating company (CPCU).[44]

Evolution of electricity grids and markets

Increasing variable RE penetration poses challenges for the existing electricity grid and does not typically fit well with traditional electricity market rules, which were designed around large generation plants delivering electricity on a centralized basis. To accommodate the changing production profile of generation assets and the increasing decentralized nature of these assets, grids and markets will need to evolve.

At the transmission level, significant investments will be required to transport electricity over long distances from areas of high RE generation to electricity demand centers such as cities and industrial facilities. One of the key technological solutions to this challenge is the development of a high-voltage direct current (HVDC) transmission network. Forward-looking network planning jointly conducted by distribution system operators (DSOs) and transmission system operators (TSOs) is essential to evaluating the cost and benefits of network upgrades and extensions. Given the long lead times for transmission system buildout, a policy timeline of at least a decade is required to address planning issues related to transmission networks. A procedural framework needs to be in place – especially in countries that have unbundled grids – to define the needed grid developments.

The creation of a meshed regional network where HVDC transmission networks cross regional or national borders can balance RE generation and have smoothing effects on load due to the bigger geographical area. To facilitate cooperation between TSOs, international forums such as the European Network of Transmission System Operators for Electricity (ENTSO-E) should be supported to improve the harmonization of grid codes.[45]

In addition, increased cooperation between DSOs and TSOs will be necessary. With the growing penetration of variable RE, TSOs will increasingly procure flexibility services for system balancing from the distribution grid. However, DSOs use these same flexibility resources for congestion management and voltage control. DSOs and TSOs will therefore need to coordinate and exchange more information to operate their networks efficiently. A possible solution to this challenge is a single open and non-discriminatory marketplace to collect and activate flexibility resources.[46]

DSOs are already facing new challenges themselves, as the energy transition means that they will be responsible for managing increasing shares of RE generation as well as demand-side response connected at the distribution level. Long-term grid planning for the integration of RE and other distributed resources is key to developing cost-effective strategies to more actively manage the network and improve monitoring. An essential component of such a strategy is the deployment of smart grid technologies, which facilitates a bidirectional flow of both electricity and data. These technologies include supervisory control and data acquisition (SCADA) systems such as distributed energy resource management systems (DERMS), and sensors that enable real-time system monitoring and automated grid management.[47] Regulators should incentivize DSOs to digitalize the networks and to manage them in the most efficient way.

Smart grid technologies also enable the provision of flexibility services to the grid through a variety of DERs. This includes utility-scale storage, BEVs and other behind-the-meter storage systems that can discharge to the grid. In addition, BEVs, electrified heat and cooling technologies, and other smart devices can shift their electricity consumption in response to electricity price signals. Emerging business models are supporting the deployment of such flexibility solutions. This includes virtual power plants (VPPs) aggregating the DERs of residential and commercial prosumers to facilitate participation in electricity and balancing markets.[48] Market rules will need to be adjusted so that such participants can access the markets.[49]

Market rules should also be designed and/or adapted to harness the full potential of variable RE, including the capability to provide grid support services. E.g. VPPs can aggregate distributed generation sources into a single operating entity to achieve the required scale and flexibility to participate in wholesale ancillary service markets and reduce power supply variability.[50] A liquid market platform for grid support services should allow RE participation.

Regulators will also need to develop new electricity market designs to consider the future high share of RE generation. Most electricity markets today are designed for a system with a high share of thermal generation, with low to moderate capital costs and high short-run marginal costs. Current market designs therefore often remunerate generation (and not capacity). In contrast, RE has high capital costs and (almost) zero marginal costs. With increasing shares of capacity, RE are becoming the price-setting technology in many hours of the year; and under the existing market design, electricity prices will decline strongly in those hours of excess RE generation. In such a market, RE technologies will most likely not be able to operate profitably solely based on revenue from the short-term wholesale market.

One solution is to re-design the market so that generation capacity is remunerated through long-term price signals, while the dispatch of generation units is still based on short-run marginal costs.[51] Some countries are (also) remunerating generation capacity based on long-term price signals, e.g. Brazil for many years or France more recently.

The structure of electricity retail tariffs will also need to evolve. Currently, retail tariffs consist of a variable element that is charged per unit of electricity consumed (kWh), while a usually smaller element is fixed based on the contracted capacity (kW). This structure is inadequately aligned with the cost structure of the power system, which has high fixed costs based on capacity, such as distribution and transmission grids, and system management. This misalignment may create difficulties for the suppliers' business model: growth in distributed energy and storage will mean that some consumers use less power from the grid and hence pay less, but still benefit from their connection to the power system. A possible solution is to increase the share of the fixed component of the electricity tariff paid by all consumers connected to the grid.[52]

3.2 Nuclear power

Decarbonization pathway

The ongoing construction of new nuclear capacity in countries such as China, the United Arab Emirates and the United Kingdom shows that nuclear power is playing a role in decarbonizing the power sector today and that some countries rely on it for meeting their targets under the Paris Agreement.

France, where the electricity mix has a major nuclear component, has been able to develop a flexible nuclear fleet: each unit is able to modulate between 20% to 100% of its capacity, varying in 30 minutes twice a day. This enables the integration of more renewables into the system. Other countries are also developing solutions to enhance the flexibility of nuclear generation to accommodate renewables.

Required actions and developments

A fall in public acceptance caused largely by the Fukushima Daiichi accident, increased costs, construction delays and the challenge of financing capital-intensive projects in recent years has led to a decrease in construction and grid connection rates of nuclear power plants.[53] Utilities have viewed **plant lifetime extensions** to be more economically attractive than building new plants; and most nuclear operators are investing in safety and operational improvements to enable such extensions.[54]

In addition to plant lifetime extensions, **countries may opt for new nuclear capacity in their energy transition**.[55] Most of the anticipated growth in nuclear capacity to 2050 is expected to come with the deployment of Generation III reactors, which offer enhanced safety. Following the budget overruns and delays faced in constructing first-of-a-kind Generation III plants, vendors should integrate lessons learned to optimize reactor designs and supply chains, and improve project management to ensure that subsequent construction projects are delivered on time and on budget. Governments might decide to provide support to reduce the risks of investment in new nuclear capacity, which is characterized by high upfront costs and long payback periods. They might also support advanced designs such as small modular reactors, advanced fuel cycles and waste management.[56]

3.3 Fossil fuel-based generation

Decarbonization pathway

Unabated coal-fired power generation (meaning not equipped with carbon capture technology) – which is responsible for 37% of power generation today[57] – will be phased out in the energy transition. This decline in coal-fired power generation is necessary to reach a net-zero emissions energy system. Even the most efficient advanced ultra-supercritical coal-fired power plant has direct emissions of 670 grams of carbon dioxide equivalent (gCO_2e) per kilowatt-hour (kWh) – substantially higher than the 350-490 gCO_2e/kWh direct emissions intensity of a combined cycle gas turbine, or 0 gCO_2e/kWh in the case of nuclear or renewable technologies.[58]

In the short- to medium-term, unabated natural gas power generation can support the transition to a decarbonized power sector. Natural gas-fired power plants have faster start-up times and response times to required changes in output. They are therefore suitable as dispatchable generation to balance a grid with substantial shares of variable renewable generation; and they currently do so at a cost that is lower than battery storage.[59]

The role of natural gas in the medium- to long-term is less certain. Despite having a lower climate impact per kWh of electricity generated compared to coal, unabated natural gas-fired power generation must also be phased out to reach a net-zero emissions economy. In the long-term, natural gas plants equipped with carbon capture could play a role in supporting grid flexibility, but they will be competing with other storage technologies (for example hydropower, batteries[60], green hydrogen[61] and heat storage), and other potential sources of grid flexibility, such as demand-side management, VPPs and BEVs.

Required actions and developments

A **competitive electricity market and a level playing field** – which includes an adequate carbon price and the removal of fossil fuel subsidies – are key to driving the transition from unabated fossil fuel-based generation.

Investments in new fossil fuel power plants should be assessed considering their compatibility with the achievement of the Paris Agreement in order to avoid technology lock-in and sunk investment costs. Such assessments will become more frequent as investors begin to react to disclosures aligned with the recommendations of the Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD), one of which advises investors to consider their climate-related risks under a 2°C compatible scenario.[62]

For countries where coal plays an important role in the economy, **the transition away from coal power plants will require a broader socio-economic transformation** as a phase out of coal may lead to substantial job losses. As this affects the political feasibility of the transition, complementary policy measures should be implemented to compensate for business portfolios/strategies that are no longer feasible, social protection systems, workforce retraining programs, and the development of alternative employment options.[63]

4 Transport

Emissions from transport amount to 7.9 $GtCO_2$ per year or 24% of global energy-related CO_2 emissions.[64] The transport sector is the most fossil fuel-intensive energy-demand sector, with alternative fuels accounting for very low shares of final energy consumption: 1% electricity and 3% biofuels. About 60% of the sector's energy consumption is related to transporting people – passenger mobility; while 40% is related to moving goods – freight transport. The solutions available to decarbonize transport are summarized in Figure 5. This section examines the solutions for each of the transport segments: Section 4.1 covers passenger mobility (light-road transport and mass transit), Section 4.2 examines the aviation segment, and Section 4.3 covers the freight transport segment (road freight and shipping).

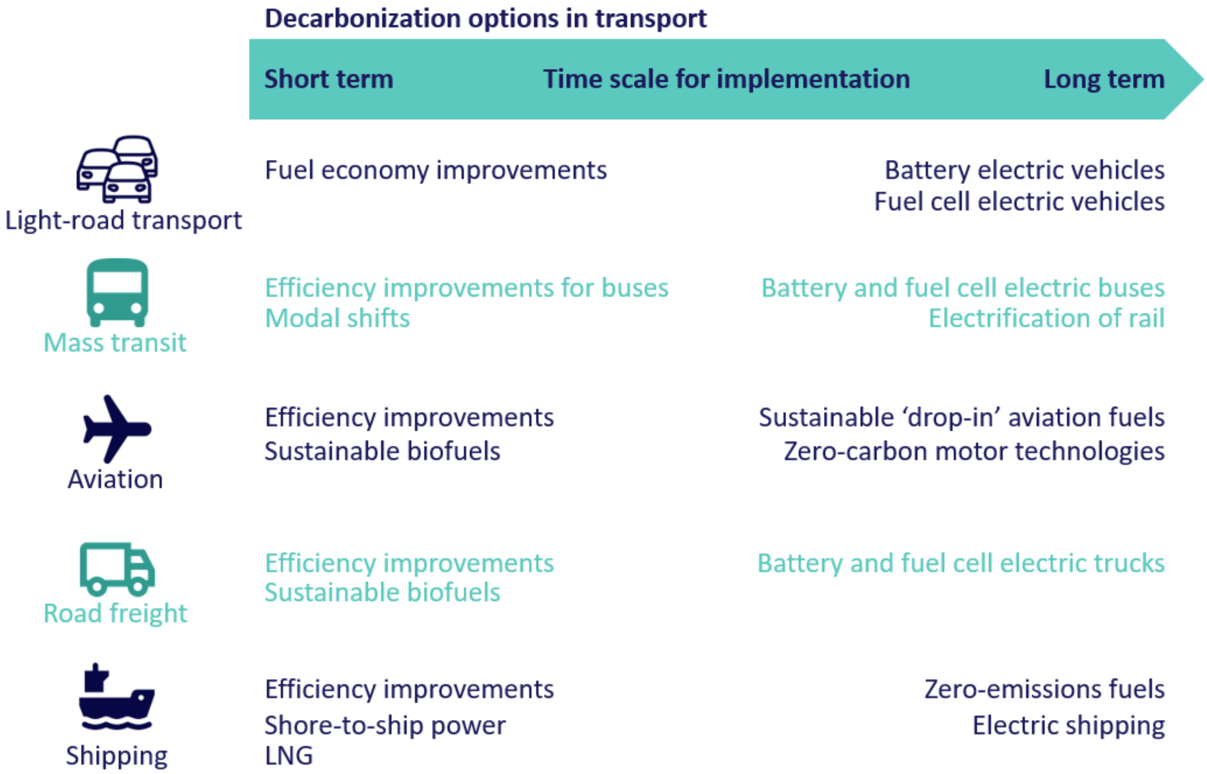

Figure 5 Decarbonization options in transport

4.1 Passenger mobility

Passenger mobility plays a central role in enabling people to move from place to place for employment and social activities, and to access goods and services. With population growth and increased urbanization, passenger mobility will need to evolve so that it meets peoples' aspirations to live in a mobile society, while at the same time being efficient, safe and compatible with diverse environmental objectives, such as climate change mitigation and noise and air pollution reductions. This section examines the evolution of light road transport and mass transit under a decarbonization pathway and the required actions and developments for a passenger mobility sector that is compatible with the Paris Agreement.

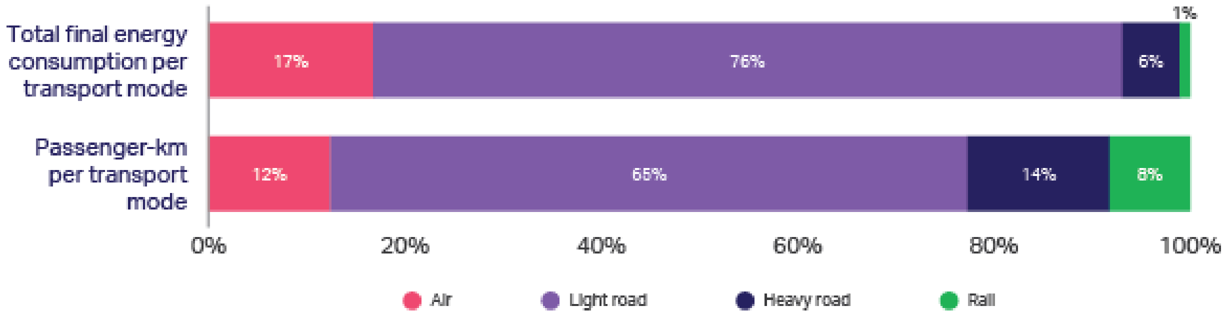

Figure 6: Total final energy consumption and passenger-km per transport mode in passenger mobility in 2014[65]

Decarbonization pathway: Light road transport

Passenger cars powered by ICEs are the most common form of light road transport. While in the long-term, full decarbonization requires the phasing out of ICEs, these engines will likely remain an important part of the transport mix in the short- to medium-term. Therefore, continued ICE fuel economy gains through, for example, improved aerodynamics, hybridization and engine improvements, are essential to reducing emissions.

In the long-term, the key lever to decarbonize light road transport is the deployment of electric vehicles (EVs) to replace ICEs. Electrification is an energy-efficient way of making transport sustainable, minimizing both pollutant emissions and the corresponding exposure of the population to health risks. Various types of EVs are available today – battery (BEV), plug-in hybrid (PHEV) and hydrogen fuel cell (FCEV) – of which BEVs and FCEVs are solutions to full decarbonization when fueled by zero-carbon electricity/hydrogen.[66]

Recent market developments indicate that BEV deployment will be more rapid than FCEVs in the coming years. The global BEV stock and operating vehicle production lines far outnumber those of FCEV passenger cars, with about 2 million BEVs on the road today compared to about 7,000 FCEVs.[67] The rapid growth in BEVs can be attributed to a large fall in battery prices – about 80% over the period from 2010 to 2017[68] – combined with purchase incentives from governments. In addition, battery capacity improvements and infrastructure developments have also reduced range anxiety in drivers. Looking ahead, the main barriers to EVs – higher upfront costs and lack of charging infrastructure – are relatively simpler to overcome for BEV technology compared to FCEV. Further reductions in battery prices can be anticipated and in certain countries analysts expect BEVs to be cheaper to purchase than ICE vehicles by the middle of the next decade.[69] In addition, the number of charging points is likely to expand through market demand and government policy. The transition to FCEVs is less defined; there could be a long-term role for FCEVs if the supply chain and fueling infrastructure develop.

With growth in BEVs, smart charging will be necessary to manage the impact of BEVs on the power system, while also enabling them to play a complementary role in the energy transition by providing flexibility services to the grid. Through smart charging,[70] the timing of BEV charging can be optimized to ensure a reasonable balance between power supply and demand, which reduces the need for additional generation capacity, increases the grid asset use factor and reduces the curtailment of renewable generation. Demand-side management via smart charging can be facilitated by dynamic tariffs such as time-of-use or real-time pricing, which will incentivize consumers to charge BEVs when prices are low. Furthermore, BEVs represent storage capacity that could be used to provide ancillary services to the power grid via vehicle-to-grid (V2G) solutions.

As CO_2 emissions from the use phase of passenger cars are gradually reduced, life cycle emissions from the construction and end-of-life phase will become increasingly important. Life cycle emissions can be reduced through the transition to circular business models in light road mobility, including car sharing platforms and mobility-as-a-service solutions that can lead to higher vehicle use rates, and the construction of longer-lasting vehicles.[71] Already, the emerging digitalization of mobility via smartphone and internet applications is encouraging people to aspire to more sustainable mobility solutions and is catalyzing a move away from vehicle ownership toward car sharing and ride hailing.[72] This move also increases access to mobility solutions. The advent of autonomous shared BEV fleets has the potential to create a significant step change in the energy efficiency of mobility.

Required actions and developments

Further **reductions in the upfront cost of vehicles** will be key to stimulating greater EV adoption.[73] **Financial incentives from governments** have traditionally been an important factor in overcoming this barrier. Incentives are most effective when they are **prioritized to accelerate the electrification of high-use vehicles**, such as public and company fleets, taxis and car-sharing vehicles. As high-use vehicles have higher annual mileages than personal-use vehicles, their electrification has a bigger impact on the share of vehicle kilometers and passenger kilometers travelled by EVs than if the equivalent number of personal-use vehicles were electrified.[74] An example of such an approach is the Indian Government's procurement of 10,000 EV passenger cars for use in various public departments.[75] In addition, the EV100 initiative encourages companies to make a commitment to integrating EVs into directly owned or leased corporate fleets.[76] Similarly, companies that are procuring mobility services from third-party providers can implement procurement standards that either set a maximum limit on their scope 3 emissions (i.e. value chain emissions) from transport or define a share of low-carbon vehicles to be used for the mobility requirements.

With falling prices and increasing deployment rates, governments can gradually shift from financial incentives to **increasingly stringent, technology-neutral regulations** (such as differentiated taxation for vehicle purchase, registration and/or circulation) based on CO_2 tailpipe emissions. Such technology-neutral approaches allow the market to decide on the lowest cost approach to passenger vehicle decarbonization and encourage competition. Many countries already have such regulations in place. For example, in Europe, the average emissions standard for fleets is set at 95 gCO_2/km in 2021. This emission standard is applied at the fleet manufacturer level and is technology-neutral based on tailpipe emissions, allowing manufacturers to define their own strategies.[77]

A growing number of cities are also influencing the development of urban zero-emissions mobility by setting emissions standards or circulation restrictions that drive air quality improvements and at the same time potentially stimulate the uptake of EVs or other low/zero emission vehicles. For example, the mayor of London has implemented an increasingly stringent emissions standard that requires drivers of passenger cars that do not meet Euro 4 standards to pay a fee in addition to the congestion charge to enter central London.[78]

Different financing mechanisms and business models are emerging to overcome the current cost barriers to EV deployment. Examples include product-as-a-service business models, battery leasing and operating leases.[79] In addition, business models are emerging to provide BEV owners with revenue from the flexibility services provided to the grid, which can also strengthen the business case.

In parallel to accelerating BEV deployment, **a standardized, interoperable and digitalized charging system needs to be created**. Such a system should consist of fast chargers installed along highways, as well as home and destination chargers, which help to address range anxiety in drivers. The system should also be designed to facilitate storage and local energy management and generation. The development of such a system requires a new service and product industry composed of charging operators and hardware providers, and new business models through which the industry can profitably deliver charging and flexibility services. Government policy can support the emergence of this industry through the provision of tax relief and changes to building codes to require BEV-ready parking in new or renovated buildings. Governments can also allow regulated utilities to invest in charging infrastructure, with cost recovery by ratepayers. Companies can support the rate of BEV adoption by offering charging infrastructure on their real estate for employees and customers. This extends to public car park operators who can install EV charging stations and move to a revenue model based on consumed/provided power, capacity and duration at the car park.

The growth in BEVs will result in new supply chains to meet growing demand for materials, particularly for lithium, cobalt and rare earth metals. When developing these new supply chains, it is important that companies carry out due diligence to identify and address human rights risks in their supply chain. For example, about 60% of global cobalt production is located in the Democratic Republic of the Congo (DRC),[80] and increasing demand is sustaining a market for artisanal extraction of cobalt in the country. Child labor is highly prevalent in artisanal cobalt mining in the DRC and the largely unregulated nature of the sector gives rise to widespread corruption and hazardous working conditions.[81] Technology improvements in batteries will reduce the quantity of rare earth metals required per battery. For example, battery manufacturers are trying to reduce the use of cobalt as much as possible given the supply chain difficulties and its relatively high and volatile cost. Technology breakthroughs such as solid-state batteries could also be a game changer which could reduce or even eliminate the cobalt content in batteries.[82]

As the BEV fleet grows in number, **end-of-life strategies** are increasingly important to ensuring the environmental sustainability of battery disposal. This process should begin by clarifying responsibilities for end-of-life treatment and by developing technical requirements for recycling. For example, the European Union's (EU) Battery Directive places the responsibility for the collection, treatment and recycling of vehicle batteries on their manufacturers and prohibits the disposal of vehicle batteries in landfills or by incineration.[83] Policies to maximize the residual value of batteries at their end-of-life, such as a requirement to recover high-value materials, can be a lever to optimize environmental sustainability and minimize human rights risks, as discussed above.

Companies are implementing various strategies to manage batteries at their end-of-life. For example, Tesla plans on extracting materials from old battery packs.[84] Alternatively, as Li-ion batteries can collect and discharge electricity for another 7 to 10 years after being taken off the roads, new business models are emerging to give batteries a second life. For example, Nissan has entered the business of energy storage and plans to use Nissan LEAF batteries to store electricity for off-grid lighting[85] and Hyundai plans to use batteries for energy storage systems.[86]

<u>Decarbonization pathway: mass transit</u>

In the context of increasing urbanization, mass transit will play an important role in the decarbonization of passenger mobility, particularly in cities, with co-benefits of reduced congestion and shorter travel times, reduced public health issues linked to local air pollution, and improved road safety outcomes. Mass transit also has positive societal impacts, particularly in developing countries, as it enables many people to access social and economic opportunities that would otherwise be inaccessible due to the high costs of private motorized transport. This section explores the decarbonization pathway of the two most common forms of mass transit: buses and rail.

Modal shifts from light road transport to buses is an important part of the decarbonization pathway for passenger mobility. While buses – currently mostly fueled by diesel – are already more carbon efficient than light road transport on a passenger-km basis,[87] cost-effective technologies are available to reduce emissions further. For urban buses, efficiency improvements such as low rolling resistance tires and hybridization can reduce CO_2 emissions by 43%, while for intercity buses, efficiency measures such as aerodynamic improvements and predictive cruise control can reduce CO_2 emissions by 25%.[88]

With battery and fuel cell electric bus technologies already emerging on the market, it is likely that both will play a role in the full decarbonization of bus transport. China accounts for the vast majority of battery electric buses, with a fleet of 370,000 BEV and PHEV buses in 2017. Outside of China, some North American and European cities have also begun to deploy battery electric buses. Despite their higher upfront costs compared to diesel buses, battery electric buses can be cheaper than diesel buses on a total cost of ownership basis, particularly for buses with high annual mileages. The likely continued fall in battery prices will further strengthen the business case.[89]

While fuel cell buses have a similar fueling time and range compared to diesel buses, they have yet to reach the same scale as battery electric buses. So far, they have mainly been deployed in demonstration projects in Europe and the US,[90] but they are not yet considered to be a mature technology.[91] Nonetheless, there are plans to expand deployment in Europe, China and South Korea. The high capital and operating costs of fuel cell buses are barriers that need to be overcome for expanded deployment.[92] In addition, investments to develop the hydrogen supply chain will be necessary.

Modal shifts from light-road transport and medium-distance aviation (between 200 and 1,000 km) to rail is another important lever to decarbonize passenger mobility. While rail transport is already a highly carbon-efficient mode of passenger transport,[93] it can be further enhanced via improvements to track design, station gradients, aerodynamic design, weight reductions through composite materials, mechanical improvements, and hybrid trains with regenerative braking.[94]

In the long-term, full decarbonization will require the complete electrification of rail transport. Two-thirds of passenger rail transport activity (i.e. passenger-km) is already electrified, including almost all urban rail links, all high-speed rail and most intercity rail activity.[95] However, on a track-length basis, only about 30% of railway tracks around the world are electrified.[96] Electric trains offer substantial benefits over diesel trains, including reduced CO_2 emissions and no local air pollution.[97] High infrastructure costs are a barrier to the electrification of rail,[98] but lower purchase and operating costs of electric rail, especially in rail network segments characterized by high activity levels, can make a profitable business case.[99] This is highlighted by India's plans to fully electrify the rail network by 2022.[100] Where the business case for electrification cannot be made, indirect electrification via hydrogen fuel cell trains is potentially a solution. Germany is deploying the first fleet of hydrogen trains for commercial service in the north of the country to replace diesel trains on non-electrified lines.[101]

The long-term decarbonization of mass transit will require zero-carbon energy carriers, including electricity and hydrogen. Companies in the mass transit sector can take actions today to decarbonize their operations through renewable electricity sourcing. For example, Dutch rail operator NS signed a long-term contract to run electrified trains on 100% renewable electricity from 2017.[102]

Required actions and developments: mass transit

Government policy measures at national and city levels play a significant role in influencing a modal shift from private transport to mass transit.[103] These include pricing measures that make mass transit cheaper than driving, such as fuel taxes, vehicle taxes, congestion charges and parking prices. Policies can also reduce the attractiveness of private vehicles by restricting their use, such as access restrictions, parking restrictions, low-emissions zones and registration caps. In addition, governments play an important role as investors in mass transit infrastructure in terms of increasing service quality or lowering costs for users, all of which can increase the use of mass transit.

In addition to cost, mass transit must also be able to compete with private modes of transportation on convenience and flexibility. **Further integrating different modes of public mass transit can influence passenger choices**.[104] This includes integrated ticketing (same ticket used for each mode of transport), integrated fares (same fare independent of the number of services used to complete a journey), integrated service information, service coordination to reduce transfer times, and physical integration via transport interchanges. Mobility-as-a-service models emerging on the market take integration a step further by bundling payments for all transport options other than private car (such as public transport, shared bikes, car share).

Investments in mass transit should be coupled with **urban planning policies that limit urban sprawl and encourage higher density land use**. This reduces demand for mobility services and can improve the business case for investments in public mass transit as it increases passenger loads.[105] Urban planning policies can also reallocate road priority from private vehicles to buses, for example through priority at traffic lights and reserved corridors/lanes. This serves to increase the speed and reliability of public mass transit, thereby attracting more passengers and increasing the energy efficiency of bus transport.[106] Urban planning measures should also promote active mobility (walking and cycling), which increases physical activity and results in positive health outcomes.

4.2 Aviation

Aviation, currently responsible for a relatively small share of energy consumption in the transport sector, will grow rapidly in the coming decades. The International Transport Forum projects that international passenger aviation activity will grow 4.1% annually between 2015 and 2050, and freight aviation activity will grow by 5.4% over the same period.[107] This section provides an overview of the decarbonization pathway for aviation and the required actions and developments needed to facilitate this transformation.

<u>Decarbonization pathway</u>

Significant opportunities still exist in the near-term to improve the energy efficiency of aviation through more efficient engines and airframe designs, improve operations through better air traffic management, and infrastructure developments such as airport gates equipped with power and pre-conditioned air. The International Civil Aviation Organization (ICAO) estimates that such efficiency improvements can reduce aviation fuel consumption by 30% by 2050 compared to baseline.[108] However, improvements in energy efficiency alone will not be enough to halt the sector's emissions growth, as demand for aviation travel is likely to expand as incomes increase, particularly in non-OECD countries.[109]

The second main lever available today to lower CO_2 emissions is the blending of conventional jet fuel with sustainable biofuels. On a well-to-wheel life cycle basis, biofuels can result in emissions reductions of 50% to 95% compared to conventional jet fuel, depending on the feedstock used.[110] The vast majority of biofuel used for aviation today is produced from animal fat or vegetable oil; however, due to a limited supply of sustainable feedstock, a transition to advanced biofuel routes is needed to significantly scale up biofuel production. In addition to availability constraints, the higher price of biofuels for aviation today constrains more widespread uptake.[111]

In the long-term, the full decarbonization of aviation will require new zero-carbon motor technologies or a considerable scale up of sustainable 'drop-in' aviation fuels that use existing engine and fueling infrastructure. Electric aircraft are at the early stages of development and some companies and countries, such as EasyJet[112] and Norway[113], are actively pursuing this technology for short-distance flights. Numerous potential pathways can be used to produce sustainable 'drop-in' aviation fuels, including advanced biofuels, electrofuels or synthesis routes based on carbon capture and use (CCU). An example of the latter includes LanzaTech's production of jet fuel from the capture of steel mill waste gases; this fuel was tested on a commercial Virgin Atlantic flight in October 2018.[114]

Required actions and developments

Energy efficiency and biofuel blending measures available today must be pursued to lower CO_2 emissions, while R&D efforts develop cost-effective solutions for full decarbonization.

As most aviation activity is international, **cooperation through ICAO is essential to decarbonizing the sector**. Several sector initiatives already exist to drive efficiency improvements and increase biofuel shares internationally. These include ICAO's adoption of a CO_2 emissions standard for new aircraft[115] and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to deliver carbon-neutral growth in international aviation compared to 2020 emissions levels.[116] In parallel, the International Air Transport Association (IATA) has adopted a target to reduce net CO_2 emissions by 50% by 2050, relative to 2005 levels.[117] International, regional or national policies such as carbon pricing, a green fuel mandate, or emissions standards on existing aircraft can complement these initiatives. Each of them provides clear signals for the gradual replacement of fossil fuels with alternative fuels or the development of alternative motors.

Multi-stakeholder supply-chain initiatives consisting of airlines, airports, technology providers, fuel producers and feedstock providers are important for a coordinated approach to scaling up solutions to reduce emissions from aviation.[118] Examples of such initiatives include long-term offtake agreements between airlines and fuel producers, as well as airlines directly investing in the development of new technologies. For instance, Cathay Pacific has invested in technology to produce sustainable biofuels and has committed to buying 1.1 million metric tons of sustainable biofuels (equivalent to covering 2% of the airline's current operations) from Fulcrum BioEnergy over a 10-year period.[119] In addition, **demand from aviation customers** – for both business travel and air freight – can play a role in advancing biofuel adoption. For example, KLM's Corporate BioFuel Programme allows companies to purchase sustainable biofuels for flights by paying a fixed supplement that makes up the difference in price between biofuels and conventional jet fuel.[120]

4.3 Freight transport

Freight transport plays a vital role in the economy, as it is responsible for moving goods across the supply chain, from raw materials and commodities to end-consumer goods. This section considers the decarbonization pathways of the two main modes of freight transport: road freight and shipping. While the former accounts for 71% of activity on a tonne-km basis,[121] road freight represents 74% of total final energy consumption due to its higher energy intensity (Figure 7).[122] Rail and aviation play limited roles in freight transport. As the decarbonization pathway for these transport modes are considered in the previous sections, they are not repeated here. The section concludes with the required actions and developments for the decarbonization of freight transport.

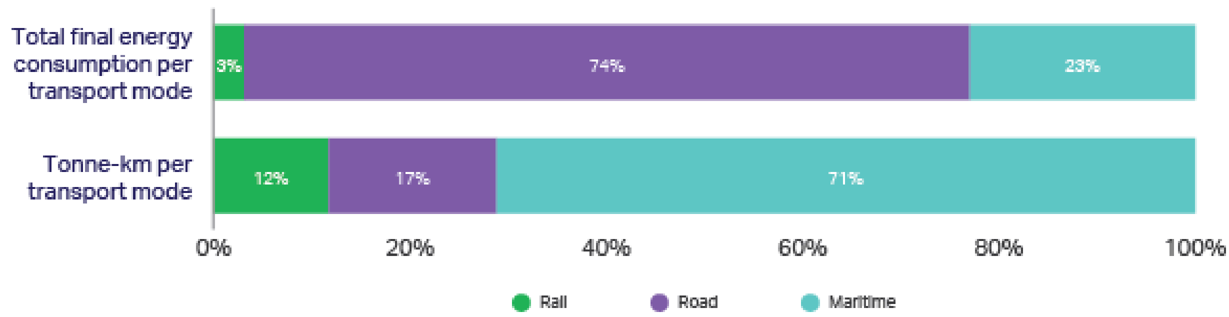

Figure 7: Total final energy consumption in 2014[123] and tonne-km of freight activity[124] per mode

Decarbonization pathway: road freight

In the short-term, the main approach to reduce emissions from road freight is via vehicle and operational efficiency improvements. A study by the International Energy Agency (IEA) estimated that the energy efficiency of new trucks could be improved by 35% within the next 20 years through measures including improved aerodynamics and light-weighting[125], while energy-efficiency improvements of greater than 50% have been demonstrated in truck prototypes developed under the US SuperTruck program.[126] Operational efficiency measures can also have significant benefits. WBCSD's Road Freight Lab found that optimized routing and resource allocation can reduce emissions by 12.5% on average, relaxed delivery windows can lower emissions by 25%, and asset sharing can reduce GHG emissions by 20%.[127]

Switching from fossil fuels to bioethanol, biodiesel and biogas is another immediate measure to reduce GHG emissions. The extent to which biofuels in road freight can be scaled up is constrained by the supply of sustainable feedstock. While trucks fueled by compressed natural gas (CNG) and liquefied natural gas (LNG) are also emerging on the market, these may not always have a significant impact on reducing the carbon footprint on a well-to-wheel basis when the impact of natural gas extraction and refinery is considered.[128] The emission reduction potential for natural gas compared to diesel on a well-to-wheel basis ranges from no net benefits up to a 20% reduction; the range of results is due to variability in natural gas production methods and upstream leakage rates, as well as engine technologies.[129]

Electric drivetrain technologies are emerging and will be important to decarbonizing the road freight sector. BEV technology developed for the passenger transport segment is being transferred to a limited extent into road freight. This applies to electrified commercial and service van fleets and medium freight trucks that operate in urban environments, such as municipal services and delivery trucks.[130] Their electrification is technically feasible using existing technologies due to the relatively low weights and distances travelled in urban environments. For long-range trucking, larger batteries are required, but this comes with a weight penalty that reduces energy efficiency and cargo capacity, and adds additional cost. A potential future solution could be to power trucks on the move through catenary overhead wiring or inductive power transfer technologies.[131] One of the main barriers to scaling up development of such technologies is the substantial investments needed to develop the energy supply infrastructure.

Hydrogen fuel cell trucks are an alternative electric drivetrain suitable for long-distance trucking. Several manufacturers have announced plans to build hydrogen FCEV trucks, including Toyota[132] and Nikola.[133] Similar to battery electric trucks, one of the key challenges to scaling up deployment is the need for hydrogen refueling infrastructure.

Decarbonization pathway: shipping

Like road freight, technical and operational efficiency improvements are key to reducing emissions from shipping in the short-term. Technical efficiency improvements include light weighting, slender hull designs and propulsion improvement devices. Efficiency gains via improved operations can be realized through speed optimization, improvements in fleet management and just-in-time vessel-terminal planning. A recent study by the Energy Transition Commission estimated that technical and operational energy efficiency could potentially reduce energy consumption by 20% to 75%.[134]

The shipping industry also considers LNG as an attractive alternative fuel: LNG-powered ship uptake remains marginal but has grown exponentially since the early 2000s.[135] Growth in LNG shipping is supported by an increase in government-backed initiatives to develop LNG bunkering infrastructure as part of their industrial policies and to meet interim GHG reduction targets. The shift to LNG is also attractive in light of the Global Sulphur Cap, which will come into force in 2020 and requires either exhaust scrubbers or shifting to low-sulphur fuels. The CO_2 mitigation potential of LNG compared to heavy fuel oil (HFO) is about 10-20%.[136]

Another technology available today to reduce emissions from shipping is shore-to-ship power, which allows ships to turn off their engines in port and connect to the port's electrical grid for their power requirements.[137] The abatement potential is relatively small, as less than 5% of CO_2 emissions from shipping are generated in ports. However, given the technological feasibility, it is a business model that many ports and shipping companies should consider (Box 2).

Box 2: Shore-to-ship power

Shore-to-ship power allows ships to turn off their engines in port and connect to the port's electrical grid for their power requirements.[138] In addition to CO_2 emissions reductions, shore-to-ship power is an important technology to reduce local air pollution from ships docked at ports, including NO_x, SO_x and particulate matter. The business case for shore-to-ship power is strongest when technology use rates are high, meaning ships dock frequently and/or have high electricity consumption when moored and ports receive many of such ships.

Mobile shore-to-ship power solutions also exist where an LNG-based electricity generation system situated on a barge or in a shipping container provides electricity to a ship.[139] While these systems currently use LNG – and therefore are not a solution for full decarbonization – they could evolve to be powered by renewable energy.

Polices and regulations in place at global, regional and country level drive the uptake of shore-to-ship power. They currently exist in some jurisdictions, such as California and the EU.[140] In addition, under China's 13th five-year plan, all new ports must be equipped with shore power and a subsidy program for financing investment is available. Regulations targeted at limiting air pollution will stimulate the uptake of shore-to-ship power, including the Global Sulphur Cap, emissions control areas for SO_x and NO_x, and the EU Sulphur Directive.[141] Where regulations are not mandatory, financial incentives such as investment support may be needed to make shore-to-ship power an attractive option.[142] A key drawback for deployment today is the fact that energy taxes are not typically charged on international shipping fuels, but are levied for electricity consumed at port, making electricity comparatively expensive. For shore-to-ship power as well as hybrid and electric ships to compete with fossil fuels, a level playing field is needed. This should include electricity tax exemptions for ships and the implementation of a carbon price on shipping fuels.

Shore-to-ship power technology can also be used to charge hybrid and/or fully electric ships, which are an emerging segment in the shipping market. Hybrid ships use batteries to displace some to all fuel consumption from internal combustion engines and provide fuel savings of 10% to 40%.[143] The number of electric ships operating on short sea shipping routes is growing. These include electric ferries operating a 4 kilometer route between Sweden and Denmark[144] and an electric cargo ship in China that is used to haul coal 80 kilometers on a single charge.[145] In addition, Stena Line has launched a project to develop a battery-powered ship; the first step of the project will see batteries used in a hybrid operation mode, followed by full operation on batteries for the entire 92.6 kilometer (50-nautical mile) voyage.[146] Due to the size and weight of batteries needed for long-distance shipping, electric ships for this application will not be feasible unless there is a major breakthrough in battery energy density.[147]

Like road freight, the options available today to reduce CO_2 emissions are not sufficient for the full decarbonization of shipping. Biofuels can be an option to significantly reduce CO_2 emissions from shipping, with the carbon intensity dependent on factors such as feedstock and direct and indirect land use change. For complete decarbonization, ships must be powered by zero-emissions fuels driven by internal combustion engines or electric motors. Possible zero-emissions fuels include electricity, hydrogen, ammonia, methanol and synthetic fuels.

Required actions and developments: freight transport and shipping

For both road and ship freight, efficiency gains and technologies commercially available today can reduce emissions substantially. Given the uncertain pathway and long timescales for the full decarbonization of freight transport, it is important that these existing decarbonization strategies are pursued while innovative drivetrains and motors and/or alternative fuels are explored.

Standards can help accelerate the uptake of energy-efficient technologies. In road freight, only four countries (Canada, China, Japan and the US) have introduced efficiency standards for heavy-duty freight vehicles.[148] In shipping, as most activity is international, cooperation and regulation through the International Maritime Organization (IMO) is essential to decarbonizing the sector. The IMO's Energy Efficiency Design Index sets an energy-efficiency level that applies to new ships.[149] A broader introduction of increasingly stringent efficiency standards is therefore key to driving improvements to both truck and vessel efficiency. In shipping, such an efficiency standard can be aligned with the IMO's recently adopted strategy to reduce GHG emissions from international shipping. The targets, based on 2008 levels, are to reduce total annual GHG emissions by at least 50% by 2050 and to reduce the average CO_2 emissions per transport work of international shipping by at least 40% by 2030, pursuing efforts toward 70% by 2050.[150]

Emissions reductions across the freight transport sector will be driven by **companies seeking to reduce their supply chain emissions**, particularly in the context of meeting science-based targets. Companies are increasingly looking to make logistics procurement decisions based on environmental performance and a growing number of logistics firms are meeting this demand through green logistics solutions that reduce supply chain emissions.[151] In addition, there are several shipping industry initiatives that monitor, rate and rank the environmental performance of shipping carriers.

For long-term decarbonization, **R&D programs supported by governments** are needed to better understand the characteristics and trade-offs between each of the potential decarbonization options and to identify the most favorable decarbonization routes for further development. Government support will be needed for early deployment and to develop new infrastructure.

5 Buildings

Residential and commercial buildings (including offices, shops, restaurants, etc.) are responsible for direct emissions of 2.9 $GtCO_2$ – or about 9% of global energy-related CO_2 emissions.[152] 75% of direct emissions are attributed to space and water heating, with cooking being responsible for 18% of CO_2 emissions (Figure 8). Indirect emissions related to electricity consumption in the buildings sector are substantial: buildings consume about half of the electricity generated worldwide and are responsible for indirect emissions of about 7 $GtCO_2$.[153] This section explores the pathway to decarbonizing the buildings sector – with a focus on direct and electricity-related emissions (i.e. Scope 1 and 2 emissions) – and explains the required developments and actions needed to move onto this pathway.

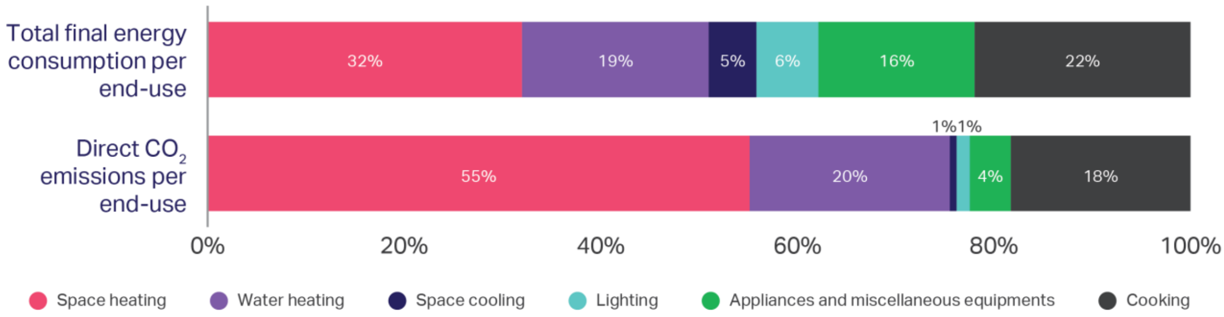

Figure 8: Total final energy consumption and direct CO_2 emissions by end use in 2014[154]

In the long-term, all buildings must be net zero-emissions buildings; the technologies needed to achieve this goal are available today (Figure 9). Space and water heating must be decarbonized via electric or renewable technologies such as heat pumps or solar thermal heating. Electricity demand from the buildings sector will grow as a result of increasing electrification rates, and economic and population growth. To minimize load on the grid, electric devices across all end uses (heating, cooling, cooking, appliances and lighting) must be highly energy efficient. In addition to technology choices, the energy required for space heating and cooling is strongly influenced by the performance of the building envelope. The key challenge to decarbonizing the sector is accelerating the renovation rate of existing buildings and ensuring that all new buildings or products are highly efficient. Policies such as renovation targets, minimum energy performance standards and energy labelling are important to stimulating these changes. Also, innovative business models and financing mechanisms can help overcome barriers related to the high upfront costs of energy-efficiency investments.

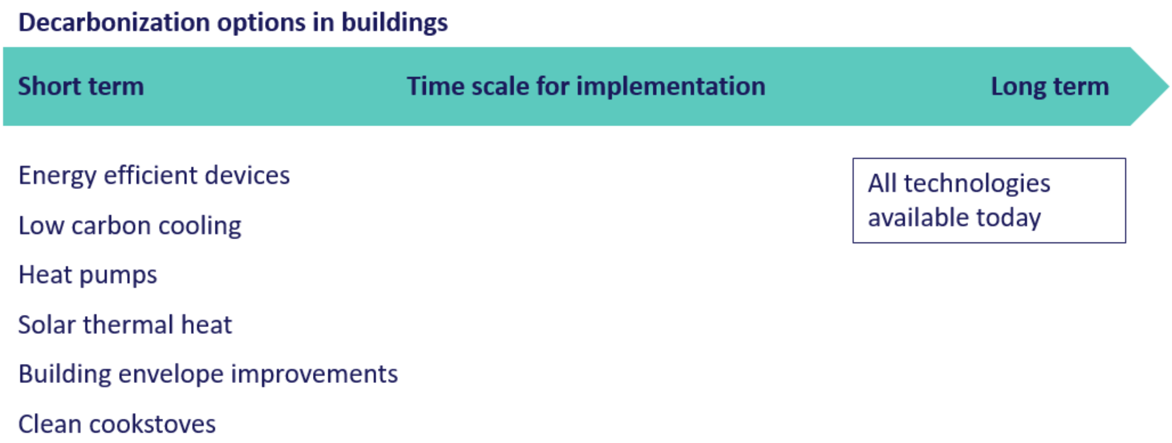

Figure 9 Decarbonization options in buildings

Decarbonization pathway

The technologies needed to achieve net zero-emissions buildings are available today. This section highlights the key transformations and technologies necessary for a building sector compatible with the Paris Agreement.

The decarbonization of space and water heating is a priority in the buildings sector due to its large contribution to the sector's CO_2 emissions. This is because 54% of energy used in space and water heating comes from fossil fuel sources – primarily natural gas – and only 11% is electrified. As a result of this energy consumption profile, heating contributes to 76% of CO_2 emissions from buildings – which is disproportionately large compared to its 51% share of final energy consumption in the sector (Figure 8).[155]

One of the main levers to reducing CO_2 emissions from heating will be the electrification of heating coupled with a decarbonizing power system. Electric heat pumps, as described in Box 3, play a critical role in this context, as they are a mature and highly efficient technology that can provide space and water heating as well as cooling.[156] Solar thermal systems will also contribute to decarbonizing heat supplies in buildings. Most commonly used for domestic water heating, systems that combine water and space heating are emerging.[157] Depending on the local solar radiation conditions and heating demand, solar thermal systems may need to be supplemented by another heating technology.

Box 3: Heat pumps for the electrification of heating requirements in buildings

Heat pumps are used in residential and commercial buildings, as well as in industry (see Section 6), with system capacities ranging from several kilowatts (kW) to over a megawatt (MW). They are highly efficient, typically generating about 3 to 4 kWh of heat per kWh of electricity consumed, offering a substantial efficiency advantage over conventional electric resistance heating technologies that generate 1 kWh of heat per kWh of electricity consumed.[158] Despite the maturity of the technology and the efficiency benefits, heat pump deployment is limited in most markets. Barriers to accelerated deployment include lack of awareness of the efficiency gains, and higher upfront investment costs compared to conventional technologies and relatively longer payback periods, both of which make heat pumps difficult to finance.

Current R&D activity aims at more compact units for an enlarged application area, lower cost and increased efficiency – all of which will further contribute to the deployment of heat pumps. Emerging application areas include the renovation segment of the heating market, district heating and cooling, and heat pumps designed for operation in cold climates.

The business case for heat pumps can be improved when connected to a smart grid and receiving revenue by providing flexibility services to the grid. Heating systems often have thermal buffer storage and buildings themselves can act as storage, meaning that heating times are flexible. A heat pump can be controlled so that it exploits periods of low electricity prices, or it can provide demand-side flexibility to the grid by switching on and off when needed.[159]

Another lever to reduce CO_2 emissions from heating is through greater uptake of district heating. For deep decarbonization, district heating systems need to be low-carbon and the emissions factor of district heating systems should be communicated clearly to users. In eastern and northern European cities, district heating is a citywide integrated system that is regulated in a manner similar to other energy utilities. In Denmark, for example, district heating supplies over 60% of household heating, with local authorities and communities owning 56% of all generation assets and 91% of all distribution assets. The benefit of large district heating schemes is the ability to tap into sources of waste or excess heat, such as heat from data centers, supermarkets or deep geothermal, which are usually not financially viable for use in smaller schemes.

While space cooling represents only 5% of total final energy consumption in buildings, it is nonetheless important to decarbonize it as it is the fastest growing energy end use in the sector. [160] One of the main measures to reduce electricity consumption and the CO_2 emissions associated with rapidly growing demand for space cooling is the adoption of more efficient air conditioners (ACs) coupled with decarbonization of the power sector. A recent study from the IEA found that under a baseline scenario, electricity demand from space cooling could triple by 2050; but growth could be cut in half through the use of more efficient ACs.[161] Under this efficiency scenario, the average AC efficiency reached in 2050 is still 40% below that of the most efficient air conditioners currently on the market, highlighting that significant efficiency gains can already be made today. A low-carbon cooling option emerging on the market today is solar thermal cooling using sorption chillers or the direct use of solar PV with a heat pump.[162] District cooling systems – currently a relatively uncommon way of cooling – might also play a role in the decarbonization pathway of space cooling, especially in places with the right cooling load scale and density.[163]

In addition to technology choices, the energy required for space heating and cooling is also strongly influenced by the performance of the building envelope – the roof, floors, ceilings, external walls, doors, windows and foundations.[164] Measures to improve the performance of the building envelope depend on the building's use and local climate conditions, and include wall and roof insulation, air sealing, advanced windows and glazing systems (in cold climates), and low-emissivity window coatings and shading (in hot climates).

Cooking is one of the largest energy uses in residential buildings, contributing to 18% of direct CO_2 emissions in the buildings sector. More than 3 billion people, the majority of whom are located in Asia and sub-Saharan African, cook using polluting and inefficient technologies.[165] Most commonly, they rely on traditional biomass techniques that are highly inefficient and release air pollutants in households and the local atmosphere. More efficient, clean cooking technologies available today can significantly reduce energy use and health impacts. These include cookstoves using cleaner fuels (LPG, electricity, natural gas, biogas, ethanol, and solar) and advanced biomass cookstoves. The accelerated deployment of such technologies is also important to meeting SDG 7 and to reducing CO_2 emissions.

Electricity demand from the buildings sector will grow as result of increasing electrification rates, and economic and population growth – particularly in developing countries. To minimize load on the grid, electric devices across all end uses in buildings (heating, cooling, cooking, appliances and lighting) must be highly energy efficient. Significant reductions in electricity consumption can be achieved by applying stringent minimum energy performance standards. For example, a study by the Climate Action Tracker found that application of the highest existing energy performance standards for appliances, lighting and cooling could reduce electricity consumption by around 4,500 TWh (approximately equivalent to the electricity generated in the USA in 2016)[166] and reduce CO_2 emissions by about 36% in 2030 under business-as-usual (BAU) evolution of the electricity grid.[167] Similarly, projected energy use in buildings can be reduced by 50% by 2030 in economically viable ways using available technology and practices.[168]

The growing digitalization of household devices in the future will also drive efficiency improvements. For example, digitalization increases the opportunities for device optimization by increasing awareness of energy consumption in real-time; and smart thermostats can use machine learning to automatically adjust room temperature in response to occupant behavior and input such as weather forecasts.[169] The IEA estimates that digitalization could cut total energy use in buildings by around 10% in 2040.[170]

In addition to efficiency improvements, demand response in the buildings sector enabled by digitalization will be important to managing load on the electricity system. The biggest potential lies in electrified space and water heating and cooling, which can be shifted over a certain number of hours or the temperature setting can be adjusted to reduce peak loads.[171] Besides, appliances such as washing machines, clothes dryers, refrigerators and dishwashers could also participate in demand response. As described in section 3.1, aggregators will play a key role in enabling the buildings sector to participate in demand response.

As direct and indirect emissions (scope 1 and 2) from the buildings sector are reduced, the embedded emissions in the buildings sector (scope 3 emissions) will become a large share of the sector's overall carbon footprint. These embedded emissions can be reduced not only by selecting construction materials based on their carbon footprint, but also via the transition to a more circular economy.[172] Material recycling, value capture at the end of life, reduced waste in construction, efficiency in building materials, lifetime prolongation and sharing to reduce floor space requirements are all measures that can reduce demand for resources and materials in the buildings sector.

Required actions and developments

As all the technologies needed to decarbonize buildings are available on the market, the key challenge for the sector is technology deployment. **For existing buildings, renovation rates must be accelerated. Policies** to support this include renovation targets, mandatory energy performance disclosure and upgrade requirements for poor performers, financing mechanisms such as subsidies or tax credits to support deep renovations, or obligations for energy companies to deliver efficiency improvements.[173] Financial mechanisms and energy company obligations can be targeted in particular at low-income households and the social housing building stock to tackle energy poverty.

For new buildings or energy consuming devices, the dominant policies driving energy-efficiency improvements are a combination of energy performance labelling, minimum energy performance standards and building energy codes and standards.[174] Standards can also help reduce the rebound effect. For example, the European Directive on the energy performance of buildings (EPBD) requires all new buildings to be nearly zero-energy buildings by 2020.[175] With time, these standards can be strengthened to reflect technological developments and further reduce energy consumption.

Even though many energy-efficiency improvements are cost-effective, meaning that they result in cost savings, the **barrier of high upfront costs often prevents their implementation**. An increasing number of **new business models and financing mechanisms** can help overcome this issue. For example, banks are increasingly dedicating funds to low-interest loans for energy-efficiency projects; and green bonds for energy-efficiency investments amounted to US$ 18 billion in 2016.[176] Energy service company (ESCO) business models can also improve access to efficient technologies. For example, the UJALA program in India has distributed over 300 million LED light bulbs, with the investment costs recovered through charges on electricity bills.[177] Such financing models can also help overcome the barrier of split incentives between the landlord and tenant.

Green procurement initiatives, government or company-led, can also drive the decarbonization of the buildings sector. Government policies can mandate minimum energy performance standards or stipulate renovation rates for the public building stock. For example, under the European Energy Efficiency Directive, EU countries must make deep renovations to at least 3% of the total floor area of buildings owned and occupied by the central government.[178] Companies are also increasingly demanding green-labelled commercial buildings; and they are paying a green premium (higher rent or sales price) compared to conventional buildings.[179] As life cycle emissions are considered in green building labelling assessments, this also potentially influences supply chain emissions. Collaborative sectoral initiatives such as the World Green Building Council's Net Zero Carbon Buildings Commitment are also important in bringing stakeholders across the supply chain together to align decarbonization actions. The signatories of the commitment – consisting of 12 companies, 22 cities and 4 states/regions – have pledged to reach net zero carbon operating emissions within their portfolios by 2030.[180]

6 Industry

Direct energy-related CO_2 emissions from industry are about 6.0 $GtCO_2$ or 19% of global energy-related CO_2 emissions,[181] with over half coming from the cement and iron and steel sectors (Figure 10).[182] Energy consumption in industry is largely fossil fuel-based, with two-thirds of energy used for heat from coal, natural gas and oil products. Industries use fossil fuels for heat at a wide range of temperatures depending on process needs: 30% of industrial heat demand is used for low-temperature applications (below 150°C), 22% for medium temperature (150-400°C) and 48% for high temperature (above 400°C) (Figure 11).[183] While the chemical industry also uses fossil fuel as feedstock, this section focuses specifically on the decarbonization pathway for energy demand in industry and the required actions and developments to trigger change in the industry sector.

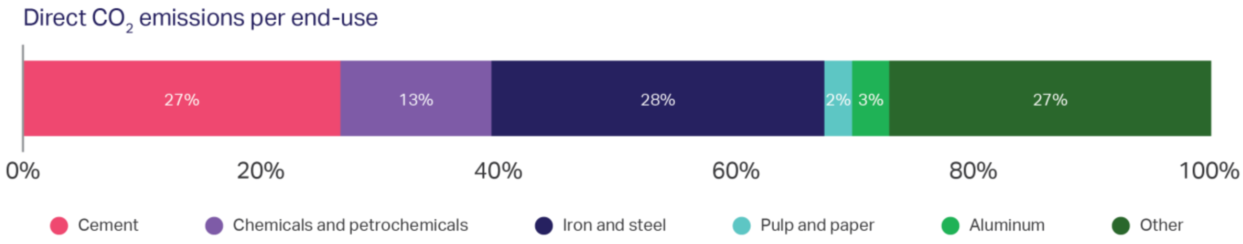

Figure 10: Direct emissions per industrial sub-sector in 2014[184]

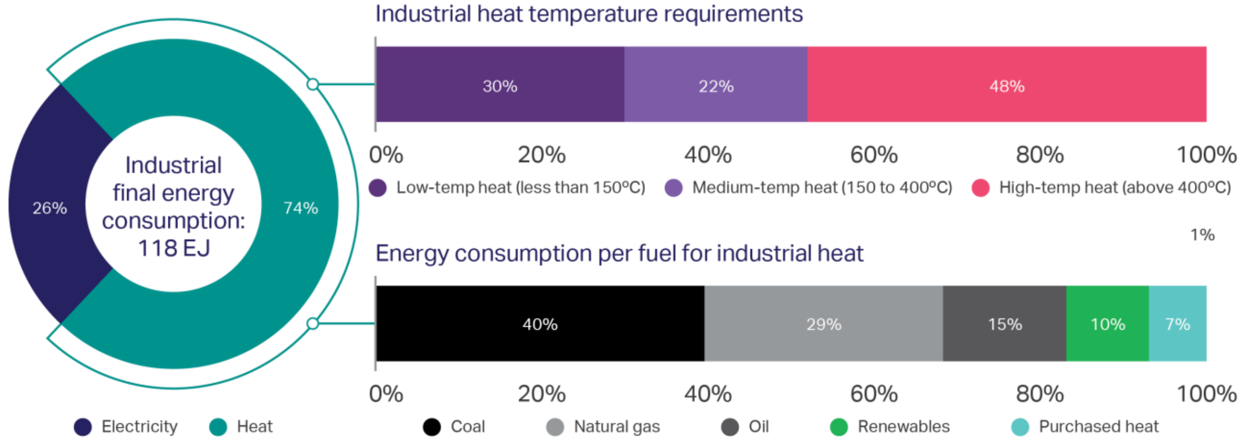

Figure 11: Energy consumption in industry per fuel in 2016[185] and temperature requirement.[186] Some of the electricity consumed in industry is also used for heat.

Existing technologies can go some way towards decarbonizing industry (Figure 12). These include electrification via the integration of heat pumps for low-temperature heat and solar heat for industrial processes using low- to medium-temperature heat. In addition, energy-efficiency measures and a transition to more circular business models will also reduce energy consumption and CO_2 emissions. For long-term decarbonization, particularly of medium- to high-temperature heat, the pathway to full decarbonization is less defined and the options differ depending on industrial process. These include the use of electrofuels, switching fuels to bioenergy or waste, and the integration of carbon capture and storage or use. The way forward will depend on several factors, including investment costs and the price differential between conventional and alternative fuels. Governments play an important role in influencing the latter, in particular by creating a level playing field driven by a long-term carbon price signal. Time-limited R&D and deployment incentives are important measures for industrial decarbonization.

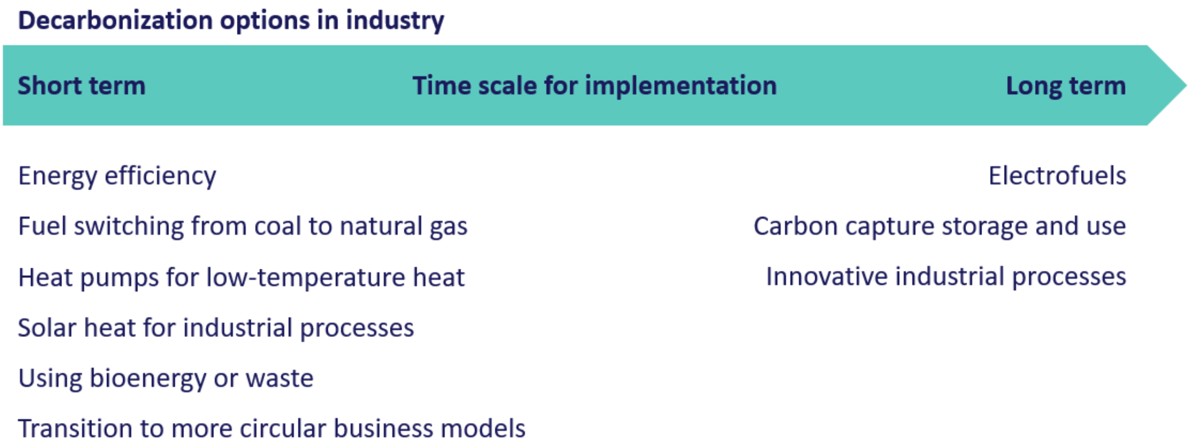

Figure 12 Decarbonization options in industry

Decarbonization pathway

Compared to other energy-demand sectors, industry is a very heterogeneous sector and decarbonization solutions for one process may not be applicable to another. Nonetheless, existing technologies can be deployed today to reduce CO_2 emissions from industry. This includes improving energy efficiency by adopting best available technologies (BAT) and switching fuels from coal to natural gas. A transition to circular economy business models can also reduce resource consumption and thereby avoid energy use. For example, an industrial symbiosis approach – where waste and by-products from one industrial process are captured and used as inputs in another – can be used to recycle waste heat. In addition, material efficiency improvements through lightweight product design, increased product lifespans and the reuse of goods and products reduce industrial energy demand.[187]

While these measures can go some way toward reducing CO_2 emissions from industry, they do not fully decarbonize the sector. For full decarbonization, the electrification of industrial heat demand combined with a decarbonizing power supply is an important lever. As described in Box 4, electrically driven heat pumps can be a solution to decarbonizing low-temperature heat. Another option for low- to medium-temperature heat supply is solar heat for industrial processes: Commercially available non-concentrating technologies such as flat-plate collectors or evacuated tubes can provide lower temperature heat (<120°C).[188] Concentrated solar heat, described in Box 5, can be used to decarbonize medium temperature heat.

Box 4: Heat pumps in industry

Heat pumps, which typically provide heat at temperatures up to 100°C, can electrify low-temperature heat provision for processes such as boiling, pasteurizing, drying and cooking.[189] Applications can be further expanded, with the next generation of heat pumps able to reach temperatures of up to 150°C. As explained in Section 5, heat pumps are three to four times more efficient than electrical resistance heaters, with even higher efficiencies possible depending on the operating conditions and temperature requirements. While heat pumps are mature technologies, their use in industry is relatively limited. Industries often face high upfront costs from integrating them in processes and payback periods are longer than the 2-3 years expected by companies.[190] Payback periods can be reduced when the heat pump efficiency is maximized, for example, in facilities where both heating and cooling are needed, or where waste heat can be used as the heat source.

Box 5: Concentrated solar heat

For medium-temperature heat, concentrated solar heat technologies such as parabolic dishes, parabolic concentrators and linear Fresnel collectors can be used. While non-concentrating technologies can be installed almost anywhere – as they use global solar irradiance – concentrated solar heat technologies can only be used in areas with good direct normal irradiance (meaning areas with clear skies and strong sunlight).[191] The barriers to solar heat for industrial processes include high upfront costs in integration into existing and optimized process heating streams and lack of awareness of the technology. In addition, limited land availability near industrial facilities can also be holding back deployment.[192] Thermal storage may be needed for industrial facilities operating 24/7 and is not yet proven for all applications and temperatures and adds to system costs. In such cases, the integration of a natural gas boiler in a concentrated solar heat facility can play a transition role.[193] Despite these barriers, several concentrated solar heat facilities have been installed, especially in Asia, Latin America and Europe.

For medium- to high-temperature heat, the options for deep decarbonization differ depending on the industrial process. These include the use of electrofuels, switching fuel to bioenergy or waste, and the integration of carbon capture and storage or use. The way forward will depend on several factors, including investment costs and the price differential between conventional and alternative fuels.

In the cement industry, the IEA and the Cement Sustainability Initiative's low-carbon transition roadmap identifies energy-efficiency improvements, switching to less carbon-intensive fuels including biomass and waste, reducing the clinker-to-cement ratio, and integrating carbon capture into cement production as the main carbon mitigation levers. Alternative binding materials offer opportunities for carbon emissions reductions in principle, but further analysis is required to produce life cycle assessments of these materials, including a comparison of their production costs and long-term performance.[194]

In the steel industry, increasing the share of scrap-based electric arc furnace (EAF) steelmaking can make a substantial contribution to increasing the electrification rate in industry. EAF is already used for one-quarter of world steel production[195] and further expansion is dependent on the availability of steel scrap at reasonable prices.[196] To decarbonize primary steelmaking in the long-term, R&D on innovative process routes is essential. Emerging options include process routes that integrate CCS/U, steelmaking processes with hydrogen as a reduction agent,[197] and iron ore electrolysis (currently in the laboratory research phase).[198]

<u>Required actions and developments</u>

As costs largely drive industrial investment decisions, governments need to establish **a level playing field for fossil fuel-based and zero-carbon industrial facilities based on CO_2 performance**. The most economically efficient way to do this is to implement a long-term carbon price signal at a level that stimulates investments in industrial emissions reduction projects. As much of industry competes internationally, compensation for asymmetric carbon pricing levels in different regional markets may be needed to avoid carbon leakage. The level playing field should also entail a removal of fossil fuel subsidies, which will enable zero-carbon energy carriers to compete on a more equal footing against fossil fuels.

In addition, to enable the long-term decarbonization of industry, governments can **support R&D into high-potential innovative process routes** through, for example, grants and competitive research awards. Once technologies are mature, they may still have **high upfront investment costs**. To overcome this barrier, governments can support deployment by providing direct financial incentives or reducing the cost of capital by providing loan guarantees. Another way for companies to access finance is through the issuance of green bonds.

Governments can also help create a market for low-carbon goods by considering the **life cycle emissions of goods in public procurement decisions**. For example, the Buy Clean California Act sets maximum life cycle emissions for different building materials, including steel and glass procured for public projects.[199] Industry initiatives can help develop a market for low-carbon goods by **advancing standards based on sustainability criteria**. Such standards will enable companies to promote and potentially monetize their environmental performance. For example, the Aluminium Stewardship Initiative (ASI) performance standard sets a limit on scope 1 and 2 emissions from aluminum production,[200] and ResponsibleSteel is developing a sustainability standard for primary and secondary steel production.[201]

Acronyms and abbreviations

AC	air conditioners
ASI	Aluminium Stewardship Initiative
BAU	business-as-usual
BEV	battery electric vehicle
capex	capital expenditure
CCS	carbon capture and storage
CCS/U	carbon capture and storage or use
CCU	carbon capture and use
CNG	compressed natural gas
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPCU	Compagnie Parisienne de Chauffage Urbain (Paris urban heating company)
CSP	concentrated solar power
DER	distributed energy resources
DSO	distribution system operator
EAF	electric arc furnace
ENTSO-E	European Network of Transmission System Operators for Electricity
EPBD	Energy performance of buildings directive of the European Union
ESCO	energy service company
EU	European Union
EVs	electric vehicles
FCEV	hydrogen fuel cell
gCO_2e	grams of carbon dioxide equivalent
$GtCO_2$	gigaton of carbon dioxide
GHG	greenhouse gas
HFO	heavy fuel oil
HVDC	high-voltage direct current
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	internal combustion engines
IEA	International Energy Agency
IEA-ETSAP	International Energy Agency - Energy Technology Systems Analysis Program
ILO	International Labour Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	kilowatt-hour
LCOE	levelized cost of electricity
LNG	liquefied natural gas
$MtCO_2$	million metric tons of carbon dioxide
OECD	Organisation for Economic Co-operation and Development
PHEV	plug-in hybrid
PPA	power purchase agreement
PV	photovoltaic
R&D	research and development
RE	renewable-based electricity
SCADA	supervisory control and data acquisition
SDG	Sustainable Development Goals
TCFD	Task Force on Climate-related Financial Disclosures
tCO_2e	ton of carbon dioxide equivalent
TSO	transmission system operator
TWh	terawatt-hour
V2G	vehicle-to-grid
VPP	virtual power plant
WBCSD	World Business Council for Sustainable Development

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Disclaimer

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A wide range of companies and organizations reviewed the material, thereby ensuring that the document broadly represents the majority view of members of the New Energy Solutions project. It does not mean, however, that every company or organization agrees with every word.

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