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Net-Zero Europe

Decarbonization pathways and
socioeconomic implications



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Preface

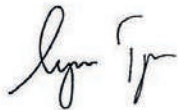
In December 2019, the European Commission introduced an ambitious proposal to make the bloc climate-neutral by 2050. Although the proposal set specific 2030 and 2050 emission-reduction goals, it did not explain how much each sector and member state should contribute to the desired emissions reductions or what achieving those reductions would cost. Much work remains to chart the European Union's course toward a climate-neutral future in which prosperity would also increase for every socioeconomic group.

To help inform the planning efforts of policy makers and business leaders and explore the implications of the required changes, McKinsey has attempted to find a societally cost-optimal pathway to achieving the emissions targets established by the European Green Deal plan.¹

We defined more than 600 emissions-reduction initiatives covering 75 economic sectors and ten geographic regions. Then we selected initiatives and combined them to form different decarbonization pathways, any of which would enable the European Union to achieve its targets for 2030 and 2050. Countless possible pathways exist, covering a wide range of costs and economic impacts. This report describes the least costly pathway among the many we identified.

This cost-optimal pathway, we believe, illustrates the technical feasibility of achieving the European Union's emissions-reductions targets. It also shows that decarbonizing Europe can have broad economic benefits, including GDP growth, cost-of-living reductions, and job creation. The effort involved in delivering these benefits would be just as broad, requiring a continent-wide effort to make significant changes to every sector of Europe's economy.

The European Commission has embraced its responsibility to help slow and halt global warming. McKinsey recognizes the importance and the urgency of the task that Europe has set for itself. In keeping with our history of exploring environmental-sustainability issues, we offer this report not to prescribe what Europe's policy makers should do but to provide a factual basis for comparing emissions-reduction approaches. Further, we hope the report will help leaders in the public and private sectors launch emissions-reduction projects that will secure a healthy, prosperous future for Europeans.



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¹ We define the "societally cost-optimal" pathway as the most cost-efficient way that society as a whole can achieve net-zero emissions by 2050.

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Key messages

What would it take for the European Union to reach its goal of net-zero greenhouse gas (GHG) emissions by 2050? This report is our attempt to answer that question. It presents the results of a comprehensive research effort on a cost-effective, feasible pathway to a net-zero Europe. Our analysis identified the optimal uses of more than 600 emissions-reduction levers in 75 subsectors and ten regions and assessed their impact on employment and other socioeconomic factors. The outcome is not a forecast, but a scenario that departs profoundly from current trends. It is a macro view; future research will examine challenges and opportunities at the company level. Here are the key findings.

Europe can reach net-zero emissions at net-zero cost.

Reducing GHG emissions would raise the cost of doing business in some sectors; savings in others would make up the difference. If these costs and savings were passed along to consumers, the average cost of living would decline slightly for low- and middle-income households.

The transition would yield a net gain of 5 million jobs.

Reaching net-zero emissions would create 11 million jobs and eliminate 6 million jobs through 2050. Up to 18 million people could need training and transition support.

Sectors would need to reduce emissions in parallel and reach net-zero in sequence.

The power sector would reach net-zero emissions first, in the mid-2040s, because most of the necessary technology is available now. Transport would approach its target in 2045, followed by buildings in the late 2040s, industry in 2050, and then agriculture.

More than half the emissions reductions could be achieved with mature and early-adoption technologies.

About 25 percent of emissions reductions would come from pilot-stage technologies, such as carbon capture and storage, and 15 percent from technologies now in the R&D phase. Accelerating the development and deployment of zero-carbon technologies will be critical.

Energy systems and land use would need to be reconfigured.

By 2050, consumption of oil, gas, and coal would decline by more than 90 percent; power demand would double; and renewable sources would generate more than 90 percent of electricity, up from 35 percent now. Some 30 Mha of marginal lands would be used to produce biomass.

Decarbonizing Europe will cost less if the burden is shared effectively.

Regions where mitigation is especially economical could pursue faster reductions, thereby reducing the overall cost. For example, the Nordics, which have large natural carbon sinks, could help offset residual GHG emissions elsewhere.

Nearly €1 trillion must be invested per year; cost savings would offset increased capital spending.

An average of €800 billion per year in capital spending—roughly a quarter of all EU capital outlays—would need to shift from carbon-intensive technologies to low-carbon technologies. An additional €180 billion would need to be invested each year. That sum would be offset by savings in operating expenses.

Policy interventions would be required to stimulate investment.

Just half of the investments needed for a net-zero pathway would turn a profit. Government financing of around €4.9 trillion could close the gap. Alternatively, a carbon price of €50/tCO₂e would make three-quarters of the necessary investments profitable, and a carbon price of €100/tCO₂e would make 85 percent profitable.

Energy security and competitiveness could increase.

Europe would become effectively energy independent, but could become more dependent on imports of climate-neutral technology components or materials. At the same time, the EU has a major opportunity to accelerate R&D, retain leadership, and penetrate new export segments.

All stakeholders must take action now.

Near-term actions include scaling up existing technologies and businesses to reduce GHG emissions over the next decade, accelerating innovation and investment to enable reductions after 2030, and investing in research and development of technologies that will complete the transition to climate neutrality by 2050.

Executive summary

The EU could achieve net-zero emissions at net-zero cost

In December 2019, the European Commission announced the EU Green Deal, one of the world's most ambitious plans to tackle climate change. If approved by the European Union's 27 member states, the bloc would commit to reaching net-zero emissions by 2050, with an interim target of reducing emissions by 55 percent compared to 1990 levels by 2030.

To reach net-zero emissions by 2050, the European Union has a long road ahead² (Exhibit 1). In 2017, the EU-27 countries emitted 3.9 GtCO₂e, including 0.3 GtCO₂e of negative emissions.³ Although this accounts for only 7 percent of global greenhouse gas (GHG) emissions, the EU achieving climate neutrality would have a big impact on the global climate challenge. Its success could serve as a blueprint for other regions, encourage other countries to take bolder action, and kickstart the virtuous cycle of increasing adoption and cost reduction of low-carbon technologies.

Five sectors emit the bulk of the European Union's greenhouse gases: 28 percent comes from transportation, 26 percent from industry, 23 percent from power, 13 percent from buildings, and 12 percent from agriculture (Exhibit 2). Across sectors, the biggest source of GHGs, accounting for 80 percent of emissions, is fossil fuel combustion. Not all of these emissions will need to be reduced to zero because negative emissions in some sectors can offset the hardest-to-abate emissions in others. Yet achieving the targets will require significant changes in all sectors.

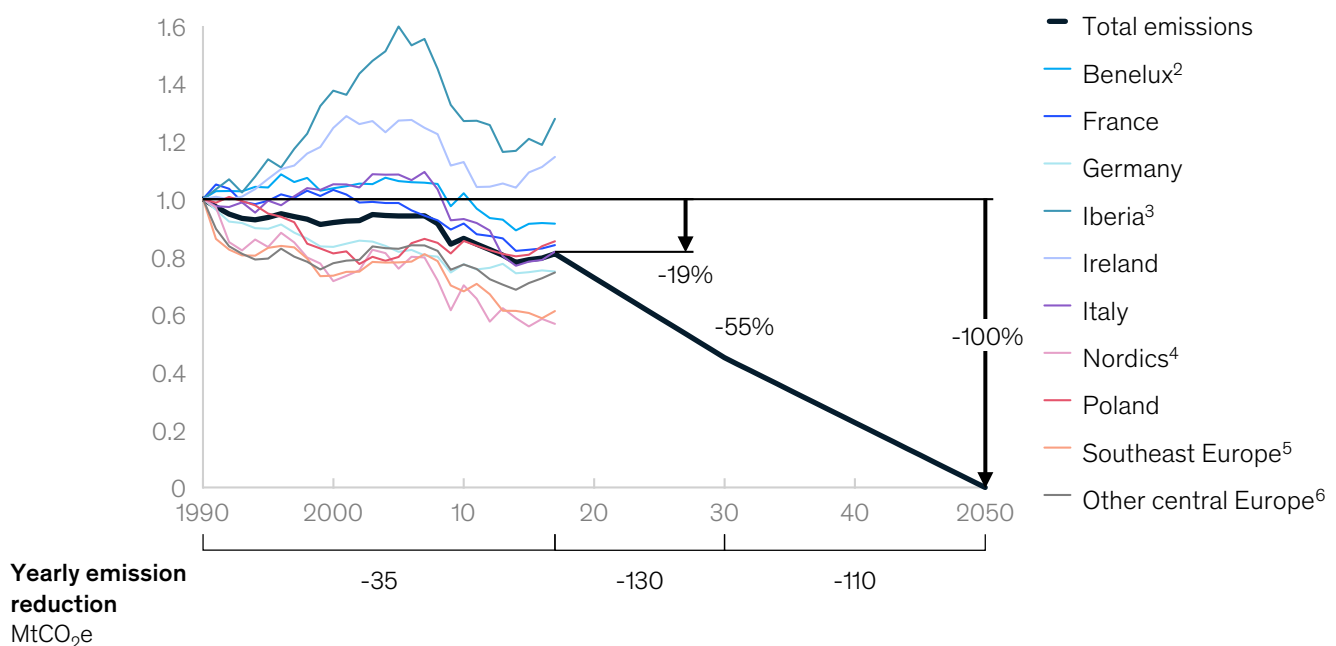
² In this report, we use "emissions reduction" to refer specifically to "GHG emissions reduction" and may also use these terms interchangeably with "decarbonization." "Net zero" or "net-zero emissions" refers to net-zero GHG emissions

³ Emissions data from 2017 was latest available at time of analysis. We use CO₂e throughout the report. For further explanation on CO₂e conversions, see the Technical appendix.

Exhibit 1

The EU will need to reduce net GHG emissions much faster to meet 2030 and 2050 climate targets.

Emission development, indexed at 1 = 1990 level¹



1. Includes impact of land use, land-use change, and forestry (LULUCF) on GHG emissions.

2. Belgium, Luxembourg, Netherlands

3. Spain & Portugal

4. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

5. Bulgaria, Greece, Romania

6. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

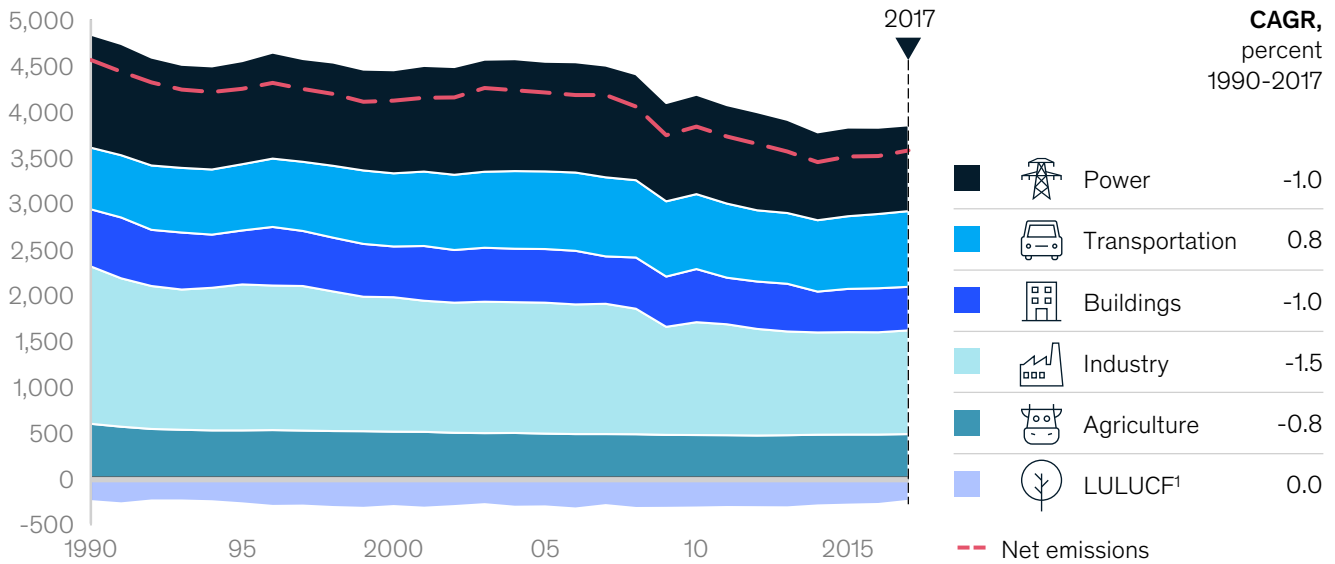
Source: McKinsey, Eurostat, EEA



The bulk of Europe's emissions are generated by five sectors.

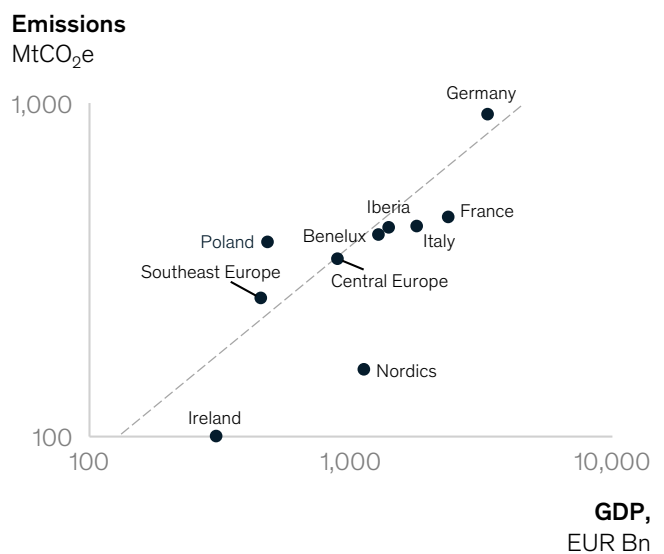
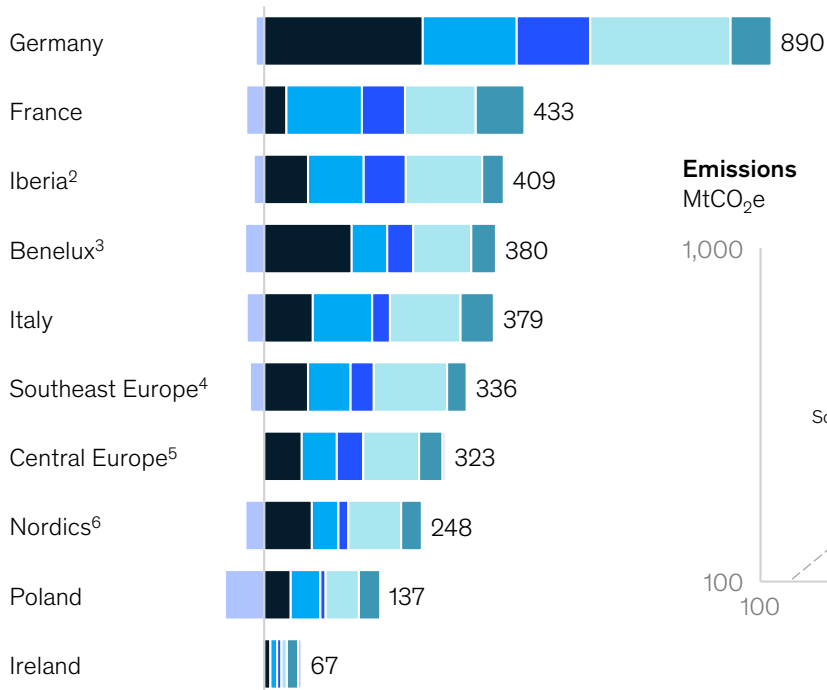
Historic emissions by sector

MtCO₂e



Emission baseline by sector and region

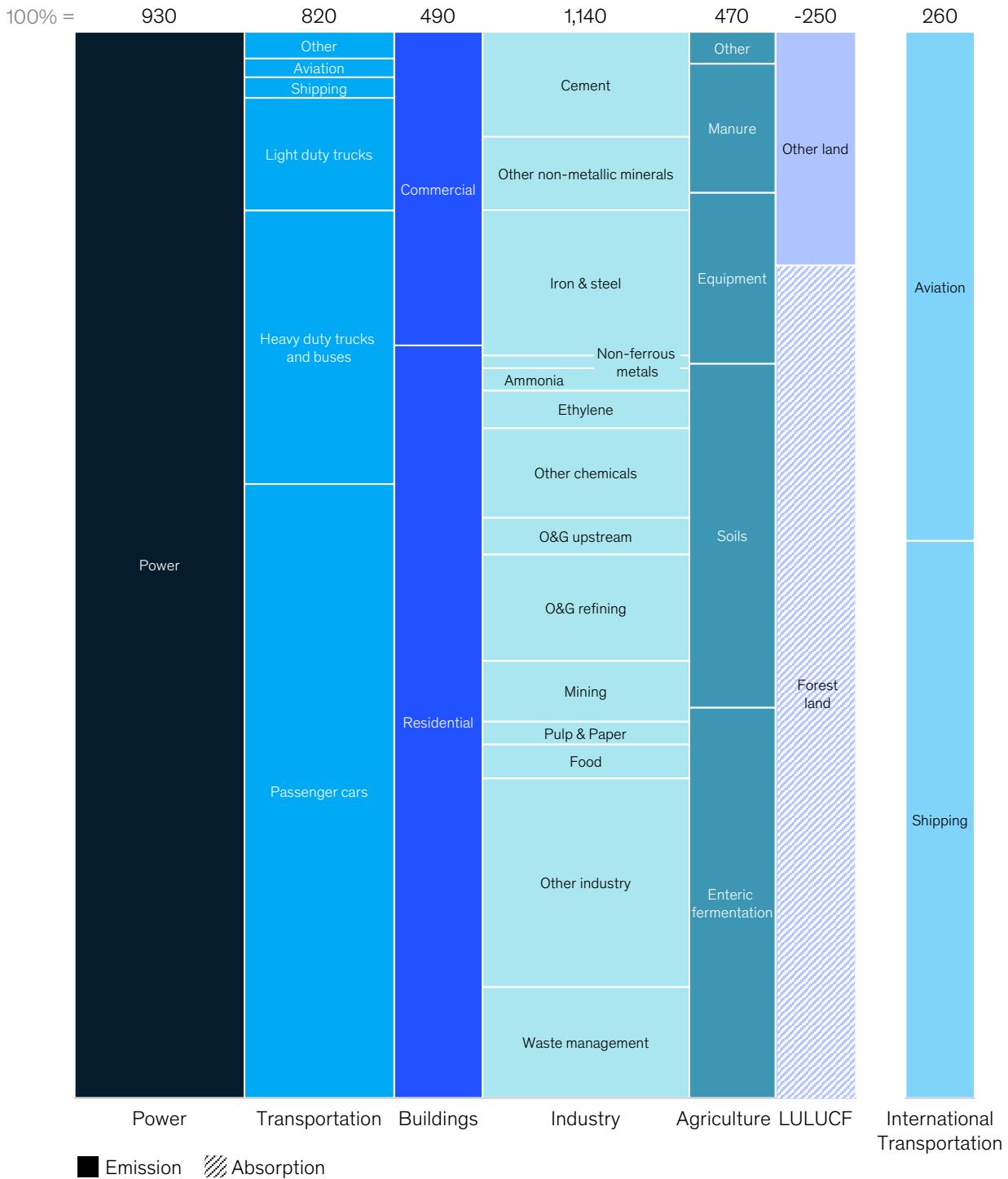
MtCO₂e, 2017



Emission baseline by sector
MtCO₂e, 2017

Emissions shared with non-EU countries

Direct EU emissions

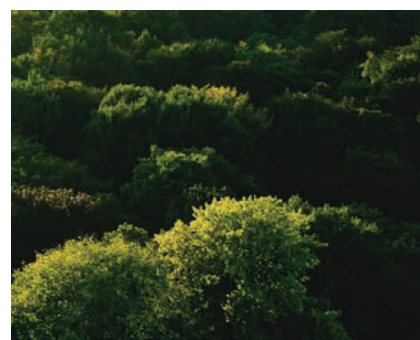
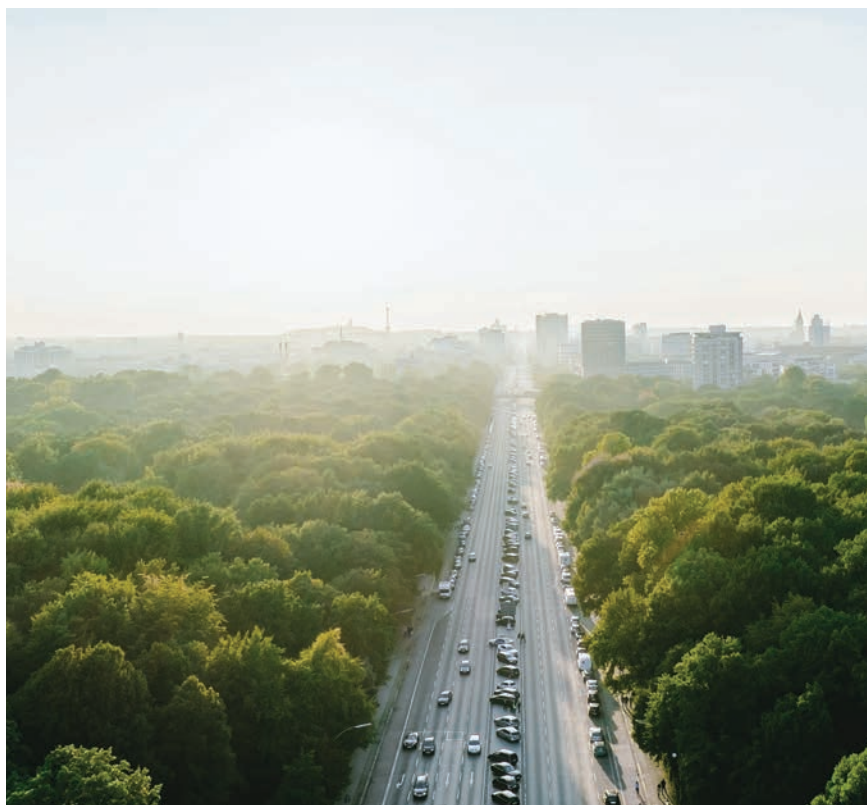


1. Land Use, Land Use Change and Forestry entails all forms in which atmospheric CO₂ can be captured or released as carbon in vegetation and soils in terrestrial ecosystems
 2. Spain & Portugal
 3. Belgium, Luxembourg, Netherlands
 Source: McKinsey, IEA, UNFCCC

4. Bulgaria, Greece, Romania
 5. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia
 6. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

The challenges in reducing emissions vary by country. Some regions such as Benelux are home to much heavy industry and serve as hubs for air freight and shipping—subsectors that are harder to decarbonize. In other countries such as Spain and Ireland, GHG emissions have grown since 1990 because of economic growth, putting them farther behind most other EU countries. Aside from these factors, the pervasiveness of a country’s use of coal-based power generation and the availability of natural carbon sinks would significantly impact how easy it is for each country to decarbonize.

We find that the European Union could achieve net-zero emissions by 2050 at a net-zero cost. The investments and cost savings would be higher in some sectors and countries than others. However, if the cost increases and savings of decarbonization were passed through to households, the aggregate cost of living for an average household in a climate-neutral European Union nation would be roughly the same as it is today. Middle- and lower-income households would see some savings, while high-income households may experience a small cost increase. And the value of the stranded assets resulting from the transition would total €215 billion.⁴ In the following sections, we break down the cost-optimal pathway by sector, region, technology, and energy and land-use system.



⁴ We calculate the “stranded” value of prematurely retired assets by multiplying the share of remaining useful life at the point of retirement with the initial capital investment. For example, retiring an asset after 30 years that cost €50 million to build and would have a useful life of 50 years produces a stranded asset value of € 50 million x (20 years/50 years) = €20 million.

Our methodology, and what this report is and is not

There are many paths to achieving EU climate neutrality by 2050. In this report, we outline and explore one particular pathway that is feasible from a technology and supply chain perspective and cost-optimal in aggregate, based on current outlooks.

To arrive at this pathway, we applied more than 600 decarbonization lever business cases across 75 subsectors in 10 regions to minimize the overall cost to the European Union of achieving the 2030 and 2050 targets. In this optimization, we accounted for many EU-wide and regional constraints such as the amount of sustainably available biomass, supply chain constraints limiting the ramp-up rates of electric vehicle (EV) production, and the total available land for generating renewable power. We did not constrain economic growth nor consumption, and we assumed that production locations will not shift. We also did not account for the value of the non-monetary benefits from reducing emissions, such as reduced air pollution and associated health benefits or reduced physical climate risks. The result is a pathway that outlines how member states could work together across sectors to reduce the European

Union's overall emissions by 55 percent (compared to 1990) by 2030 and 100 percent by 2050. For more details on our methodology and assumptions see the Technical appendix, Section 6, and for a view on the uncertainties in our modeling, refer to Pathway ambiguities, Section 2.4.

This is not a forecast. Achieving the European Union's climate goals would require a substantial departure from the current trajectory. Since the impacts of the transition would be unevenly distributed and create challenges for many individual companies and actors, significant changes to policies and regulations would be required. And while we lay out a pathway optimized for net costs, other factors would impact the decarbonization pathway the European Union ultimately takes. Nonetheless, we believe investigating this pathway is valuable for two reasons; first, it provides a helpful roadmap based on current best understanding, and second, it is a valuable tool to explore the magnitude of the challenge and the resulting socioeconomic implications.

It also is primarily a "macro" view. Our scenario minimizes net system costs using a societal discount rate. It is important to bear in mind that the

perspective of individual stakeholders and the decisions they would take in the absence of changes in regulation and incentive structures may differ, both because there are disparate impacts on individual stakeholders and because they may apply different costs of capital and payback expectations in investment decisions; for an investigation of the latter point and how capital could be mobilized, refer to Bridging the finance gap, Section 4.1.3. While we explore macro-level socioeconomic implications such as employment displacements, impacts on household costs, structural cost changes on the sector-level, and risks and opportunities for trade and production, we do not investigate the specific challenges that the zero-emissions transition creates for individual companies. These can be significant. And while we explore some of the potential actions that business leaders and policy makers can take to navigate and shape the transition in Section 5.2, detailed perspectives on how players in each sector can navigate and thrive in the transition are not within our scope. These sector-specific company-level "micro" views will be the subject of future publications.

Sector perspective:

Interdependencies and supply chain scale-ups

Although achieving net-zero emissions will require sustained effort across sectors, some could meet the target more quickly than others (Exhibit 3). In our pathway, the sectors would reach their emission-reduction goals in the following order:

1. Power: With wind and solar power generation technologies already available at scale, power would be the quickest sector to decarbonize, reaching net-zero emissions by the mid- 2040s. Since the demand for power will double as other sectors switch to electricity and green hydrogen, the sector must rapidly scale renewable production and expand its storage capacity.

2. Transportation: This sector would approach climate neutrality by 2045. EVs are already in early adoption, but it will take the better part of 10 years to set up supply chains to support a switch to 100 percent EV sales, from mining the raw materials for batteries to assembling EVs. Once this happens, emission reductions can happen quickly, except for those from aircraft and ships that are too big and travel too far to rely on batteries or fuel cells. They must opt for the more expensive solution of switching to biofuels, ammonia, or synfuels.

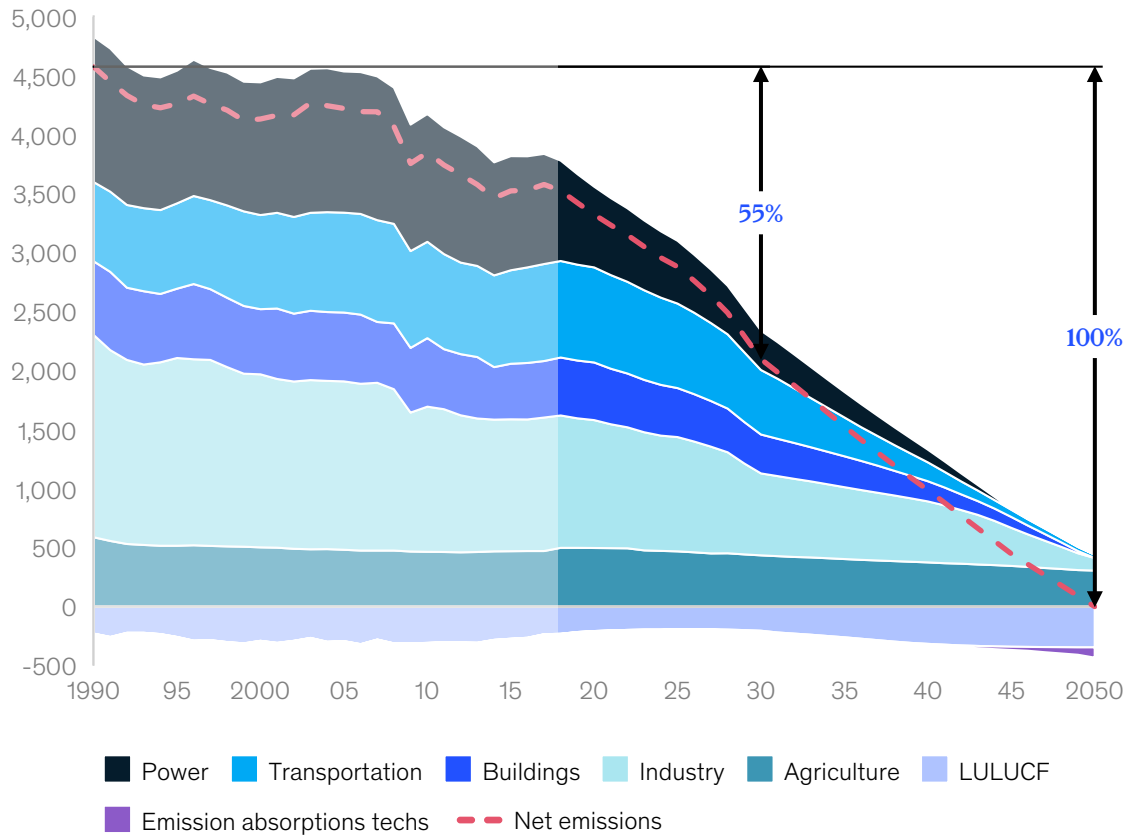
3. Buildings: Most of the technology required to decarbonize the buildings sector is already available. However, renovating large portions of the European Union's buildings stock is a massive undertaking. The percent of dwellings using renewable heating sources would need to increase to 100 percent from just 35 percent today. Gas usage in buildings would also need to drop by more than half. The buildings sector would reach net-zero in the late 2040s.

4. Industry: The industrial sector would be close to climate-neutral only by 2050. The most expensive sector to decarbonize, industry would require new technologies that are still under development. Already in the next decade, about 40 percent of emissions will have to be reduced. An accelerated maturation of hydrogen based steel making would kickstart the low-carbon hydrogen industry. Even when applying BECCS on some industrial sites towards 2050, the sector would continue to generate residual emissions from activities such as waste management and heavy manufacturing, which would have to be offset by negative emissions in other sectors or natural carbon sinks.

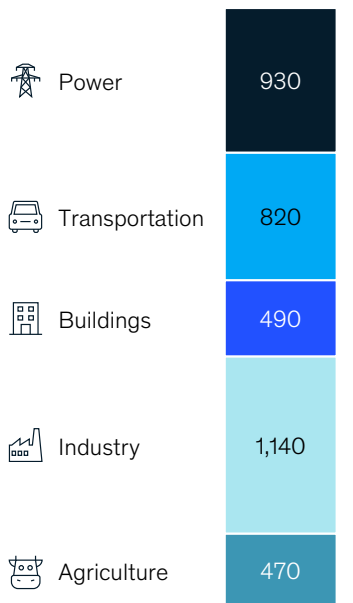
5. Agriculture: Using more efficient farming practices, such as managing manure, switching farm equipment to alternative fuels, and using enhanced efficiency fertilizers, could reduce some agricultural emissions, but it's by far the hardest sector to abate without changes in consumption. The transition of this sector might strain its competitiveness and will require aligning regulatory frameworks, changing farming practices, and adopting consumption changes at large scale. The latter is because more than half of agriculture emissions come from raising animals for food, which can't be reduced without significant changes in meat consumption or technology breakthroughs, such as vaccines or next-generation feed additives that inhibit enteric fermentation. Because we didn't factor in dietary shifts, our cost-optimal pathway for this sector requires offsetting agriculture emissions with land-use changes that would create more carbon sinks and drawing on negative emissions generated by other sectors.

The power sector would reach net-zero emissions before the others.

Total emissions per sector in cost-optimal pathway for EU-27
MtCO₂e, excluding international aviation and shipping



Current emissions
MtCO₂e, 2017

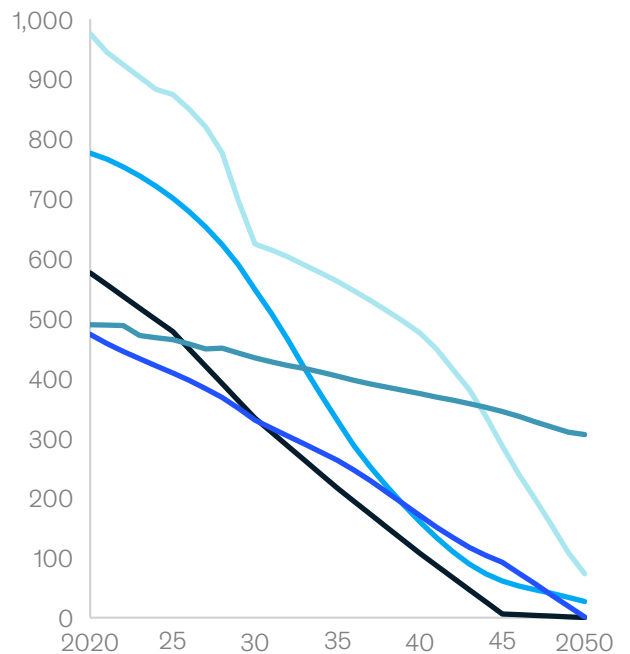


Decarbonization cost¹
EUR/tCO₂e

2020-30 30-40 40-2050

Sector	2020-30	30-40	40-2050
Power	-31	18	145
Transportation	-92	-149	-70
Buildings	-66	37	40
Industry	30	86	120
Agriculture	-27	-121	35

Emissions evolution
MtCO₂e



1. Weighted average

Source: McKinsey, UNFCCC

Regional perspective: Stronger together, on individual pathways

Four geographical factors will determine how easy it is for each country to reduce emissions and which decarbonization measures would be the most cost-optimal. Those are local climate, CO₂ storage opportunities, local agriculture practices, and the amount of land available for reforestation and construction of wind farms and solar plants. For example, the Northern EU countries would benefit from the shallow waters and more hours of wind in the North Sea, including 30 to 60 percent more hours of onshore wind than in the south. The North also has the majority of possible carbon storage sites, most of which already have oil and gas pipelines. Southern countries would benefit from the 1,000 more hours of sunlight they receive per year.

Because of these differences, a cost-optimal pathway would see EU member states achieve climate goals collectively rather than individually, so they can pool their relative advantages and lower transition costs (Exhibit 4). For example, cross-border collaboration would allow countries with recent emissions growth to catch up without resorting to expensive near-term reduction measures. Countries with more abundant solar resources or natural carbon sinks could also help other countries reduce or offset their emissions at a lower cost than through measures such as capturing and storing CO₂ from residual emissions locally. In a scenario in which the European Union's climate goals were achieved at the individual member-state level instead of in aggregate, the cost of the transition would increase by roughly €25 per tCO₂e.

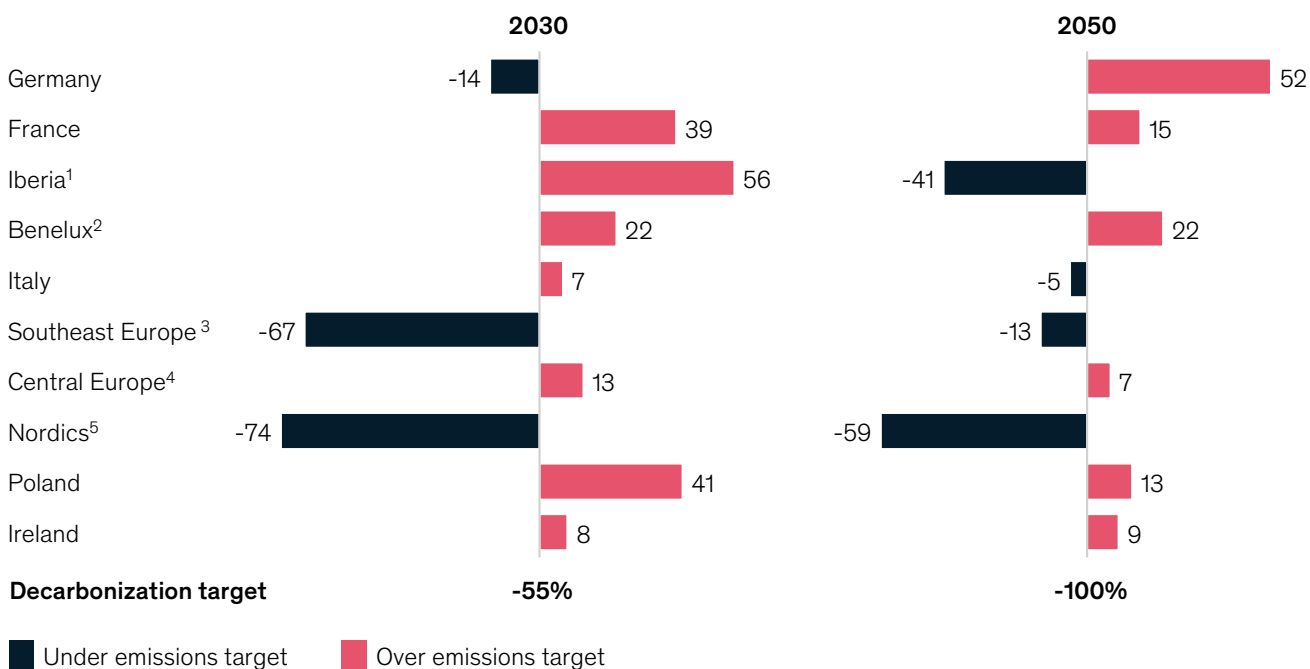
Technology perspective: Most of the required technologies are available, but accelerated innovation will be critical

Through 2030, some 64 percent of the European Union's emissions reduction would be achieved by large-scale electrification and increases in energy efficiency, accounting for 47 percent and 17 percent, respectively. Demand-side measures and circularity would reduce emissions an additional 15 percent. Hydrogen would contribute another 13 percent. The remainder would come from ramping up the use of biomass, land-use changes, and other innovations such as inert anodes in aluminum production (Exhibit 5). The rest would come from ramping up the use of hydrogen and biomass, land-use changes, and other innovations such as inert anodes in aluminum production (Exhibit 5).

Exhibit 4

On the cost-optimal pathway, some countries' emissions reductions would compensate for others'.

MtCO₂e over/under EU-wide decarbonization targets



1. Spain & Portugal

2. Belgium, Luxembourg, Netherlands

Source: McKinsey

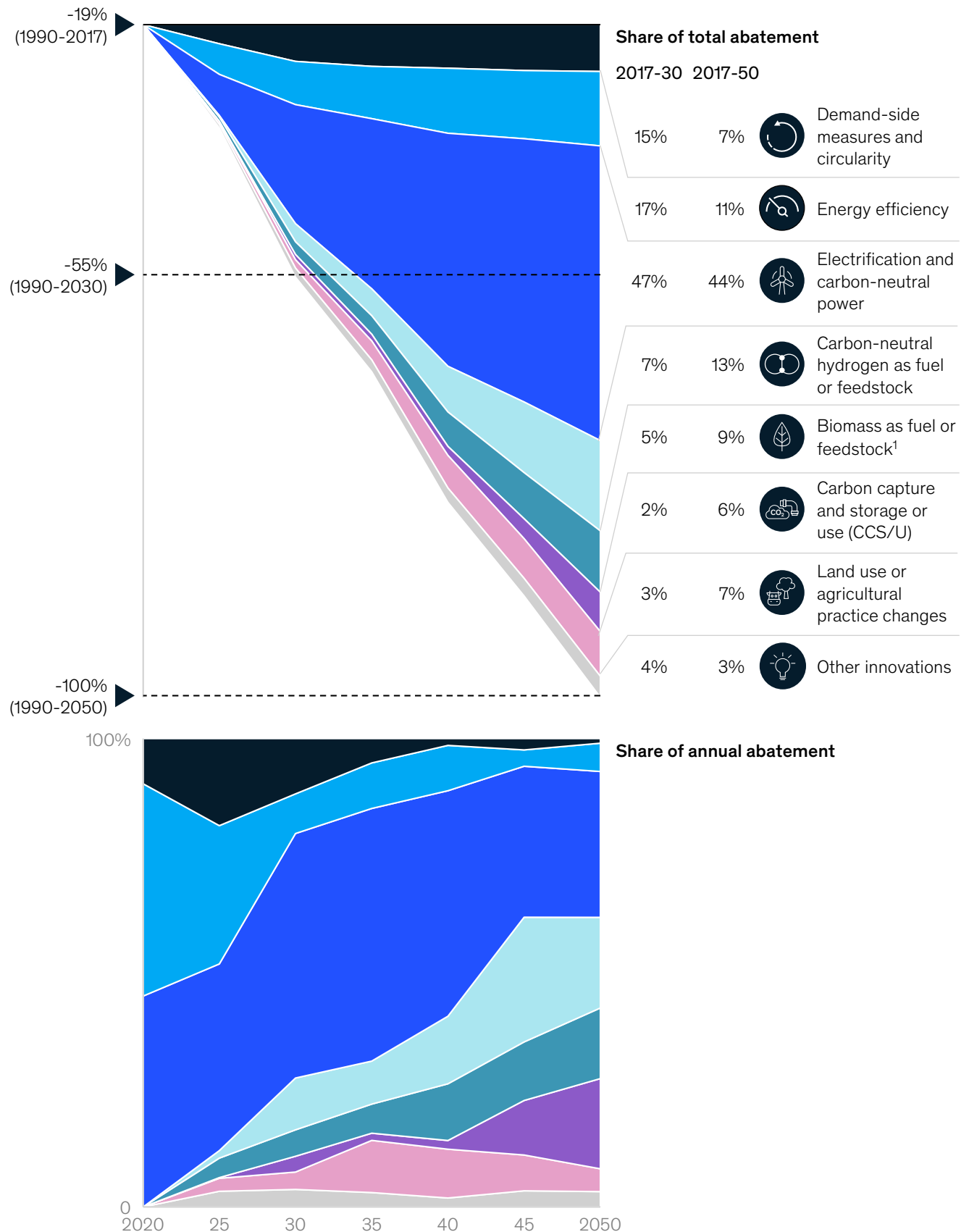
3. Bulgaria, Greece, Romania

4. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

5. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

Through 2030, nearly two-thirds of emissions reduction could be achieved with energy efficiency and electrification.

GHG abatement, relative reduction of CO₂e vs 1990 in EU-27



1. Of the total of the emissions reduced by Bioenergy Carbon Capture and Storage (BECCS), half are attributed to biomass and the other half to CCS
Source: McKinsey



From now until 2030, three-fourths of abatement would be achieved by expanding already mature and early-adoption technologies such as heat pumps in buildings, heat cascading in industry, and EVs in transportation. Through 2050, these technologies would achieve maximum market penetration, contributing 60 percent of the required abatement to reach climate neutrality. Demonstrated but not yet mature technologies like CCS or low-temperature hydrogen heating would need to be rapidly scaled after 2030 to reduce emissions by an additional 25 to 30 percent. Solutions still in the R&D phase such as direct air capture and high-temperature electric heating with electric furnaces would be required to abate the remaining 10 to 15 percent.

Even though most emissions would be abated using mature and early-adoption technologies, continued innovation and scale effects will be important to drive down transition costs. Solar panels are a good example of a solution that has become much cheaper because of continued innovation and the industrialization of production. In the next 20 years, EVs and electrolyzers could achieve analogous price drops.

The pathway we outline does not factor in consumption shifts or other behavioral changes that would make reaching climate neutrality easier and less expensive. To determine how much these shifts could reduce the cost of the transition, we analyzed the impact of 12 consumption shifts across sectors ranging from replacing cement with cross-laminated timber (CLT) in construction to people driving less and eating less meat. In a decarbonization pathway that incorporates these behavioral changes, the transition would generate an average cost savings of €15 per tCO₂.

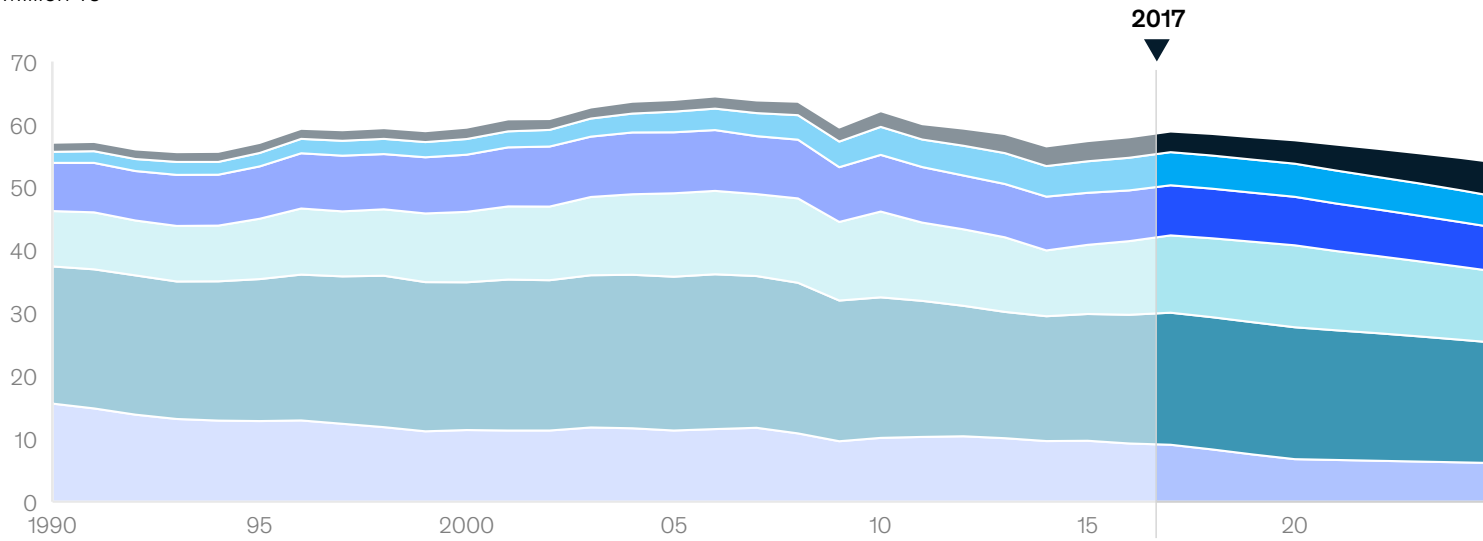
Energy system and land-use perspective: Reconfiguring the energy system and rethinking land use

Energy system reconfigured: Today, the European Union meets 75 percent of its primary energy demand with fossil fuels. On the pathway we outline, fossil fuel use would decline significantly over the next three decades. Most coal consumption would be eliminated by 2030, and oil and gas consumption would drop to less than 10 percent by 2050. Renewable power would satisfy more than 80 percent of primary energy demand by 2050, with most of the rest from bioenergy. Seventy-five percent of renewable energy would be used directly as electricity. Another 25 percent would be converted into green hydrogen to replace fossil fuels in subsectors such as iron and steel production, long-haul trucking, aviation, and shipping. The power sector would become the central switchboard of the EU energy system, creating and channeling renewable power into other sectors (Exhibit 6). Meeting this renewable power demand would require a significant expansion of solar and wind power, increasing solar capacity additions from 15 gigawatts (GW) per year today to 45 GW per year during 2030-50, and wind additions from 10 GW per year in 2019 to 24 GW per year during 2030-50. The EU would also need to increase interconnections among its power grids threefold by 2030 and its battery storage capacity to 25 GW by 2030 and to more than 150 GW by 2050.

The power sector would become the central switchboard of the climate-neutral EU energy system.

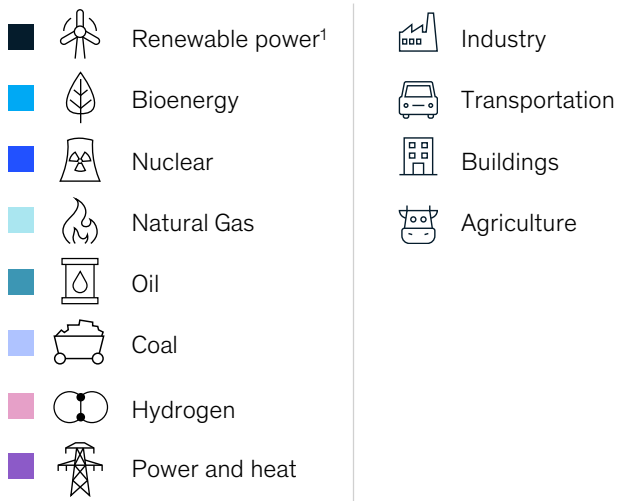
Total primary energy demand

Million TJ



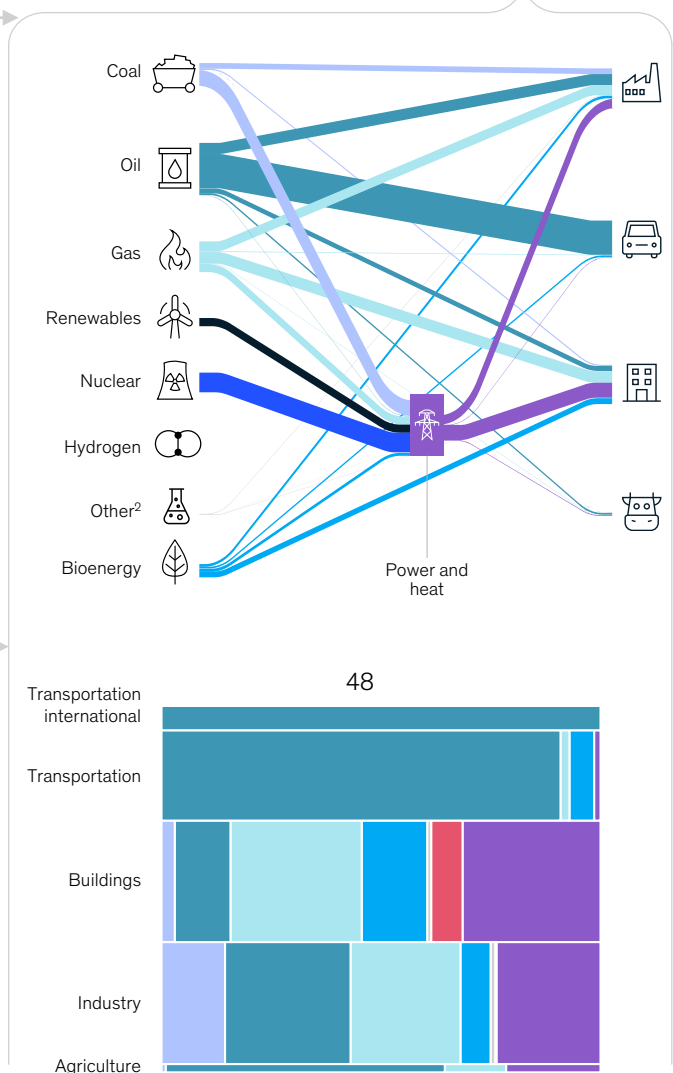
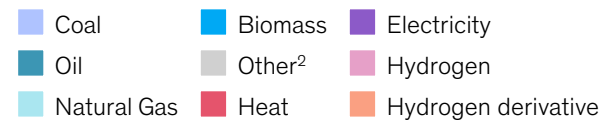
Primary energy demand to final energy consumption

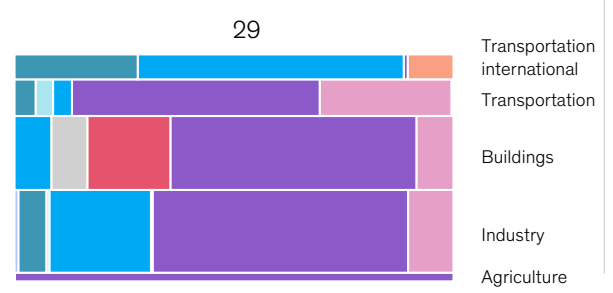
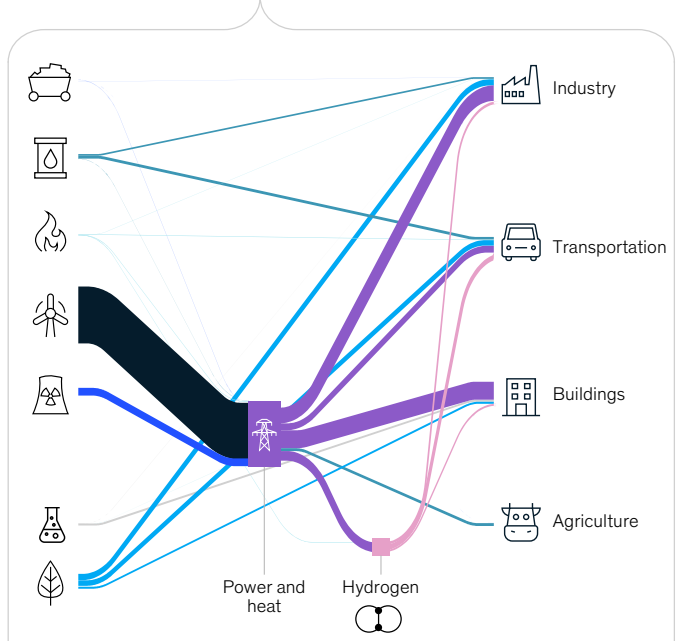
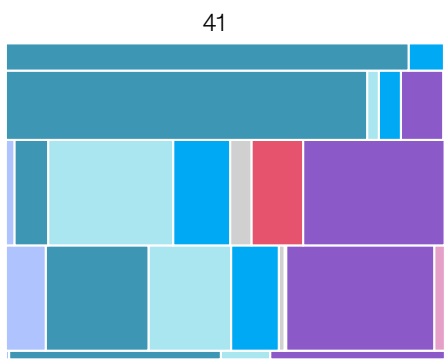
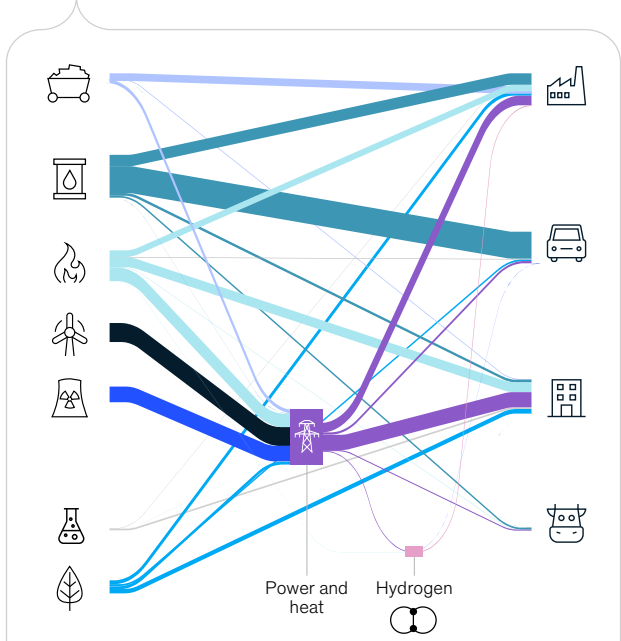
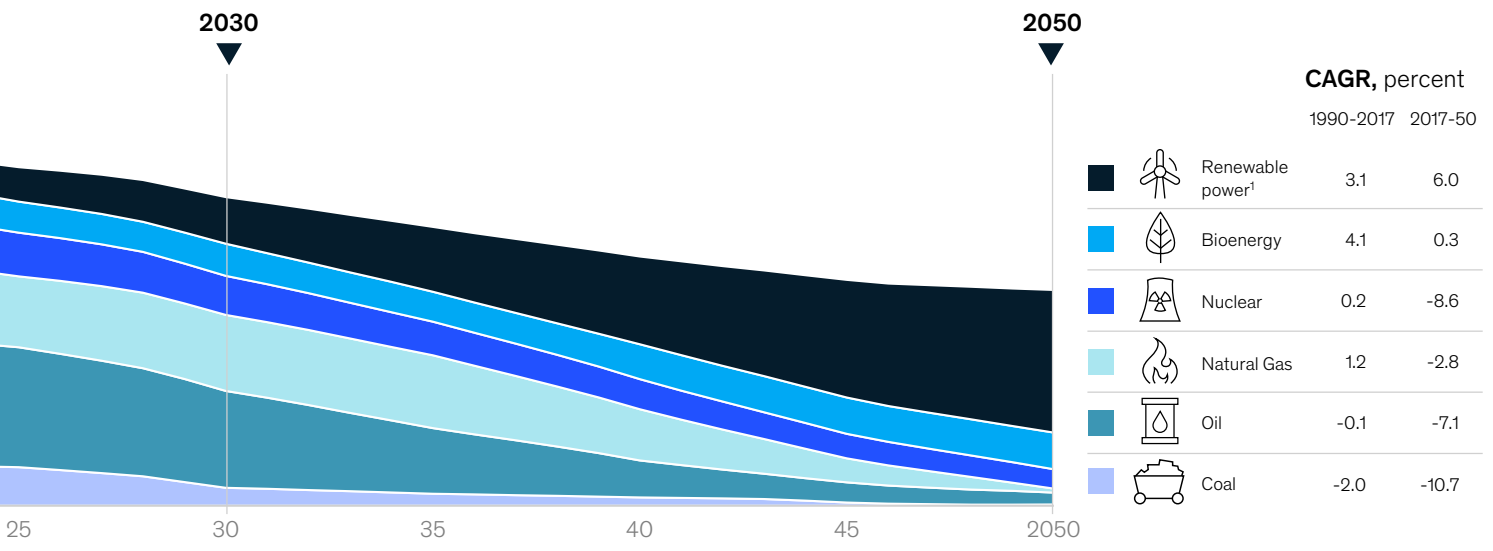
Million TJ



Total final energy consumption

Million TJ





1. Includes solar PV, solar thermal, wind power, and hydro power
 2. Other miscellaneous sources, e.g. non-renewable waste

Source: McKinsey

Land use expanded: Climate neutrality would require increasing the level of natural carbon sequestration to offset residual hard-to-abate emissions and scaling sustainable bioenergy production, especially for the transportation and industry sectors. We estimate that natural carbon sequestration in the European Union could be increased to 350 megatons (Mt) per year, mainly through reforestation 12 Mha of land freed up by greater efficiency in the agriculture sector. Also, 62 Mha of land in the European Union are unused or abandoned and lack high biodiversity value. Of this, about 30 Mha (45 to 50 percent) would be used for bioenergy production in the cost-optimal pathway (Exhibit 7).

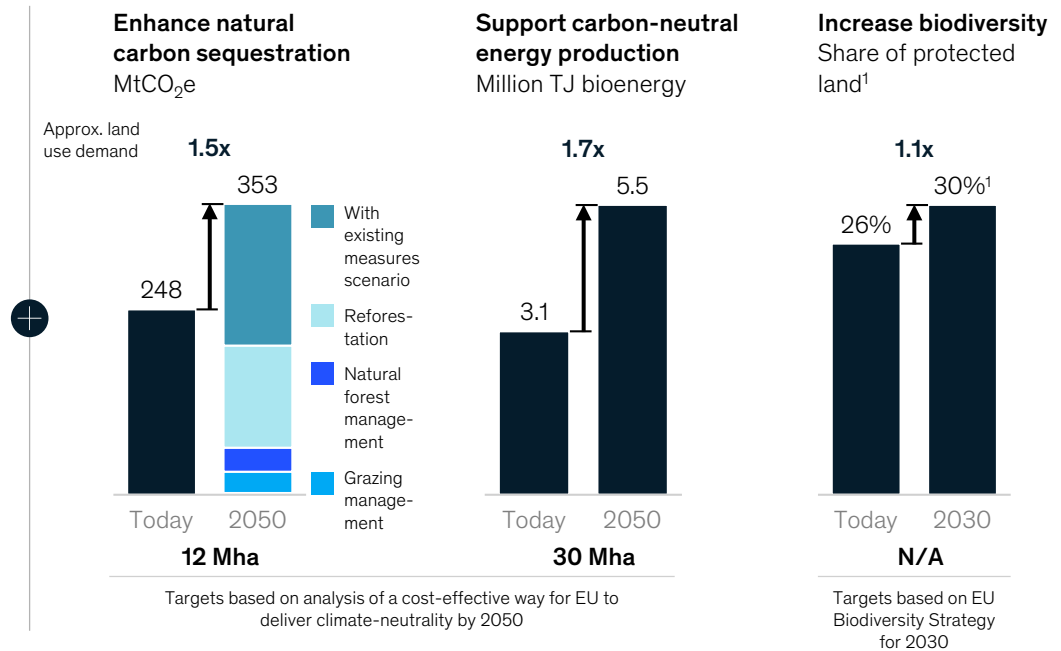
Exhibit 7

On the cost-optimal pathway, land use would support carbon sequestration and bioenergy production.

Additional focus themes

Focus of Common Agricultural Policy

- Maintain rural welfare
- Support agricultural production
- Maintain socio-cultural and landscape heritage



1. EU Biodiversity Strategy states that at least 30% of the land should be protected in the EU. This is a minimum of an extra 4% of land as compared to today.

Source: McKinsey, EU Biodiversity Strategy for 2030: Bringing nature back into our lives

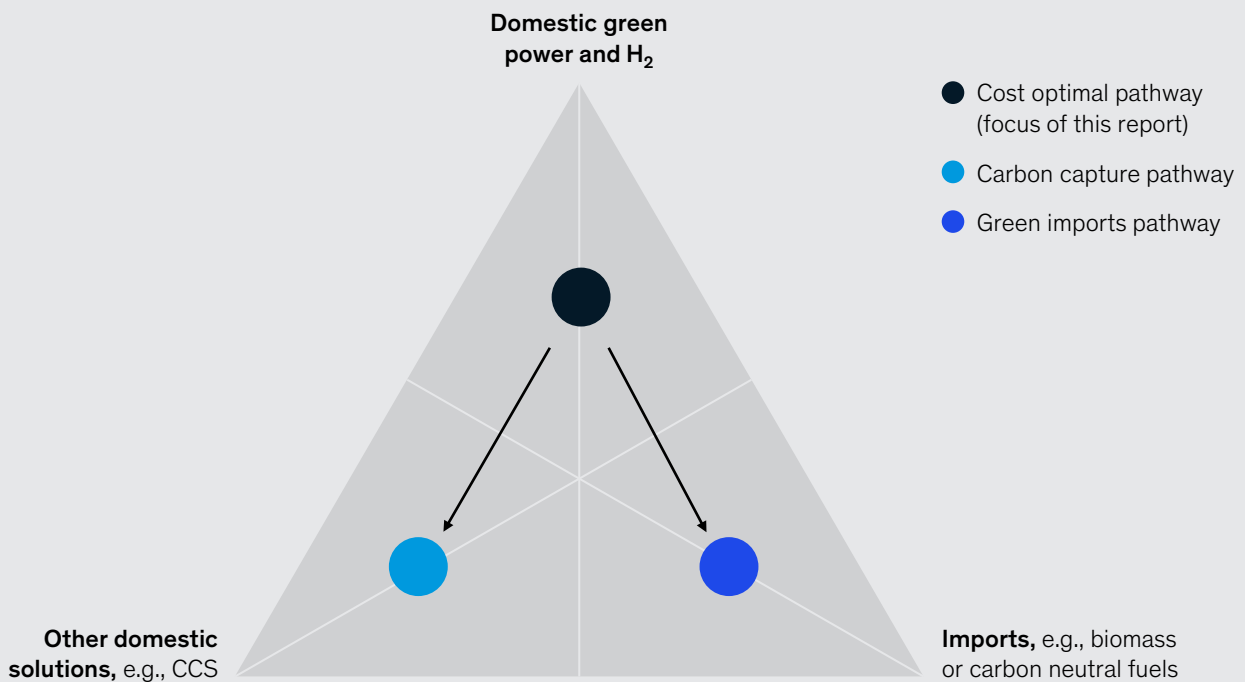


Alternative pathways and pathway ambiguities

Alternative pathways: Although we lay out a technically feasible, societally cost-optimal pathway to achieve climate neutrality, other factors will undoubtedly influence the emissions-reduction pathway the European Union ultimately takes. One challenge may be the required build-out of renewable power, which could face resistance because of the amount of land it requires. While exploring other possible pathways, we identified two archetypal alternative approaches to achieving climate-neutrality by 2050 (Exhibit 8).

Exhibit 8

There are two main alternatives for the EU energy system to our cost-optimal pathway.



Source: McKinsey

- **Carbon-capture pathway:** This route would rely more on CCS to reduce emissions from power and industry. Limiting the renewable power build-out to half the levels in our cost-optimal pathway, this alternative pathway would raise transition costs by 15 percent. The marginal cost of power would go up by 50 percent, and hydrogen, primarily produced via the blue route, would be 30 to 40 percent more expensive. This pathway would avoid many of the challenges of scaling up renewables. However, it would come with its own implementation hurdles, such as requiring over three times the amount of carbon-capture capacity and developing extensive carbon transportation and storage systems across the European Union.
- **Green-energy imports pathway:** In this scenario, green energy would be imported from abroad in the form of electricity, green or blue hydrogen, or sustainably harvested biomass. Limiting the renewable power build-out to half the levels in our cost-optimal pathway, this alternative pathway would raise transition costs by 10 to 20 percent. Whilst on the whole relying more on energy imports leads to higher costs, some local opportunities, e.g., importing hydrogen via cheap pipeline transport, can actually be cost beneficial. Importing fuels would of course also fail to produce other benefits such as job creation and increased EU energy independence.

Pathway ambiguities: In some cases, there is ambiguity about the most cost-optimal decarbonization technology. Based on today's cost projections, there's a clear cost-optimal technology for reducing 80 percent of emissions. For the remaining 20 percent, there are two or three options expected to be close in cost. Depending on technology developments in the next ten years, one of these options could become more affordable than another, making it difficult to determine a clear winner now.

The greatest cost uncertainty is whether it will be cheaper to reduce emissions by using biomass, hydrogen, or CCS in some instances. More specifically, it's unclear whether it will be cheaper to replace gas heating with biomethane or hydrogen, using other heat sources such as waste heat, or implementing CCS for industrial heat. It's also hard to decipher the most cost-optimal split of biofuels and syngas in aviation and shipping and what solution would provide the best long-term flexibility in the power system (hydrogen peakers, biogas peakers, thermal with CCS, or flexible demand options). The ultimate cost will vary by country, depending on local biomass prices and availability, the cost of hydrogen, and the proximity of low-cost storage for carbon capture. In a hydrogen breakthrough scenario, where costs of production fall more quickly, we see demand that is eight-times higher than today, compared to five-times for the base case.

Unexpected technology breakthroughs in nuclear and other areas might also occur, which could also influence what a cost-optimal decarbonization pathway looks like.

The socioeconomic implications of decarbonizing Europe

The transition to net-zero emissions would have significant socioeconomic implications, from capital re-allocation and employment to trade and production.

Capital re-allocation: Achieving climate neutrality would require redirecting roughly a quarter of current investments and increasing capital outlay by 1 percent of GDP but result in lower operating costs.

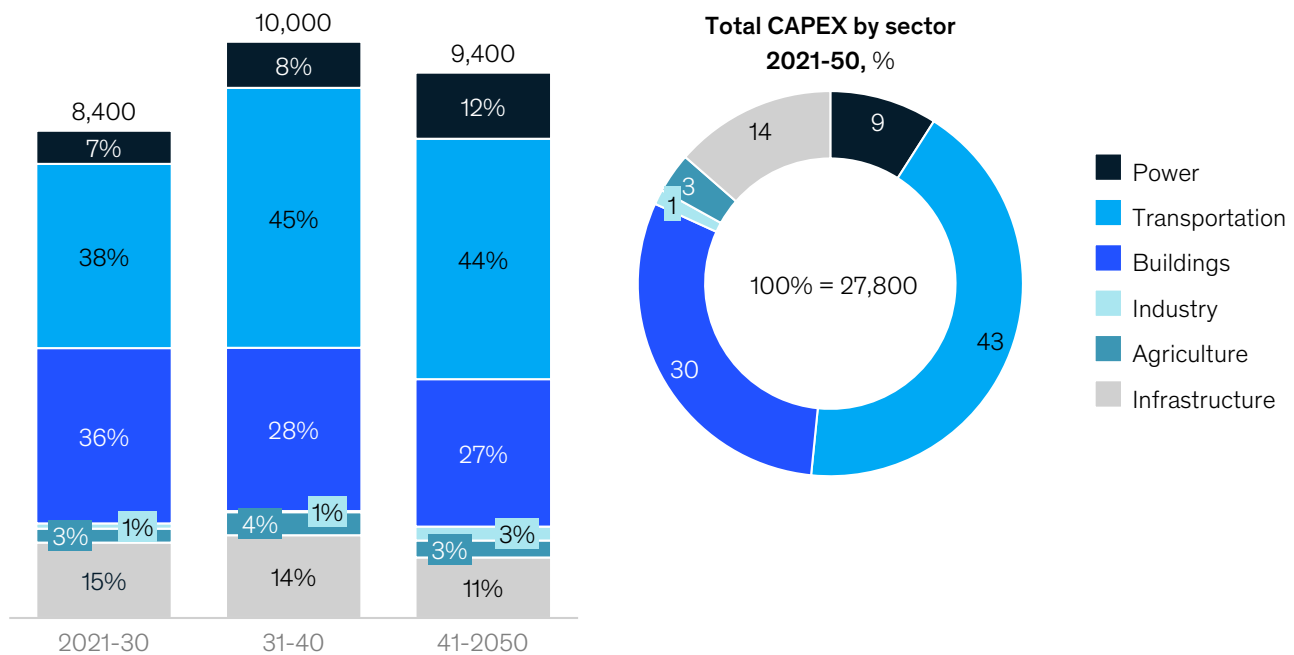
Reaching net-zero would require investing an estimated €28 trillion in clean technologies and techniques over the next 30 years (Exhibit 9). About €23 trillion of this investment—an average of €800 billion a year—would come from redirecting investments that would otherwise fund carbon-intensive technologies.

This amounts to 27 percent of the annual capital investments currently made in the European Union, or 4 percent of the current EU GDP. The European Union would also have to allocate an additional €5.4 trillion (an average of €180 billion a year) to clean technologies and techniques (Exhibit 10). This is the equivalent of increasing the EU's current total annual investments by 7 percent, or by 1 percent of current EU GDP.

Exhibit 9

Reaching net-zero would require an estimated €28 trillion in investments over the next 30 years.

Total CAPEX in EU-27, bn EUR (total within time bracket)



Source: McKinsey

Of that €5.4 trillion, about €1.9 trillion would be invested in the buildings sector (29 percent), €1.8 trillion would be used for power (33 percent), €410 billion for industry (8 percent), €76 billion for agriculture (about 1 percent), and €32 billion in transportation (less than 1 percent). About €1.5 trillion (28 percent) would fund infrastructure to improve energy transmission and distribution in all sectors.

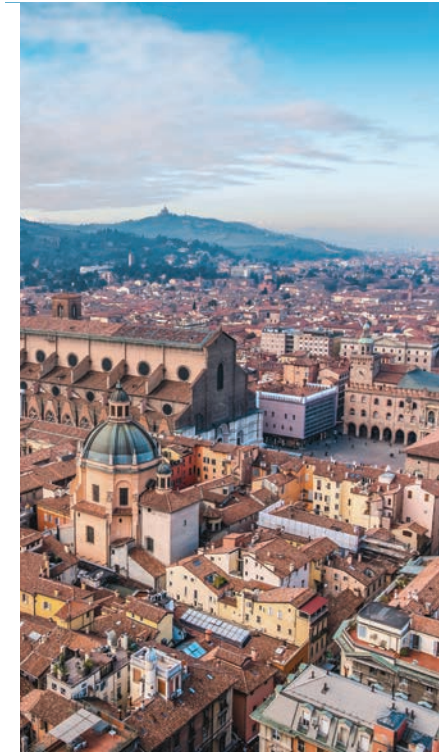
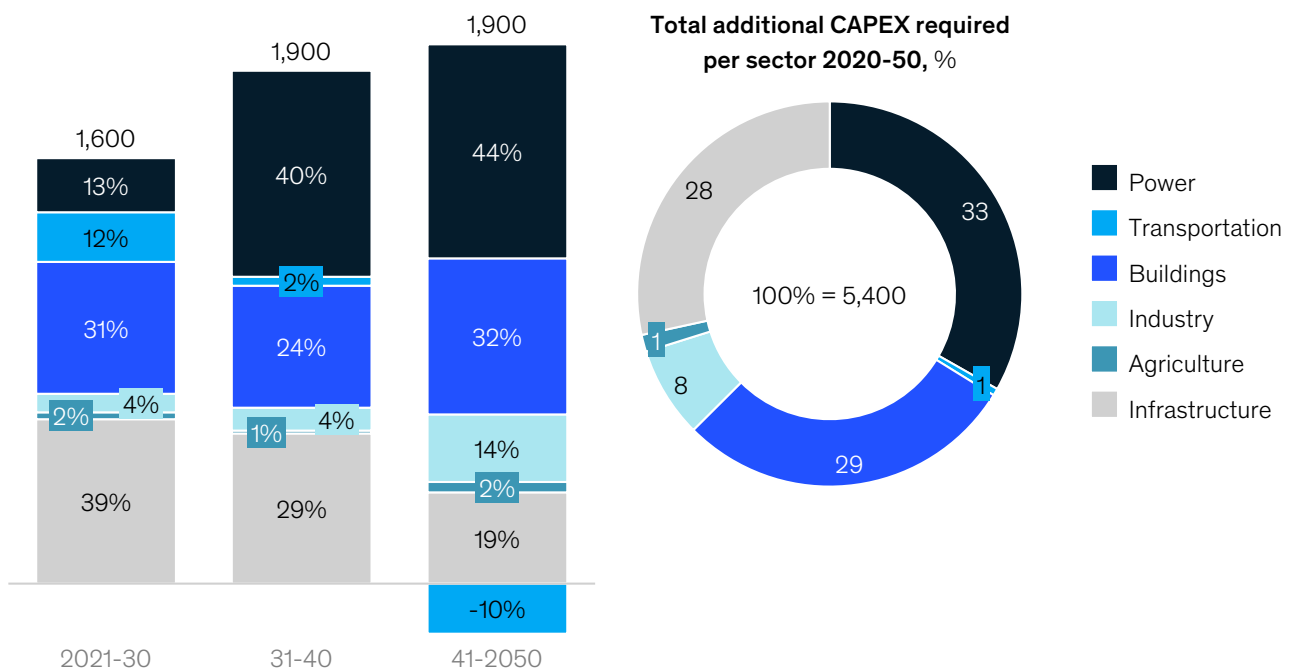


Exhibit 10

About €5.4 trillion of the €28 trillion is incremental, compared to no climate action.

Additional CAPEX in EU-27, Bn EUR (total within time bracket)



Source: McKinsey

Although implementing clean technology would require additional investment, it would ultimately lower operating costs. From 2021 to 2050, the EU would save an average of €130 billion annually in total system operating costs (Exhibit 11). By 2050, these measures would reduce total system operating expenditures by €260 billion per year, more than 1.5 percent of the current EU GDP. Most of the operating-expenditure savings would come from domestic transportation. However, operating expenditures in sectors such as international aviation and industry would increase on top of the additional investments.

Mobilizing capital: Roughly half of the necessary investments require interventions

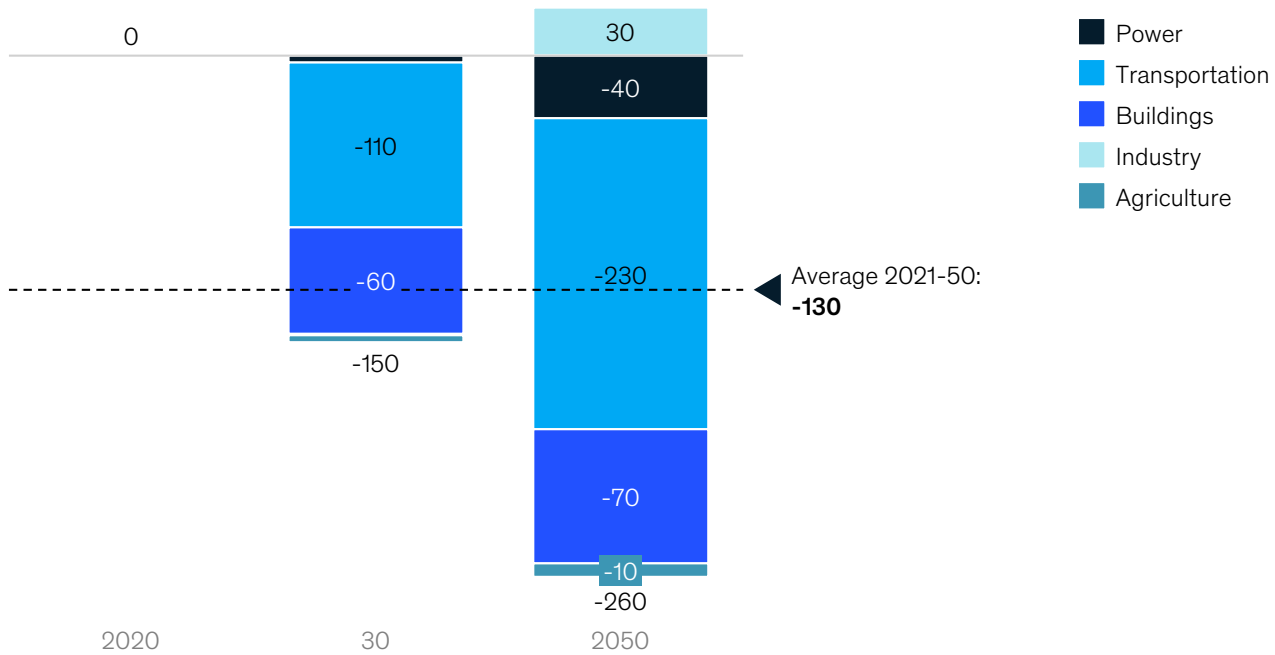
The pathway we lay out optimizes net system-level costs under a societal discount rate. However, individual stakeholders will make spending decisions based on their cost of capital and payback period expectations. So, without targeted intervention, these businesses and consumers would likely make decisions different from those laid out in our cost-optimal pathway. About half of the required €28 trillion capital outlay would not have positive investment cases. This may be because of differences in the cost of capital or because the stakeholder doesn't consider the investment's long-term benefit.

For example, car buyers usually look more at the upfront purchase price than the total ownership cost. The share of capital expenditures without a positive investment case varies by sector. For industry, 95 percent of capital expenditures lack positive business cases; for buildings, it's 85 percent; for power 46 percent; for transportation 36 percent; and for agriculture 11 percent (Exhibit 12).

Exhibit 11

Implementing clean technology would lower the EU's operating costs.

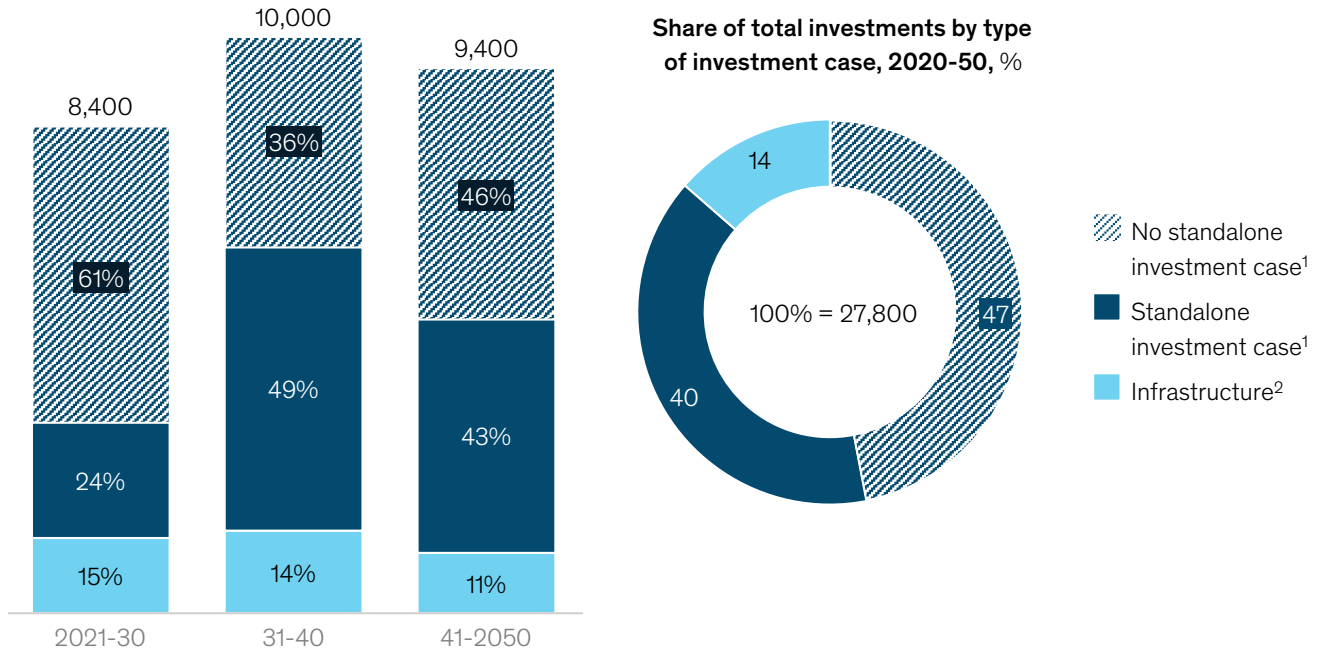
Total OPEX^{1,2} in EU-27, Bn EUR p.a.



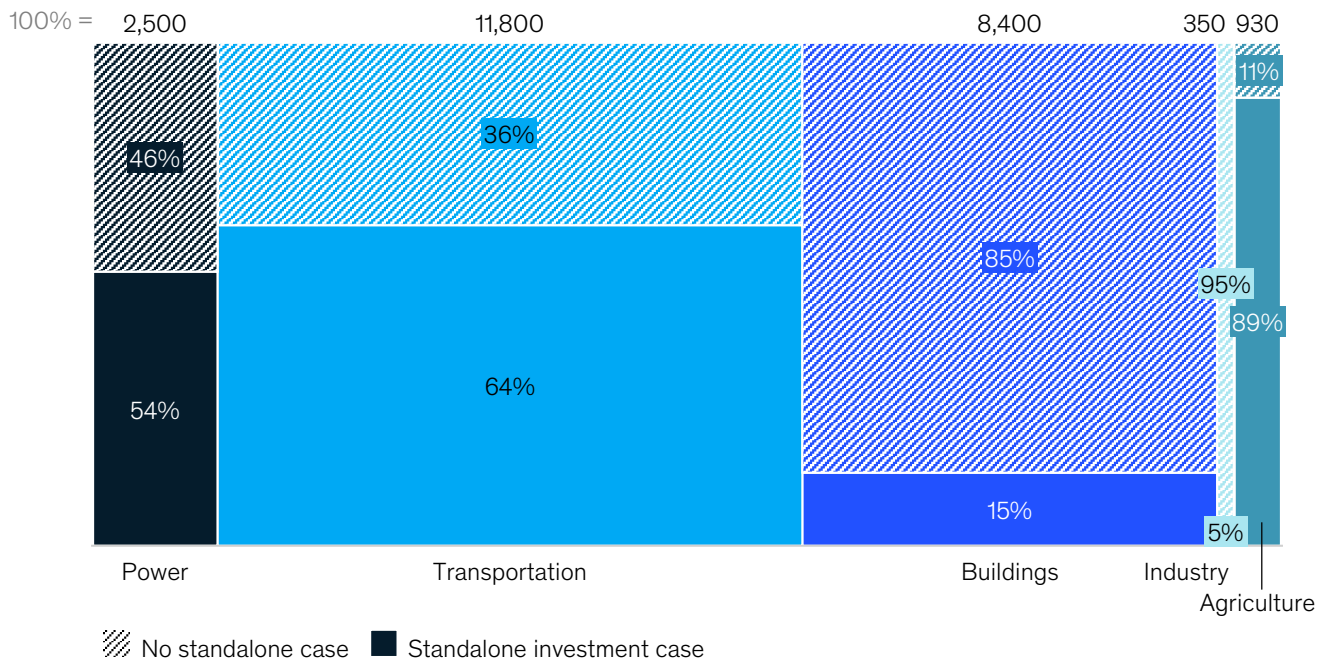
1. Fuel and feedstock OPEX
 2. Excluding OPEX reduction in refining sector (which is mainly due to reduction of the refining activity)
 Source: McKinsey

About half the required investments do not have positive investment cases for their stakeholders.

Emissions-reduction investments by type of investment case for individual stakeholders
 Total CAPEX in EU-27, Bn EUR (total within time bracket)



Emissions-reduction investments by type of investment case for individual stakeholders by sector
 Total CAPEX¹ in EU-27, total for 2020-50, Bn EUR



1. Investment cases that are NPV positive. For assumptions (including WACC and lifetime expectancy) see technical appendix
 2. Profitability of infrastructure investments are not modelled as business model is often unclear and asset base is often regulated
 Source: McKinsey

Mobilizing financing for these investments would require interventions, particularly in subsectors with high abatement costs, such as aviation, shipping, and heavy industry. There are many ways to do this, including:

- **Direct financing interventions.** We estimate that closing gaps to positive investment cases for individual stakeholders through direct public financing such as carbon contracts for difference or feed-in-tariffs would require €4.9 trillion by 2050.
- **Price measures such as carbon prices or cap-and-trade systems.** A carbon pricing or emissions trading scheme could create incentives for individual stakeholders to reduce emissions. At a carbon price of €50 per tCO₂e, an additional 21 percent of required capital, on top of the 40 percent already in the calculation, could be unlocked through 2050. A carbon price of €100 per tCO₂e could unlock another 10 percent, giving more than 80 percent of all capital expenditures a standalone investment case. The remainder would require carbon prices of over €100 per tCO₂e to create a positive investment case.
- **Commercial derisking and bringing in long-term investors.** Capital could be mobilized by reducing investment risks and employing new financing models and products such as adding insulation costs to house mortgages. This could help bring more long-term investors into markets dominated by short-term decisions, like the heating system or auto market.

Long-term investors could see viable business cases in at least 10 percent more of the total capital expenditures than individual stakeholders would.

The sustained low-cost capital available from capital markets today may be an opportunity to significantly lower the cost of the transition. Capital market innovations such as asset-backed securities, utility and corporate power purchase agreements, government incentives, and risk guarantees could accelerate decarbonization by reducing the cost of capital through securitizing decarbonization projects.

Increased costs could also be passed on to end customers through regulatory backstops such as banning gas boiler installations after a specific date or establishing portfolio standards that require a minimum share in the renewable power sector.

Impact on households: middle- and lower-income households would see lower costs

If consumption patterns remain the same, and the cost increases and savings of decarbonization are directly passed through to consumers, the aggregate cost of living for an average household in a climate-neutral European Union nation would be roughly the same as today. Power and heating/cooling bills would be somewhat lower, and mobility would be more affordable, while the cost of food and flights for vacation would increase. Middle- and lower-income households would see slight decreases in costs, whereas high-income households would see no real change.

It is worth noting that cost increases due to decarbonization are often much higher for intermediate than final

products. For example, the cost of steel may rise by 25 percent, but the price of a car produced with this steel would increase by less than a percent.

The labor market: A net gain of 5 million jobs, but reskilling and support needed

The net-zero transition would create an estimated 11 million jobs while eliminating 6 million, resulting in a net gain of 5 million jobs. Many of the new jobs would be in renewable energy (1.5 million), agriculture (0.1 million), and buildings (1.1 million). For example, in the buildings sector, the EU would need 1.1 million skilled workers to retrofit homes and other structures with higher insulation and to install green heating and cooking systems. Meanwhile, the biggest job losses would be in oil & gas (1.3 million) and transportation (0.2 million).

Although regions may experience different levels of job displacement, most would see net employment increases.

Although the number of job displacements from emissions reduction is expected to be much smaller than that caused by other trends such as automation, reaching net-zero emissions could still require retraining up to 18 million workers. Training and reskilling are especially relevant for workers in jobs that currently do not exist (almost 3.4 million by 2050) and in positions that would entirely disappear (2.1 million by 2050). This is not an impossible challenge. Some of the new jobs would require skills similar to those that disappear. For instance, oil and gas engineers could transition into the CCS industry. Also, many of the sectors with high job losses such as coal mining often have an older workforce.

So, retirements could reduce the amount of job changes and retraining required. At the same time, it is important to look beyond the statistics and recognize that every job displacement may cause worry and hardship for those affected, no matter their number. Therefore, care needs to be taken to offer people support and create new opportunities, with particular attention given to regions with concentrated job losses.

Trade and production: energy independence, new risks and opportunities

As a result of decarbonization, the EU could become effectively energy independent. Between 2020 and 2050, oil, gas, and coal demand would decline 80 percent, from 43 exajoules (EJ) to 6 EJ, and reducing the fossil fuel trade deficit by two-thirds (Exhibit 13).

Although the EU would no longer depend on fossil fuel imports, it might develop new dependencies on imports of technologies vital to a zero-emissions economy. Today, for example, solar panels are primarily imported into the EU, and some critical raw materials, such as cobalt for batteries or iridium for electrolyzers, have a limited supplier base. These new dependencies would need to be monitored and managed.

The shift to zero-emissions technologies could also influence competitive dynamics and lead to shifting production locations. As clean technology innovation continues to accelerate globally, the innovators continue to gain market share from those that fall behind. Navigating the transition and making the strategic and operational adjustments to thrive in a zero-emissions world is no easy task for many incumbents. This threatens engines of the EU economy such as the

automotive sector. At the same time, the EU has a significant opportunity to accelerate R&D across sectors, retain leadership in clean technology, and expand into new export segments. For example, exporting heat pumps, electric furnaces, electrolyzers, and zero-emission agriculture technologies could generate more than €50 billion a year by 2050.

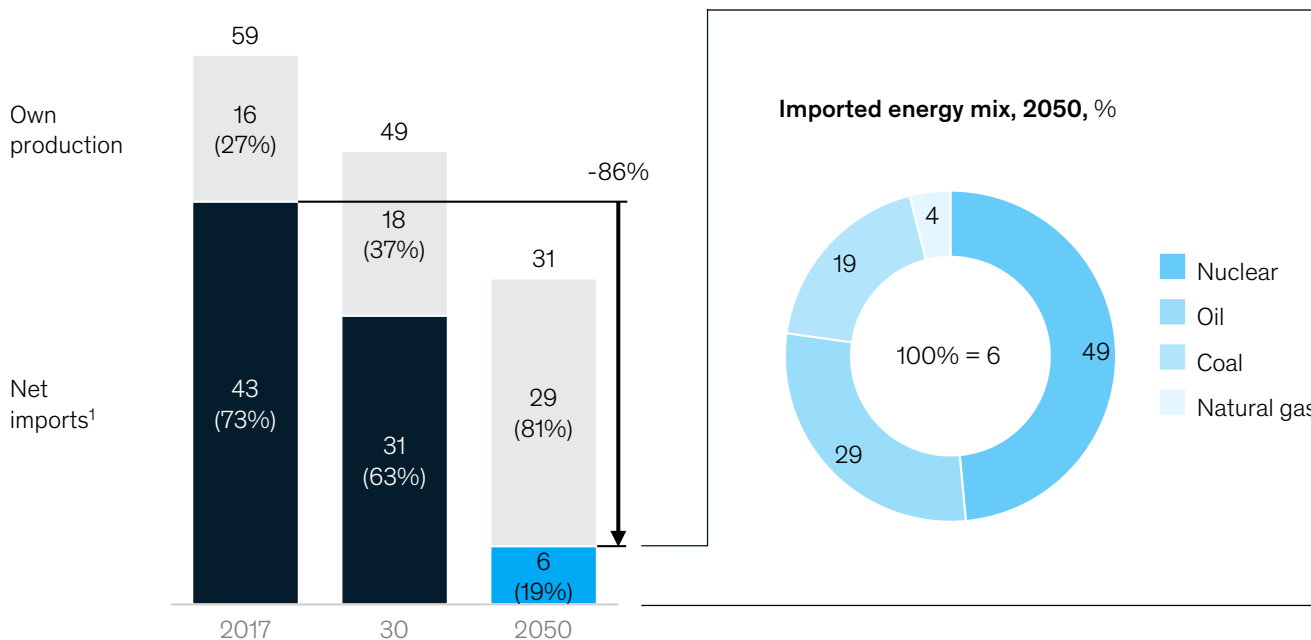
Finally, Europe's industrial topography could be reshaped as production locations for products such as ammonia, cement, or steel gravitate to European regions where zero-emissions inputs or enablers, such as hydrogen, renewable electricity, and CCS, are least expensive.

Exhibit 13

As a result of decarbonization, EU fossil fuel imports could decline more than 80%.

Million TJ

Trade balance of fossil fuels in 2017 and evolution under cost-optimal pathway in EU-27



1. Assumption: 85% of fossil fuels is imported by 2030; 100% by 2050. All nuclear remains imported

Source: McKinsey, UN Comtrade (2016)

Charting a way forward

Although the case for decarbonization and the pathway are clear, it will take decisive action to achieve the European Union climate goals. Stakeholders would need to address five hurdles to accelerate the transition:

- **Shift social norms and consumer and investor expectations to make climate-neutral the new normal.** Consumers and business leaders would need to make decisions in their expectation and in support of a shift to net-zero instead of business-as-usual as the public and business default.
- **Create secure and stable policy frameworks and regulatory environments.** Successful decarbonization depends on public sector leaders who adopt robust regulatory frameworks proportionate to the emission-reduction goals rather than incremental policies. This would provide stable planning and investment signals that would create incentives for low-carbon technologies and business models.
- **Encourage constructive industry dynamics.** Business leaders that lean into the transition and demonstrate a commitment to overcoming transition hurdles through collective action rather than worrying about first-mover disadvantages will be critical.

- **Mobilize green capital and investment.** Much more public and private money would need to be invested in precommercial technologies and rapidly deploying commercially mature infrastructure. Investors that provide environmental, social, and corporate governance (ESG)-aligned funding mandates that require businesses to quantify their exposure to climate risks and emissions could also play an important role.
- **Accelerate net-zero technologies along their learning curves.** Achieving the necessary technological breakthroughs to reduce emissions in hard-to-abate sectors and accelerating their progress to market would require consistent public and private investment. It would also require greater willingness among business leaders and policy makers to adopt new technologies.

Successful decarbonization requires deploying and scaling net-zero technologies. The journey for any one technology from early-stage R&D and proof-of-concept to early deployment and commercial competitiveness depends on a complex system of support models and stakeholders. Accelerated innovation is critical, along with commercial pilots and capturing industrial scale effects to drive down costs. Achieving net-zero by 2050 would require the following immediate actions:

1. **Rapidly scale cost-competitive technologies and business models to reduce near-term emissions.** Expediting the scale-up of available mature and early-adoption zero-emissions technologies is crucial to meeting near-term reduction targets. These include solar and wind power, EVs and charging infrastructure, better building insulation, and district heating systems.
2. **Accelerate next-generation technologies and invest in enabling infrastructure to reduce emissions after 2030.** To boost industry-wide innovation, funding mechanisms for deploying early technology should encourage collaboration. Policy makers could create regulatory certainty with CO₂ and hydrogen price floors, regulated returns on infrastructure, and the like to mobilize capital for essential infrastructure such as carbon and hydrogen pipelines.
3. **Invest in R&D and negative emissions to close the gaps to net-zero by 2050.** Over the long term, increasing public and private investments in R&D that drive down the cost of things like direct air capture technologies will be critical for achieving net-zero. It will also be essential to invest in reorganizing land use to generate negative emissions through efforts like reforestation. Lawmakers can also start passing legislation that creates glide paths for each sector to reach net-zero emissions, such as automotive emissions standards now in effect in the transportation sector.



Actions for CEOs and policy makers

Achieving net-zero within 30 years will require governments to set a clear direction and provide adequate support while business becomes the engine of innovation and delivery.

Here, we explore some of the actions that business and public sector leaders could consider to achieve this.

CEOs

Create strategic alignment

- Value climate risk. Establish processes and governance to measure and assess climate risk exposure and integrate that assessment into strategic and capital planning. Quantify the business' exposure to physical, transition, and liability risks from climate change.
- Align strategic narrative. Craft a strategic narrative that includes a clear stance on the risks and opportunities arising from climate change and the role the organization aims to play in the transition.

Reallocate capital and people

- Pivot capital. Review the business from a zero-emissions budget perspective, co-optimizing for "Return on Carbon" (determining where each ton of emissions adds the most business value). Reduce portfolio exposure to climate risk and deploy capital to capture opportunities from the green transition.
- Invest in reskilling. Enhance productivity by anticipating labor shifts brought by new technologies, and consider reskilling, outsourcing, and replacing talent where necessary. Conduct workforce planning with long time horizons, and consider collaborating with others on reskilling, including organizations developing digital talent.
- Invest in R&D. Capture opportunities in the green transition by investing in next-generation technologies that would help enable a net-zero future. Derisk capital investments through commercial, technical, and policy innovation.

Engage stakeholders to shape the transition

- Constructively shape regulation. Dialogue between business leaders and policy makers will be critical to creating win-wins in the green transition. Business leaders will need to consult with policy makers to determine what's required to accelerate emissions reduction and how they can help meet climate targets. They can also influence how environmental performance is measured and reported while setting the bar on reporting and disclosures.
- Form coalitions for action. To make their efforts and investments go further, business leaders can also form alliances with peers at the industry and value-chain level. This would enable companies to create mass demand for green products and accelerate the innovation and scale-up of green technologies.

Policy makers

Strengthen interventions and cooperation

- Strengthen interventions. Policy makers can accelerate and reduce the cost of the transition to net-zero by influencing corporate and consumer behavior. These interventions could include extending subsidies, enacting stricter emission standards, and banning sales of higher-emissions products.
- Resolve agency issues. Throughout this process, policy makers will need to address agency issues across sectors, technologies, and regions that could slow decision-making and action.
- Create internationally harmonized commitments. Policy makers can strengthen international cooperation to decarbonize the aviation and shipping industries with measures such as harmonizing technology standards and refueling infrastructure at airports and harbors. Common product standards could help reduce the cost of the transition.

Lean forward on capital and investments

- Mobilize capital. Policy makers can help mobilize capital for green initiatives by removing process barriers that introduce costs, standardizing contracts, providing carbon price floors and public guarantees, and offering tax incentives. Policy makers can also incorporate green principles into government procurement processes. Public investment in R&D to pursue breakthrough technologies could also reduce transition costs.
- Lean forward on infrastructure spending. The lack of infrastructure needed for switching to clean technologies and techniques often requires public intervention in the form of regulation, direct investments, or public-private partnerships.

Do not leave the vulnerable behind

- Address distributional challenges. Although the transition to net-zero would be cost neutral at an aggregate level, it will impact some people more than others. These socioeconomic disparities would need to be carefully managed.
- Provide financial and in-kind support to developing countries. Working together can yield better outcomes than individuals acting alone. Providing support across borders can generate better results for society as a whole while reducing global emissions.

1. Getting to net-zero by 2050





1.1 Aiming for climate neutrality

In December 2019, the European Commission (EC) announced the European Green Deal, a new policy framework intended to accelerate greenhouse gas (GHG) emissions reduction across the European Union.⁵ Among the policies under consideration is a law that would require the bloc to reduce GHG emissions by 55 percent relative to 1990 by 2030 and reach net-zero by 2050.

The European Union has a history of meeting its decarbonization targets. When it signed the Kyoto Protocol in 1997, the European Union committed to reducing its GHG emissions by 8 percent by 2012. It over-delivered, reducing them by 18 percent. In 2010, the EC set another target: reducing the continent's emissions by 20 percent by 2020. The EU surpassed that goal by 2018.

Although the EU accounts for only 7 percent of global GHG emissions, the benefits of a net-zero Europe would far exceed having fewer heat-trapping molecules in the atmosphere.

A Europe on net-zero trajectory would accelerate investment in green technologies, test and refine global industrial strategies and market designs, and provide lessons from which the rest of the world could learn. By taking the lead on this issue, the European Union would encourage other countries to make their own climate change goals more ambitious. At the same time, EC climate change proposals, such as imposing a carbon border tax, would influence the carbon footprint of supply chains around the world.



⁵ In this document, the European Union refers to the 27 member states that will together constitute the European Union after Great Britain leaves. We use “emissions reduction” to refer specifically to “GHG emissions reduction” and may also use these terms interchangeably with “decarbonization.” “Net zero” or “net-zero emissions” refers to net-zero GHG emissions.

1.2 The situation today

1.2.1 EU GHG Emissions

In 2017, the European Union's total GHG emissions were 3.6 GtCO₂e (including 0.3 GtCO₂e negative emissions, excluding international transportation).⁶ Although this accounts for just 7 percent of global GHG emissions and is much lower than the continent's 20 percent contribution to the global GDP, it's slightly higher than the European Union's 6 percent share of the global population.⁷

About 80 percent of the European Union's greenhouse gases are CO₂ emissions from fossil fuel combustion. The remaining 20 percent are other types of GHG, such as methane and nitrous oxide emitted in the industrial and agricultural sectors.

At a high level, these emissions originate from five sectors: power, industry, buildings, transportation, and agriculture. Since 1990, emissions in these sectors have declined by 1 to 2 percent a year, except in transportation where, despite energy efficiency improvements, emissions have increased by 0.8 percent a year. Industry is the largest source of emissions today, followed by power and transportation. A sixth sector, land use, land-use change, and forestry (LULUCF), absorbs CO₂ and partly offsets emissions from these other sectors.

When looking at GHG emissions by country, we see, as expected, that emissions strongly correlate with a country's GDP. Some exceptions to this rule are the Nordic countries, which have lower net emissions than other high-GDP countries because of their vast stretches of land that absorb CO₂. Some Central European countries have higher emissions than their GDP would suggest because of their higher dependence on coal for power generation.

1.2.2 The EU energy system

Although the European Union's total primary energy demand has remained constant, emissions have declined slightly since 1990 because its energy efficiency improvements have offset economic growth (Exhibit 14).⁸ However, the underlying energy mix has changed since 1990, with coal demand declining by 2 percent a year and biomass and other renewable energy sources increasing by 4 percent annually and 3 percent annually, respectively.

Energy uses vary considerably by sector. Transportation consumes mostly oil and almost no other fuel. Power draws on a wide variety of energy sources, using nuclear, solar, and wind for electricity generation in addition to fossil fuels. Industry and buildings use a mix of fossil fuels. Natural gas is more prevalent in the buildings sector for space heating and cooking purposes. In the industry sector, oil is mainly used in the chemicals sector.

This profile of fossil fuel consumption is similar across the EU. The biggest differentiator of fossil fuel dependency between regions is the power generation mix. For instance, the energy system's fossil fuel share in France and the Nordics is lower than in other regions because they use more nuclear and hydropower. In the other sectors, the percentage of fossil fuel consumption is similar across countries (Exhibit 15).

⁶ We use 2017 as the base year for our pathways because it is the most recent year for which good data are available. In our calculations, we follow the established practice of using a production-based rather than consumption-based emissions measurement. We only include emissions in the EU-27. One exception is our inclusion of the implied emissions from fuel use for international aviation and marine vessels bunkered in the EU even though they aren't necessarily emitted there.

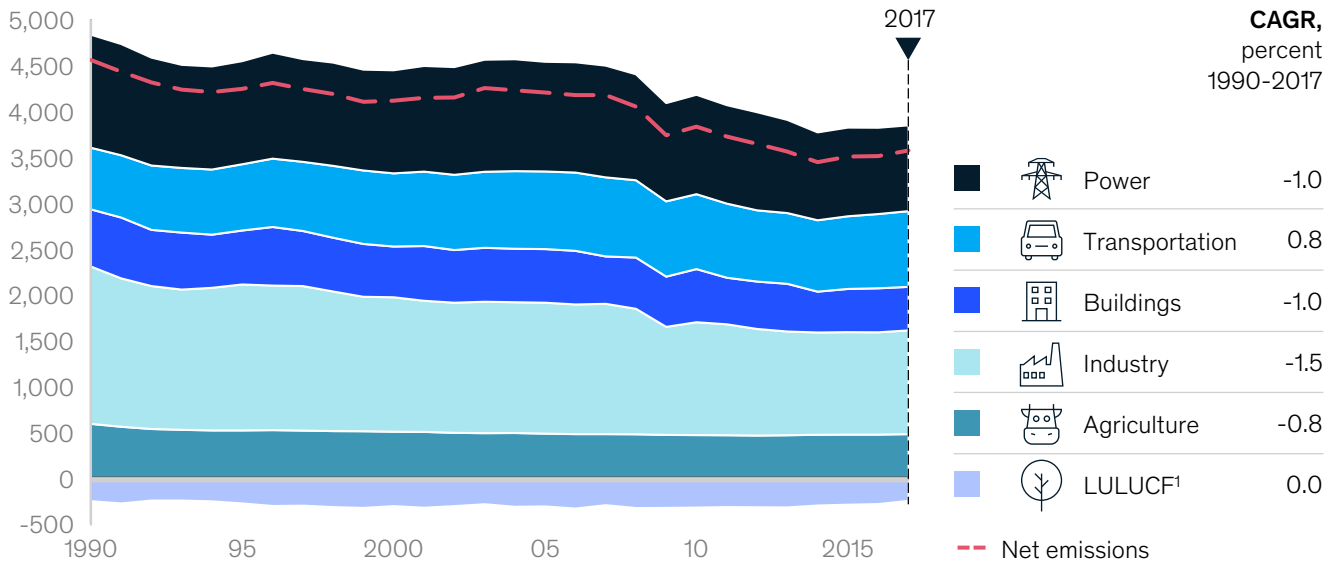
⁷ In 2017, global emissions were 55 GtCO₂e, and EU-27 emissions were 3.9 GtCO₂e (including LULUCF and international transportation). We excluded international transportation from our modeling, leaving 3.6 GtCO₂e for the EU-27. Global GDP was \$80.3 trillion in 2010 and the EU's GDP was \$16 trillion in 2010 (World Bank). The global population was 7.5 billion, and the EU population was 0.45 billion (World Bank)

⁸ The demand for energy in its raw form, before it has been converted to secondary energy such as electricity or district heating.

The bulk of Europe's emissions are generated by five sectors.

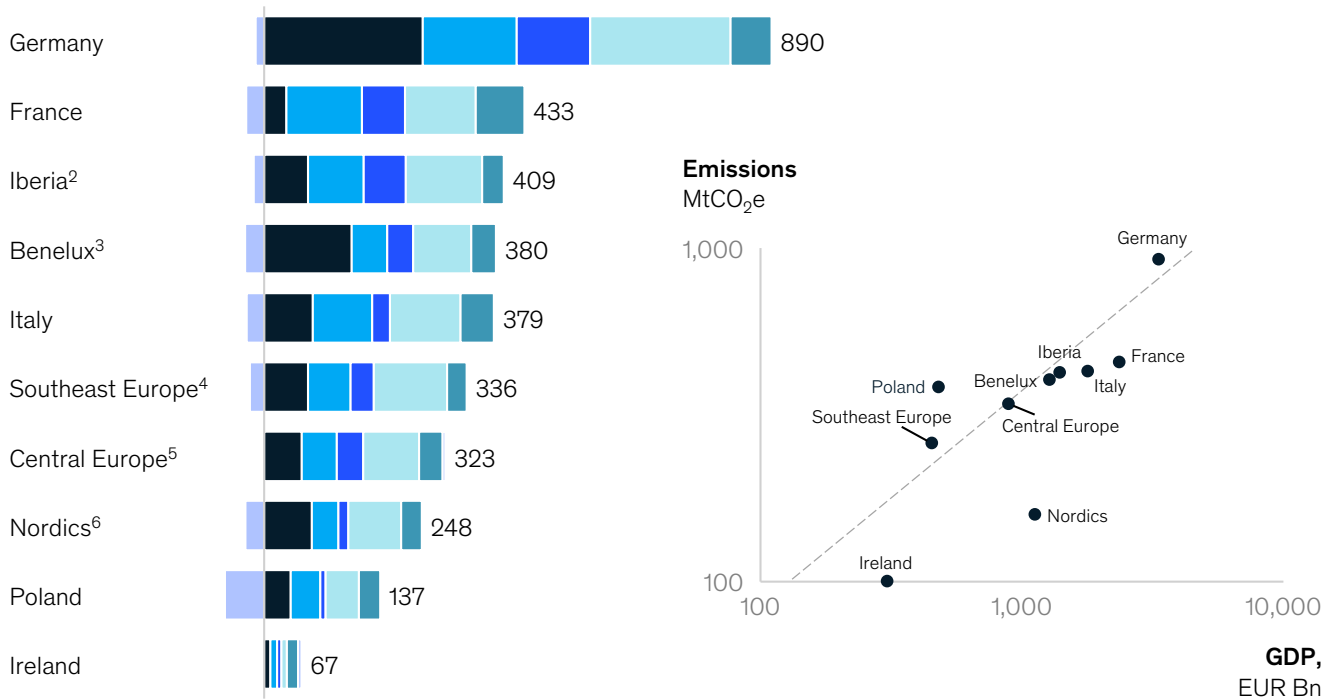
Historic emissions by sector

MtCO₂e



Emission baseline by sector and region

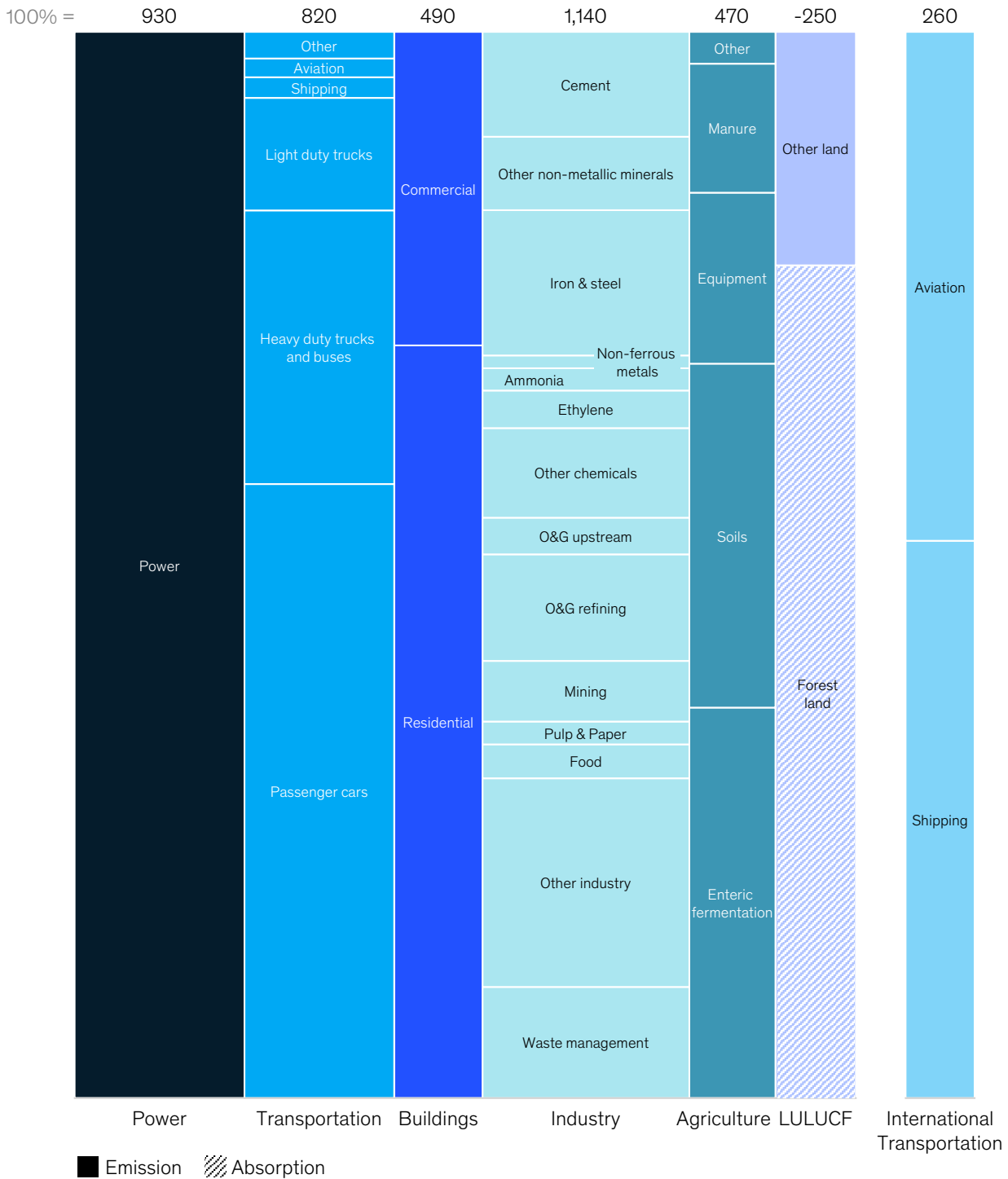
MtCO₂e, 2017



Emission baseline by sector
MtCO₂e, 2017

Emissions shared with non-EU countries

Direct EU emissions



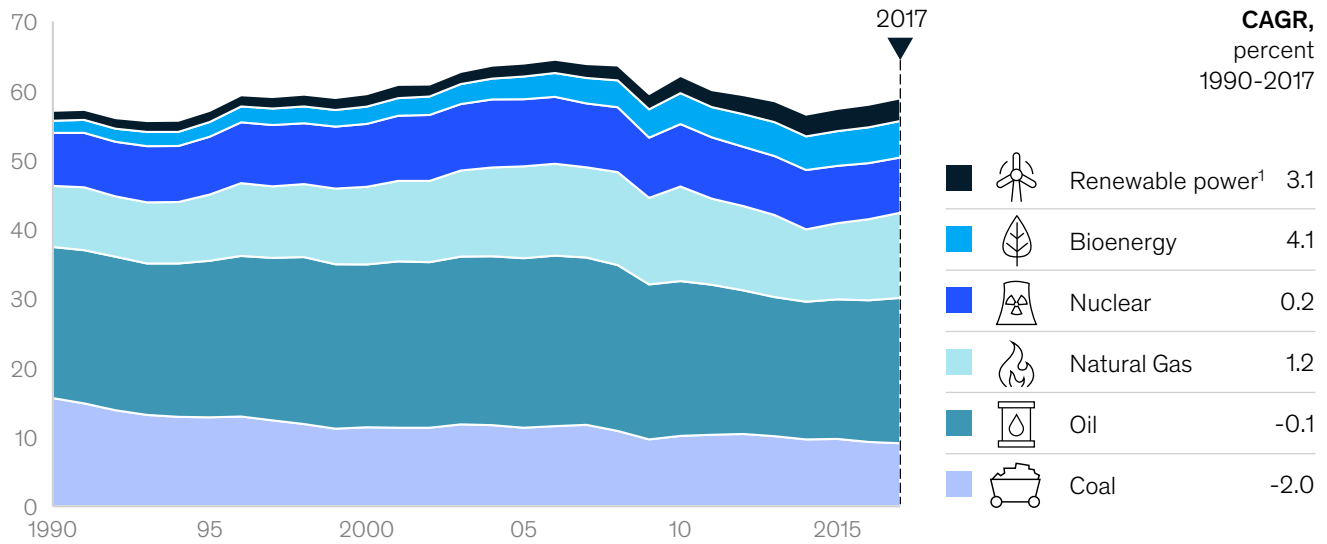
1. Land Use, Land Use Change and Forestry entails all forms in which atmospheric CO₂ can be captured or released as carbon in vegetation and soils in terrestrial ecosystems
 2. Spain & Portugal
 3. Belgium, Luxembourg, Netherlands

4. Bulgaria, Greece, Romania
 5. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia
 6. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

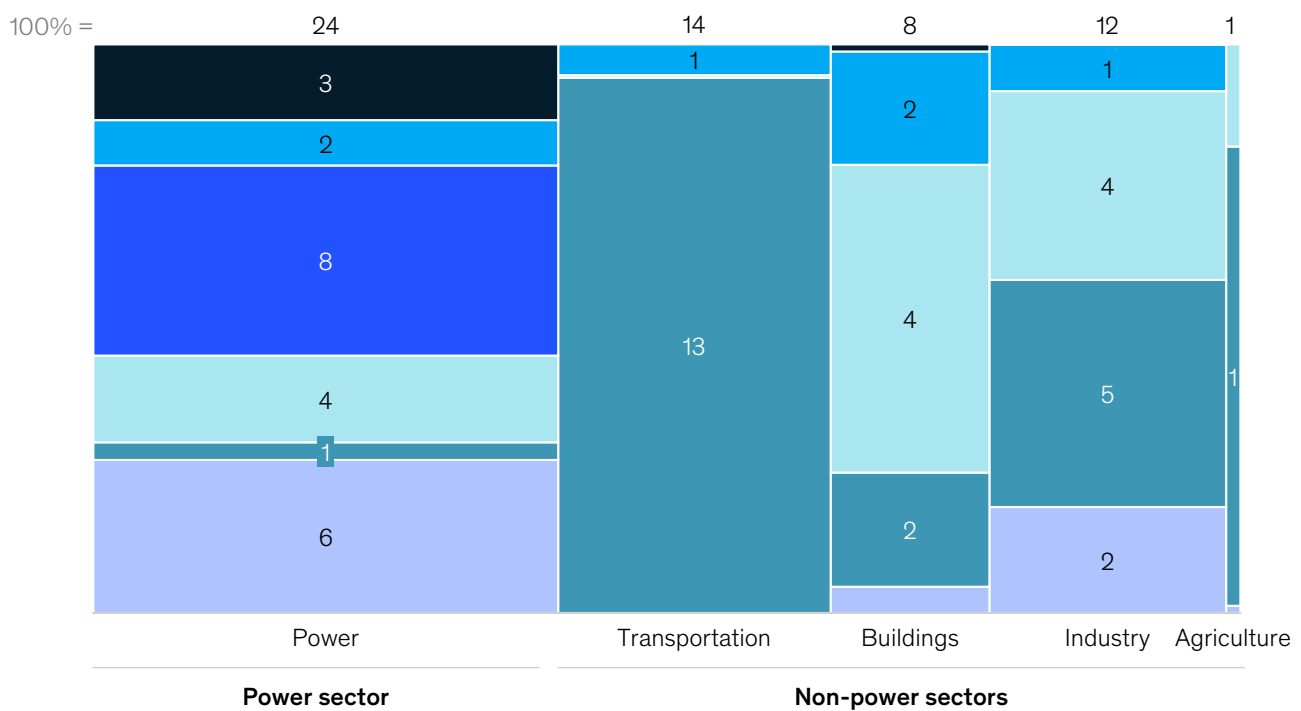
Source: McKinsey, IEA, UNFCCC

As of 2017, fossil fuel use varied widely across EU-27 regions in the power sector, but every region relied heavily on fossil fuels for non-power sectors.

Historic total primary energy demand by source
Million TJ

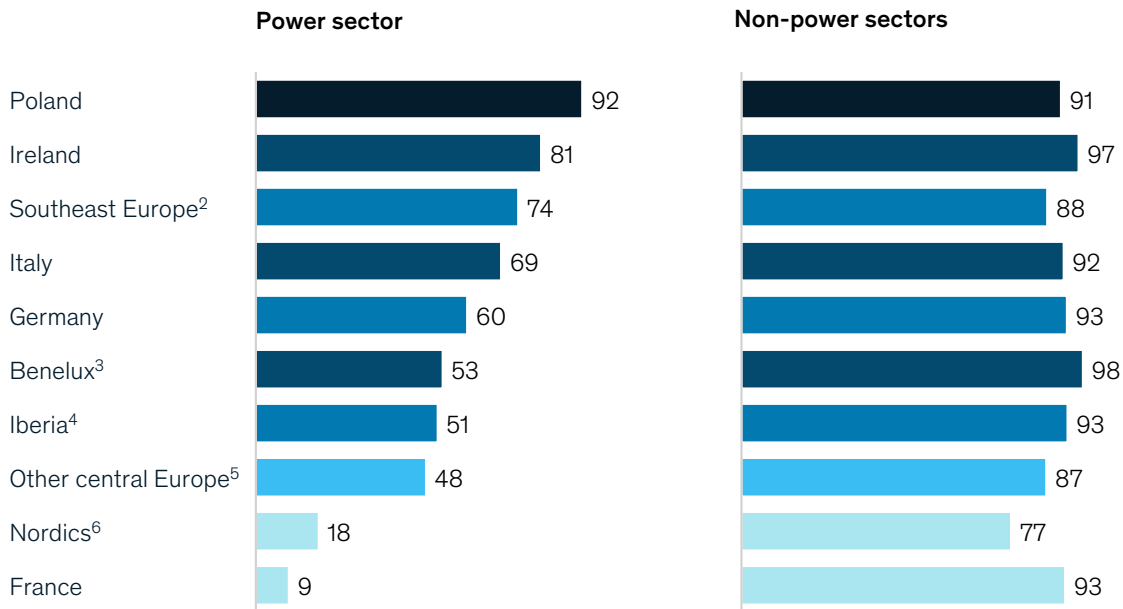


Total primary energy demand by sector
Million TJ, 2017

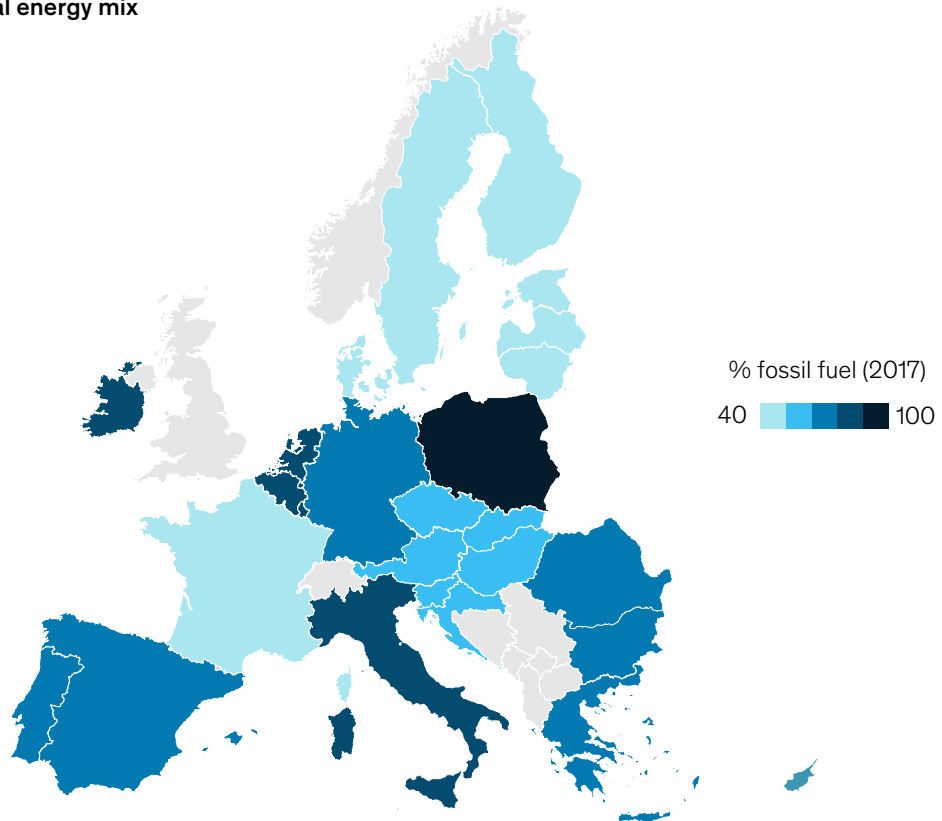


Sectoral fossil fuel use

Percent



Fossil fuel use in total energy mix



1. Includes solar PV, wind power and hydro power

2. Bulgaria, Greece, Romania

Source: McKinsey, IEA, UNFCCC

3. Belgium, Luxembourg, Netherlands

4. Spain & Portugal

5. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

6. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

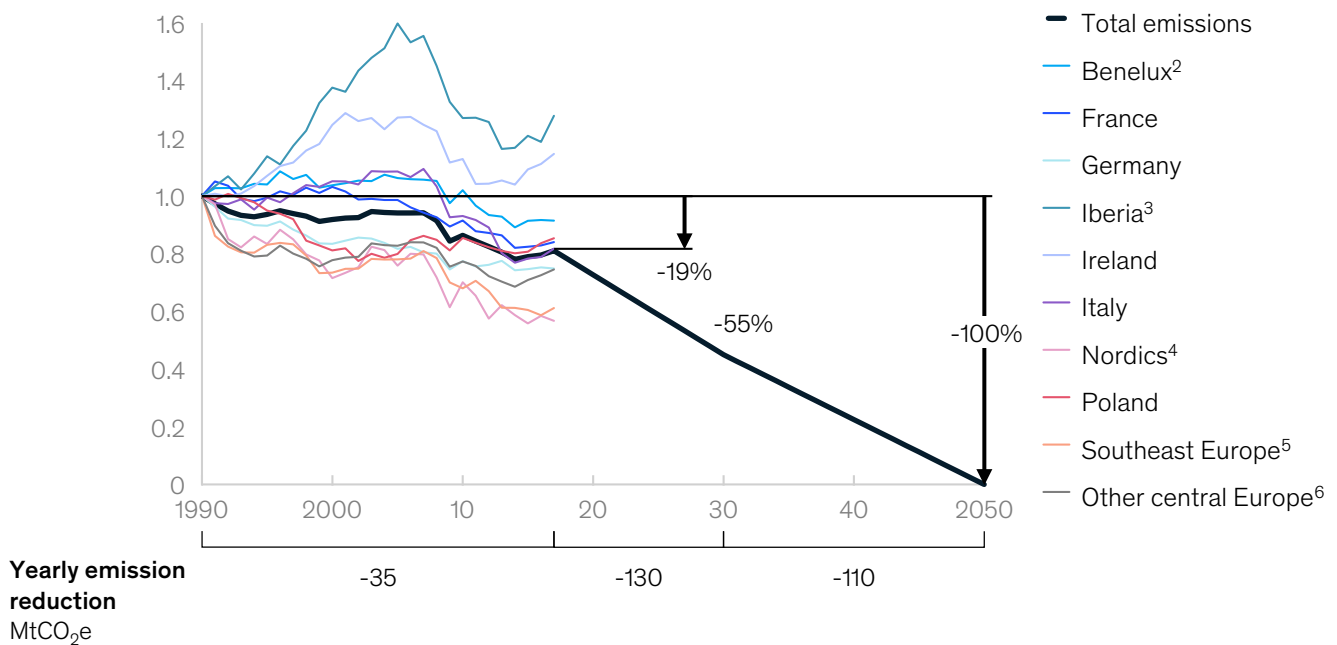
1.3 The road ahead

From 1990 to 2017, the EU's GHG emissions dropped 19 percent, driven by greater energy efficiency and renewable electricity use. Despite this progress, the EU would need to decarbonize three to four times more quickly to meet its emissions-reduction targets (Exhibit 16). Regional differences in today's energy systems, such as the carbon intensity of the power grid and the industrial landscape, will require different local approaches. There are easy ways to decarbonize in some places, but the overall gap to the 2030 and 2050 targets is much larger than the emissions reductions the EU has achieved before.

Exhibit 16

The EU will need to reduce net GHG emissions much faster to meet 2030 and 2050 climate targets.

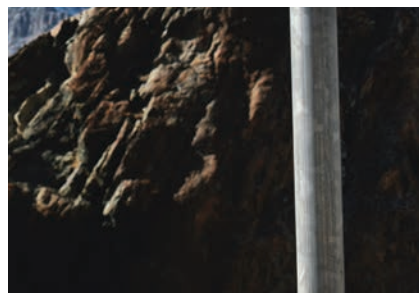
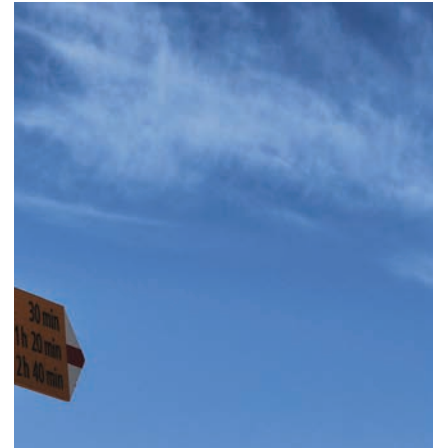
Emission development, indexed at 1 = 1990 level¹



1. Includes impact of land use, land-use change, and forestry (LULUCF) on GHG emissions.
 2. Belgium, Luxembourg, Netherlands
 3. Spain & Portugal

4. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden
 5. Bulgaria, Greece, Romania
 6. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

Source: McKinsey, Eurostat, EEA



Our methodology, and what this report is and is not

There are many paths to achieving European Union climate neutrality by 2050. In this report, we outline and explore one particular pathway that is feasible from a technology and supply chain perspective and cost-optimal in aggregate, based on current outlooks.

To arrive at this societally cost-optimal pathway⁹ to net-zero emissions, we applied more than 600 decarbonization lever business cases across 75 subsectors in 10 regions to minimize the overall cost to the European Union of achieving the 2030 and 2050 targets. To create a sector pathway, we split EU emissions into more than 100 segments and projected the demand for the product (such as cement) or service (such as passenger kilometers travelled) for each segment. We identified the emission-reduction levers for each segment and incorporated regional commodity price trends and developments. In this optimization, we accounted for many EU-wide and regional constraints, such as the amount of sustainably available biomass, supply chain constraints limiting the ramp-up rates of EV production, and the total available land for generating renewable power. We did not constrain economic growth or consumption, and we assumed that production locations do not shift.

And we did not account for the value of the non-monetary benefits of reducing emissions, such as reduced air pollution and associated health benefits or reduced physical climate risks. The result is a pathway that outlines how member states could work together across sectors to reduce the European Union's overall emissions by 55 percent (compared to 1990) by 2030 and 100 percent by 2050. For more details on our methodology and assumptions, refer to the Technical appendix, Section 6, and for a view on the uncertainties in our modeling, refer to Pathway ambiguities, Section 2.4.

This is not a forecast. Achieving the EU climate goals would require a substantial departure from the current trajectory. Since the impacts of the transition would be unevenly distributed and create challenges for many individual companies and actors, significant changes in regulation and incentives would be required. And while we lay out a pathway optimized for net costs, in reality, other factors would undoubtedly impact the decarbonization pathway the European Union ultimately takes. Nonetheless, we believe investigating this pathway is valuable for two reasons; first, it provides a helpful roadmap based on current best understanding, and second, it is a valuable tool to explore the magnitude of the challenge and the resulting socioeconomic implications.

It also is primarily a “macro” view. Our scenario minimizes net system costs using a societal discount rate. It is important to bear in mind that the perspective of individual stakeholders and the decisions they would take in the absence of changes in regulation and incentive structures may differ, both because there are disparate impacts on individual stakeholders and because they may apply different costs of capital and payback expectations in investment decisions; for an investigation of the latter point and how capital could be mobilized, see Bridging the finance gap, Section 4.1.3. While we explore macro-level socioeconomic implications such as employment displacements, impacts on household costs, structural cost changes on the sector level, and risks and opportunities for trade and production, we do not investigate the specific challenges that the zero-emissions transition creates for individual companies. These can be significant. And while we explore some of the potential actions that business leaders and policy makers can take to navigate and shape the transition in Section 5.2, detailed perspectives on how players in each sector can navigate and thrive in the transition are not within our scope. These sector-specific company-level “micro” views will be the subject of future publications.

⁹ We define the “societally cost-optimal” pathway as the most cost-efficient way in which society as a whole can achieve net-zero emissions by 2050. In technical terms, we minimize the sum of the net present values (NPVs) of all measures/investments, with individual NPVs calculated for the point in time the first associated investment is made. We use a common societal discount rate and reflect the total cash flows borne from the investments needed in the net-zero transition, irrespective of how the costs and benefits are divided between different stakeholders.

How to read this report

The high-level results of our pathway modeling, from the primary abatement measures to the required redesign of the energy system, are discussed in Chapter 2.

Each sector has a different starting point and faces unique challenges in reaching climate neutrality. We present the cost-optimal pathways for each sector in Chapter 3, and discuss the roles of hydrogen, CCS, and biomass.

Reaching net-zero by 2050 will have significant socioeconomic implications such as financing challenges, changes to the labor market, transforming trade and production, and shifting land use. We discuss these implications in Chapter 4.

The road to net-zero emissions starts today. We provide recommendations on how to overcome the barriers to achieving the EU's ambitious climate targets in Chapter 5.

We provide more details on our modeling approach in the Technical appendix.

COVID-19's impact on long-term emission-reduction pathways

During the writing of this report, the societal and economic impacts of the COVID-19 pandemic on EU countries remained unclear. For many reasons, we don't believe the pandemic will result in long-term changes in energy consumption; the challenges that governments and businesses face in getting to net-zero remain the same.

For example, even though energy consumption in the transportation sector plunged during lockdowns, when people resumed driving their cars, there was no difference in fuel consumption or emissions per kilometer. That would require more permanent behavioral changes, such as drivers switching to electric vehicles.

Instead, the impact of the pandemic on the pathways will likely depend on its secondary effects, such as companies and consumers delaying investments in lower-emitting technologies because they are cash-strapped; government stimulus programs that accelerate investments in infrastructure, R&D, and supply chains; and businesses that decide to permanently adopt remote working.

2. The EU pathway to climate neutrality





2.1 Net-zero emissions at net-zero cost

Net-zero emissions by 2050 should be achievable at a net-zero cost without compromising overall economic growth or prosperity.

On the pathway we present, which does not constrain GDP growth or consumption, the net cost of achieving net-zero emissions is €0 per tCO₂e. Cost increases in sectors such as industry, with average abatement costs of €85 per tCO₂e, are offset by net savings in sectors such as transportation, with average savings of €100 per tCO₂e.

2.1.1 The costs of emissions-reduction by sector

Up to 2040, our analysis indicates that decarbonizing the power system could reduce the average cost of electric energy compared to today's system cost with grid expansion costs offset by the cost savings of switching to renewable power. The final leg to decarbonization—that is, eliminating the last 15 percent of power emissions from 2040 to 2050—would require more flexibility and cost more than €120 per tCO₂e.

Overall, the total decarbonization of the power sector would be cost-neutral by 2050.

With an average net savings of €120 per tCO₂e, the transportation sector would see the largest structural cost decreases. The electrification of cars, buses, and trucks reduces the total cost of road transportation, along with the proposed switch to hydrogen-fueled heavy road transportation after 2030. Decarbonizing aviation and shipping would be more expensive because it requires using advanced biofuels and synfuel instead of fossil fuels, which would cost more than €100 per tCO₂e.

Decarbonizing agriculture and buildings would require a mix of low- and high-cost actions. Agricultural emissions can be reduced through cost-saving measures such as switching to electric farming equipment and low-tillage practices, which would cancel out more expensive measures such as giving feed additives to livestock. Abatement in agriculture saves an average of €25 per tCO₂e. Similarly, cost-saving abatement options for buildings would nearly cancel out more expensive measures.

For example, the savings from introducing solar thermal and district heating in densely populated areas could offset the increased costs of using ground-sourced heat pumps, electric cooking, hydrogen, and biomethane blending elsewhere. The average abatement cost in buildings is €5 per tCO₂e.

Industry is the most expensive sector to decarbonize because of the challenge of reducing emissions without wholesale changes to manufacturing processes. High-cost options such as electric boilers and bioenergy with carbon capture and storage (BECCS) are only marginally offset by cost-negative measures such as heat cascading. The average abatement cost in the industry sector is €85 per tCO₂e.



2.1.2 The pace of emissions-reduction by sector

The cost-optimal decarbonization pathway follows a specific order in which sectors reach net-zero. This order is based on the interdependencies between and among sectors, relative costs, and the maturity of the technology required in each sector. Based on these factors, the first sector to reach net-zero would be power, then transportation and buildings, followed by industry and agriculture. Decarbonizing power could be achieved quickly because most of the technology for generating renewable power is already mature.

- By 2030, the power sector could reduce emissions by over 60 percent through low-cost options such as using wind and solar to generate electricity.
- As this capacity grows, power could abate 90 percent of emissions by the early 2040s.
- Eliminating the remaining 15 percent would be challenging because it requires implementing expensive measures to cover long-term seasonal flexibility needs.

Ramping up decarbonization in transportation would take time. The amount of emissions that can be reduced by 2030 depends on how fast EVs can replace petroleum-fueled vehicles.

- In road transportation, the required technologies are already in the early-adoption phase. However, scaling supply chains that could support the transition to 100 percent EV sales, from mining the raw materials for batteries to assembling EVs, is at least a decade-long process. This limits the sector's short-term abatement potential to 30 percent by 2030.
- After 2030, EV and hydrogen supply chains could be at scale, accelerating decarbonization. By 2045, more than 95 percent of today's transportation emissions could be abated. Aviation and shipping are the exceptions

because they have fewer scalable low-carbon alternatives and would need to rely on the more expensive option of switching to biofuels or synfuels to decarbonize by 2050.

Decarbonization of the buildings sector is likely to be slow but steady. Its potential is limited in the short term, but full decarbonization can be achieved by 2050.

- The technologies required to decarbonize the buildings sector, such as better home insulation and heat pumps, are already widely available. However, long renovation turnaround times and the need for skilled labor would limit the pace of change. By 2030, buildings may only be able to reduce emissions by 30 percent.
- After 2030, decarbonizing the buildings sector would steadily continue while requiring more costly measures such as hydrogen and biomethane heating. Towards the end of the 2040s, the sector could achieve 95 percent decarbonization.

Industry would be the most expensive sector to decarbonize because most of the emissions-reduction options are either cost-prohibitive or unavailable at scale.

- From 2021 to 2030, industry could reduce emissions by 35 percent, more than 75 percent of which would cost €50 per tCO₂e to €150 per tCO₂e. Because supply side constraints would limit the transportation and buildings sectors' contributions to the 2030 reduction target, industrial companies would have to implement more expensive decarbonization technologies, such as electric boilers and CCS, to get the EU to the 55 percent reduction target.
- After 2040, when power, transportation, and buildings reach almost their full abatement potential, industry would need to abate another 40 percent of its last, most expensive emissions. Part of the very hard-to-abate industrial

emissions are offset with BECCS on processes like ammonia or cement production. As a result, industry emissions could be reduced by more than 95 percent in 2050. The residual emissions would be offset outside the sector, for example by natural carbon sinks such as reforestation.

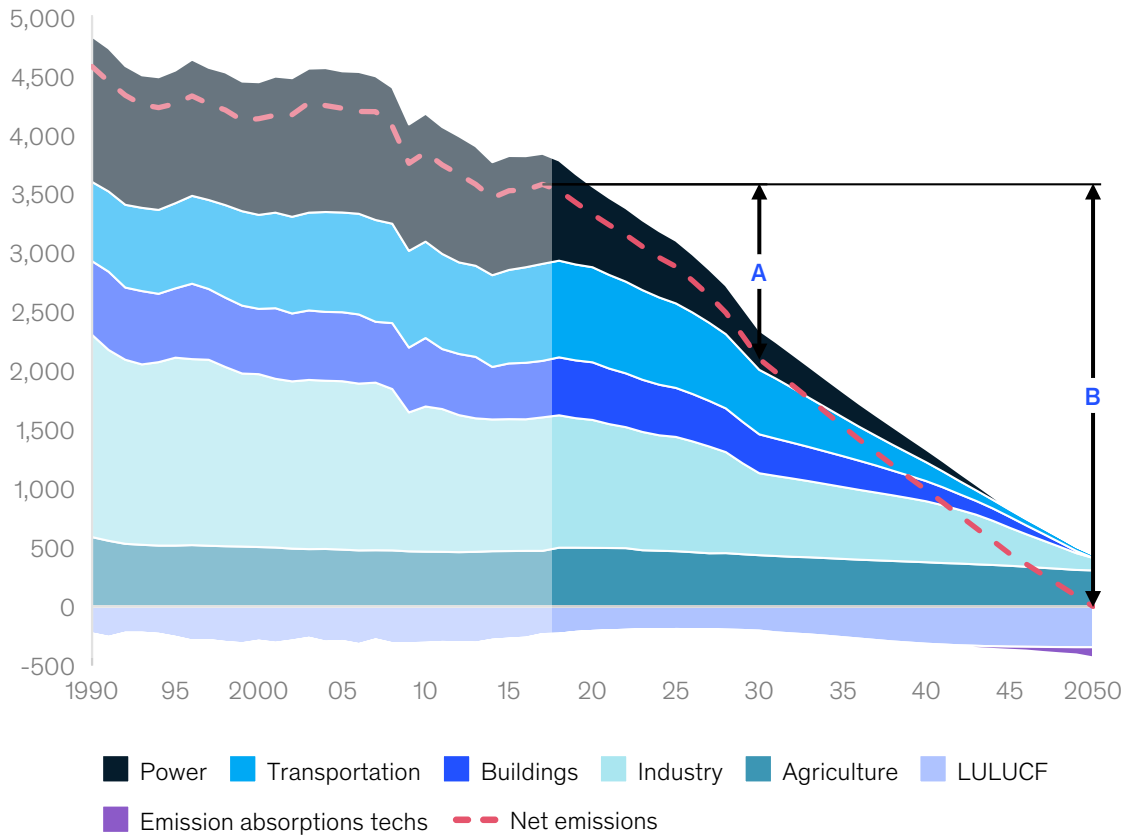
Agriculture has the most limited potential for reducing carbon emissions and cannot achieve net-zero by 2050.

- By 2030, only 5 percent of agricultural emissions would be abated because the most effective ways to reduce emissions require changes in human behavior and other developments that take time. The projected rise in agricultural activity in the future would also increase the abatement challenge.
- The agriculture pathway we outline reduces carbon emissions only 40 percent by 2050. The sector would still emit 300 MtCO₂e a year without, for example, a significant reduction in the amount of livestock raised for food.

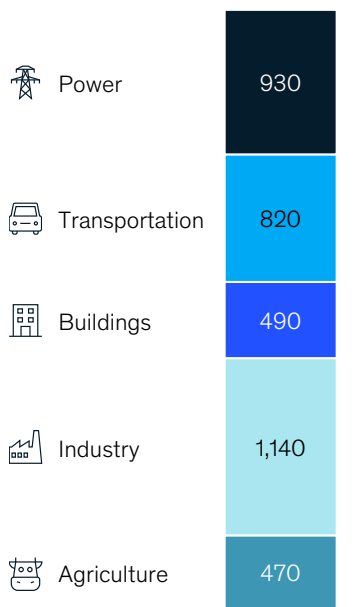
Once these five sectors have reduced all possible emissions by 2050, the remaining emissions would have to be offset by negative emissions generated by afforestation and emission absorption technologies like CCS. By 2050, energy system emissions would be negligible compared to agricultural emissions. So, although the pathway to net-zero emissions would depend on switching to low-carbon technologies, sustaining climate neutrality beyond 2050 would hinge on establishing a new approach to land use. (Exhibit 17)

The power sector would reach net-zero emissions before the others.

Total emissions per sector in cost-optimal pathway for EU-27
MtCO₂e, excluding international aviation and shipping



Current emissions
MtCO₂e, 2017

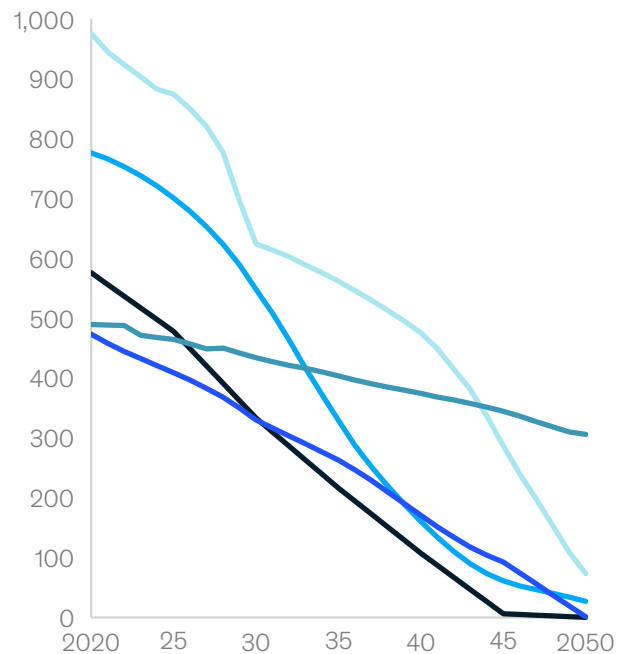


Decarbonization cost¹
EUR/tCO₂

2020-30 30-40 40-2050

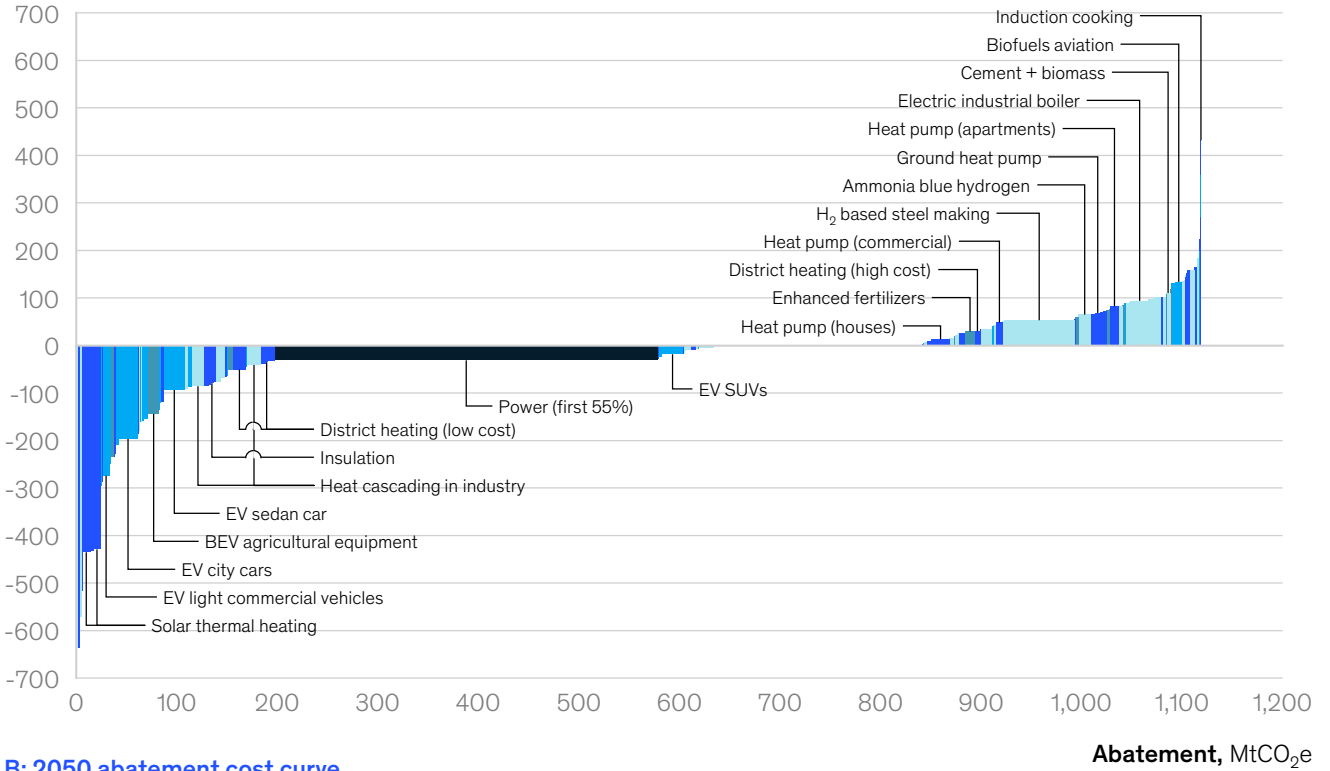
Sector	2020-30	30-40	40-2050
Power	-31	18	145
Transportation	-92	-149	-70
Buildings	-66	37	40
Industry	30	86	120
Agriculture	-27	-121	35

Emissions evolution
MtCO₂e



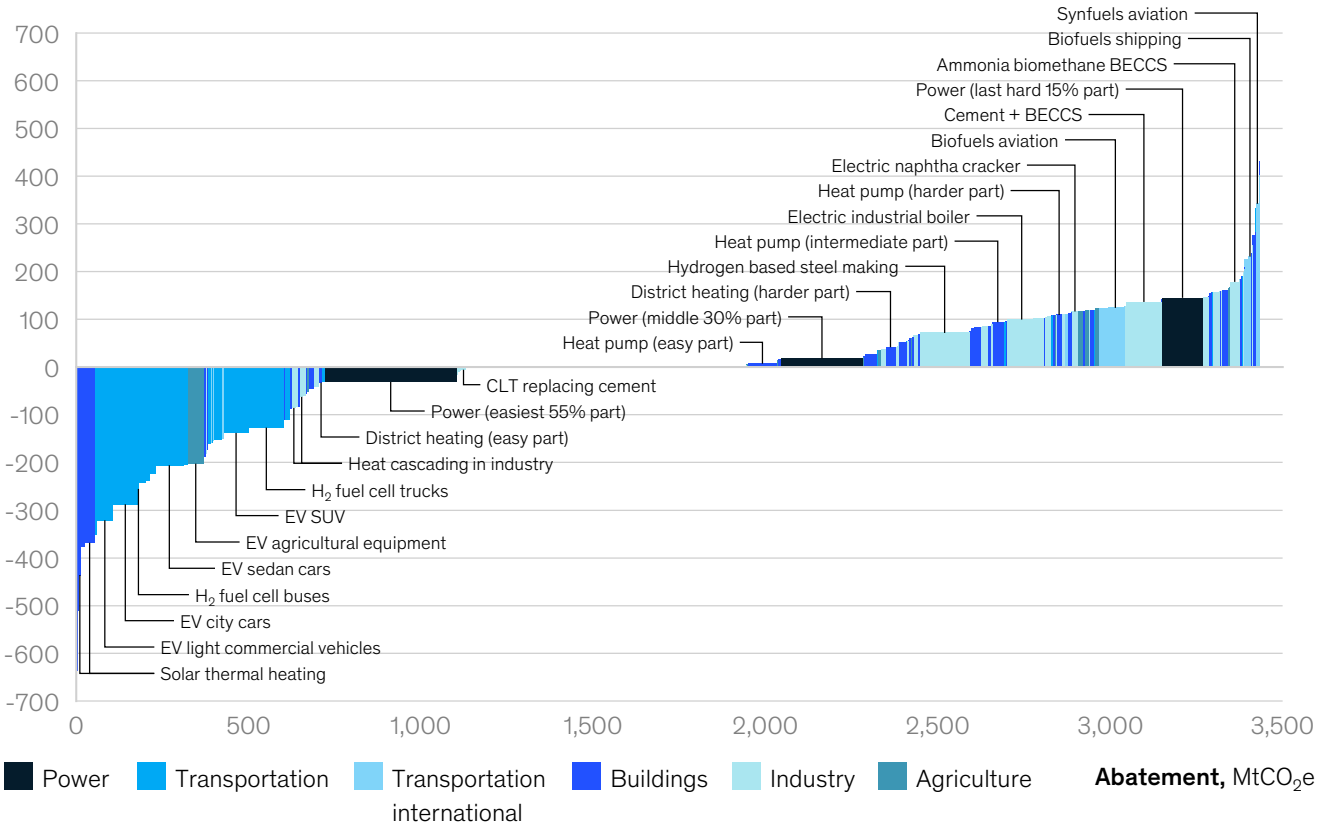
A: 2030 abatement cost curve

Abatement cost, EUR/tCO₂e



B: 2050 abatement cost curve

Abatement cost, EUR/tCO₂e



1. Weighted average
Source: McKinsey, UNFCCC

2.1.3 Key geographic differences in emissions-reduction pathways

The mix of cost-optimal measures for reaching net-zero varies by country depending on the following four factors:

1. Proximity to CO₂ storage locations. Because most of the European Union's known CO₂ storage locations are in the North Sea, CCS is expected to be less expensive in the adjacent regions. This would make CCS a more attractive decarbonization option for industrial clusters in Northern Germany, Benelux, and the Nordics than those in the south. As a result, according to the pathway we outline, more than 70 percent of CCS would be located in Northern Europe (See section 3.7).
2. Climate. The weather in each EU member state determines the decarbonization potential of heating technologies, renewables, and hydrogen, including:
 - Heating degree days. Countries with more heating degree days (those in which buildings need to be heated because the temperature is below 18° C) can better justify large capital expenditures such as better insulation and district heating. That's why 75 percent of all highly insulated houses and 65 percent of the district heating proposed in our pathway would be located in Northern European countries. District heating would be used in densely populated areas close to industrial clusters within these countries to take advantage of waste heat.
 - Solar irradiance. The amount of sunlight an area receives would determine the effectiveness of solar thermal heating and the cost of solar power. As a result, the solar thermal penetration in our pathway for Southern Europe is more than double that of northern regions. And more than 60 percent of the total 1,200 GW of added solar installations would be in Southern Europe. Access to low-cost renewable power is also expected to make green hydrogen production costs lower in the south than in the north. Lower hydrogen costs in the south would lead to faster hydrogen fuel adoption, especially for building and industry heating.
3. Wind speeds. Onshore and offshore wind speeds are generally higher in Northern Europe than in the south, resulting in lower wind-generation costs. Consequently, over 70 percent of the European Union's wind generation capacity additions through 2050 would be located in the north.
3. Agricultural decarbonization opportunities. Although agriculture is a difficult sector to decarbonize, there are cost-effective carbon abatement opportunities, particularly in regions like the Nordic countries, as well as in Iberia and Southeast Europe, where farmers can use new crop-management techniques to reduce emissions.
4. Available land for carbon sequestration. Land that can be repurposed for carbon absorption could help offset other, more expensive abatement implementations. Some regions have significant opportunities to increase GHG absorption through afforestation, including Iberia (38 MtCO₂) and France (29 MtCO₂).

Member states can better achieve EU climate targets together

Because of the differences in each country's starting point and their decarbonization options, taking a collective approach would be the most affordable way to achieve a climate-neutral European Union (Exhibit 18).

For example, it would be more challenging for Iberia to meet a national 2030 reduction target of 55 percent because the region's emissions have risen by 28 percent since 1990. Iberia would have to reduce its emissions by 65 percent to reach the 2030 target, which would require expensive technologies. In the near-term, focusing instead on lower-cost decarbonization opportunities in countries such as Germany, which has already reduced

emissions since 1990, would lower overall transition costs.

By 2050, those positions could reverse as Iberia begins to capitalize on afforestation and low-cost hydrogen from its abundant solar resources. Just as Germany's decarbonization efforts could offset Iberia's through 2030, Iberia could then offset residual emission from German industry to ensure the entire European Union achieves its 2050 target.

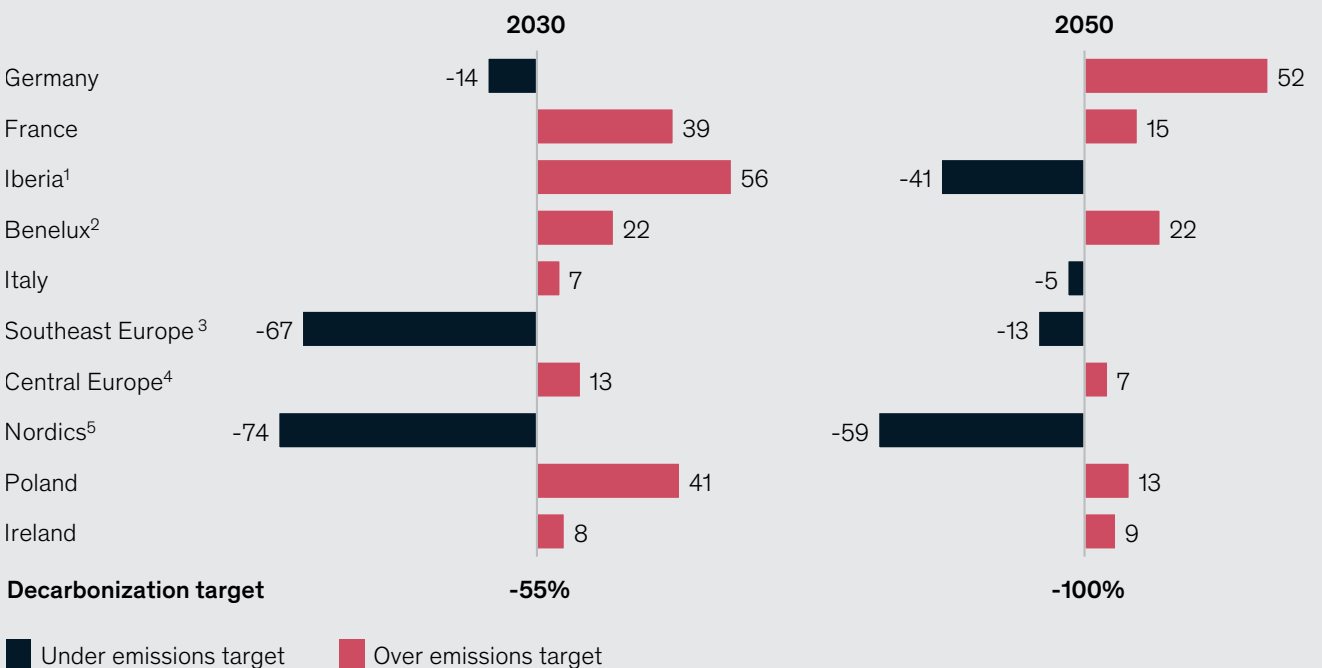
Aside from being costlier, taking an individual-country approach to meeting decarbonization targets could result in lock-ins on sub-optimal technologies in regions with more difficult abatement challenges. For example, regions with larger gaps to the 2030 target would likely invest in CCS to reduce industrial

heating emissions instead of waiting for electric furnaces to become more affordable. But after 2030, electric furnaces are expected to be cheaper than CCS for decarbonizing industrial heating. So, countries that invested in CCS to meet short-term targets run the risk of missing out on these kinds of opportunities. With inter-regional optimization, industrials can buy a few more years to decarbonize, allowing them to choose what may eventually prove to be less expensive technology.

Exhibit 18

The cost-optimal path involves some countries exceeding decarbonization targets to compensate for shortfalls in others.

MtCO₂e over/under EU-wide decarbonization targets



1. Spain & Portugal
 2. Belgium, Luxembourg, Netherlands

3. Bulgaria, Greece, Romania
 4. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

5. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

Source: McKinsey

2.2 Technologies and techniques required to reach net-zero emissions

Reaching net-zero emissions by 2050 would require significant changes in all five sectors. These changes can be grouped into eight categories (or levers) that range from reducing energy or resource use to switching to zero-carbon fuels or changing land-use and agricultural practices (Exhibit 19).

Each of the eight levers contains several specific measures, and some of those measures span more than one category. For example, BECCS is an abatement technique that involves using biomass as fuel (one lever) and CCS to capture and store the resulting CO₂ emissions (another lever).

From 2021 to 2030, more than 65 percent of the European Union's decarbonization would be achieved using two levers: increasing energy

efficiency and electrification. The third category of levers, demand-side measures and circularity, such as modal shifts in transportation and reusing waste heat in buildings and industry, would reduce emissions an additional 15 percent. The remaining 20 percent would come from four other levers: ramping up hydrogen use, increasing biomass use, land-use changes, and other innovations such as switching to a non-fossil fuel feedstock to make cement.

As we move toward 2040, direct electrification opportunities would start to reach their maximum potential, and other solutions would need to be implemented to meet the 2050 target. By 2050, 45 percent of the EU's total emissions would have been abated by switching from fossil fuels to electrification, and 30 percent would have been eliminated by using hydrogen, biomass, and CCS (Exhibit 20).

Exhibit 19

The EU could use eight decarbonization levers to reach net-zero emissions by 2050.



Demand-side measures and circularity

Lower the demand for primary resources by increasing circularity of products, e.g., reuse, recycling



Energy efficiency

Decreasing the energy intensity of equipment or infrastructure, e.g., building insulation or heat recovery improvements



Electrification and carbon neutral power

Replace fossil fuel with renewable electricity, e.g., from wind and solar farms



Carbon neutral hydrogen as fuel or feedstock

Replace carbon-intensive fuel or feedstock with carbon neutral hydrogen, e.g., in ammonia production



Biomass as fuel or feedstock

Replace the fuel or feedstock with sustainably-produced biomass or biogas, e.g., bio-based feedstock in chemicals production



Carbon capture and storage or use (CCS/U)

Use of technology to capture the CO₂ emitted in processes or fuel consumption for storage (CCS) or use (CCU)



Land use or agricultural practice changes

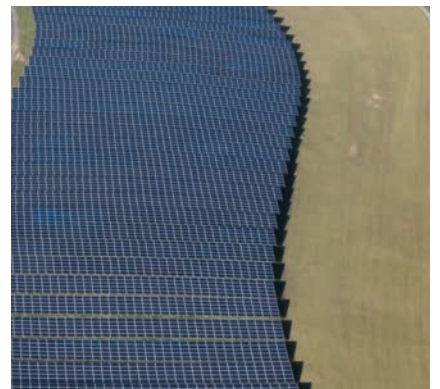
Change land use or agricultural practices to reduce net emissions, e.g., through afforestation (for negative emissions) or changing livestock feed



Other innovations

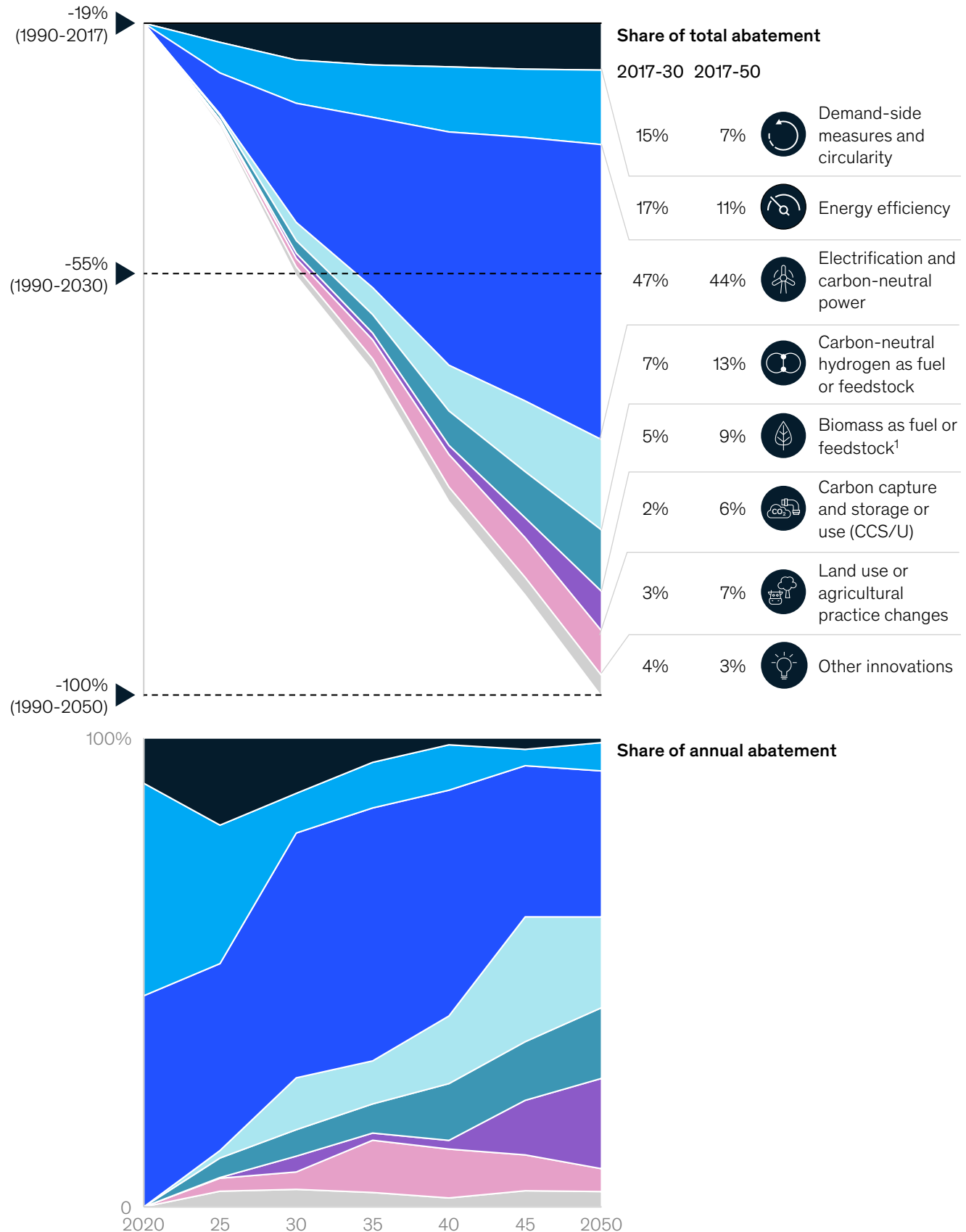
Innovative processes e.g., electrochemical production process
Non-fossil fuel feedstock change, e.g., change in cement feedstock

Source: McKinsey



Achieving net-zero GHG emissions by 2050 on the cost-optimal pathway depends on a mix of decarbonization technologies.

GHG abatement, relative reduction of CO₂e vs 1990 in EU-27



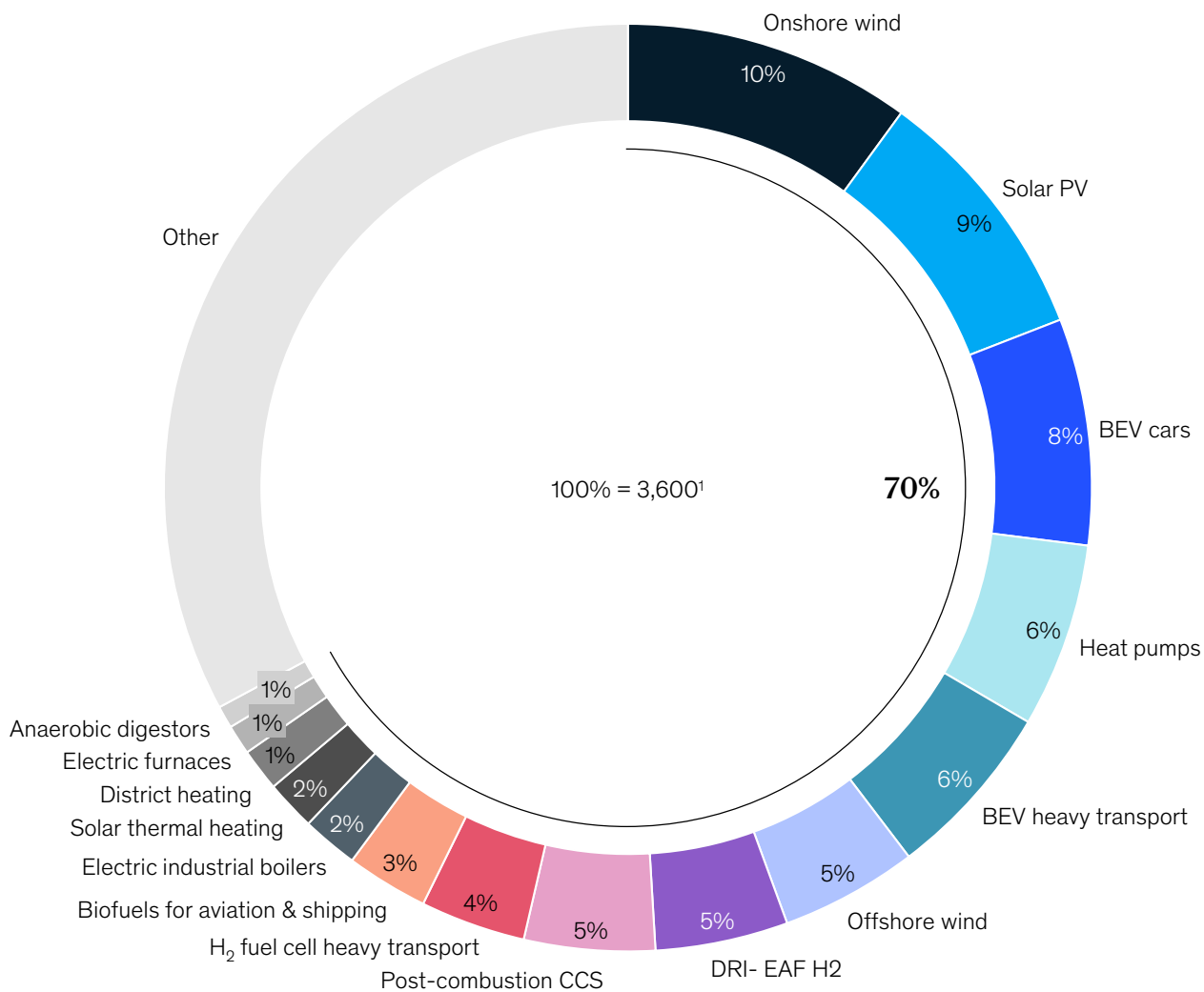
1. Of the total of the emissions reduced by Bioenergy Carbon Capture and Storage (BECCS), half are attributed to biomass and the other half to CCS
Source: McKinsey

A large proportion of abatement could be achieved using only a few technologies. The top 15 decarbonization technologies would eliminate 70 percent of the European Union's emissions by 2050. The top four alone—using onshore wind and solar photovoltaic (PV) technologies in power, switching to battery electric vehicle (BEV) for passenger transport, and installing heat pumps in buildings—would account for one-third of decarbonization (Exhibit 21).

Exhibit 21

Onshore wind, solar power, and battery electric vehicles make the biggest contributions to reaching climate-neutrality on the cost-optimal pathway.

Percent of total MtCO₂e abatement for EU-27, 2020-50



1. Net emissions after negative 0.3 GtCO₂e impact of LULUCF on GHG emissions

Source: McKinsey

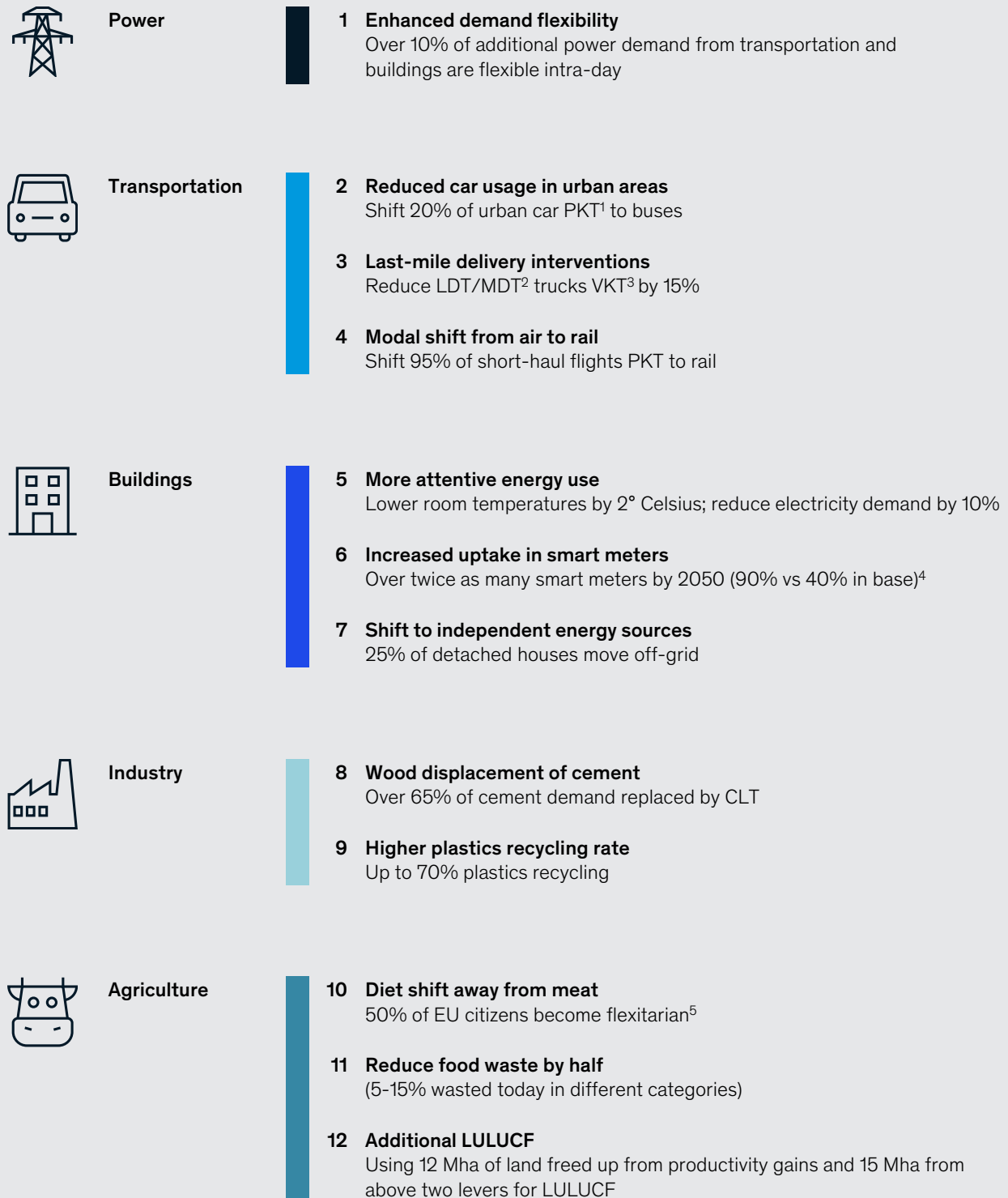
Behavior change and consumption shifts

One uncertainty over the next 30 years is how human behavior will impact the European Union's emission-reduction efforts. We did not include behavioral changes in our pathway because they are more difficult to influence and predict. However, these kinds of behavioral shifts, such as reducing meat consumption and car usage, could reduce the European Union's emissions by up to 15 percent. And these types of behavioral changes are typically much more cost-effective than technology-driven ones. Encouraging people to change their behavior to reduce the demand for fossil fuels and other GHG-emitting processes would make reaching the decarbonization target far less dependent on more expensive measures, such as implementing CCS in the industry sector. To explore the potential impact of these behavior changes, we analyzed 12 consumption shifts across sectors, ranging from replacing cement with CLT to people driving less and eating less meat (Exhibit 22).

The behavior changes we investigated in the buildings and transportation sectors would reduce emissions an additional 120 MtCO₂e a year by 2030, which would allow industry more time to develop new technologies and pursue lower-cost solutions. This would decrease the average cost of abatement by one-third through 2030.

Increasing LULUCF absorption by 130 MtCO₂e per year would also help eliminate the need for costlier measures to decarbonize the industry and agriculture sectors. When we include these behavior shifts, the average cost of decarbonization decreases by 15 percent to €55 per tCO₂e from 2040 to 2050. When we factor them into the entire transition from 2021 to 2050, they generate a cost savings of €15 per tCO₂e.

12 behavioral changes not included in the cost-optimal pathway model could lower EU emissions another 15 percent.



1. Passenger Kilometers Travelled (PKT)
 2. Long-Distance Truck (LDT); Medium-Distance Truck (MDT)
 3. Vehicle Kilometer Travelled (VKT)
 4. Expected to lead to reduction in energy use as heating turns off when you are not at home
 5. Eating meat once per week and roughly 70% lower dairy consumption

Source: McKinsey

Although a large share of emission reductions could be achieved with only a few mature technologies, accelerated innovation across the full technology portfolio will be critical to reaching complete climate-neutrality. Over half of abatement by 2030 could be achieved using already mature (but not necessarily commercially competitive) technologies, such as heat pumps in buildings, heat cascading in industry, and onshore wind adoption in power. Over a third would come from scaling technologies now in the early-adoption stage, such as EVs. To reach the 2030 target, the last 10 percent of abatement would come from proven technologies like CCS.

By 2050, those mature and early-adoption technologies would reach their maximum market penetration, accounting for 60 percent of total abatement. Demonstrated technologies such as CCS and low-temperature hydrogen heating would need to be rapidly scaled after 2030 to reduce emissions an additional 27 percent. The last 14 percent of decarbonization would depend on the successful development of technologies such as electric and fuel cell technologies for

aviation, shipping, and long-haul road transport, and long-term flexibility solutions in power (Exhibit 23).

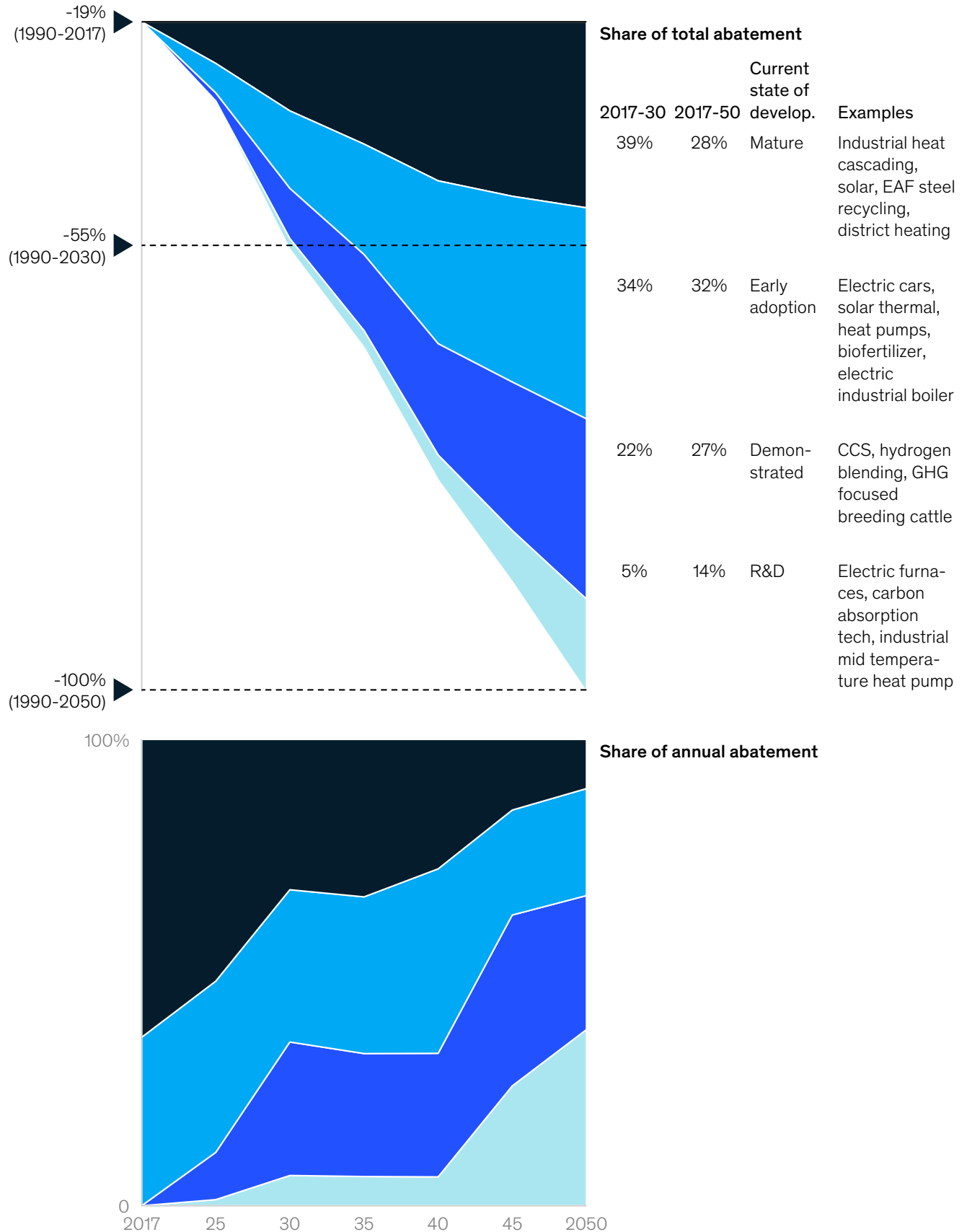
To meet the 2050 target, continued R&D in these emerging technologies would be critical. It may turn out that these technologies do not pass the R&D stage (or only with significantly smaller applicability), so alternative solutions would be needed.

Although most abatement would come from already mature and early-adoption technologies, it will be essential to accelerate innovation and industrialization across the entire zero-emissions technology portfolio to enable at-scale deployment and drive down transition costs. For example, solar panels have become much cheaper due to continued innovation and the industrialization of production. In the next 20 years, products such as EVs and electrolyzers could undergo analogous price drops.



More than 85 percent of cost-optimal GHG abatement can be achieved with technologies that are mature, in early adoption, or already demonstrated.

GHG abatement, relative reduction of CO₂e vs. 1990 for EU-27



Source: McKinsey

2.3 Redesigning the EU energy system and changing land use

2.3.1 Transforming the EU energy system

Today, the European Union depends on fossil fuels to meet 75 percent of its primary energy demand. To reach climate neutrality by 2050, more than 80 percent of demand would need to be satisfied by zero-emissions alternatives. However, this transition would require more than just switching primary fuels. The new energy system would rely much more on the power sector.

Today, 40 percent of the European Union's demand for primary energy comes from the power sector, which then supplies energy in the form of electricity to other sectors. Those sectors—industry, transportation, buildings, and agriculture—account for the other 60 percent of the primary demand.

As we get closer to 2030, the power sector would start consuming a larger proportion of primary energy as the other sectors switch to electricity. For example, reaching net-zero emissions in the transportation sector would require shifting from petroleum-fueled cars to electric. In the buildings sector, houses would need to switch from oil and gas for space and water heating to electricity, waste heat, and solar thermal. The industry sector would shift from over 70 percent reliance on fossil fuels to a mix of electricity, hydrogen, and biomass for manufacturing processes. And in agriculture, farm equipment would become electric.

As a result, the EU's energy system would be almost entirely dependent on the power sector by 2050. The power sector would become the central switchboard of the EU energy system, channeling renewable power to the

other sectors (Exhibit 24). More than 75 percent of the total primary energy consumption would come from power, most of which would be supplied by new wind and solar energy. The final energy consumption mix would be 55 percent electricity, supplemented by 10 percent hydrogen, 20 percent bioenergy in hard-to-abate sectors, and 15 percent other fuels, such as fossils plus CCS or heat.

Phasing out fossil fuels

In our pathway, the use of coal and oil would steadily decline from now until 2050. Most coal reduction would occur before 2030, as coal power plants continue to close throughout the EU. The remaining coal that's used to make steel and generate heat would be phased out over time, as electricity, hydrogen, and bioenergy consumption increase. Oil consumption would also drop significantly, falling 27 percent by 2030 and 91 percent by 2050, as oil consumption in sectors such as road transportation is replaced by electricity and hydrogen.

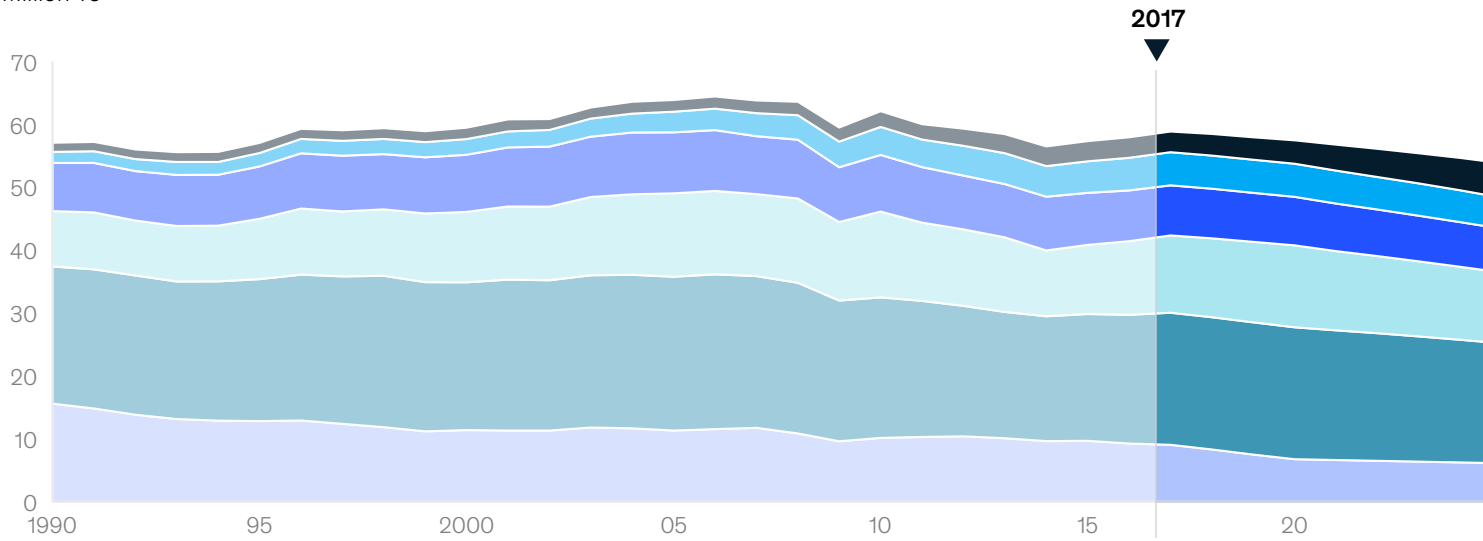
As coal use phases out in the power sector, natural gas use would rise in the short term to cover the gap that cannot yet be supplied by renewables (Exhibit 25). This would slightly increase the demand for gas to generate power until 2030. However, this increase would ultimately be offset by a drop in demand for gas in the buildings and industry sectors, as gas heating and gas feedstock uses are converted to low-carbon alternatives. Over the long term, gas would serve as a flexible generation provider to ensure security of supply and renewables would replace gas for most power production. As a result, the EU's demand for natural gas would fall more than 90 percent by 2050.



The power sector would become the central switchboard of the climate-neutral EU energy system.

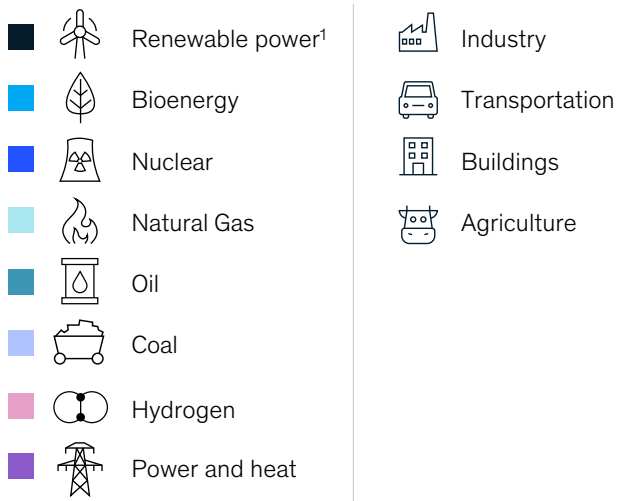
Total primary energy demand

Million TJ



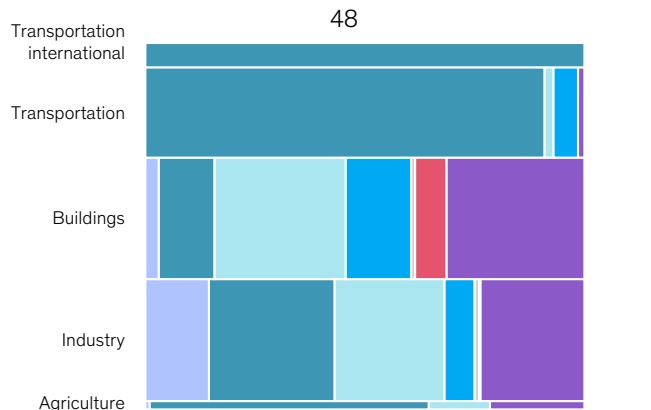
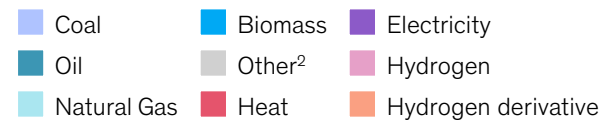
Primary energy demand to final energy consumption

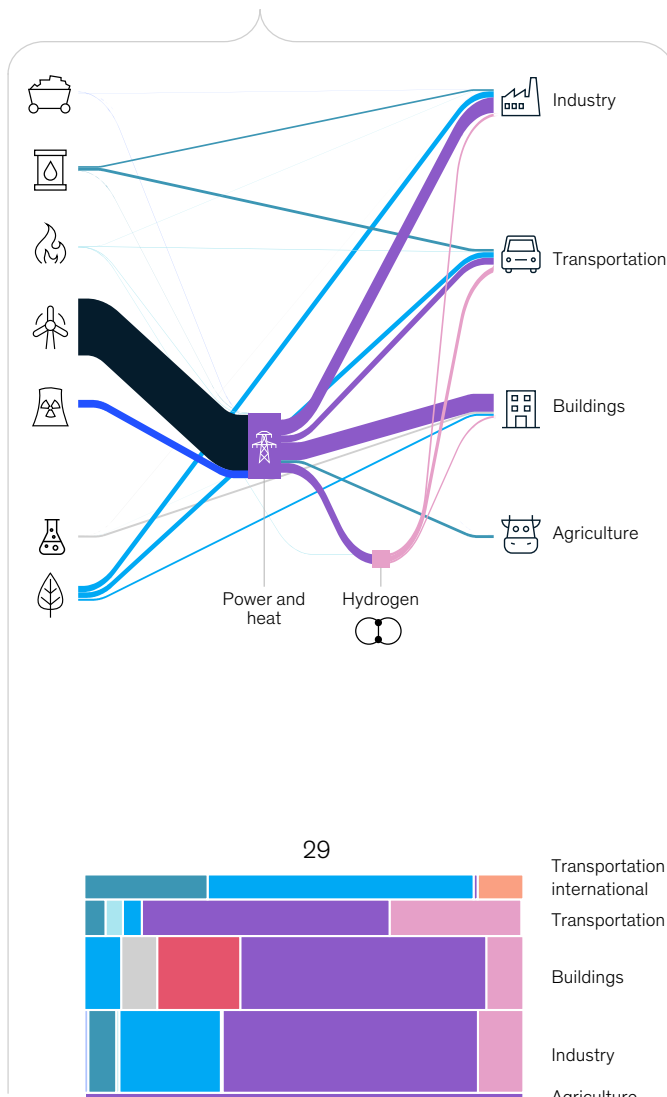
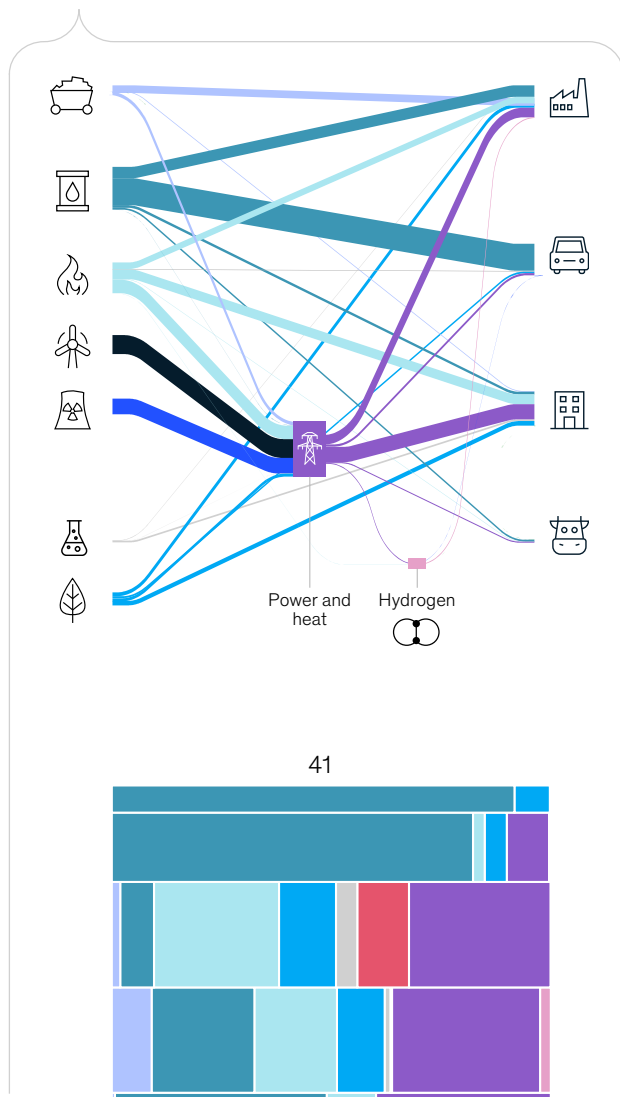
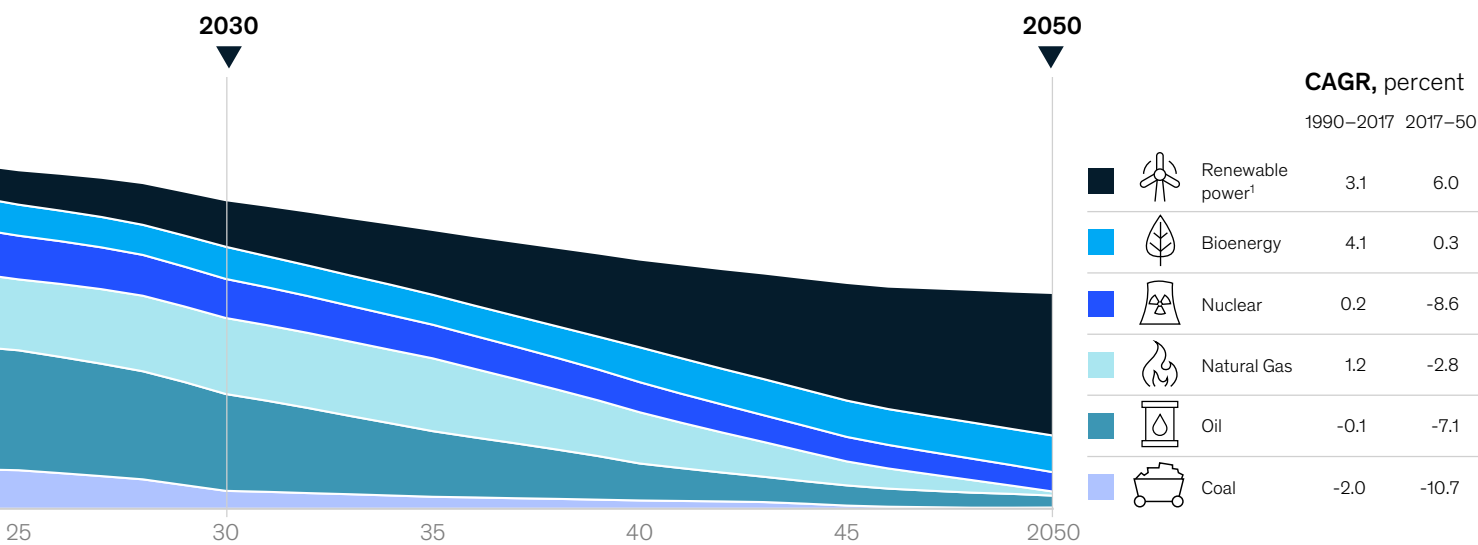
Million TJ



Total final energy consumption

Million TJ





1. Includes solar PV, solar thermal, wind power, and hydro power

2. Other miscellaneous sources, e.g. non-renewable waste

Source: McKinsey

Phasing in new fuels and technologies

Our pathway requires a much greater reliance on electricity, along with hydrogen and biomass as replacements for fossil fuels in hard-to-abate subsectors such as aviation and shipping. In even harder-to-abate sectors like heavy industry, CCS would be critical for reducing GHG emissions that couldn't be eliminated without overhauling manufacturing processes (Exhibit 26).

Decarbonizing the European Union's power supply would require building an additional 1.1 terawatts (TW) of solar power and 0.7 TW of wind by 2050. This would reduce power sector emissions by 700 MtCO₂e a year and provide 3,000 terawatt-hours (TWh) per year of additional electricity that would enable 1 GtCO₂e per year of abatement through electrification and 0.4 GtCO₂e per year through the use of hydrogen in the industry, buildings, transport, and agriculture sectors. (See Section 3.1 for more on changes in the power sector.)

Using hydrogen instead of fossil fuels in the hardest-to-abate subsectors such as iron and steel production, long-haul trucking, aviation, and shipping would reduce the European Union's total GHG emissions by 400 MtCO₂e a year by 2050. Hydrogen consumption would start to scale rapidly after 2030, with transportation becoming the largest source of demand by 2050. (See Section 3.6 for more on the role of hydrogen.)

Increasing the use of sustainable bioenergy is critical to reaching net-zero GHG emissions in the European Union, particularly in hard-to-abate sectors, significantly reducing the cost of delivering a climate-neutral Europe. Most of the biomass now used in the EU's energy sector is solid biomass, much of which is imported from other countries or not sustainably sourced. Over time, the demand for biomass would be satisfied by sustainable, domestic sources. The EU has the potential to sustainably generate 9 EJ of biomass annually, doubling the

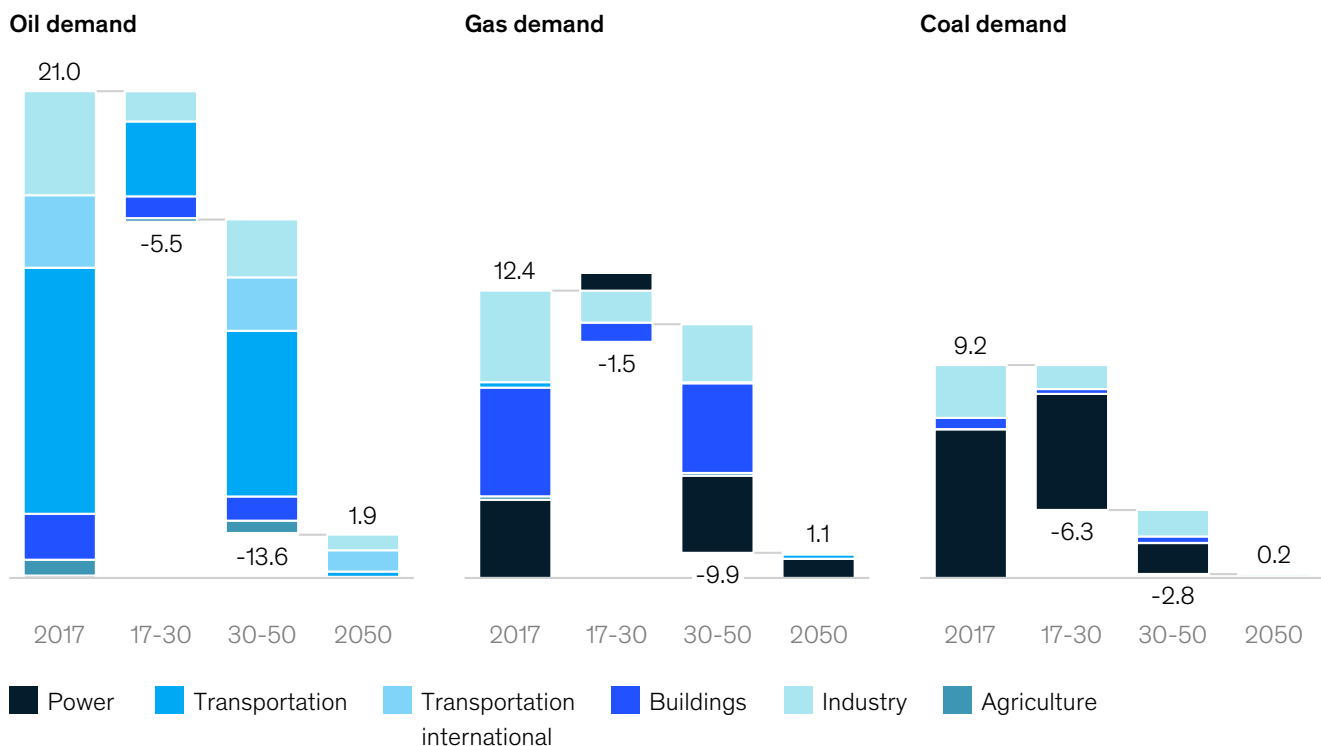
amount used today. About 50 percent of this could come from energy crops such as rapeseed and Miscanthus, which would require the conversion of about 30 Mha of low-value lands to bioenergy production. On our pathway, the quantity of solid biomass used in the buildings and power sectors is limited to enable more liquid biomass consumption in aviation and shipping. Also, biogas is used to generate heat in the industry and buildings sectors. (See Section 3.8 for more on the role of bioenergy.)

CCS would play a dual role in decarbonizing the European Union's energy system, capturing emissions from fossil fuels and the CO₂ released from biomass when burned primarily in industrial processes. In the short-term, industrial sites would continue to use fossil fuels while implementing CCS as a bridge towards using BECCS by 2050. For instance, the process of making hydrogen to produce ammonia would continue to use fossil fuel feedstock along with CCS to reduce

Exhibit 25

On the cost-optimal pathway, natural gas use would rise in the short-term, but low-carbon renewables would replace nearly all fossil fuel usage by 2050.

Total primary energy demand for EU-27, million TJ



Source: McKinsey

emissions through 2040, then would switch to biomethane feedstock after 2040, resulting in negative emissions. Although negative emission generation would play only a small role in reaching net-zero, it would be critical for offsetting the hardest-to-abate heavy industry emissions. (See Section 3.7 for more on the role of CCS.)

2.3.2 An expanded view on EU land use

Land use is critical to achieving and sustaining a climate-neutral Europe. Land has a vital role in carbon sequestration and producing bioenergy, which enables and reduces the cost of reaching climate neutrality. Increasing sequestration and bioenergy production levels would require land-use changes,

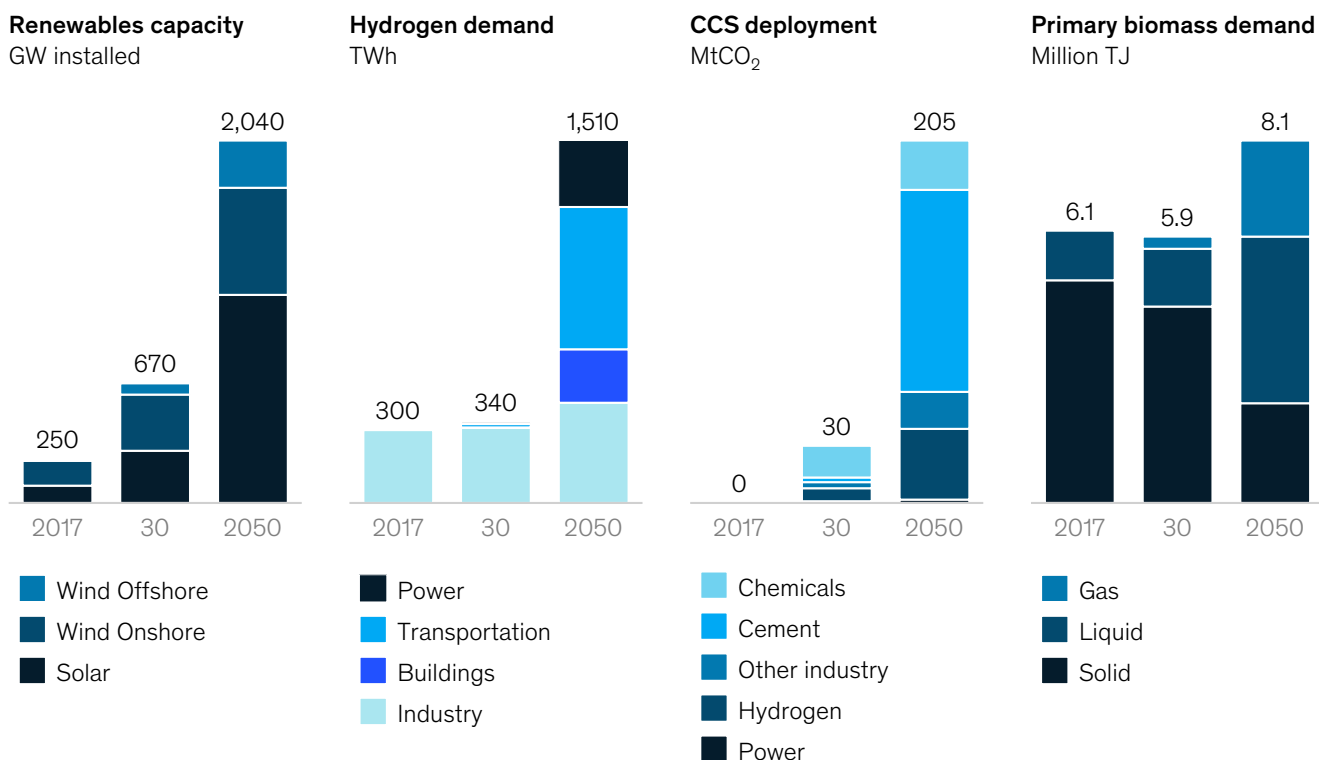
including switching from agriculture to forestry and from unused and abandoned land to bioenergy production.

Climate neutrality requires further changes in EU land use

The European Union has long shaped land use to support a range of policy objectives, including agricultural production, rural welfare, and sociocultural and landscape heritage. As we look towards a climate-neutral European Union, land would have to serve additional goals, including enhancing natural carbon sequestration, supporting climate-neutral energy production, and increasing biodiversity (Exhibit 27).

Exhibit 26

The cost-optimal pathway relies on the uptake of four key technologies.



Source: McKinsey

Of the 412 Mha of land in the European Union, 40 percent is used for agriculture and a third is forest. EU forests, along with EU soils, today store about 524 GtCO₂e. Delivering these additional policy objectives would require two significant changes to land use (Exhibit 28):

- From unused and abandoned land to bioenergy. Bioenergy supply could be expanded by growing energy crops on 30 Mha of the 62 Mha of low-value lands that aren't currently used for forestry, food production, feed, or biofuels and aren't rich in biodiversity.
- From agriculture to forest. About 12 Mha of land that would no longer be required for agriculture due to

ongoing efficiency gains could be reforested to support a significant increase in the level of natural carbon sequestration. This reduced land demand for agriculture is in line with historical trends; from 2009 to 2015, agricultural land shrank by 6 percent (9 Mha) while forest land increased by 2 percent (2.5 Mha).

We estimate that increasing sequestration and bioenergy production levels could create an economic opportunity of up to €50 billion per year, primarily benefitting structurally disadvantaged rural regions. For example, a large share of the marginal lands suitable for conversion to expanded bioenergy production lies

in the rural areas of Western Iberia, Southern Italy, and Greece.

Reconciling sequestration with other land-use needs

There are policy objectives, in addition to bioenergy and carbon sequestration, that require land. With the right approach, these do not have to be at odds.

The European Union's Biodiversity Strategy target is to increase the proportion of protected land from 26 percent to 30 percent. This could be achieved alongside decarbonization with a mixed land-use approach. For example, protected land could also be used as a natural forest or for grazing.

Exhibit 27

On the cost-optimal pathway, EU land-use policies have to balance multiple competing objectives.

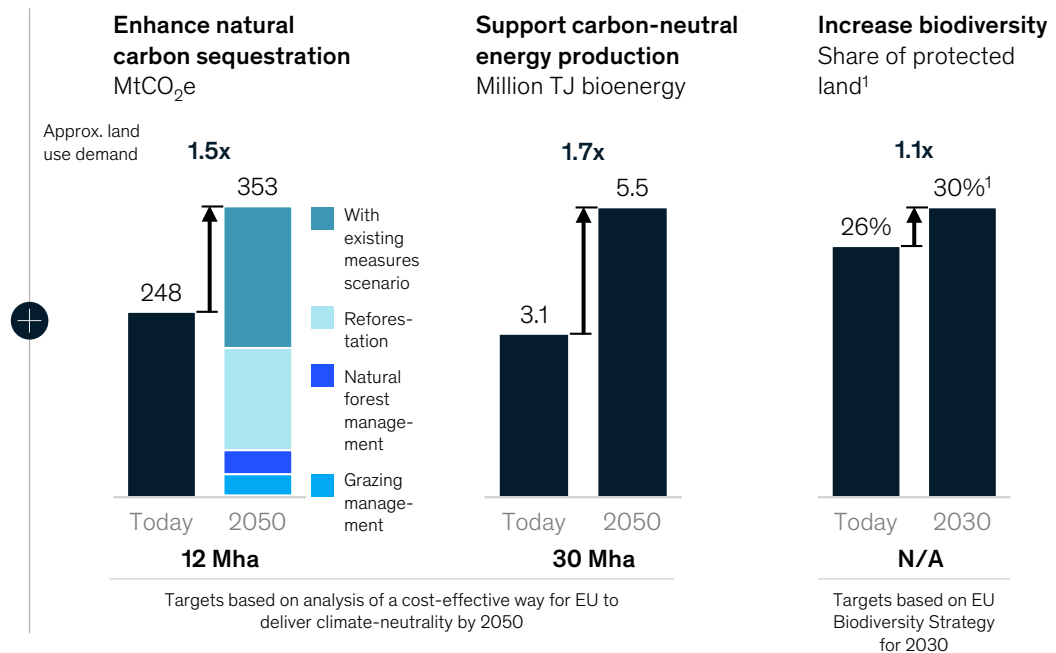
Additional focus themes

Focus of Common Agricultural Policy

Maintain rural welfare

Support agricultural production

Maintain socio-cultural and landscape heritage



1. EU Biodiversity Strategy states that at least 30% of the land should be protected in the EU. This is a minimum of an extra 4% of land as compared to today.

Source: McKinsey, EU Biodiversity Strategy for 2030: Bringing nature back into our lives

The build-out of renewable electricity generation to reach a zero-emission electricity system would require 6 to 12 Mha, about 30 percent of which would be for solar PV and 70 percent for onshore wind. This is equivalent to 1.5 to 3 percent of the total EU landmass. Electricity generation and transmission infrastructure would become more prominent in our habitats and may provoke resistance from locals. This is likely to be a bigger problem in areas with high energy demand and population density, such as in Germany or Italy. There is already some societal pushback against solar PV and onshore wind developments.

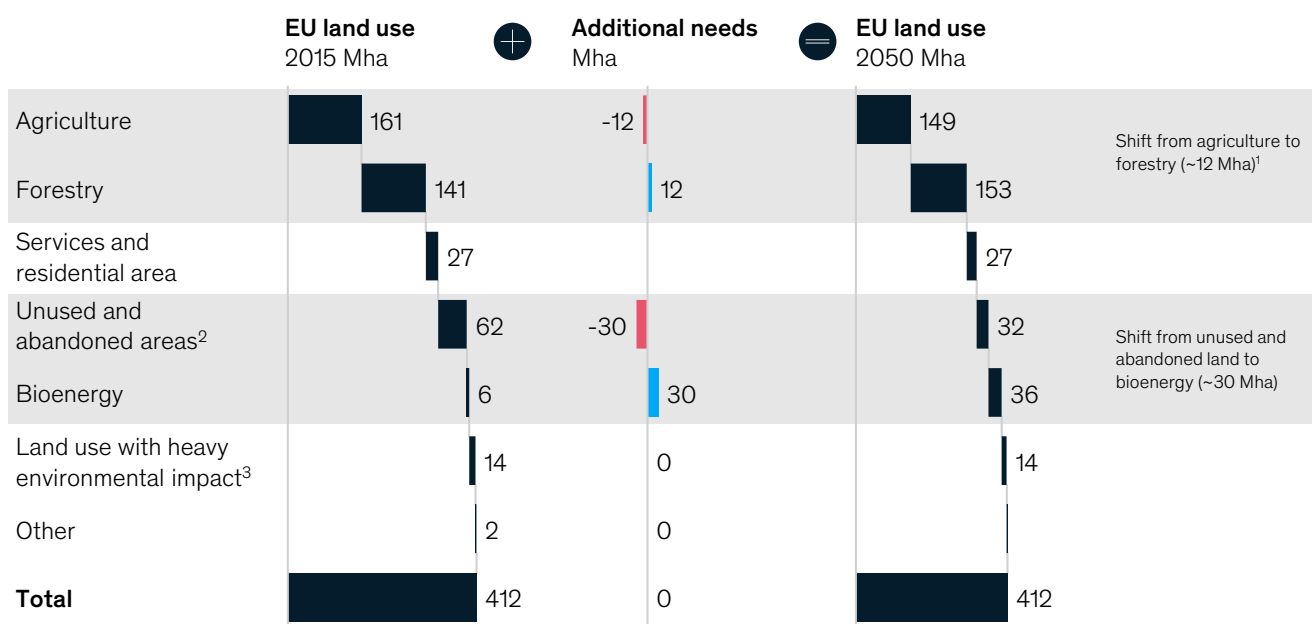
Resolving these challenges would require technical innovation and community engagement. On the technical side, further innovation in generation technology may improve land-use efficiency. This could be through bifacial, high efficiency, two-

axis tracking solar PV or larger onshore wind turbines. Innovation would also be necessary to support the expansion of renewable power within existing land uses, such as integrating solar PV and onshore wind into agricultural land or making more extensive use of rooftop solar PV.

Improved community engagement could be achieved by reaching out to impacted communities and linking the need for electric infrastructure to the growing public support of decarbonization. Another approach may be to increase local communities' share of the financial return associated with renewable power. Community energy projects in which citizens own or participate in sustainable energy generation already use this approach.

Exhibit 28

The cost-optimal pathway involves a slight shift from agriculture to forestry, plus the cultivation of energy crops on 30 million hectares of low-value, abandoned land.



1. Aligns with 2019 Report of the FABLE Consortium on 'Pathways to Sustainable Land-Use and Food Systems'

2. Eurostat, Based on current EU member states for which data was available at 2009 and 2015. Excludes unused and abandoned areas for which data was not reported in 2009

3. Includes mining and quarrying, energy production, industry and manufacturing, water and waste treatment, and construction

Source: Eurostat, Land use overview by NUTS 2 regions 2015 (accessed 10/06/2020)

The landscape of possible zero-emission futures

The focus of this report is to present a technologically feasible, societally cost-optimal pathway to achieve the European Union's emissions-reduction targets. However, many factors will undoubtedly impact the decarbonization pathway the European Union ultimately takes.

Under current cost projections and our boundary constraints, the lowest-cost way to reach net-zero emissions would rely on a rapid rollout of renewable power in Europe. By eliminating current power sector emissions and enabling mass electrification and green hydrogen use, renewable power would contribute to 70 percent of total emission reductions. Although this would be feasible under the known technical and resource availability constraints, implementing the changes to provide this level of renewable power would be a significant undertaking.

It would require an annual deployment of 20 GW a year of wind and 17 GW of solar from 2021 to 2030. This is comparable to the annual installation rate in 2019, but the pace would need to double from 2030 to 2050. By 2050, the European Union would need to add more than 1,100 GW of solar and 850 GW of wind.

This level of deployment would also require a significant amount of land to be used. As renewable power continues to ramp up through 2050, more wind and solar farms would need to be built closer to densely populated areas. If the public protests these developments, it could slow the build-out of renewable power required to reach net-zero.

To explore the landscape of possible pathways, we also investigated two archetypal alternative approaches to achieve climate-neutrality in the European Union's energy system by 2050. Those alternatives include:

The carbon-capture pathway.

Our cost-optimal pathway already uses the European Union's maximum potential of sustainable biomass production and most of the available circularity and demand reductions. That leaves CCS as the primary alternative technology to a larger-scale

wind and solar rollout to meet reduction targets in the power and industry sectors.

An alternative pathway that would require only half the rollout of renewable power in our cost-optimal pathway would significantly reduce the pressure on land use. But it would also be 15 percent more expensive in aggregate, with the marginal cost of power being 50 percent higher. The additional costs would be generated by both the energy supply and demand sides.

On the energy supply side, the decarbonization of power would need to rely more on CCS and negative emission technologies such as BECCS, resulting in a higher power price. The constrained supply of low-cost green power would limit the uptake of green hydrogen. As a result, hydrogen would primarily be produced via the blue route at a 30 to 40 percent higher price than green hydrogen.

On the demand side, higher power and hydrogen costs would likely reduce the amount of electrification and hydrogen use. Electrification would still occur in transportation since the cost differential between electric road transportation and the alternative zero-emissions options would be significant even with higher power prices. But with higher power prices, the electrification levers we've proposed in the buildings and industry sectors would likely be replaced by lower-cost alternatives. For high-temperature processes, the industry sector would need to rely on more CCS or switch to biomethane if it's available. The buildings sector would require more district heating and solar thermal as heating sources, as well as more insulation to lower the total heating demand.

From an implementation perspective, this decarbonization pathway would avoid some of the likely challenges associated with developing renewable power at scale. However, the rollout of CCS would come with its own technical and public perception hurdles. Setting up a CCS network to reduce emissions by 700 MtCO₂ a year by 2050 (instead of the 200 MtCO₂ a year in our pathway) would end up being the size of the European Union's gas transmission system operators (TSO) network and require more than

50 percent of the known capacity in the North Sea for carbon storage. CCS has also already faced public resistance in countries across the EU.

The green-energy import pathway.

Instead of relying entirely on domestic production, clean energy could also be imported (Exhibit 29). However, a scenario in which imports replace half of the renewable power in the pathway could be 10 to 20 percent more expensive, depending on which fuels are imported and in which way (e.g. pipeline or ship). This is because the cost of transporting them to the EU would likely outweigh the lower production costs of green fuels in other countries.

The most promising approach would likely be importing clean energy from regions close to the European Union, such as North Africa. For example, Spain could import cheap wind and solar power from Morocco through a high-voltage direct current (HVDC) cable or as hydrogen via pipelines. Border regions of the European Union could pursue cross-border projects to complement their energy mix, then scale up to create large import corridors into Europe. Hydrogen could be transmitted long distances through the European Union's gas-network infrastructure, while new HVDC lines could carry renewable power from outside the European Union deep into Europe.

Another option is importing low-carbon hydrogen via ship from places like the Middle East. We estimate that this would result in a landed cost of €4 to €5 per kg of hydrogen in the short term and €2 to €3 in the long term, compared to an estimated domestic production cost of €2 to €3 per kg in the short term and €1 to €2 in the long term. Hence, the additional cost of transportation would likely result in a landed hydrogen price that would be almost double the local production cost under the cost-optimal pathway in most regions. That would likely motivate many potential hydrogen consumers to consider lower-cost alternatives.

A third alternative is importing sustainable biomass from places like Canada. This would be no more than 5 to 10 percent more expensive

than domestic production and, in some cases, could even be cheaper depending on the production costs abroad. However, sustainably sourced biomass would likely become a scarce resource in a world increasingly pursuing sustainability and decarbonization. Estimates of global sustainable biomass production range from 30 to 200 EJ a year, which already makes the European Union's domestic biomass potential of 9 EJ a year more than its fair share based on population, emissions, and GDP. Importing an additional 10 to 15 EJ biomass a year may not only face objections abroad but contribute to tightening the global market for sustainable biomass and driving up prices.

So, although importing green energy in various forms is possible, it likely comes with cost challenges. A green-energy import pathway would also require expanding

ports as well as pipeline and transmission corridors to neighboring regions of the EU. To some extent, existing infrastructure could be reused, such as turning liquid natural gas (LNG) port terminals into liquid hydrogen terminals. But in other cases, importing green energy would require new, large-scale infrastructure projects. It would diminish two critical benefits of the cost-optimal pathway: job growth and greater reliance on domestic energy sources.

To account for possible delays in building out renewable power and the significant lead time required to pursue the alternative pathways, a good strategy could be investing in "pathway optionality" to maximize the likelihood that the EU meets its emission-reduction targets.

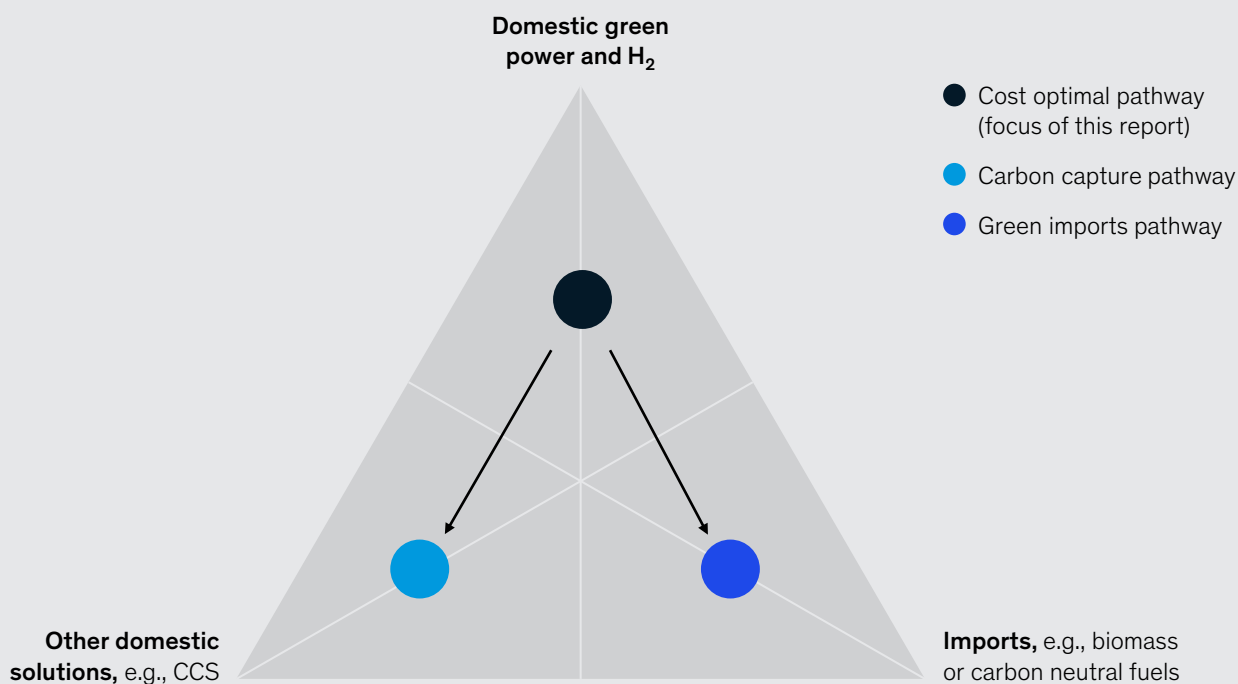
In the short term, this would require making additional investments—beyond those needed to meet renewables build-out targets—in CCS and low-carbon

import options. This could include requiring those pursuing CCS projects to have a plan for how they can rapidly expand the CO₂ pipeline network beyond the pilot. This would be similar to how the Rotterdam project included blueprints for incorporating the Ruhr area into the same CCS cluster. Those ports-and-border corridors could ensure they are "hydrogen-ready" by pursuing exploratory off-take agreements for green fuels from places like the Middle East. This would, in turn, encourage green investments beyond the European Union.

Although these measures would create additional costs, they could be considered an insurance premium, allowing the rapid scaling of CCS or green energy imports to contribute to the last 45 percent of decarbonization from 2030 to 2050.

Exhibit 29

There are two main alternates for the EU energy system to our cost-optimal pathway.



Source: McKinsey

2.4 Pathway ambiguities

Based on today's cost projections, the technologies and techniques that we outline in our pathway are the lowest-cost way to reduce 80 percent of the EU's GHG emissions by a wide margin. Even with significant price changes, the second-best options would be much more expensive.

However, the most cost-effective way to abate the remaining 20 percent of emissions after 2030 is less certain. There are two or more similarly priced abatement options for these emissions, and it will be hard to say which is the lower-cost one until after 2030. There are a number of reasons for this uncertainty. For instance, it's difficult to predict whether biomass, hydrogen, or CCS would be the best choice in a particular situation until we know how much the price of hydrogen will drop in the next 10 years, how available biomass will become, and whether there is accessible CO₂ storage for CCS. All these factors would also vary by region.

These known unknowns could result in deviations from our cost-optimal pathway in four areas: heating for industry and buildings, aviation and shipping, the final 10 percent of power decarbonization, and short-term hydrogen production.

Heating for industry and buildings accounts for up to 25 percent of emissions today. Most of the abatement technology pathway is clear. Coal and oil heating would be phased out in favor of renewable power, and gas heating could be replaced by district heating in densely populated areas. However, for part of the existing gas heating, several abatement options have similar costs, such as switching to gases like biomethane or hydrogen, using other heat sources such as waste heat, and implementing CCS. The ambiguities are particularly relevant for the following three decarbonization decisions:

1. **Blending hydrogen versus blending biomethane into the gas grid.** Hydrogen and biomethane prices may converge in some regions so that they compete. Which fuel would be more affordable by 2050 would depend on the availability and price of biomethane compared to the local availability of cheap power to drive down the cost of producing hydrogen. This uncertainty affects 5 to 7 percent of the total emissions abatement. Some 10,000 terajoules (TJ) of final energy demand that would be fulfilled by hydrogen in our pathway could be satisfied by biomethane if local prices decline 20 percent further than our current assumptions. Because biomethane supply is limited, the potential for this to happen will depend on its future availability.
2. **Reusing gas networks or building new district heating networks.** Buildings with gas connections can be decarbonized by blending carbon-neutral gases, such as hydrogen or biomethane, into the system. But in some neighborhoods, installing new district heating networks could be the better option because waste heat is much cheaper than hydrogen or biomethane, and the savings could offset the initial investment of installing a new system. These two options are generally close in cost, and location specifics would determine the best choice.
3. **Applying CCS, blending low-carbon gas into a furnace, or replacing the entire installation with an electric furnace.** Industrial high-temperature heating is notoriously hard to decarbonize. Options range from adding CCS to a furnace, blending biomethane or hydrogen into the furnace fuel, or switching to an electric furnace. Depending on the region, the cost of each option would range from €70 to €120 per tCO₂e abated. Site-specific CCS costs, the availability of a local CCS network, the success of electric furnace R&D, and the availability of cheap local hydrogen or biomethane would determine the most cost-optimal option.

By and large, the favored solution for each region is evident. About 5 percent of abatement in the optimal pathway is more ambiguous and may differ if local prices diverge substantially from our projections.

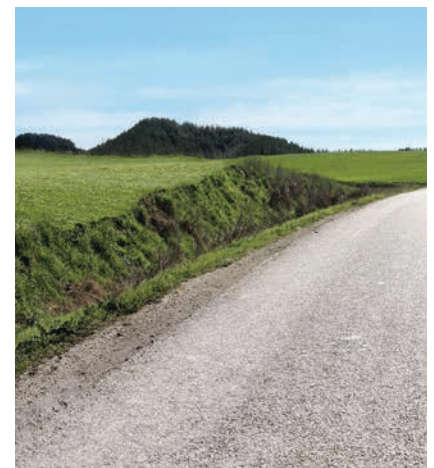
Aviation and shipping have only a few abatement options. Emissions can be reduced by switching to advanced biofuels or synfuels, both of which would cost more than €100 per tCO₂e abated. Our pathway anticipates that most of aviation and shipping would switch to biofuels, which would be somewhat less expensive than renewable synfuels. But faster development of the synfuel production process or more rapidly falling hydrogen costs could change the preferred fuel for 3 percent of overall abatement. If synfuel costs fall more rapidly, roughly 60,000 TJ of final biofuels demand could be satisfied instead by synfuels.

The last 15 percent of power decarbonization will likely be expensive and technically complicated.

Variable wind and solar power would need a flexible generation or demand source to balance the surpluses and deficits over long periods. By 2040, when the power system approaches climate neutrality, this could be provided by low-carbon sources such as hydrogen or biogas peaker plants, gas peaker plants with CCS, or flexible demand options such as electrolyzers. The preferred choice will depend on regional factors such as biogas and hydrogen prices, the proximity of CO₂ storage, and the type of flexible demand available. About 2 percent of the total abatement would be affected by these choices.

In the short term, the optimal mix of technologies for producing hydrogen is uncertain. Over the long term, green hydrogen production from the electrolysis of water is expected to be cheaper than blue hydrogen created by reforming natural gas and capturing the emitted CO₂ with CCS. However, it remains unclear which production route would be most cost-effective from 2021 to 2030. That depends on how quickly the cost of electrolyzers declines, as well as local renewable power prices and the proximity to CO₂ storage in various regions.

Finally, there are unknowns, such as potential innovation breakthroughs in fusion power, that could materially alter the picture.



3. Sector deep-dives

The next section presents the cost-optimal pathway for each of the five sectors and the role of hydrogen, CCS, biomass, and carbon sinks in reaching net-zero. To get the big picture of the efforts required, it's not necessary to read all nine sections. You can read those of greatest interest to you.

We chose to present the pathways by sector rather than region because they share more similarities than regions. In the following sections, we follow the same structure for each topic. First, we discuss the baseline—the state of play today—followed by a description of the sector pathway to net-zero and close with the uncertainties and enablers that could impact those pathways.





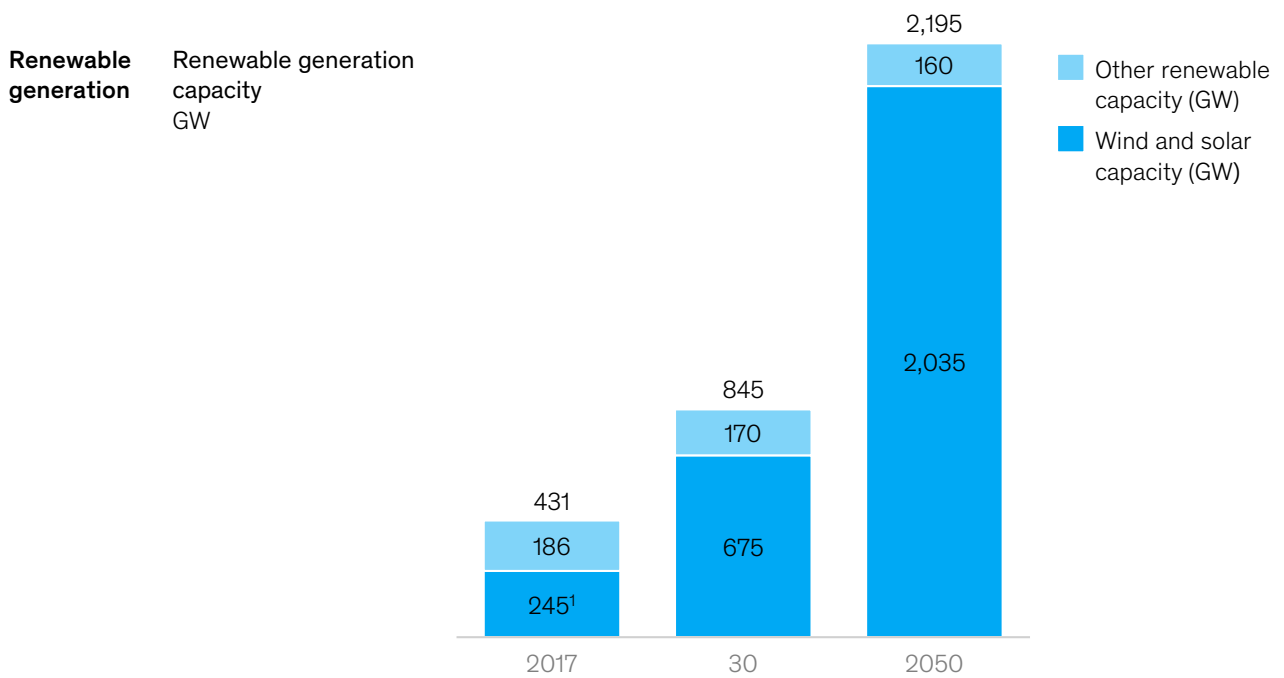
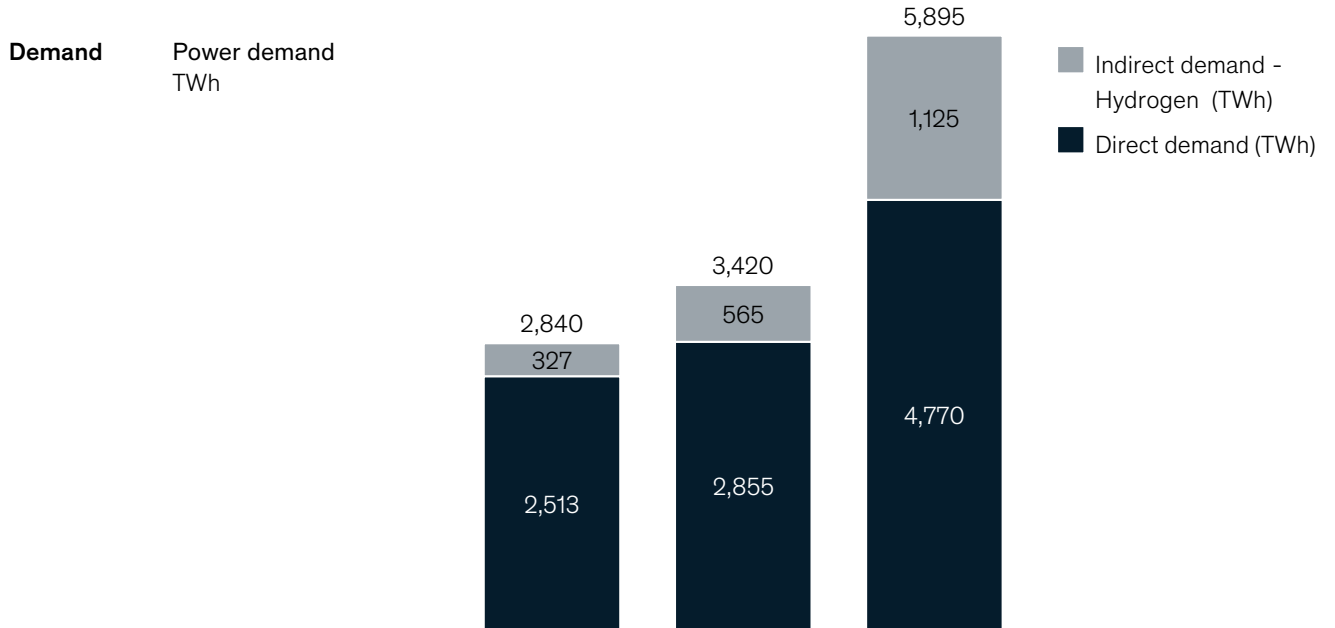
3.1 Power



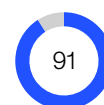
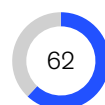
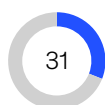
Power pathway in brief



Power demand may double by 2050, but renewable energy should provide more than 90 percent of the supply



Renewable generation share of total production %



1. In 2019, total installed wind and solar power capacity increased to 285 GW, accounting for about 35% of the total generation in 2019

Source: McKinsey, www.enerdata.net

3.1.1 Power emissions today

Europe is a global leader in low-emissions generation but still has a way to go to reach full decarbonization.

The power sector emitted 935 MtCO₂e in 2017, accounting for 25 percent of total EU emissions.¹⁰ Since 1990, the European Union has reduced its power emissions by 40 percent as power producers have diversified into more low-carbon energy sources (Exhibit 30). As a result, the European Union is a global leader in renewable energy generation, producing 35 percent of its power from wind, solar, hydro, and biomass in 2019, compared to China with 27 percent and the United States with 18 percent.¹¹

At the country level, however, EU member states vary in their dependence on fossil fuels. For example, the emissions intensities of electric power production in Poland, the Czech Republic, and Bulgaria are much higher than the EU average of 296 gCO₂e per kilowatt-hour (kWh) because they still rely on a large share of coal and lignite power plants.¹² On the other hand, France's emissions are only one-fifth of the EU average because France relies on nuclear power plants (Exhibit 31).

3.1.2 The role of power on the path to net-zero

To reach the EU climate targets, the power sector is in a much different position than the other sectors. Not only must power producers switch to using more renewable sources to generate power, but they must also scale production volumes to meet the rising demand for power as other sectors switch from fossil fuels to electricity and hydrogen.

On our pathway, the demand for electricity in the European Union is expected to nearly double in the next 30 years, from 2,840 TWh in 2017¹³ to 5,895 TWh in 2050. Direct electrification will account for 63 percent of this growth, with demand rising fastest in the transportation sector as electric passenger cars and buses become the norm. The other 37 percent will come from increased demand for green hydrogen as a replacement fuel for use cases that can't be electrified, such as long-haul trucks and buses, as well as industrial processes such as steelmaking, chemicals manufacturing, and food production.

¹⁰ The power sector's GHG emissions in 2018 declined to 875 MtCO₂e, according to latest available GHG inventory data from the United Nations (as of October 2020).

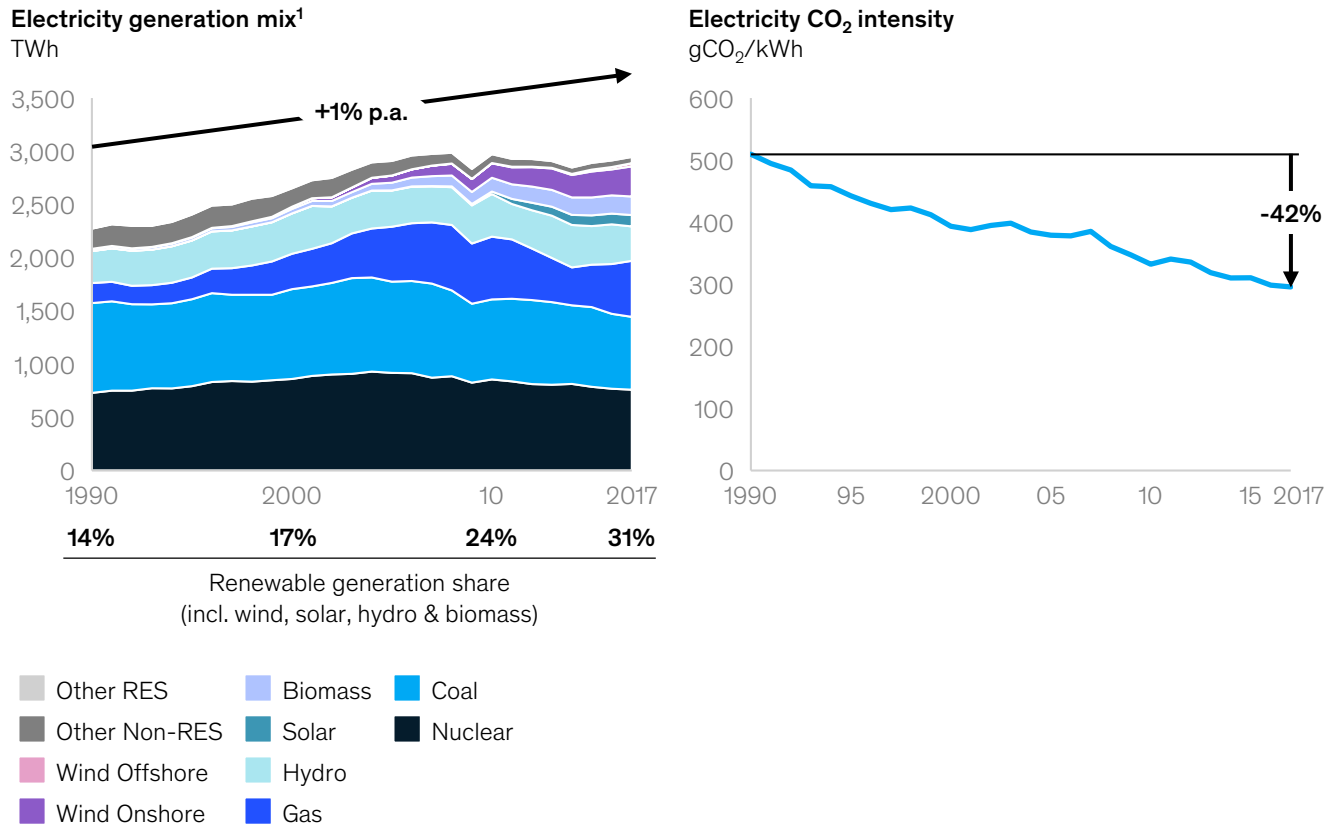
¹¹ Historical actuals based on data from Enerdata.

¹² "CO₂ intensity of electricity generation." European Environment Agency, latest available CO₂ intensity of electricity production for EU member states (as of October 2020).

¹³ "Electricity in Europe 2017." ENTSO-E, June 2018.

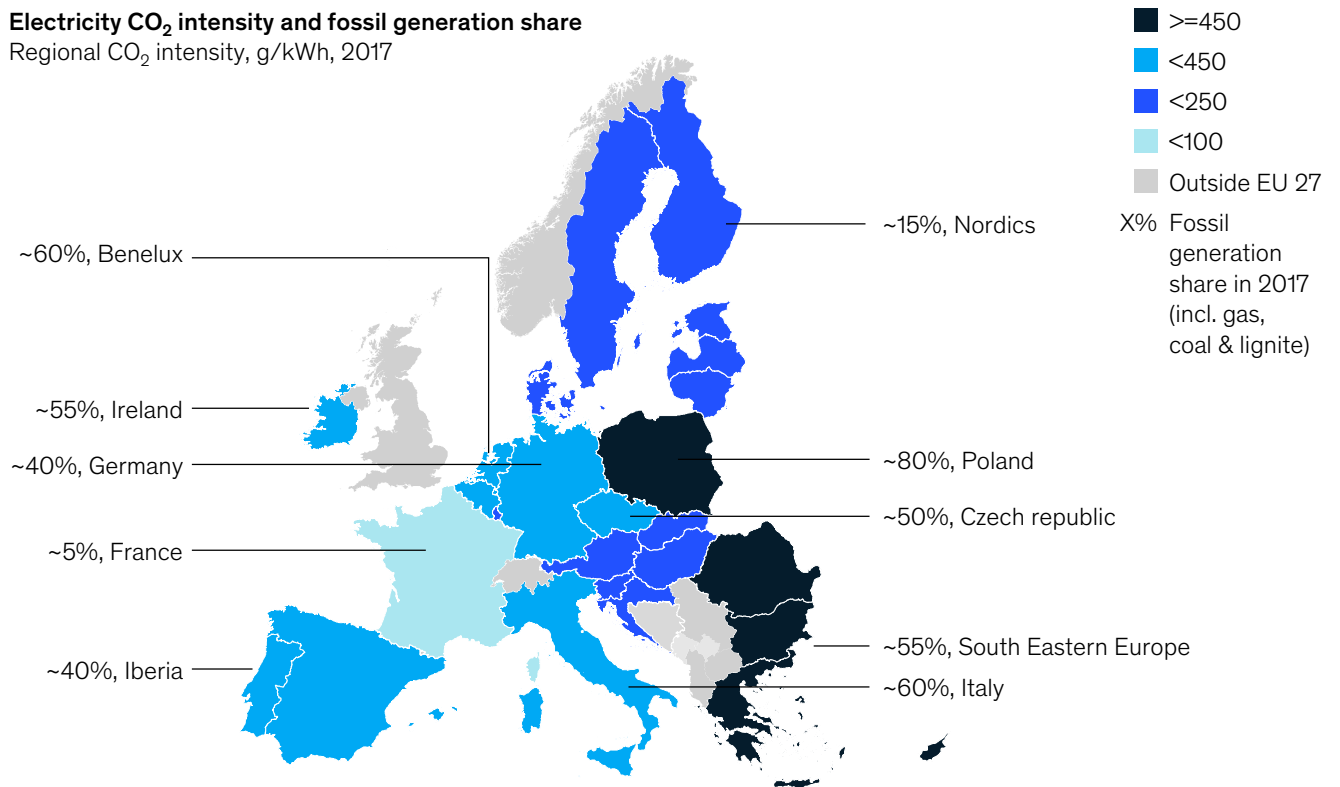
Since 1990, the renewable energy share of EU power generation has more than doubled, leading to steady declines in CO₂ produced per kWh.

Power sector baseline for EU-27



Electricity CO₂ intensity and fossil generation share

Regional CO₂ intensity, g/kWh, 2017

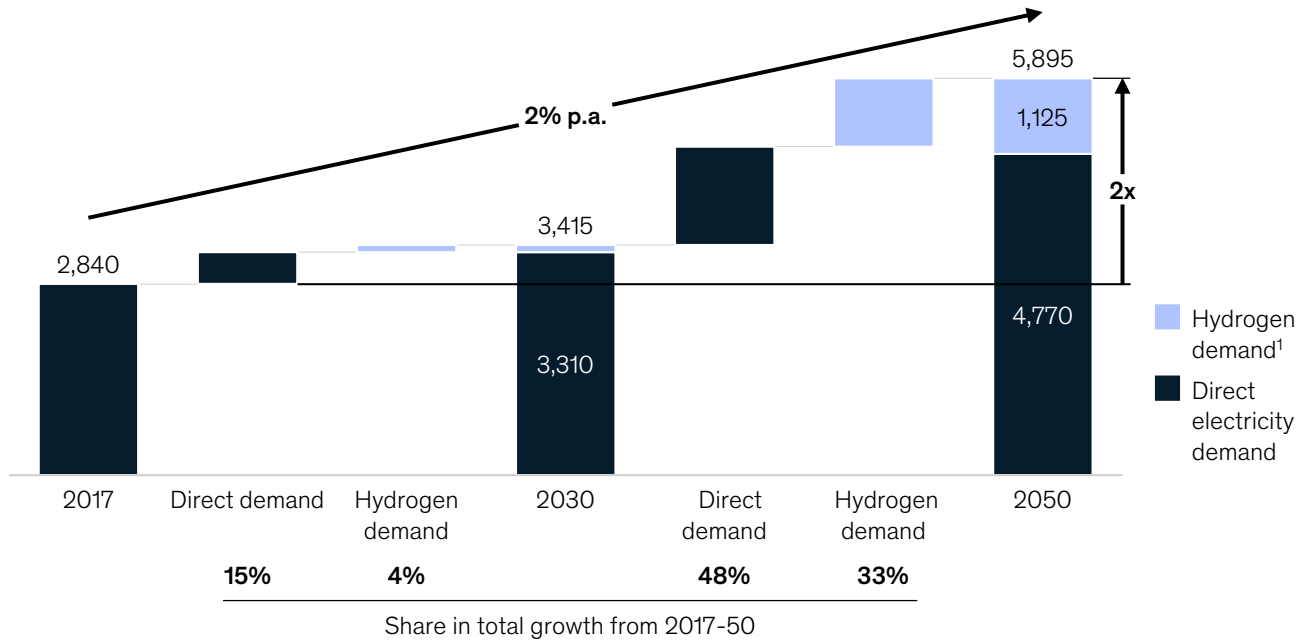


1. Historical numbers up to 2016 from Enerdata, 2017 is based on model results which match well with Enerdata historical figures
 Source: McKinsey, IEA, UNFCCC

With significant investments in wind and solar power generation, the EU power sector could meet growing demand and still reach net-zero emissions by 2050.

Electric power demand

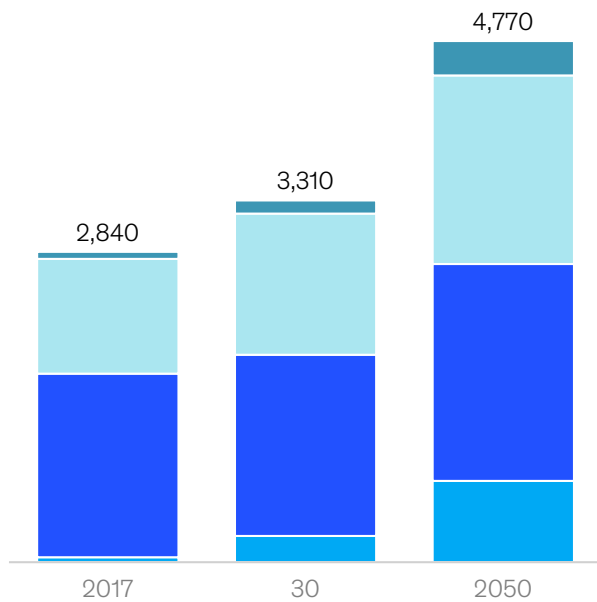
Net electricity demand in EU-27 (excluding grid loss and own consumption), 2017-50, TWh



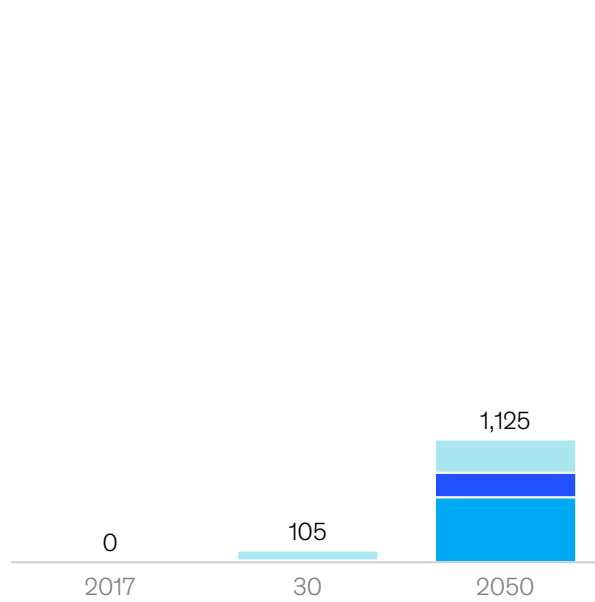
Evolution across sectors

TWh

Direct electricity demand



Hydrogen production with electrolysis

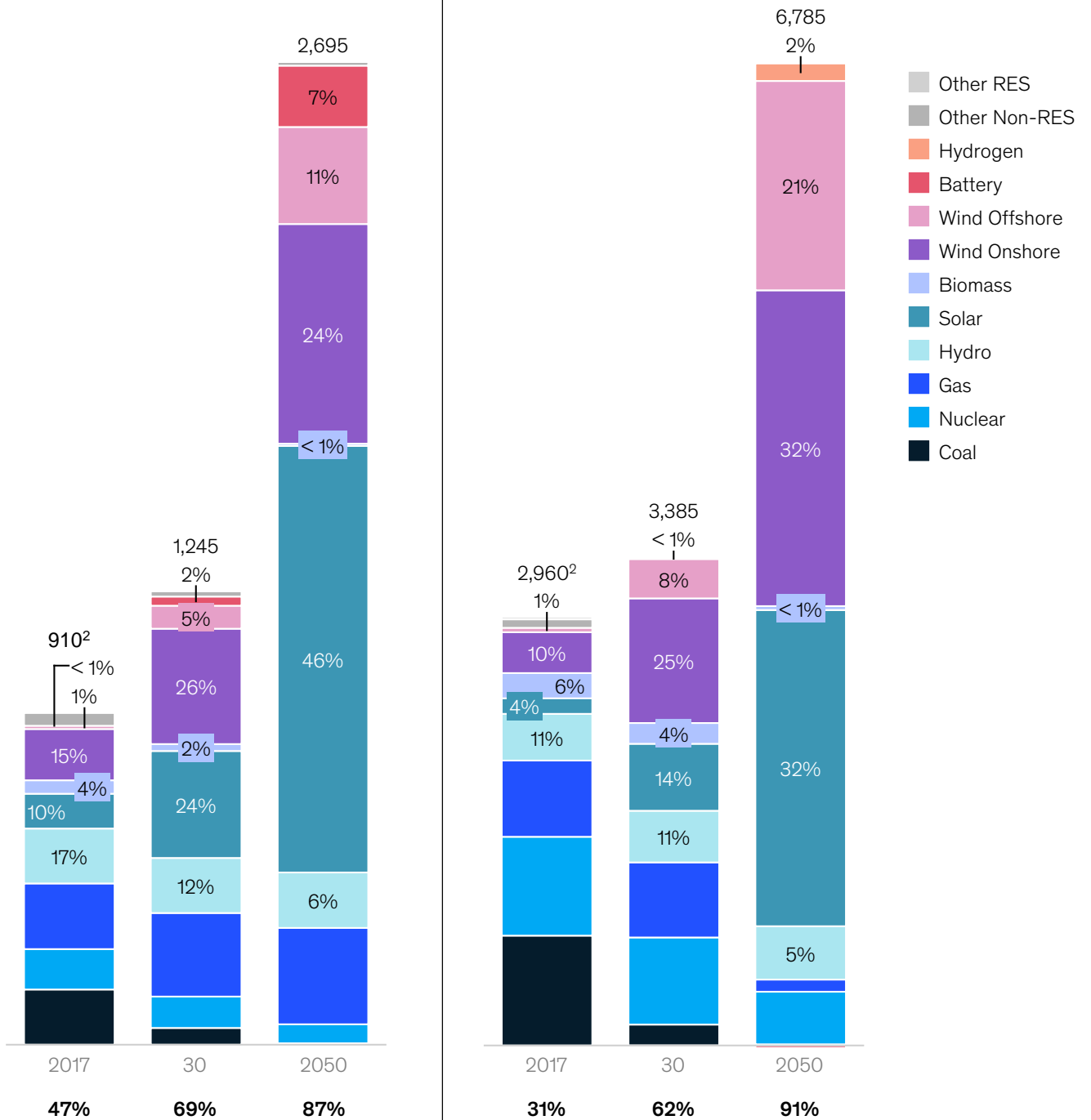


Legend: Transportation (light blue), Buildings (dark blue), Industry (light cyan), Agriculture (dark teal)

Capacity and generation mix in EU-27, 2017-50

Capacity
GW

Generation
TWh



Renewable share (incl. wind, solar, hydro and biomass)

NOTE: Share of capacity and generation shown only for renewable technologies
 1. Excluding conventional Hydrogen demand used in refining and ammonia
 2. Total installed capacity in 2019 was 955 GW and generation was 2905 TWh

Source: McKinsey, www.enerdata.net

Technologies to decarbonize the power sector are already available and are expected to become more cost-competitive, especially compared to those available to other sectors of the economy. As a result, the power sector could reach net-zero faster than other sectors, reducing emissions 75 percent by 2030 and 100 percent by 2045. Getting there will require significant investments in wind and solar power generation, finding ways to ensure that power grids fueled by renewables can handle demand fluctuations, and greater inter-regional connection of power systems (Exhibit 32).

The most cost-effective pathway to reaching net-zero would require the following:

1. Increase the proportion of electricity produced from renewables to 91 percent, up from 31 percent in 2017.
2. Rapidly phase-out coal while using gas as a transitional fuel.
3. Balance and secure the power supply with flexibility solutions including low-emissions generation, hydrogen, storage, and demand-side management.
4. Triple the capacity of inter-regional interconnections by 2050 to ensure the lowest system cost at the EU level.

Increase the supply of electricity produced from renewables

In the last decade, the cost of solar and wind power has fallen faster than has been forecast. In many European countries, the lifetime benefits of renewable technologies already outweigh the investments required in new systems, and they are expected to become even more cost-competitive. For example, declining costs for balance-of-system equipment and the installation of next-generation solar

could reduce the cost of solar PV energy another 65 percent. Similar results may be attainable for onshore and offshore wind generation (Exhibit 33).

Under our cost-optimal pathway to reach the EU climate targets, 62 percent of the European Union's electricity would come from renewables by 2030. Most of this would be generated by onshore wind (25 percent), solar (15 percent), hydro (11 percent), and offshore wind (8 percent). Achieving this level of growth in renewables generation would require some countries to go beyond their current national energy and climate plans (NECP).¹⁴ For instance, Germany would need to reach total capacity of 210 GW of wind and solar power by 2030, which is 20 GW more than its planned target of 189 GW.¹⁵

To fully decarbonize by 2050 on our pathway, the European Union would need to generate 91 percent of its power from renewable energy sources. Solar power would account for 32 percent, onshore wind 32 percent, offshore wind 21 percent, and hydro 5 percent. The remaining 10 percent of power production would have to be provided by nuclear power and systems such as gas-fired power stations with carbon capture.

The cost-optimal pathway would require adding an average of 37 GW of renewable power every year from 2021 to 2030, with 17 GW of solar PV, 15 GW of onshore wind, and 5 GW of offshore wind, later increasing to an average of 68 GW per year from 2030 to 2050. This would mean almost doubling the 17 GW per year pace of capacity expansion of the last five years from now until 2030 and increasing capacity even faster from 2030 to 2050.¹⁶

Rapidly phase-out coal while using gas as a transition fuel

Many countries have plans to accelerate the phase-out of coal-fired power stations, retiring them before the end of their expected lifetimes. The most cost-effective decarbonization pathway would require retiring 70 percent of existing coal capacity (105 GW) by 2030, which is 32 GW more than EU countries have planned so far.¹⁷ This would require countries such as Poland, Slovenia, and Romania to set agendas to phase out coal, and countries such as Germany that already have these agendas to advance their timelines.

In the short term, natural gas usage would rise to cover the gap from coal retirements that cannot yet be supplied by renewable power.

After 2030, as the supply of renewables increases, gas will be used primarily to provide flexibility and security of supply. This will cause the share of gas-based power to drop from 15 percent today to 1 percent in 2050.¹⁸ As a result, the utilization of gas plants would drop from 30 percent in 2017 to 4 percent, while hydrogen-fueled plants would run at 14 percent. Investments in the necessary gas plant additions of 49 GW by 2030 and 84 GW by 2050 are not likely to happen under the existing market regime. Market design would need to evolve to allow the development of new power plants and the operation of existing ones at these significantly lower utilization levels. This would include, for example, mechanisms similar to the capacity market introduced in Italy to maintain the required capacity while developing up to 5.5 GW of new thermal capacity.¹⁹

¹⁴ "Final National Energy Climate Plans, as of September 17, 2020," European Commission, Accessed Nov 11, 2020.

¹⁵ "Integrated National Energy and Climate Plan: Germany," European Commission, June 10, 2020.

¹⁶ Historical capacity installations are based on Enerdata database.

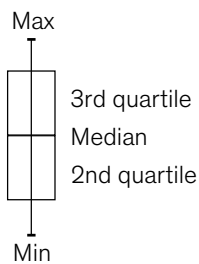
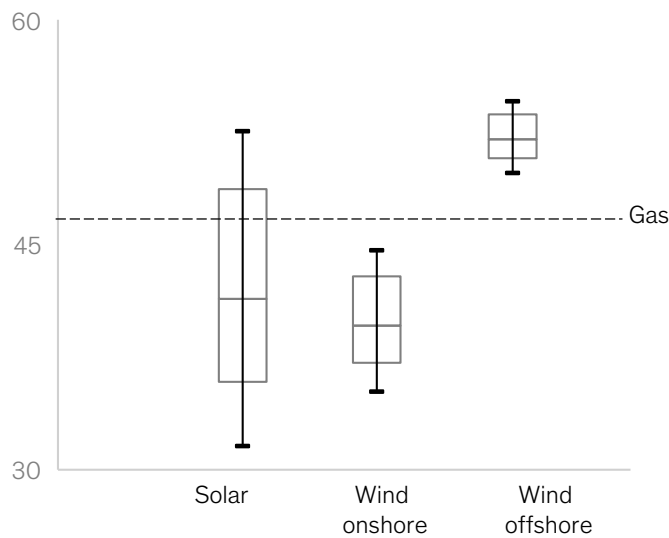
¹⁷ A total of 72.8 GW of coal power capacity is located in countries that have announced they will phase out coal by 2030 or earlier. For more information, see "Overview: National coal phase-out announcements in Europe," Europe Beyond Coal, October 2020.

¹⁸ Historical actuals based on Enerdata.

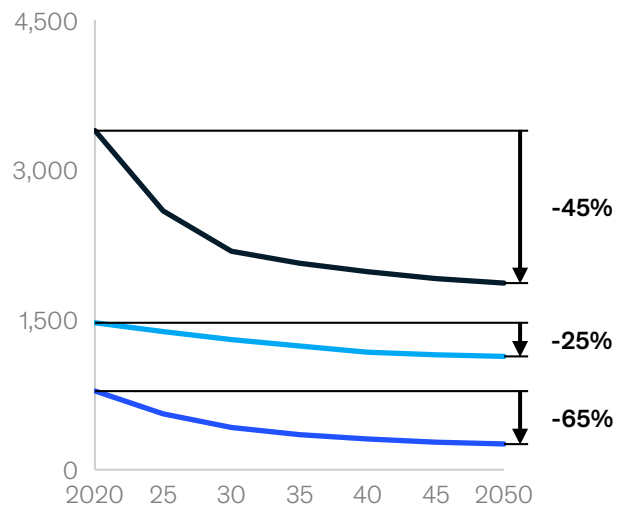
¹⁹ "Capacity market," Terna, Accessed Nov 11, 2020.

Capital expenditure costs for renewable power systems may drop dramatically by 2050.

LCOEs¹ of renewable new builds vs. SRMC² of existing gas plants
EUR/MWh, 2020



Renewable capex
EUR/kW



— Wind onshore — Solar PV (utility scale)
— Wind offshore

1. LCOEs for new build renewables in 2020, excluding grid connection costs and power export infrastructure for offshore wind
2. SRMC - Short Run Marginal Cost of existing gas power plants

Source: McKinsey

Balance and secure energy generation with a mix of flexibility solutions

The need for system flexibility will rise as the power system becomes more dependent on renewables, as many countries have already experienced. In the long term, the system would require the flexibility to provide power for weeks and months because renewable generation surpluses and deficits would occur more often. This can be addressed in various ways, including making grid improvements, adding flexible generation, expanding demand-side management, and installing energy storage systems (Exhibit 34). The most cost-optimal flexibility solutions include the following:

— *In the short term:* Between now and 2030, the power system would initially require flexibility for periods of less than six hours. Battery storage could provide the needed balancing if the installed capacity increased to 25 GW by 2030 and 170 GW by 2050. To enable such an increase, the battery storage cost of a four-hour lithium-ion system would need to decline to half of the €185 per kWh it is today by 2030 and drop further by 2050. This would make battery storage cheaper than new and existing gas power plants and progressively cheaper through 2050.

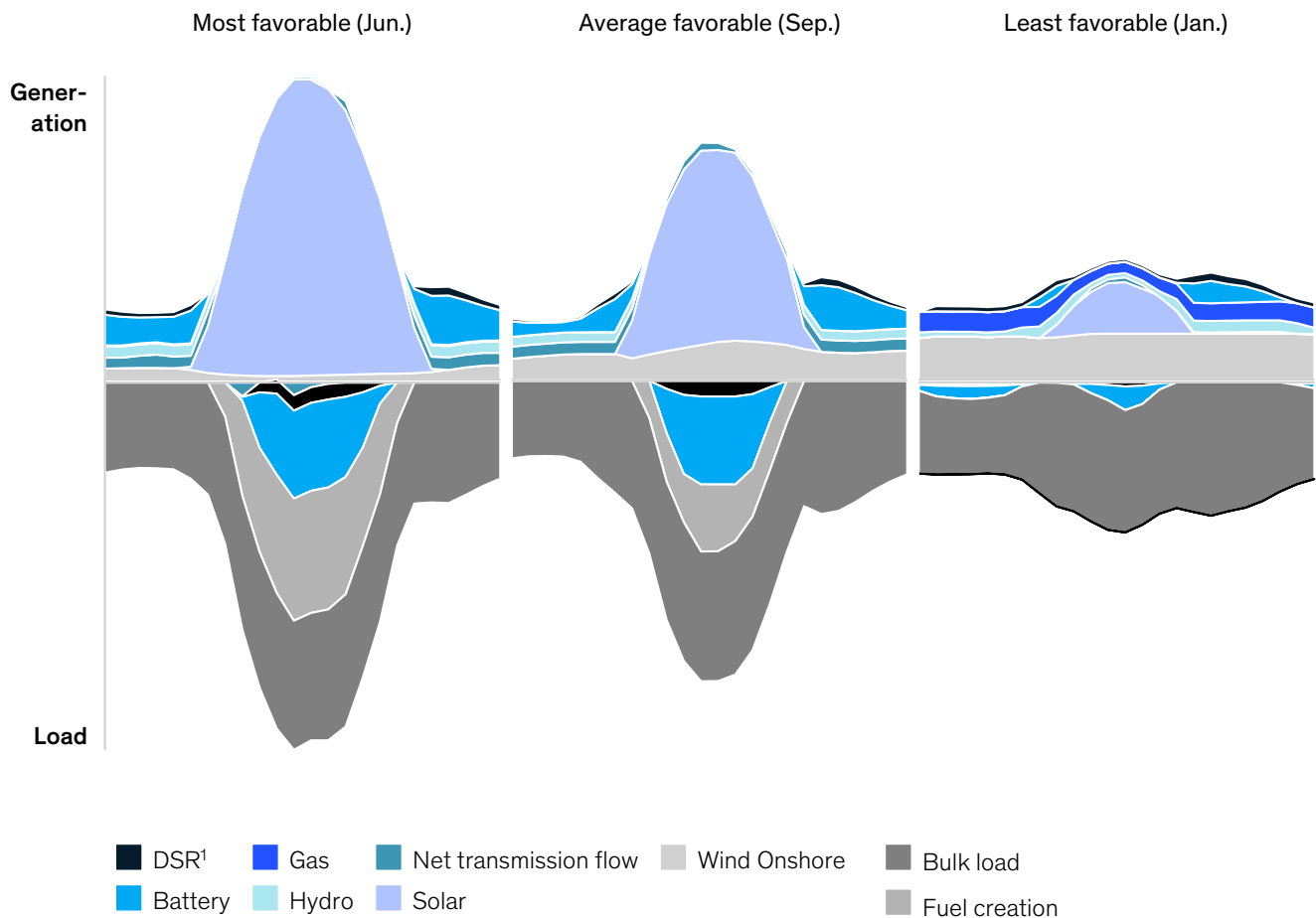
As a result, battery storage use would rise to help integrate renewables into the grid and improve power quality characteristics such as ramp rate, frequency, and voltage stability. Existing gas assets, pumped hydro storage, and demand-side response in the buildings industry and electrified transport sectors would also help provide short-term flexibility.

Exhibit 34

As they become more dependent on renewables, power systems will need to become more flexible to cope with surpluses and deficits.

Three representative daily generation and load profiles, Southern European country, 2050

Renewable conditions



1. DSR – demand side response which includes V2G (vehicle to grid) and flexible industrial load in this study

- *In the medium term:* As the penetration of renewables increases after 2030, power systems would need to become more flexible to cope with surpluses and deficits that last from days to weeks. The system would rely on gas plants to cover the shortages and use hydrogen production via electrolysis during periods of oversupply or as an additional form of demand management.
- *In the long term:* To cover seasonal balancing from weeks to months after 2040, the last 5 percent of demand would have to be provided by zero-emissions flexibility solutions. Even the most cost-effective zero-emission technologies, such as natural gas power stations with carbon capture, hydrogen as a fuel, and BECCS, are more expensive than other energy sources. They would increase the average system cost, but more cost-effective solutions may emerge in the interim.

Triple interregional power flows by 2050

The future power generation mix will differ by region, depending on each country's natural resources. It will also depend on how willing EU member states are to connect their power transmission systems to compensate for local weather changes that impact their ability to generate renewable power from day to day. For example, the wind may be blowing hard enough in the North Sea to power offshore

wind turbines in the Netherlands, while cloudy skies over Italy could prevent solar power generation there. Managing these imbalances most cost-effectively would require EU member states to increase the interconnectivity of their transmission systems—a significant change from the current practice of balancing power generation fluctuations mainly at the individual country level. Countries would rely more on each other for the security of their power supplies in the most cost-effective scenario.

To integrate the systems, interregional transmission flows would need to more than triple in the next 30 years, from approximately 435 TWh in 2017.²⁰ That would require increasing the interconnection capacity 40 percent by 2030 from approximately 85 GW today,²¹ in line with European Network of Transmission System Operators for Electricity (ENTSO-E) ten-year development plans,²² and then more than doubling it by 2050 (Exhibit 34).

Strong interconnections between EU member states would enable the most cost-efficient pathway for climate neutrality but require a fundamental change from managing power systems at the level of individual countries. Unless this approach changes significantly, the system could evolve as a sum of national systems with higher investments and operational costs in generation capacity and flexibility, rather than an optimized Europe-wide system.

²⁰ Historical, based on ENTSO-E. Total future interconnection flows are assumed to grow at the same pace as major interconnection flows between regions.

²¹ ENTSO-E, Mid-term Adequacy Forecast

²² ENTSO-E, Mid-term Adequacy Forecast

The required investments and power generation cost changes

Decarbonizing the power sector would require an investment of €6 trillion from now through 2050, an average of 1 to 1.5 percent of EU GDP. About 55 percent of that investment would go toward improving the grid, while 40 percent would go toward enabling the system to run on renewables.

In the next 30 years, the total annual investment that EU member states would make in the power sector would rise to an average of €200 billion a year, more than double the average €85 billion investment they've made in each of the past ten years.²³ After 2030, these costs would include conversion-capacity investments, including battery storage and electrolysis, flexibility, and fulfilling the demand for green hydrogen.

Because of the cost competitiveness of wind and solar generation compared to the current mix, the average cost of power generation is expected to drop 20 percent by 2050. But these savings may be partially reduced, particularly from 2040 to 2050, by an increase in grid costs on end consumers.

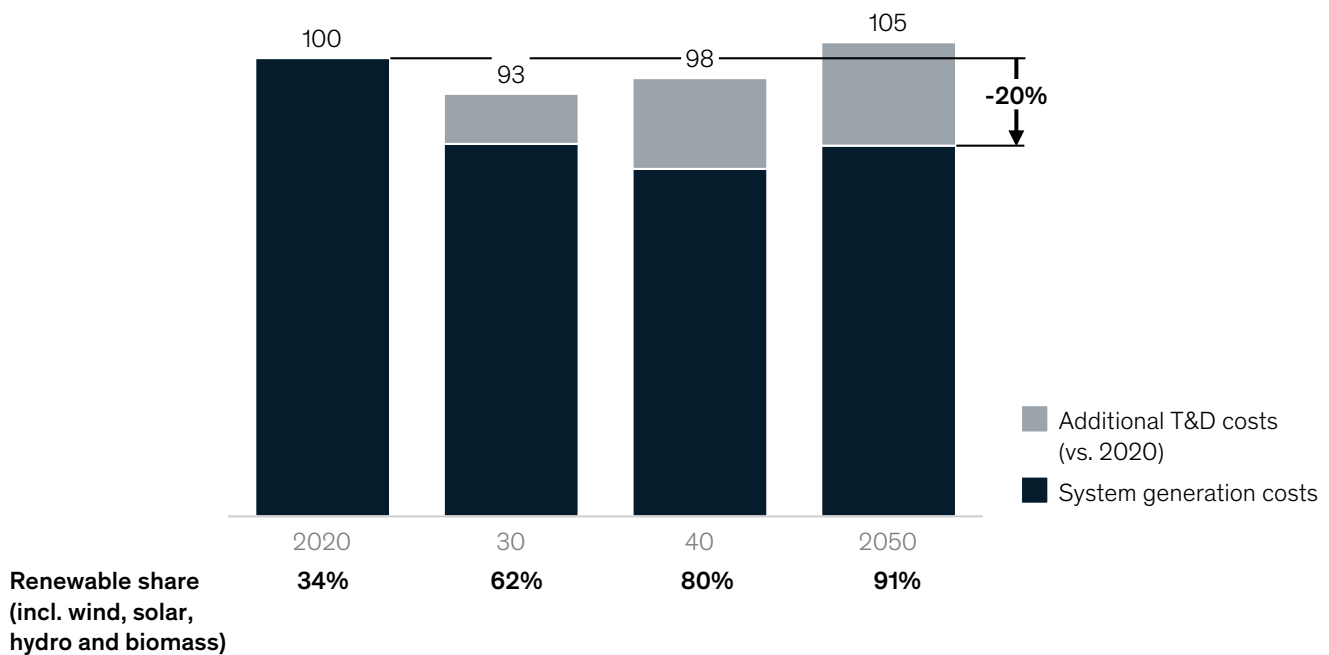
However, greater digitization and new technologies such as smart substations could offset the increase (Exhibit 35). Countries with more natural resources like solar radiation and wind will benefit from even higher cost savings.

²³ Estimations prepared by Trinomics based on several studies. For more information, see Luc Van Nuffel, Koen Rademaekers, Jessica Yearwood, and Verena Graichen, "European energy industry investments," prepared for the European Parliament ITRE Committee, February 2017.

Exhibit 35

By 2050, power generation costs could fall nearly 20 percent, but higher transmission and distribution costs may offset these savings.

Electricity costs, EUR/MWh, EU-27, indexed to 2020 = 100



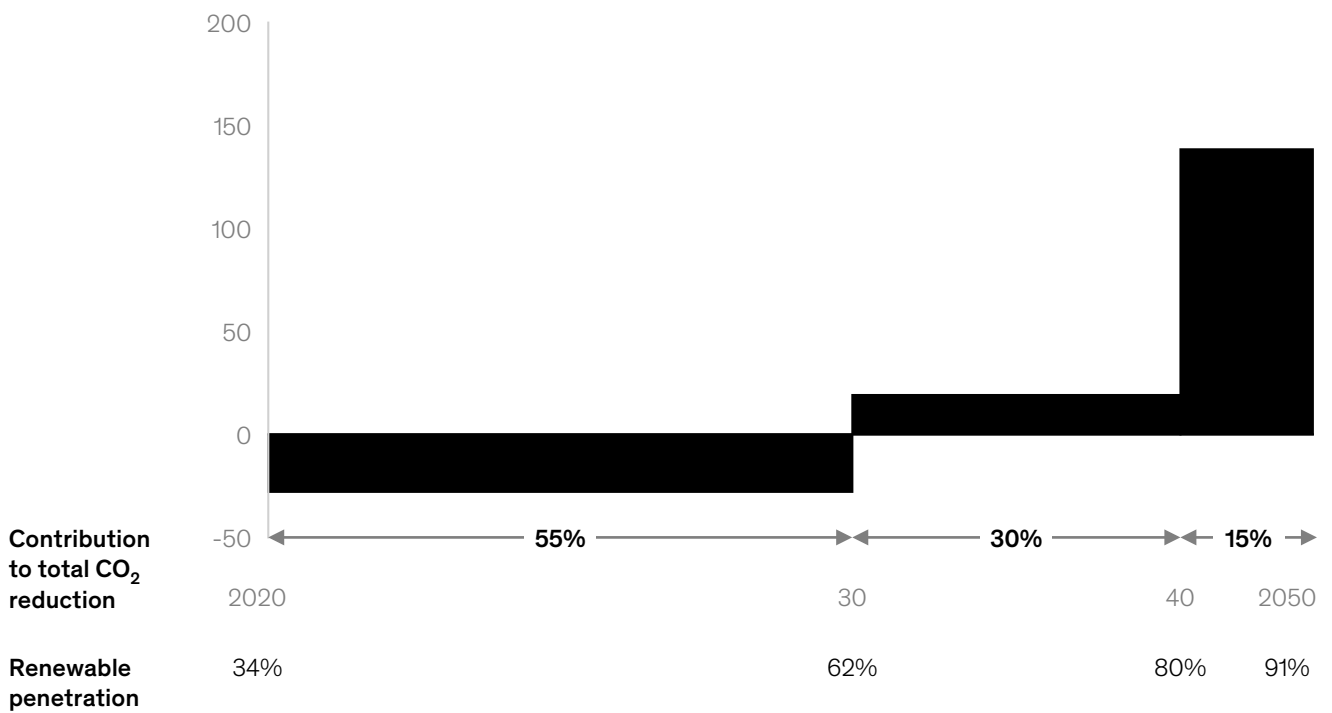
Source: McKinsey, „A Clean Planet for all”, https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

Although the savings from decarbonizing the EU's power sector would more than offset the cost of reducing 85 percent of its emissions, eliminating the last 15 percent would be expensive because they are the hardest to replace with renewable energy sources. Based on current technology, these emissions would have to be abated using more costly solutions such as CCS, BECCS, and power-to-gas (Exhibit 36).

Exhibit 36

Savings should exceed decarbonization costs for 85 percent of the EU's power sector emissions, but eliminating the last 15 percent would be expensive.

Average abatement costs, EUR/ton CO₂ abated , EU-27



Source: McKinsey

3.1.3 Key uncertainties and enablers

Key uncertainties: Technology, social preferences, and demand shifts

Many factors could delay or accelerate GHG reduction in the European Union and change what today appears to be the most cost-effective pathway for the power sector, including:

- **Faster-than-expected technology advancement.** Accelerated cost reduction, performance improvements, and innovative solutions such as floating offshore wind farms could expedite the uptake of renewable power. If new flexibility solutions such as compressed air storage, aqueous storage, and molten-salt batteries mature more quickly than expected, the cost-optimal mix of technologies would also change. Breakthroughs in CCS solutions, such as more efficient capture membranes, could displace some hydrogen use, reducing the volume of renewable power required. Ultra-high-voltage direct-current interconnectors could make cross-regional energy flows cheaper. Also, innovations such as distributed energy resources management systems (DERMS) and other non-wire alternatives could lower grid costs by reducing investments in physical assets. New technologies would need to emerge in the next decade for them to scale and make a meaningful contribution by 2050.

Nuclear generation might also develop differently than assumed in the pathway. Potential breakthroughs in fission technology, such as step-changes in engineering or construction efficiency or small modular reactors or advances in fusion, could improve the competitiveness of nuclear power in the long run.

- **Social preferences.** Building enough wind and solar capacity to decarbonize the power sector will likely require dedicating more land to the greater public good. But if people resist making way for a wind farm or grid interconnection, it will increase the cost or slow the process. Public resistance to potential job losses in the oil, gas, and mining industries could also delay the transition to renewable power, as could concern among government leaders about increasing their dependence on neighboring countries for renewable power. Nuclear technology would also need to attract public support to play a more significant role in decarbonization.

- **Evolving demand and economic shifts.** Electrification and technology changes in every sector of the economy and large industry players relocating businesses or reconfiguring their supply chains to localize production could change the overall power demand, move it geographically, and change the optimal pathway. Evolving energy prices could influence where power producers make new investments over the next 30 years, creating a feedback loop. Overall economic conditions and differences in collaboration levels among companies, governments, and investors could also make it challenging to obtain the capital they need for decarbonization.

Key enablers: Regulation, new market design, and cross-regional cooperation

Governments, regulators, market operators, associations, and investors would all have important roles to play in creating a feasible, cost-effective pathway to decarbonizing the European Union's power sector. The key enablers include:

- **Mechanisms that drive and deploy innovation at scale.** Eliminating the last 15 percent of power emissions will be difficult because there are currently no economically viable options for long-term, seasonal flexibility of the power system. Available technologies, such as gas-fired power stations with CCS or using hydrogen as a fuel, are expensive. However, a supportive ecosystem with financing and piloting opportunities could encourage the

development and deployment of new technology solutions.

- **New market design for the long term.** Some decarbonization investments, such as renewable generation plants and power transmission lines, are expected to be profitable under existing market mechanisms. Others, such as battery storage, gas- and hydrogen-fired power stations for backup capacity, and renewable plants at high penetration levels, would require a new market design that provides the right price signals and adequately remunerates for risk. Long-term perspective and clarity on the strategic direction of the market would enable investments, private sector engagement, and the necessary reskilling of the workforce.
- **Policy support.** To accelerate the shift to renewable power, policy

makers in many countries would need to simplify the regulations for authorizing and permitting new power and grid installations, closures, and conversions. Leaders in countries most impacted by the transition would also need to focus on reskilling the workforce and developing new branches of the economy in the most affected areas.

- **Stronger cross-regional cooperation.** Minimizing the cost of decarbonizing the power sector would require countries to increase cross-border renewable energy flows. Building the necessary interconnections, such as ultra-high-voltage direct-current transmission lines, would call for EU-wide collaboration at a much bigger scale than demonstrated over the past few decades.



3.2 Transportation



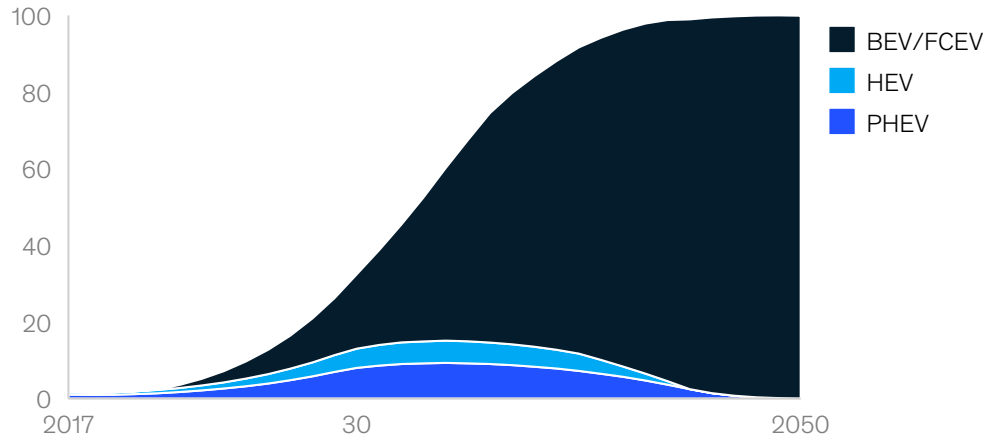
Transportation pathway in brief



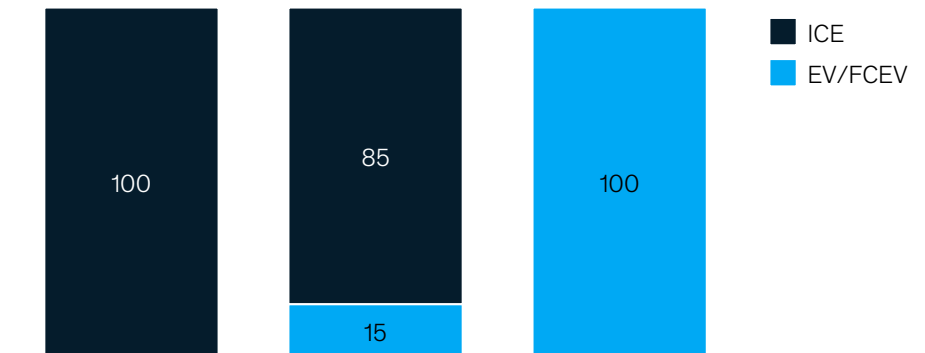
The low-cost pathway in the transportation sector depends on EV passenger car sales, carbon-neutral trucking, and greater adoption of biofuels and synfuels.

EV passenger car sales ¹ % of total	2017	2030	2050
HEV/PHEV	3	20	0
BEV/FCEV	1	>60	100

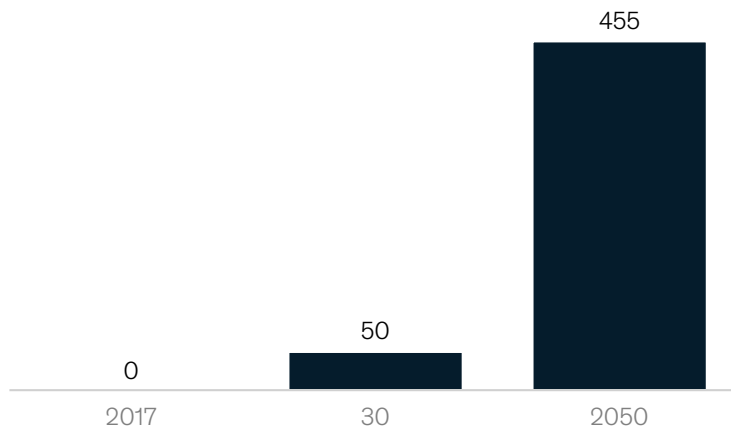
EV passenger car fleet¹
% of total VKT²



Carbon neutral trucking
% of total VKT²



Bio- and synfuel in marine and aviation
MBOE



1. Includes plug-in hybrid EV and Fuel Cell EV

2. Vehicle Kilometer Travelled, excluding Light Commercial Vehicles and Buses

Source: McKinsey

3.2.1 Transportation emissions today

Cars, trucks, and buses generate 95 percent of domestic transportation emissions.

Domestic transportation emits 820 MtCO₂e a year, accounting for 21 percent of EU emissions. One-third of these emissions are generated by the bloc's largest economies, Germany and France. Passenger cars account for 60 percent of these emissions, followed by heavy-duty trucks and buses with 25 percent and light-duty trucks with 10 percent. The remaining 5 percent is emitted by railways, domestic aviation, and domestic marine vessels (Exhibit 38).

International transportation, such as refueling international planes and ships within the European Union, emits 260 MtCO₂e a year—an additional 5 percent on top of the European Union's domestic emissions. Although we excluded international emissions from our analysis because they are not included in the EU climate targets, they would also be reduced by the domestic decarbonization efforts in our pathway. For example, 45 percent of international flights are between EU countries, so

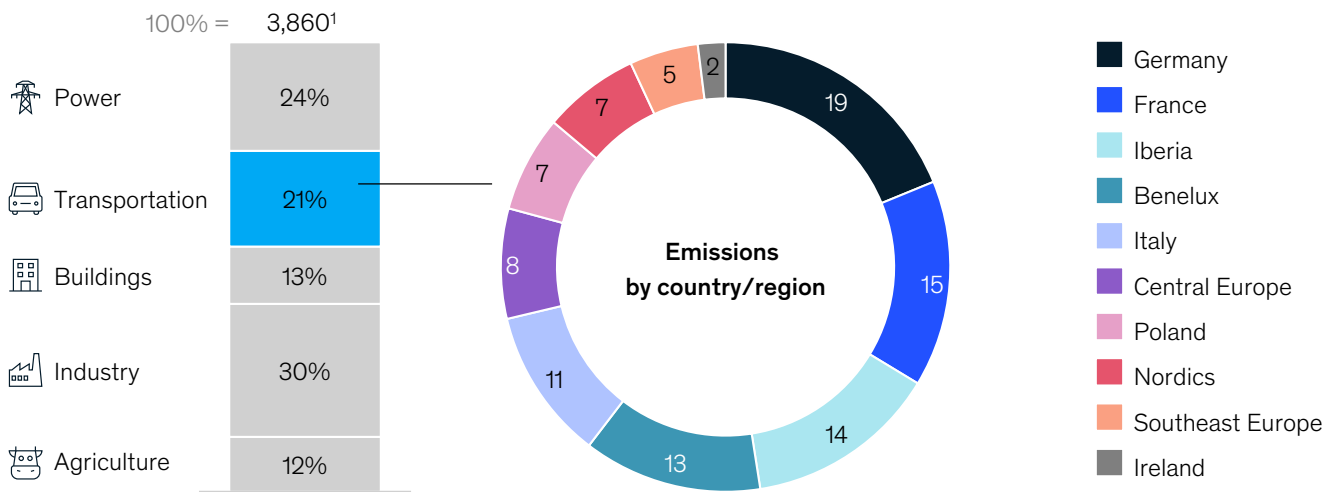
the energy efficiency and fuel changes we propose for domestic aviation would reduce the emissions of those flights as well.

Despite rising interest in EVs, they account for less than 1 percent of the cars, less than 1 percent of trucks, and less than 5 percent of buses in the EU. Most vehicles have internal combustion engines (ICE) powered by diesel or gasoline, although 5 percent use biofuel. Nearly all planes and marine vessels also run on fossil fuels. Rail is the only sector that is already 80 to 90 percent electric.

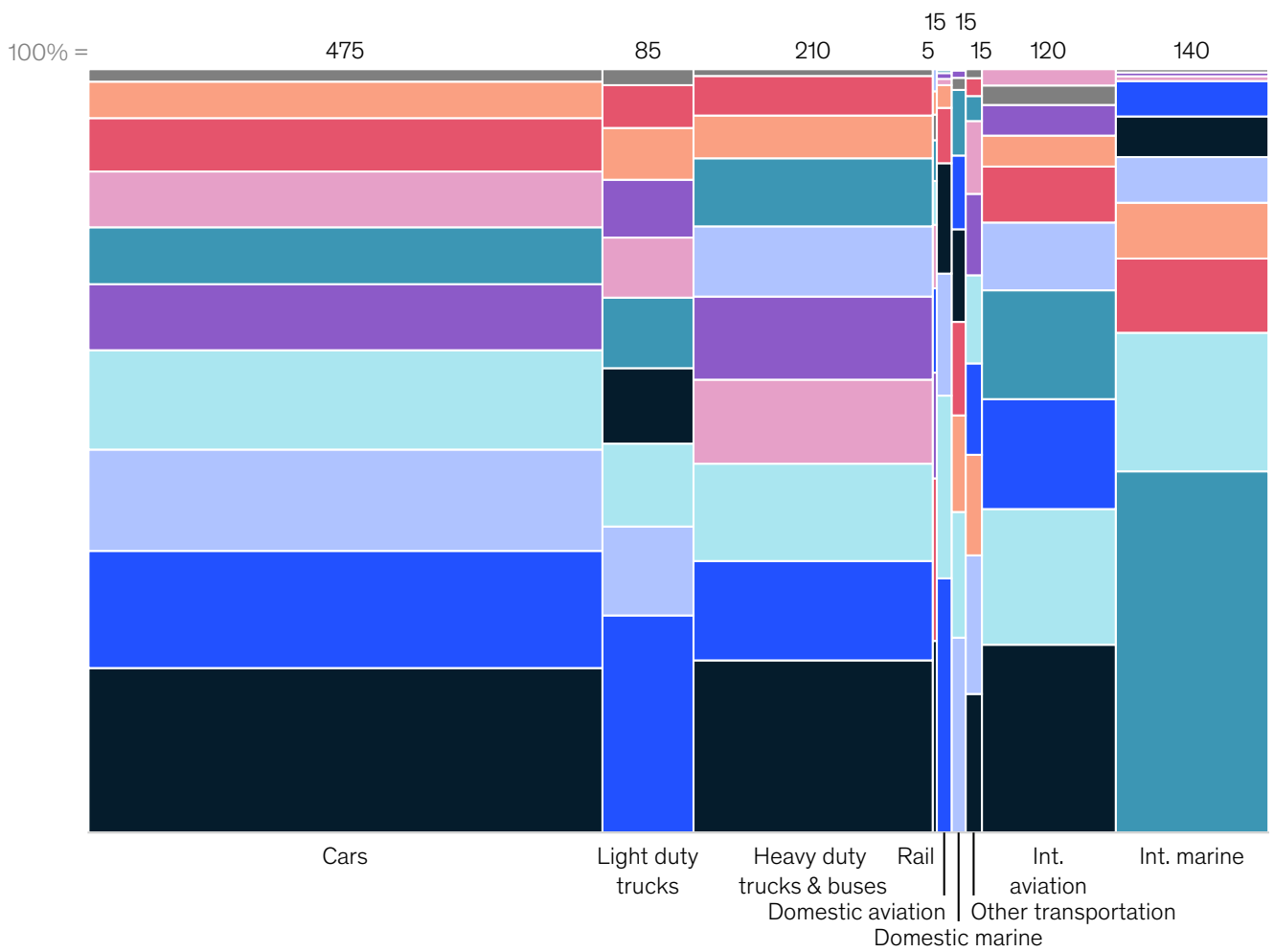
Without intervention, the EU's transportation emissions would rise 30 percent by 2050. This is because transportation activity is expected to grow 1.5 percent per year until 2030, slowing to 0.7 percent a year from 2030 to 2050 as population growth stagnates. In terms of kilometers traveled, aviation is expected to grow the fastest as the propensity to travel increases with consumers' growing disposable income.

The transportation sector accounted for more than 20 percent of EU GHG emissions in 2017.

Emissions by sub-sector and country/region, 2017, MtCO₂e



Emissions by sub-sector and country/region



Road transportation: ~70%

Other: ~30%

1. Total EU-27 emissions excluding international aviation and marine

Source: McKinsey

3.2.2 The role of transportation on the path to net-zero

For the European Union to become net-zero, transportation emissions would need to be reduced at least 30 percent by 2030 and 95 percent by 2050.

This is a significant departure from the current path. Today's EU emissions standards call for reducing emissions from new vehicles by 37.5 percent for cars and 30 percent for trucks by 2030. Together, these efforts would only reduce emissions by 15 percent.

Key transportation levers

1. *Electrify cars, buses, and trucks*

At least 80 percent of new cars would need to be electrified (HEV, PHEV, BEV, or FCEV) by 2030, reaching 100 percent by 2035 (compared to less than 5 percent today). At least 90 percent of new short-haul buses and trucks and 30 percent of long-haul trucks and buses would need to be battery electric or fuel cell electric by 2030 (compared to less than 3 percent today).

Hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) could serve as transition technology. By 2030, 20 percent of the cars on the road would need to be hybrid, up from 3 percent today. This would help reduce emissions in the next decade as the auto industry builds the capacity to be fully electric.

2. *Improve energy efficiency*

The energy efficiency of ICE vehicles, aircraft, and ships would need to increase by 10 percent to 30 percent by 2030.

3. *Increase the use of hydrogen and alternative fuels*

At least 15 percent of aviation and marine would need to use biofuel or synthetic fuels by 2030 and 60 percent by 2050.

4. *Electrify remaining railways*

Catenary infrastructure would need to be installed on the remaining high-use train routes. The remaining lines would use fuel cell or electric trains with battery extenders.

5. *Drive modal shifts to lower emission transportation through regulation and growth of consumer options*

Transportation would need to shift from using planes and heavy-duty trucks to move people and goods to using more rail.

People may need to be offered incentives to switch from driving cars to using higher density transportation modes like buses and trains as well as e-hailing, micromobility, and car sharing.

The cost-optimal pathway for transportation uses similar abatement levers across EU countries (Exhibit 39). However, the transition would need to move faster in some regions than others to make up for the greater challenges that some countries face in reducing transportation emissions. For example, Nordic countries would have an easier time switching to EVs than those in Southeastern Europe because their electricity prices are lower and they import fewer secondhand cars.

Rapid adoption of electric and fuel cell vehicles

It's well established that electrified and fuel cell vehicles will be essential to reducing global emissions. Depending on the type of vehicle, EU regulations require 15 to 50 percent of new buses, commercial vehicles, and cars to be EVs by 2030, which would reduce emissions by 15 percent.²⁴ In the cost-optimal pathway, road transportation emissions would need to decrease at least 34 percent by 2030, more than double the amount under current policies.

Reducing emissions by 34 percent in the next decade would require two critical actions. First, 80 percent of car and light commercial vehicle sales and 30 percent of long-haul truck sales would need to be electric or fuel cell by 2030, which would reduce emissions by 20 to 25 percent. This would require

a significant acceleration from the current path. However, BEV sales are already picking up, with 143 new EV models launched in 2019 and an additional 450 models announced for 2022. Second, the total cost of ownership (TCO) of EVs would need to become less than ICEs, which is expected to occur in the EU by 2025. As battery prices continue to drop, it will be €250 cheaper per year to own a BEV than an ICE car by 2030.²⁵

Hybrid vehicles (i.e., HEV and PHEV), now 3 percent of EU vehicles, would play an important role in decarbonization in the next ten years as the auto industry transitions to an electric value chain, which will require scaling battery capacity and building new infrastructure. By 2030, hybrid vehicles could grow to 20 percent of new car sales.

However, as the TCO for fully electric cars drops below that of hybrids, switching to fully electric cars would keep society on the lowest cost decarbonization path, growing to 60 percent of new car sales. In places with conditions that would make electrification difficult, such as those with long distances between charging points or colder climates that limit battery capacity, hydrogen and biofuels could also play a role in decarbonization.

Among commercial vehicles, electric short-haul trucks and city buses are expected to reach TCO parity with their diesel counterparts by 2026. For long-haul trucks and buses, battery-electric or fuel cell electric vehicles (FCEV) would be the best option because both are expected to reach TCO parity with ICEs by 2030. For FCEVs to become the lowest cost choice, pump prices

²⁴ Current European Union regulations require that EVs account for 40 to 50 percent of new car sales, 25 to 30 percent of light commercial vehicle sales, and 15 to 25 percent of truck and bus sales by 2030.

²⁵ Assuming the car is owned for five years by the first owner, driven 13,000 km per year and has a residual value proportional to the remaining full vehicle lifetime.

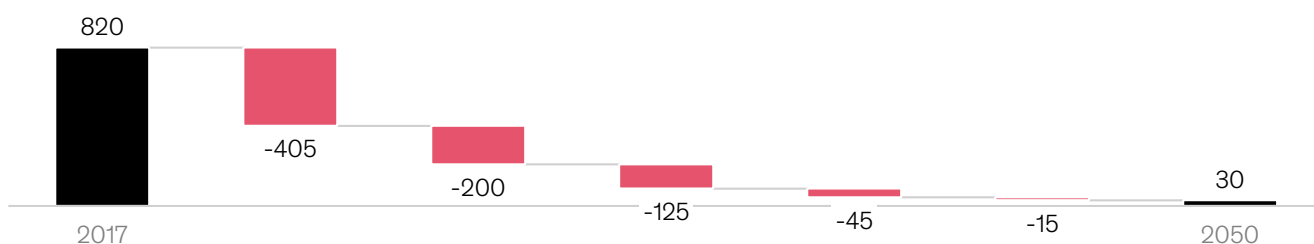
Exhibit 39

Electrification and hybridization account for half of the emissions abatement in transportation.

Domestic transportation emissions for EU-27, MtCO_{2e}

Domestic transportation base case emission reduction 2017-50

MtCO_{2e}



Key levers	Electrification & Hybridization	Energy efficiency	Hydrogen	Demand reduction	Alternative fuels ¹
Description	Electrification of cars, urban/regional trucks and city buses	Improved energy efficiency through vehicle design (e.g., engine efficiency) and operational efficiency (e.g., speed reduction, higher utilization)	Fuel cell vehicles, predominantly in long-haul truck and bus applications	Demand reduction and behavioral shift driven by e.g., ICE bans, congestion charging and smart parking solutions	Alternative fuel (bio- and synthetic) use in aviation and marine
Share of emission reduction	51%	25%	16%	6%	2%

Levers can be combined in multiple ways and the most cost-optimal reduction path is uncertain.

1. Includes domestic marine and aviation transportation

Source: McKinsey

for hydrogen would need to drop significantly, while the attractiveness of BEVs depends on how much battery prices decline. FCEVs have the advantage of faster refueling times and higher energy density than batteries.

Small BEVs like cars would become price competitive first, followed by larger vehicles like heavy-duty trucks. They are both expected to reach TCO parity more quickly in regions with low electricity prices and high fossil fuel prices such as the Nordics, and more slowly in regions with high electricity prices like Germany. EV adoption is also expected to be faster in countries with a higher percentage of new car sales, such as Germany and France, and slower in countries with high demand for used cars, such as Poland and the Czech Republic.

In the meantime, making ICEs more energy efficient would be critical to bridging the transition to electrification. Implementing fuel-saving technologies that reduce an ICE's emissions by just 2 percent a year would cut total car emissions by 5 to 10 percent by 2030.²⁶

Increase efficiency in aviation, use sustainable fuels and new propulsion technology

In the cost-optimal pathway, domestic aviation emissions would need to be reduced 90 percent by 2050. Aviation has historically reduced its emissions through efficiency improvements. However, reaching the 50 percent reduction target set by the International Air Transport Association (IATA), let alone net-zero, would require additional measures, such as using alternative fuels and new propulsion technology.

Reducing aviation emissions is particularly challenging because planes transport high payloads over long distances, and the industry is by nature international, which makes it difficult to create an equal playing field. It doesn't help that planes have 25+ year

lifetimes, innovation and development cycles are long, and alternative fuels aren't likely to become competitive with fossil kerosene before 2050. The use of aviation is also expected to grow 25 percent by 2030.

In the short term, emissions-reduction efforts would continue to focus on improving energy efficiency and using advanced biofuels. Today's aircraft can already use up to 50 percent blend-in advanced biofuels, and 100 percent could be possible without significant aircraft design changes.

In the midterm, smaller short-haul aviation could be powered by batteries or fuel cells.²⁷ For larger aircraft, using hydrogen turbines or direct hydrogen propulsion could be technically feasible but would take longer to develop and scale.²⁸ The longest flights would likely continue to use high-energy-density fuels such as advanced biofuels and synthetic fuels.

Although using advanced biofuels or synfuels would cut aviation's CO₂ emissions to zero, it wouldn't reduce the emission of nitrous gas, water vapor, and contrails that also contribute to global warming. Switching to biofuels and synfuels would reduce the full climate impact by 30 to 60 percent, but using hydrogen would have an even greater effect.²⁹ Using hydrogen turbines could reduce the climate impact by 50 to 75 percent, and using hydrogen fuel cells could decrease the impact by 75 to 90 percent.

Increase energy efficiency in marine, switch to alternative fuels long-term

In the cost-optimal pathway, domestic marine emissions would need to be reduced 65 percent by 2050. The marine industry has significantly improved its energy efficiency in recent years, and today's ships are much more efficient than the ones sold a decade ago. The International Marine Organization

(IMO) has also set 50 percent reduction targets for the industry and implemented regulations that limit the sulfur content of fuels, which reduces airborne pollution from ships.

However, to reach the IMO target and ultimately net-zero, marine would need to continue pursuing energy-efficiency improvements while adopting new technologies and fuels. Energy efficiency could be increased at least 10 percent by 2030 through measures that enhance vessel technology, such as propulsion and hull design, and operations, such as speed limitations and just-in-time arrival. New propulsion technologies, advanced biofuels, and synthetic fuels are likely to be expensive, costing an additional €100 per tCO₂.

Reducing emissions in vessels ranging from the largest ocean-faring cargo ships to short-range ferries would require multiple solutions. Smaller ships and those traveling shorter distances can already use hydrogen and electricity, such as the fully electric Ampere ferry in Norway. In the short term, larger vessels could use blend-in advanced biofuels because they don't require significant equipment changes.

In the long term, large ships could also start using hydrogen-based fuels, such as pure hydrogen, synthetic marine gas oil, ammonia, and methanol, as they become affordable. At a sufficient scale, hydrogen-based fuels could become competitive with advanced biofuels between 2030 and 2040.

Electrify remaining rail

Although only 65 percent of the European Union's railway is electric, 80 to 90 percent of trains use those electric lines. However, emissions could be cut further by electrifying more lines in densely populated areas. In lower use areas where the cost of electrifying the lines is prohibitive, electric trains

²⁶ Corresponding to 15 to 25 percent efficiency improvement in new cars by 2030 compared to 2017; key improvement levers include downsizing, turbo-charger, and electrifying auxiliary engine components (mild-hybridization).

²⁷ 500 km to 1,000 km for batteries and 2,000 km to 3,000 km for fuel cell (dependent on passengers carried).

²⁸ For example, Airbus recently announced development of a hydrogen A320 to be launched by 2035.

²⁹ For more information, see "[Hydrogen-powered aviation—A fact-based study of hydrogen technology, economics, and climate impact by 2050.](#)" McKinsey & Company for the for the Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU, May 2020.

with battery extenders or fuel cell trains could be used instead.

Drive modal shifts to lower emission transportation

The cost-optimal pathway requires a shift to higher density transport low-emission modes, such as rail and shared mobility. In the last ten years, the rise of mobility as a service (MaaS) has allowed consumers to choose from new transportation modes such as e-hailing, car sharing, and shared micromobility. There's a risk that MaaS offerings could tap into latent demand, encourage modal shifts away from public transport, and increase the total vehicle kilometers traveled due to multiple passenger pick-ups, which could increase transportation emissions. On the other hand, micromobility and pooled MaaS services could create greater efficiency by replacing large, low-fill-rate buses with smaller shuttles

and using electric scooters instead of cars. That's why increasing the efficiency of these transportation systems through well-designed MaaS would be another critical lever for reducing emissions.

According to our 2019 global mobility survey, more than 20 percent of consumers say they frequently use micromobility services, such as the bike, moped, and electric scooter share programs in major cities. By 2030, our modeling forecasts that micromobility could cover 20 to 30 percent of last-mile trips in a city like Munich if local governments create incentives for it and citizens adopt it. In the case of Munich, this could reduce emissions by 80 ktCO₂e per year, the equivalent of the annual CO₂ emissions of 10,000 Germans.

Dynamic shuttle services, a form of ridesharing that groups passengers by travel time and destination, would also reduce transportation emissions by increasing the number of people using high-density transportation. Today's dynamic shuttle services and pooled e-hailing would get an additional boost with the adoption of autonomous vehicles. By 2030, autonomous EV taxis and shuttles could cut private car usage by up to 20 percent in a city like Berlin.

The path to net-zero would also improve air quality and save lives

In addition to greenhouse gases, industry sectors emit pollutants such as sulfur dioxide, lead, nitrogen oxide, carbon monoxide, and benzene that damage air quality. Although air quality in the European Union has improved over the last few decades, it still contributes to more than

400,000 deaths each year, making it the largest environmental cause of premature deaths.

A pathway to net-zero emissions would not only reduce greenhouse gases but also many of these pollutants. For example, transportation is the biggest emitter of nitrogen oxide, and power emits

the most particulate matter and sulfur dioxide. By 2030, the cost-optimal pathway would reduce the air pollutants from road transportation by at least 30 percent. This would improve air quality and, in turn, reduce asthma, respiratory problems, and premature deaths.

3.2.3 Key uncertainties and enablers

Key uncertainties: Prices, technology advancements, and behavior

Many uncertainties could change what now appears to be the cost-optimal pathway for transportation, including:

- **Oil prices below \$40 a barrel** could delay the TCO parity of EVs and ICEs by up to five years. An 80 percent increase in electricity prices by 2030 would have a similar effect.
- **Rapid battery price declines** could alter the pathway for trucks and buses. If battery prices drop 80 percent by 2030 instead of the 45 to 50 percent we forecast, BEVs would become less expensive than FCEVs for long-haul trucking. Technological innovations such as high-density battery chemistries and longer battery lifetimes could make BEVs even more affordable.
- **A faster drop in hydrogen, fuel cell, and hydrogen tank prices** could make FCEVs more competitive than BEVs. For example, if hydrogen prices drop to €3.4 per kg at the pump, and fuel cell stack costs fall to €130 per kW by 2030, FCEVs could also become the lowest cost option for regional trucks and buses.
- **Technology and fuel price developments** could change the cost-optimal pathway for aviation and marine. If advanced biofuel prices don't drop over time, hydrogen-based fuels like ammonia could become the cheapest option by the early 2030s. If synthetic fuel prices decrease more than 55 percent by 2040, synthetic kerosene and marine gas oil could also become less expensive than using biofuels. And if hydrogen prices drop 80 percent by 2030, it could give hydrogen propulsion for mid-haul large aircrafts a more significant role in the transition.
- **More rapid adoption of MaaS** could speed up emission reduction and lower the transition costs of our cost-optimal pathway. If 30 percent of the annual kilometers driven by passenger cars switched to MaaS offerings by 2030, passenger car emissions could drop another 25 percent. And scaling autonomous EV shuttles could cut transition costs an additional 5 to 10 percent. However, the convenience of low-cost rideshare and autonomous vehicles could also increase the number of people who choose ridesharing over public transportation, increasing emissions.
- **Shifts in consumer preferences** such as greater interest in EVs beyond government incentives could speed up EV adoption. Emission reductions would also accelerate in line with the power sector's decarbonization. For example, during the 2020 pandemic, EV purchases proved more resilient than traditional ICEs, signaling the beginning of a potential shift in consumer preference.
- **Technological advancements** within private non-electric vehicles could reduce road transportation emissions. Efficient routing would reduce CO₂ emissions by enabling drivers to avoid traffic jams. Advanced analytics could be used for traffic or parking management, which would also reduce emissions. There is also ongoing research on using syngas in non-electric vehicles during the transition period.

Key enablers: Government policies and collective investments

Several things must happen to make this pathway feasible and cost-effective, including:

- **Ambitious policy support.** The cost-optimal pathway is highly dependent on regulators setting targets for the adoption of zero-emission technologies and fuels. For example, the rapid EV adoption of cars, trucks, and buses requires much more ambitious targets and other regulatory support. New policies accelerate EV adoption by incentivizing their use in car fleets or within mobility-as-a-service so that EVs are owned by those that drive the most. They could also create incentives for retiring old ICE vehicles in favor of EVs and encourage higher use of lower emission transportation modes, such as public transportation and shared mobility.
- **Large-scale increase in renewable electricity generation.** The European Union would need at least an additional 200 TWh a year by 2050 to support the influx of

electric and fuel cell vehicles. The affordability of hydrogen is also highly dependent on having a low-cost renewable electricity supply.

- **Significant build-out of EV and fuel cell infrastructure.** Switching to EVs would require scaling new charging and refueling stations with better EV charger density, speed, and interoperability. Enabling FCEV usage would require building a hydrogen distribution network of trucks and pipelines that could transport hydrogen gas and liquified hydrogen throughout the European Union.
- **Major investment across the value chain of electric and fuel cell vehicles.** The transition to zero-emission cars would require retooling auto manufacturing and building new recycling facilities. For example, increasing battery production capacity to 750 gigawatt-hours (GWh) a year by 2030 would require expanding the supply of lithium, nickel, and cobalt to make them. Producers would need to enter into offtake agreements at prices and time horizons that allow new mines to

be developed. Continued battery chemistry innovation and greater recycling could help reduce the risk of these metal supplies becoming constrained.

- **Investment in alternative fuels and new technology.** To reach net-zero emissions, the transportation sector would need at least 100 million tons of alternative fuels a year by 2050. Fulfilling this demand would require investments in feedstock collection infrastructure, zero-emission electricity supply, production facilities, storage, and transportation infrastructure. It also calls for funding the development of new powertrain technology and airport and port infrastructure. Policymakers could make these investments more attractive with better CO₂ pricing and incentives that enable aviation and marine players to get a fair return on their investment and stimulate R&D in equipment and fuel supply infrastructure.



3.3 Industry

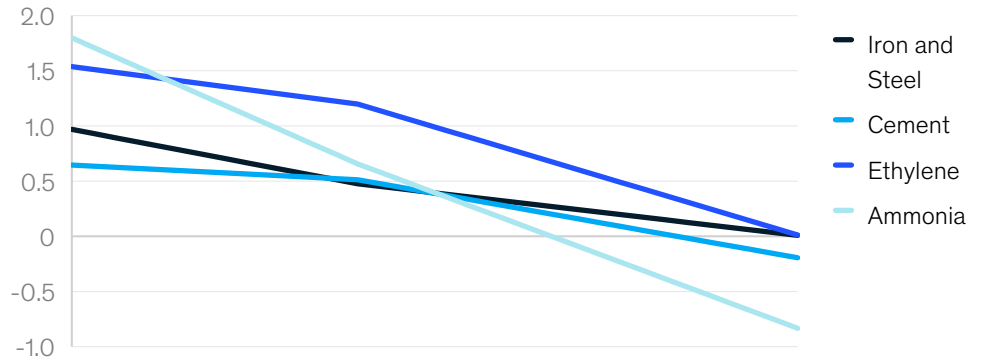


Industry pathway in brief

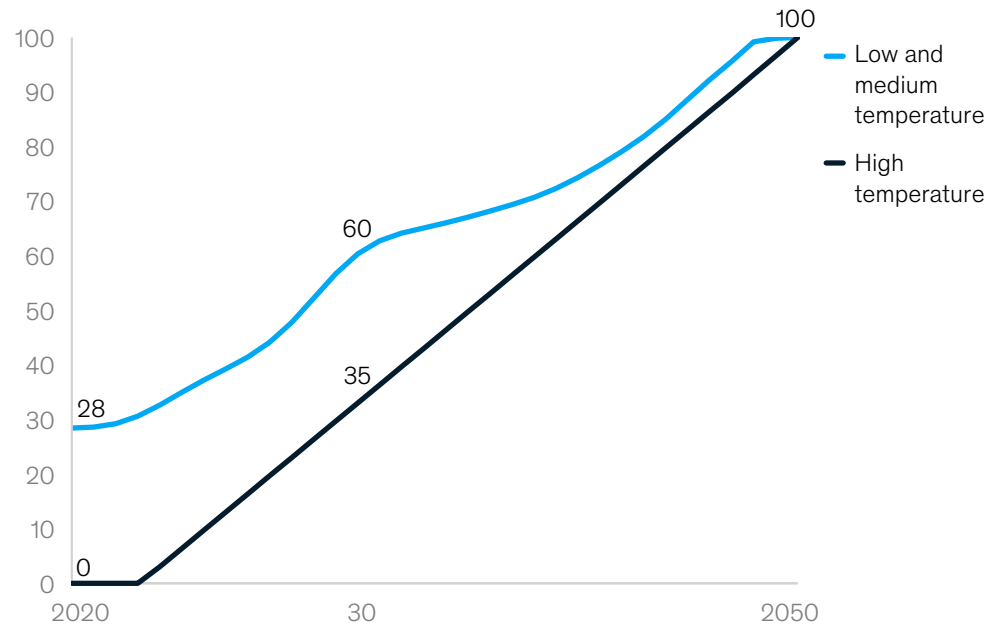
Renewable heat generation and carbon capture could help EU industry cut emissions 96 percent by 2050



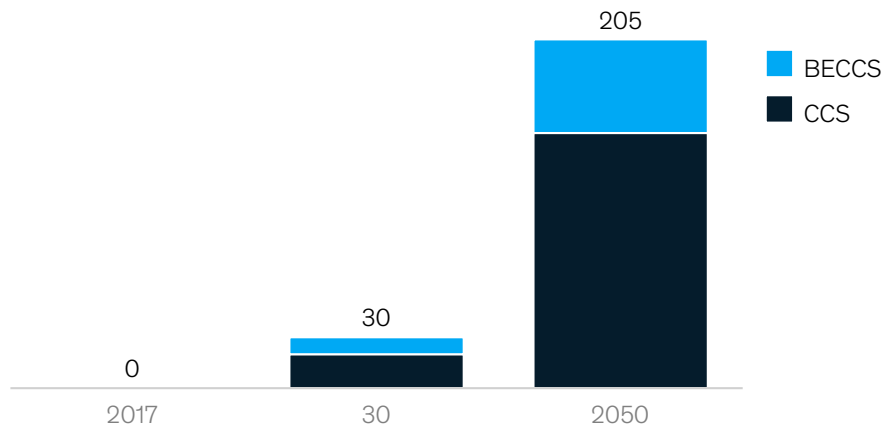
Average carbon intensity
Ton CO₂e emitted by ton product produced



Heat renewably generated¹
% of total



Carbon capture²
Mt of CO₂ per annum



1. Share of heat from renewable fuels (e.g. biogas, electricity)
2. Technologies includes CCS, BECCS and other carbon sinks. Demand includes power
Source: McKinsey

3.3.1 Industry emissions today

Nearly half of industrial emissions come from heavy industries such as cement, steel, ethylene, and lime production.

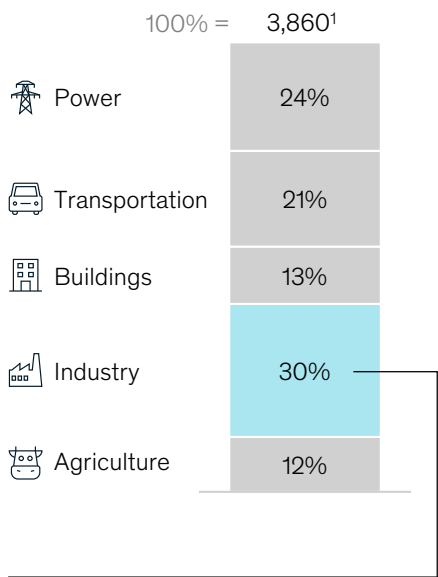
In 2017, industry emitted 1,140 MtCO₂e, accounting for 30 percent of EU

emissions (Exhibit 41).³⁰ The industry sector consists of numerous processes, including the production of industrial materials such as cement and steel, chemicals such as ammonia and plastics, fuels like gasoline and coal, and consumer products such as food, clothes, and paper. The largest industry segments are iron and steel (accounting for 13 percent of emissions, followed by waste management (10 percent), petroleum refining (10 percent) and cement (7 percent) (Exhibit 41).

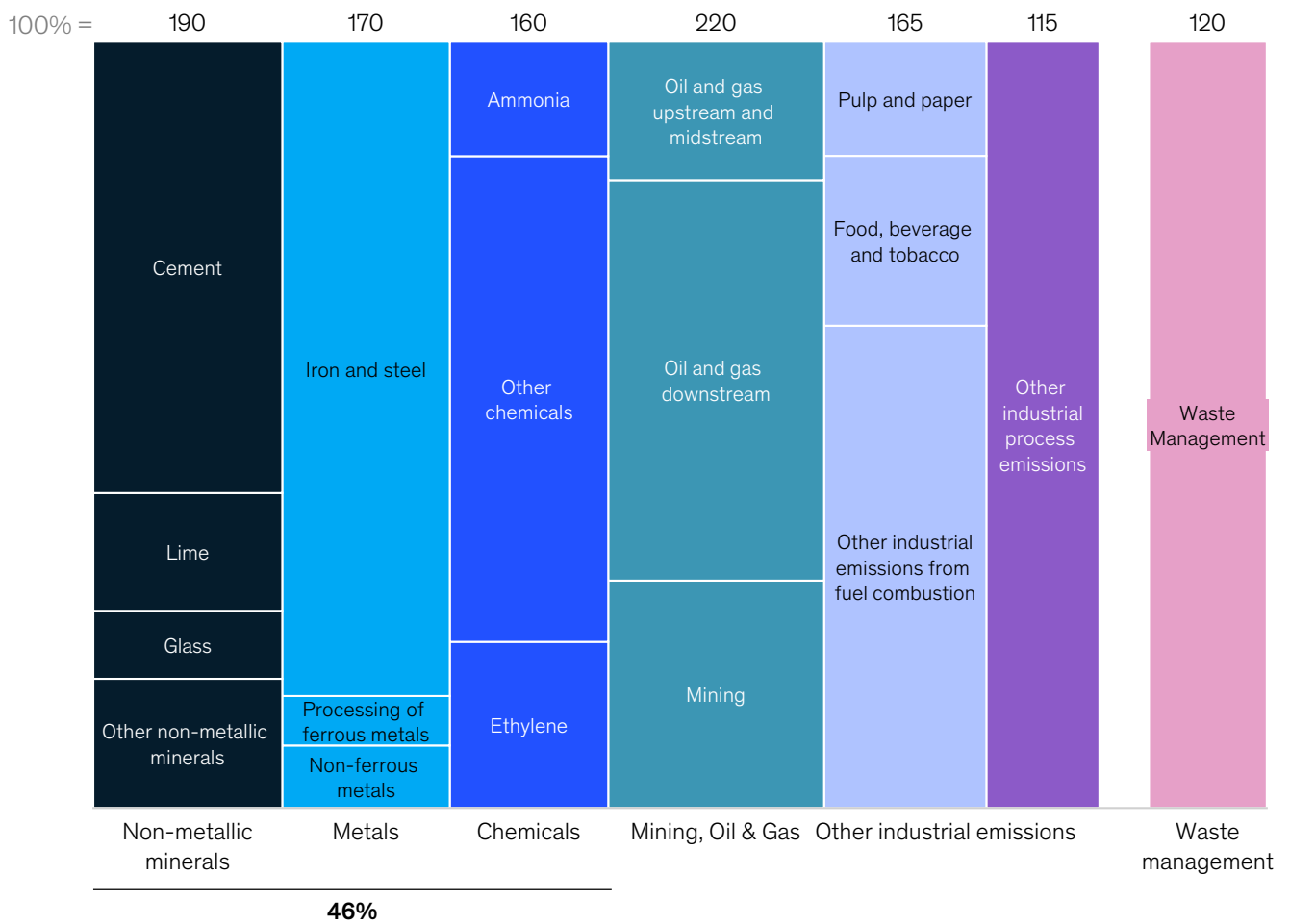
³⁰ Share of total emissions including international transport and LULUCF sector.

Heavy industry accounts for nearly half of EU-27 industry GHG emissions.

Emissions by sub-sector for EU-27, 2017, MtCO₂e



Emissions by sub-sector



1. Total EU-27 emissions excluding international aviation and marine

Source: McKinsey, Eurostat, UNFCCC National Inventory Reports, EEA ETS

About half (52 percent) of industrial emissions comes from the fuel combustion used to supply process heat for manufacturing. The other half (48 percent) is GHGs emitted in chemical reactions while processing feedstocks, such as natural gas processing for ammonia production or preparation of iron ore to make steel. Process emissions include fugitive GHG emissions, such as methane leakage from natural gas pipelines (Exhibit 42).

The industrial sector comprises segments that use a variety of production techniques that can be grouped based on their process characteristics and the types of GHGs they emit. They include:

- **Heavy industry** accounts for 46 percent of industry emissions.³¹ Within its segments—non-metallic minerals, metals, and base chemicals—manufacturers specialize in making basic products such as cement, glass, steel, and plastics that require high temperatures to produce. For example, the blast furnaces used to make steel must reach 1,800°C, and the kilns used to calcinate limestone to make cement reach temperatures above 1,600°C. Nearly half of the emissions produced in these segments are CO₂ process emissions, such as those emitted while heating the limestone to turn it into lime to make cement.³² Eliminating these emissions would require changing the feedstock and redesigning the production process. Both the high temperatures required and the process emissions they produce make these segments hard-to-abate.
- **Oil, gas, and mining** account for 19 percent of industry emissions. About 25 percent of these emissions are from methane leakage, primarily from the pipelines that transport natural gas. Most CO₂ emissions come from producing the heat required to crack and distil petroleum—processes that require temperatures up to 400°C for fractionated distillation.
- **Pulp and paper, and food, beverages and tobacco** and several other industrial sectors account for 14 percent of industrial emissions. These come primarily from fuel combustion to generate medium temperature process heat or to drive machinery. The main exception is the lime production step in pulp and paper that releases process emissions.
- **Other industrial process emissions and waste management** account for 20 percent of industrial emissions. About half of these emissions are industrial process emissions which consist for the largest part of fluorinated gases that escape during refrigeration and from cooling systems in various industries. By 2050, the EU aims to reduce these emissions by 80 percent through its own 2015 regulation to minimize the use of hydrofluorocarbons and by complying with hydrofluorocarbons consumption limits imposed by the Montreal Protocol.³³ The other part of these emissions is fugitive methane from landfills. By 2050, the EU plans to reduce these emissions by up to 73 percent through legislation that would require the waste treatment sector to increase its recycling of municipal waste and limit the amount of municipal waste allowed in landfills to 10 percent.

³¹ For more details on emission reduction of these sectors, see "[Decarbonization of industrial sectors: the next frontier](#)," McKinsey & Company, June 2018.

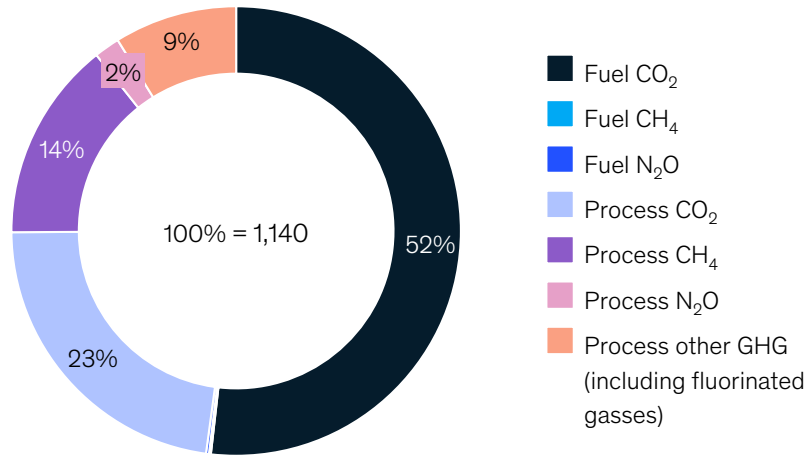
³² Other process emissions in the heavy industry sectors are nitrous oxides, methane, and other gases from various chemical production processes, including nitric acid and ammonia production.

³³ [The Montreal Protocol on Substances that Deplete the Ozone Layer](#)

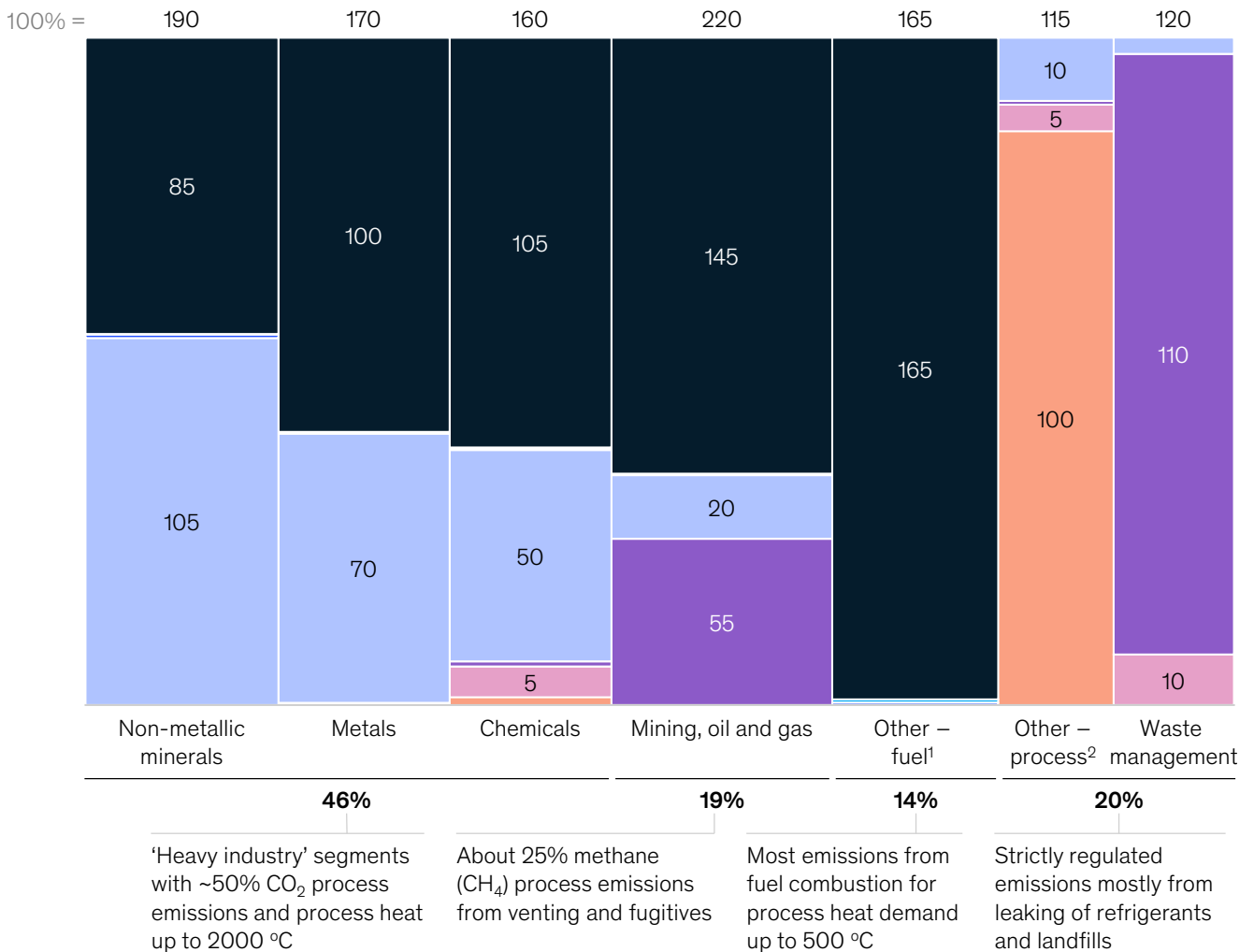
Industrial GHG emissions are almost evenly split between fuel combustion emissions and process emissions.

Industry emissions for EU-27, 2017, MtCO₂e

Share per type of emissions



Emissions by end usage



1. Includes pulp and paper, food, beverage and tobacco, and other industrial emissions from fuel combustion

2. Includes other industry process emissions

Source: McKinsey, Eurostat, UNFCCC National Inventory Reports, EEA ETS

Although each sector is present in each of the regions, the size and relative shares vary. For example, Germany is the largest industrial hub in the European Union and the biggest emitter of industry GHGs (22 percent). Regions with a larger share of heavy industry sites will face higher costs to lower their industrial emissions.³⁴ (Exhibit 43)

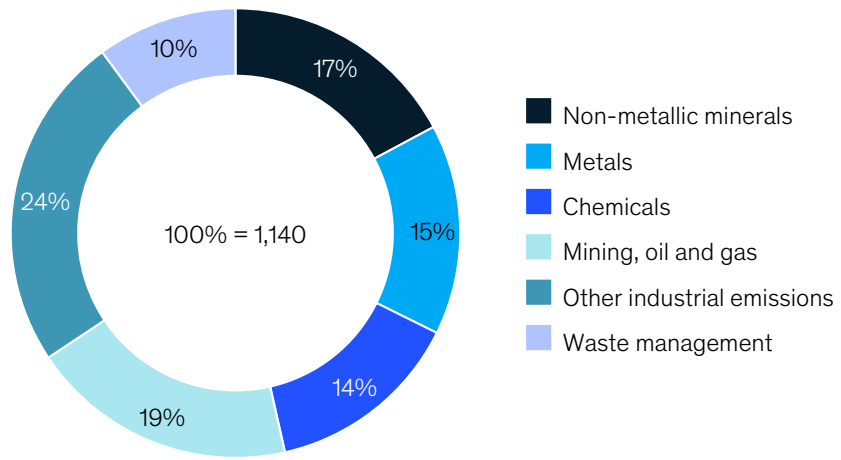
Since 1990, industrial GHG emissions have decreased 2 percent a year, which is twice as fast as the decline in total EU GHG emissions. However, this pace is not enough to reach the 2030 decarbonization targets, or net-zero by 2050. Without intervention, the EU industry sector will balance an increase in emissions from the growing demand for industrial products with reductions from gradual energy efficiency improvements, likely maintaining the same net level.

³⁴ Not all products used in the EU-27 are produced within the member states. Emissions from imported products are not included in the discussion in this chapter.

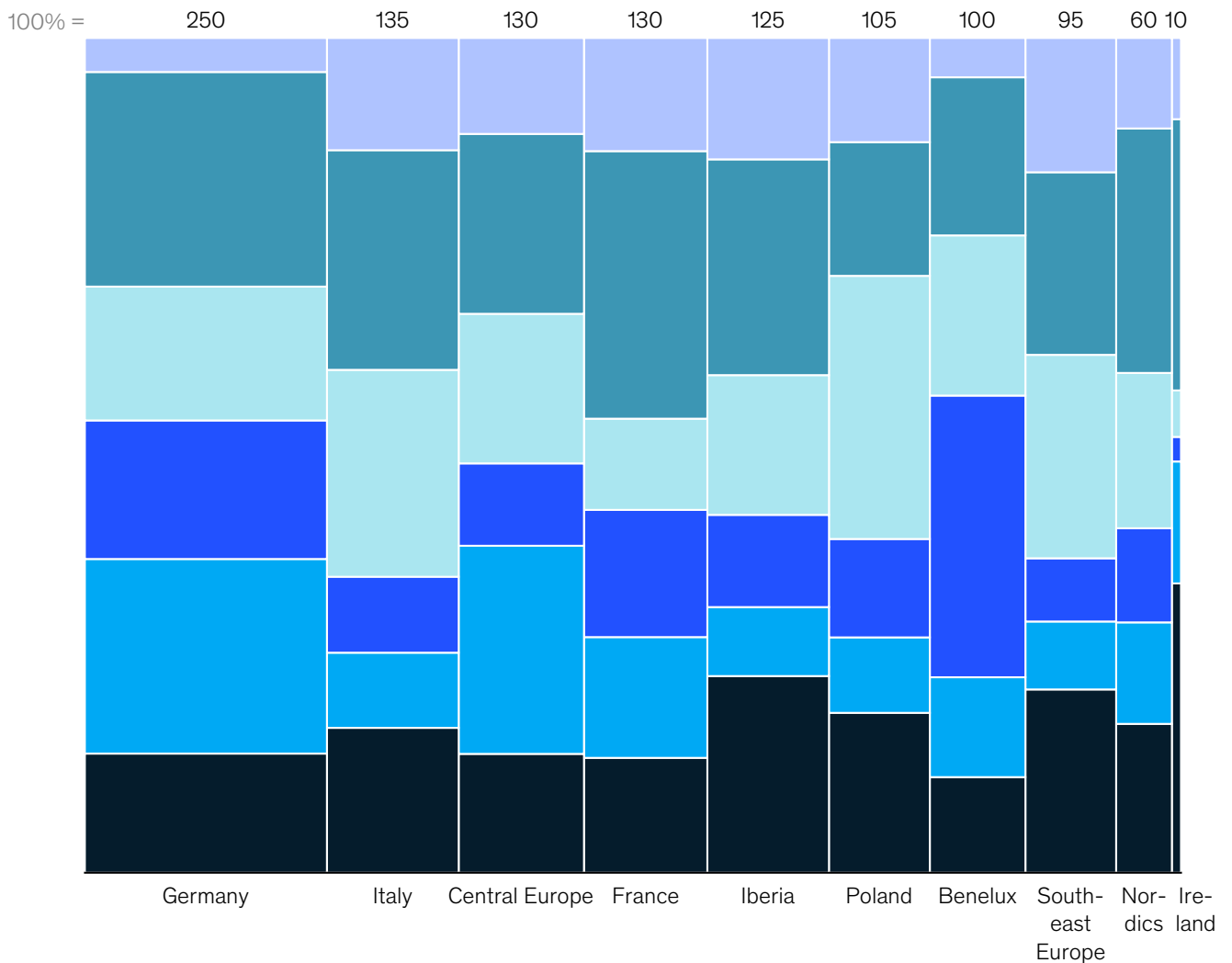
Germany has the highest industrial GHG emissions of any EU region, emitting nearly as much as the next two regions combined.

Industry emissions in EU-27, 2017, MtCO₂e

Share of total



Emissions by region and segment



Source: McKinsey, Eurostat, UNFCCC National Inventory Reports, EEA ETS

3.3.2 The role of industry on the path to net-zero

On our cost-optimal pathway to net-zero, 15 percent of emissions would be abated by a reduction in demand for fossil fuels, which will drive down activity in the mining and oil and gas sectors (Exhibit 44). But to achieve the EU's net-zero ambition using our pathway, industry emissions would need to drop by almost 40 percent by 2030 and around 96 percent by 2050 (including about 7 percent negative emissions from industrial processes). Because industrial equipment often has a lifetime of more than 50 years, emissions-reduction efforts would need to focus on retrofitting or rebuilding existing sites. About 80 percent of those sites would require significant changes to reach net-zero by 2050.

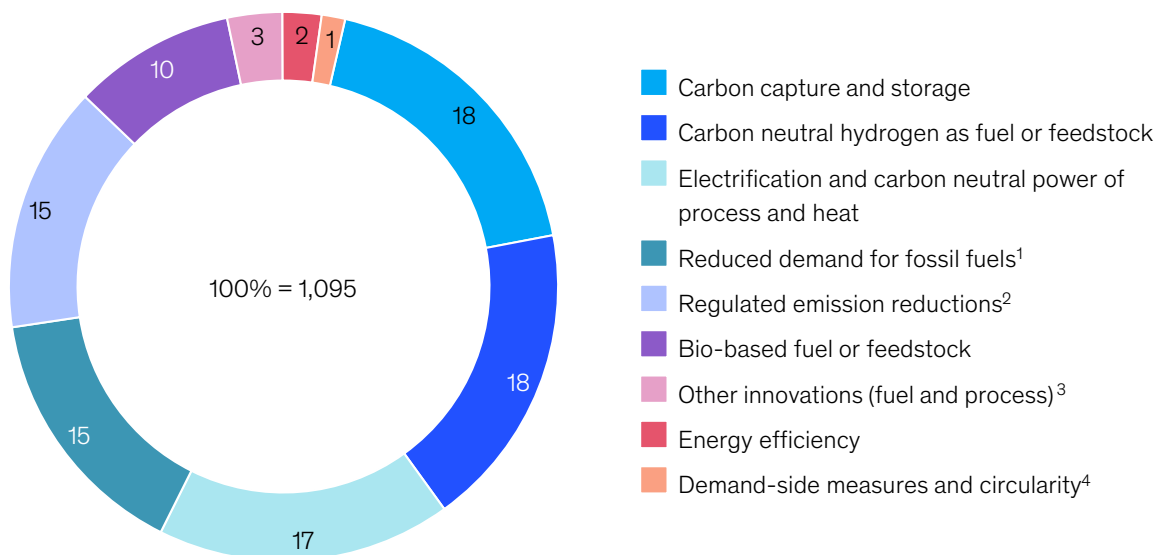
The transformations would include making production process changes at 25 percent of sites, such as rebuilding coal-based steel production sites to sites for direct-reduced iron production. About 20 percent of the sites would need to install carbon capture equipment. Half of these sites would switch to bioenergy fuels as well, to generate negative emissions. A further 36 percent would need to switch to alternative fuels, such as bioenergy, electricity or hydrogen. Only 18 percent of the sites would require little or no change.

Aside from these technical changes, industry emissions can also be reduced by product substitution; for instance, replacing cement for construction with CLT or new plastics with recycled. Emissions can also be reduced by changes in consumer preferences such as switching to public transportation, thereby reducing the need for steel for car manufacturing.

Exhibit 44

CCS, hydrogen, and electrification would contribute nearly half of all industry sector emissions abatement through 2050.

% share of total emissions abatement per technology until 2050, EU-27



1. Includes emission reduction from mining and O&G

2. Includes emission reduction from F-gasses, waste and non specified industrial emissions

3. Includes other technologies such as waste as fuel, inert anode technology in smelting, geothermal heating

4. Includes cross-laminated timber, recycling in ethylene and increased scrap steel ratios

Source: McKinsey

The most cost-effective pathway (Exhibit 45) to accomplishing emission-reduction targets in the industry sector includes:

Use bioenergy and/or carbon capture storage for cement, ammonia, and some steel production (abating 200 MtCO₂e a year)

- A quarter of cement production converted to BECCS by 2045, rapidly increasing to more than 55 percent by 2050
- 28 percent of conventional cement kilns using CCS (without biomass) by 2050
- Electrification in cement and lime reaching only 6 percent by 2050

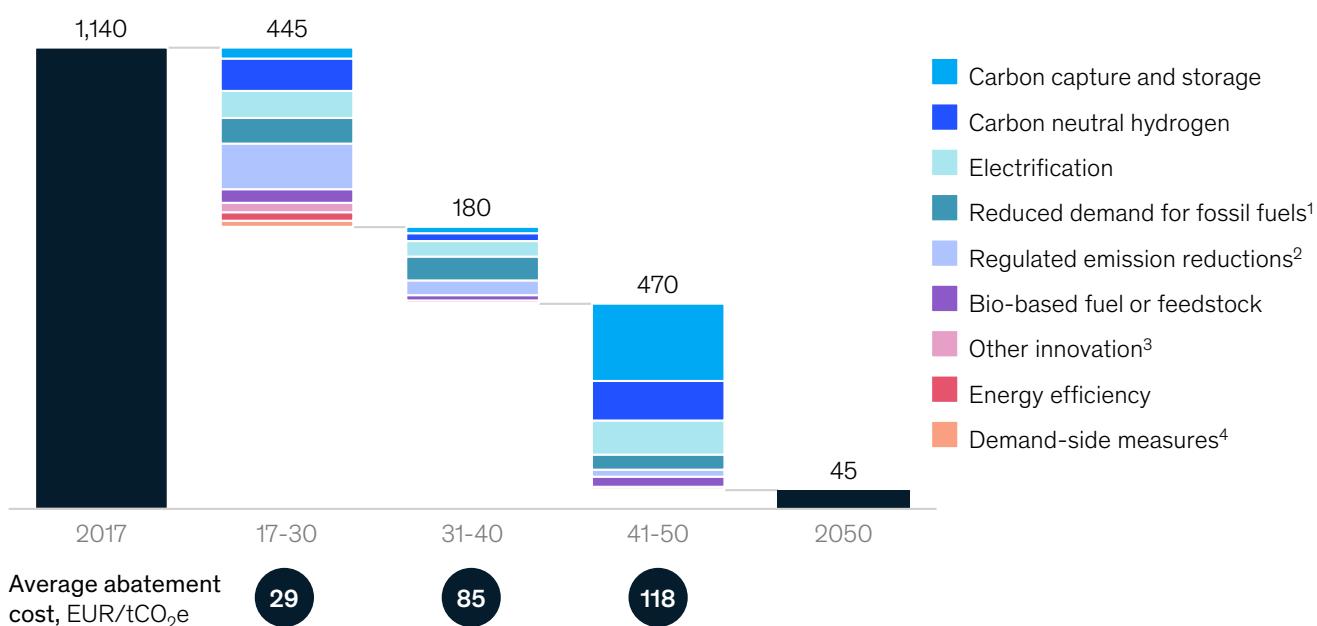
Electrification of processes and heat generation (145 MtCO₂e)

- 35 percent of all low- and medium temperature heat generation moved to electric boilers and 26 percent to heat pumps by 2050
- 55 percent of high temperature heat generation electrified by 2045
- 72 percent of ethylene steam cracking electrified by 2050

Exhibit 45

Average CO₂ abatement costs for industry would rise sharply over the next three decades.

Total CO₂ abatement per technology for EU-27, MtCO₂e



1. Includes emission reduction from mining and O&G
 2. Includes emission reduction from F-gasses, waste and non specified industrial emissions
 3. Includes other technologies such as waste as fuel, inert anode technology in smelting, geothermal heating
 4. Includes cross-laminated timber, recycling in ethylene and increased scrap steel ratios

Source: McKinsey

Use bioenergy as fuel and feedstock across sectors (103 MtCO₂e)

- 5 percent of high temperature heat furnaces switched to biogas and 33 percent of low- and medium-temperature heat generated from biomass
- 100 percent of conventional electric arc furnaces using biogas instead of natural gas for preheating

Use hydrogen for steel production and some ammonia production (195 MtCO₂e)

- 56 percent of steel produced in 2050 from electric arc furnaces fed with iron ore reduced by hydrogen
- 20 percent of ammonia production using electrolysis as a way of producing hydrogen

Reduce consumer demand for emission-intensive industrial products like cement and plastics (15 MtCO₂e)

- 10 percent of the current demand for cement replaced by CLT by 2050
- 5 percent of the current demand for ethylene replaced with plastics recycling by 2050

Bioenergy as fuel and feedstock

Switching to bioenergy will be critical to reducing industry emissions in regions where the average electricity prices are higher than bioenergy prices, such as in Poland and Iberia. Those regions can electrify lower temperature processes, such as rinsing, washing, and evaporation, while switching to bioenergy for the boilers and furnaces needed for higher temperature processes like annealing of steel or ceramics production.

Using bioenergy instead of fossil fuels to heat boilers and furnaces would reduce industry emissions by 10 percent by 2050. Because it doesn't require process changes, industrial sites can make this switch quickly. And depending on the region and application, using bioenergy to reduce emissions will cost an average of €100 per tCO₂.

Two types of bioenergy can play significant roles in industry emissions reduction: solid biomass, produced from forest residues and energy crops, and gaseous bioenergy, made by gasifying solid matter, such as waste from agricultural composting sites and garbage at waste treatment plants. Innovative production processes could create carbon-based chemicals, such as plastics, from liquid or solid biomass instead of petroleum. Some industry segments, such as pulp and paper manufacturing, already use biomass as fuel. With time, more biomass is expected to be used for low- and medium-temperature generation. Gaseous bioenergy, on the other hand, can serve as a substitute for natural gas in ammonia production or in high-temperature gas furnaces.

CCS in heavy industry and refining

Using CCS in heavy industry would reduce industry emissions by 8 percent (90 MtCO₂e) by 2050. Implementing CCS will be critical to reaching emission-reduction targets in heavy industry segments such as cement, steel, and oil refining, where current technology solutions can't eliminate process emissions. For example, CCS is the only way to reduce process emissions when calcinating limestone to make cement. Depending on the region and segment, it will cost €40 to €130 per tCO₂ to implement.

The affordability of CCS depends on the cost of capturing, transmitting, and storing CO₂ at different industrial sites. It's more expensive to capture CO₂ when it's mixed with other exhaust gases than from a pure flow because of the large volume of gas that must be processed and the additional energy it requires. Some newer approaches to manufacturing, such as the Hlsarna process to make iron and steel, have made CCS more affordable because it increases the amount of CO₂ in the exhaust gas. In the cement industry, players are experimenting with innovative technologies to capture the CO₂ during combustion, such as oxy-fuel carbon capture, which has

lower operational costs than post-combustion capture technologies. The other CCS costs—transmitting and storing CO₂—vary depending on how far the industrial site is from the storage facility.

BECCS to generate negative emissions

Using BECCs would reduce industry emissions by 10 percent (110 MtCO₂e) by 2050. With this approach, industrial manufacturers can use bioenergy as feedstock or fuel and then employ CCS to mitigate the resulting CO₂ emissions. This results in net-negative emissions that can compensate for residual emissions from sources where emissions reduction is impractical or impossible, such as waste or fluorinated gases.

One of the best candidates for BECCS is ammonia production because two-thirds of the emissions are a pure flow of CO₂. And its current feedstock, natural gas, can be easily substituted with biomethane without changing the process. In our pathway, 78 percent of ammonia plants would use BECCS by 2050, at an average cost of €200 per tCO₂.

Cement production is another good candidate for BECCS because 60 percent of the GHGs produced while making the base material for cement are process emissions that can't be fully decarbonized without CCS. By replacing fossil fuels with biomass and installing CCS infrastructure to capture fuel and process emissions, industrial sites could generate net-negative emissions at an average cost of €150 per tCO₂.

Electrifying process heat

Electrifying the boilers and furnaces that now use fossil fuels would cut industry emissions by 13 percent. Electric boilers and some electric furnaces are already commercially available, and some industrial sites already use energy-efficient electric heat pumps.

Electric heat pumps are a good alternative for low-temperature processes because they are relatively affordable to install and can reach temperatures of up to 120° to 140°C. Electric boilers and furnaces can reach much higher temperatures of up to 400°C and 1000°C, respectively. Because the most expensive part of owning a boiler or furnace over its lifetime is the fuel cost, whether manufacturers decide to switch to renewable fuels or buy new electric boilers or furnaces will largely depend on the difference between electricity and renewable fuel prices.

Using electric boilers and furnaces will be more financially attractive in regions where renewable electricity sources can provide stable baseload power at low

costs, such as offshore wind in Germany and hydropower in the Nordics.

The role of hydrogen in steel and some ammonia production

Hydrogen produced from zero-emissions electricity accounts for 18 percent of the emission reductions on our industry pathway. By 2030, zero-emissions hydrogen should become an affordable feedstock alternative in steel production. That's when its cost will come down, and the technology to produce steel at scale using the hydrogen-based DRI-EAF process will be more developed. Zero-emission hydrogen will also become a replacement for natural gas in ammonia production in regions where bioenergy prices are too high and electricity prices are low.

However, some of the downsides of using zero-emissions hydrogen are the low heat emissivity of hydrogen flames, which limits the amount of heat transferred to large industrial systems, the nitrous oxide emissions from hydrogen burners, and the need to manage the risk of explosions when using hydrogen in large quantities.

Changes in consumer demand for fossil fuels

Fifteen percent of the industry emissions reduction in our pathway come from a change in demand for fossil fuels in other sectors that pursue decarbonization. Coal mining and oil and gas upstream, midstream, and downstream activity are expected to drop in line with the reduced demand for coal, oil, and natural gas. The remaining emissions from the oil, gas, and mining sectors can be reduced by implementing other abatement measures. In coal mining, these include electrifying or using hydrogen fuel cells for mining equipment and capturing methane fugitives. In upstream and midstream oil production, measures would consist of reducing fugitive methane emissions by detecting leaks and fixing pipes and electrifying equipment. Oil refineries can achieve close to net-zero emissions in 2050 by electrifying heat and using CCS.

Fuel production in refineries for a net-zero emission EU

A drop in refining activity could lead to a significant shift in the industry. Refineries can keep playing a role in producing zero-emissions fuels such as biofuels and hydrogen. The biofuel

and hydrogen demand in the pathway can be produced with 5 to 10 percent of present refinery capacity. Biofuels and bio-based oils would be produced by hydrotreating units formerly producing middle distillates, while hydrogen would be generated

from existing hydrogen production capacity and new electrolyzer units.

3.3.3 Key uncertainties and enablers

Key uncertainties: Changes in demand, fuel prices, and public concern

Many factors could delay or accelerate GHG reduction and change what now appears to be the most cost-optimal pathway for the industry sector, including:

- **Increased circularity.** If the demand for industrial materials drops below current projections, it would also reduce the amount of industrial emissions that need to be mitigated. For example, the industry sector could cut another 100 MtCO₂e per year by 2050 by stepping up plastics recycling to replace 70 percent of the current demand for ethylene and replacing 65 percent of the demand for concrete with CLT. This would also reduce the capital costs of emissions reduction in the industry sector by 17 percent (€55 billion), mostly because it would eliminate the need for cement manufacturers to implement BECCS.
- **Commodity prices.** Because fuel and feedstock are such a large share of industrial production costs, price changes could make other approaches to emissions reduction more financially attractive. For example, the cost of using renewable power or solid biomass in cement kilns or in boilers is typically lower than using biogas, hydrogen, and CCS. But if any of these price gaps narrowed within 20 percent of each other, the most cost-efficient pathway could change.
- **Public concerns about CO₂ storage safety.** Some regions in Europe might not adopt CCS because of public concerns about the perceived risks of storing CO₂ underground. If this resistance prohibits CCS from being used in the European Union, the industry sector would not be able to reach net-zero. Nor would it be able to generate negative emissions using BECCS in the hard-to-abate segments of making ammonia and cement.
- **Environmentalist resistance to bioenergy use.** In regions like the Netherlands, environmental groups have opposed importing biomass and allocating land for fuel production. If this resistance reduces the amount of available biomass needed for our pathway by only 50 percent, it will be difficult to use BECCS to generate negative emissions. In that case, some segments would have to resort to changing their heating sources to hydrogen or electrification, which would increase annual fuel costs by €2.1 billion to €8.5 billion.³⁵



³⁵ Electricity and hydrogen cost €1 to 4 more than biomass and biogas.

Key enablers: Incentives and infrastructure

Several things must happen to make this pathway feasible and cost-effective, including:

- **Encouraging product substitution.** Most of the decarbonization solutions that we present in this report focus on maintaining the status quo—producing the same materials but with a different type of fuel or heating system. What would reduce emissions the most is to completely change how we do things, such as using CLT to construct buildings instead of concrete. However, making these wholesale changes would require governments to incorporate these alternatives into a variety of regulations, such as upgrading building codes to require CLT. It would also require government support for R&D to find other viable, net-zero alternatives to current industrial materials.
- **Policies to accelerate emissions reduction.** Emissions-reduction efforts will increase costs for industrial companies, so governments and other stakeholders would need to provide incentives to offset these investments. Those incentives could include providing long-term regulatory predictability for taxation and greater access to capital for initial costs. However, these measures should avoid limitations or requirements that could prompt companies to move their industrial operations outside the European Union.

- **Scalable zero-emission technology and business models.** Most of the emissions-reduction options for industrial companies are either cost-prohibitive or not available at scale. Future innovation is critical to increasing the number of ways that industrial companies can reduce emissions at a lower cost. Both government officials and businesses need to drive these changes by:
 - Rapidly deploying proven innovations, such as heat pumps and waste heat recovery in low-temperature processes and replacing cement with CLT by 2030.
 - Accelerating proof-of-concept for technologies now in the development phase so that they can be deployed at scale starting in 2030. These technologies include oxy-fuel systems that lower carbon capture costs, DRI-EAF steelmaking systems with hydrogen reductants, electric cracking furnaces, and innovative bioplastics.
 - Investing in new business models and R&D-phase technologies that result in breakthrough solutions, such as the chemical recycling of plastics, electro-chemicals, and using non-carbon reductants in non-ferrous metal smelting.
- **Bioenergy supply chain development.** By 2050, the industry sector will need 2.5 EJ per year of pellet biomass or biogas to make the switch from fossil

fuels. This bioenergy will need to reach industrial sites across the EU. To facilitate the development of the necessary supply chains, governments will need to have clear land use, production, and distribution systems in place in the next 5 to 10 years.

- **Carbon storage regulation and infrastructure.** CCS requires a network of pipelines to bring the captured CO₂ emissions to storage locations, which makes it attractive for large industrial sites because it captures emissions at scale. However, current regulations don't account for creating CCS supply chains. To reach 63 MtCO₂ carbon storage levels by 2030, governments and businesses would need to:
 - Implement a regulatory framework that addresses cross-country transport and storage and alleviates current industry concerns about long-term responsibility for CO₂ storage.
 - Outfit existing pipelines or build new ones to transport CO₂ from industrial sites to storage locations.
 - Address public concerns about the safety of CO₂ storage.
 - Create CO₂ reduction markets to provide incentives for industrial manufacturers that have the potential to generate negative emissions, such as cement manufacturers that implement BECCS, to adopt these alternatives.

3.4 Buildings

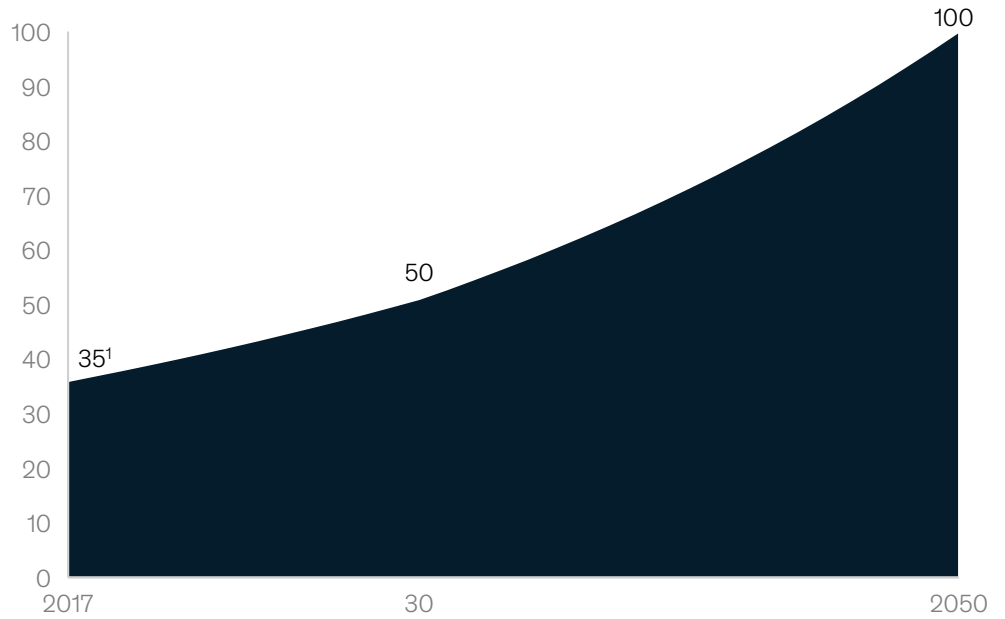


Buildings pathway in brief

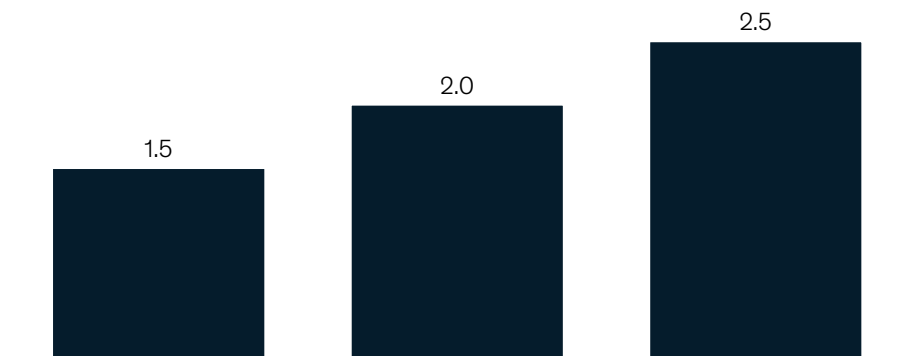


The building sector could reach net-zero cost by improving building insulation and switching to renewable heating technologies.

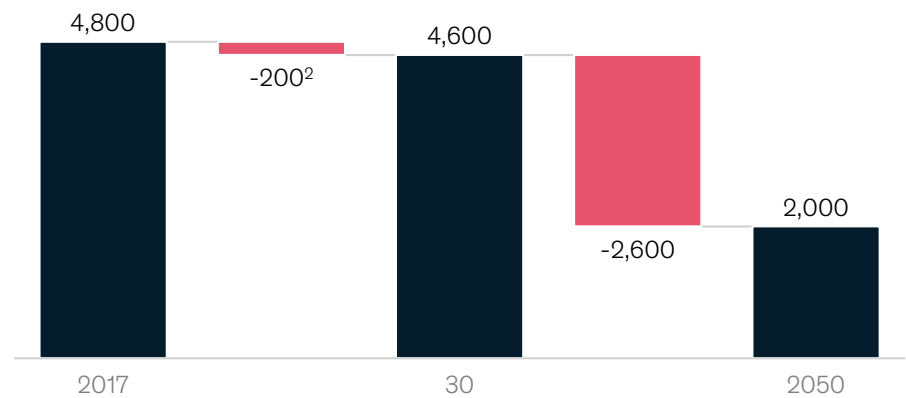
Dwellings on renewable heating
% of total dwellings



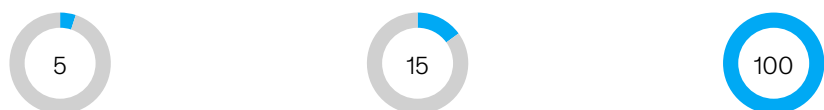
Insulation rate
% yearly insulated



Total buildings gaseous fuels use
PJ



Of which carbon-neutral gas³
% of total gas



1. Share of heat from renewable fuels (e.g., biogas, electricity)
 2. Reduction in building gas use over time period
 3. e.g., hydrogen or biomethane

Source: McKinsey

3.4.1 Building emissions today

Residential buildings account for 70 percent of buildings emissions.

In 2017, buildings emitted 490 MtCO₂e, accounting for 13 percent of EU emissions.³⁶ Residential buildings accounted for 70 percent of these emissions, while 30 percent came from commercial buildings. Most residential building emissions are generated by five regions: Germany, Italy, France, Poland, and Benelux. These regions account for 60 percent of the EU's total residential floor area, with higher emissions per square meter generated by Germany, Poland, and Benelux because of their colder climates and higher use of fossil fuel-based heating compared to regions like the Nordics (Exhibit 47).

Europe's building stock is composed of more than 200 million structures, most of which are in Germany, France, Italy, and Iberia. By square meter, three-quarters of EU buildings are residential. The rest are commercial buildings such as shops, offices, schools, hotels, restaurants, and hospitals. In both residential and commercial buildings, most energy is used for space and water heating (70 percent). The rest is consumed by appliances (15 percent), lighting (5 percent), cooking (5 percent), and space cooling and other (5 percent). We expect the proportion of energy used for space and water heating could drop if the efficiency of heating technologies improves. However, the proportion of energy used for appliances could increase as people buy more small electric appliances and devices.³⁷

An efficient way to decrease the amount of GHGs emitted from buildings is to reduce the heat demand. By improving building insulation and installing heat-control systems, heat demand for poorly insulated houses can be reduced by up to 80 percent, depending on the building type, insulation measures taken, and climate conditions. To decarbonize the remaining energy use, owners would need to switch to electricity, district heat, and renewable fuels for space heating, water heating, and cooking.

More than half of Europe's building stock is poorly insulated. This is primarily the case in warmer areas, like Southeast Europe, where three out of four buildings are poorly insulated. Also about two-thirds of EU homes are still heated by burning gas, coal, or oil.³⁸ Boilers are the dominant technology across regions, but the heating technology mix and share of renewables vary by region. For example, gas boilers are common in Benelux (70 percent), coal boilers are more prevalent in Poland (33 percent), and electric heating is popular in France (24 percent).

District heating is the predominant heating technology in the Nordics (50 percent), which is fueled by biomass, power plants, and large heat pumps.³⁹ Going forward, district heating that runs on renewable energy, such as solar, geothermal, and excess heat from industry, may play a more significant role in heating buildings. This is particularly true in areas with high building density, such as city centers, and in places where other renewable solutions aren't technically feasible or affordable.

3.4.2 The role of buildings on the path to net-zero

To reach its climate targets, EU building emissions will need to be reduced by 29 percent by 2030 and 100 percent by 2050. Most of this reduction could be achieved by retrofitting and replacing the heating systems in existing buildings, which will still account for 75 to 90 percent of EU real estate in 2050. The most cost-effective pathway to reaching net-zero includes:

Improve energy efficiency through insulation.

- All new buildings highly insulated.
- 55 percent of existing building stock has better insulation by 2050.
 - 75 percent of these buildings would upgrade low insulation to medium or high insulation, depending on the climate.
 - 25 percent would upgrade medium insulation to high insulation, particularly in colder regions such as the Nordics and Central Europe.

Switch to renewable technologies for heating and cooking.

- 60 percent of cooking would be electrified by 2050 (compared to 40 percent now); the rest using biogas, hydrogen, or sustainably produced biomass.
- 9 percent of residential and commercial buildings would use heat pumps for space and water heating by 2030, reaching 40 percent by 2050 (compared to 2 percent now).

³⁶ This number represents only direct emissions (i.e., emissions that occur from fuel combustion in a gas boiler to provide heating and cooking in buildings). Emissions that occur indirectly, such as through the production of electricity that is transmitted for use in buildings, are accounted for in the power pathway [Section 3.1]. Emissions generated for building construction and renovation, such as the CO₂ emitted while making cement, are covered in the industry section [3.3].

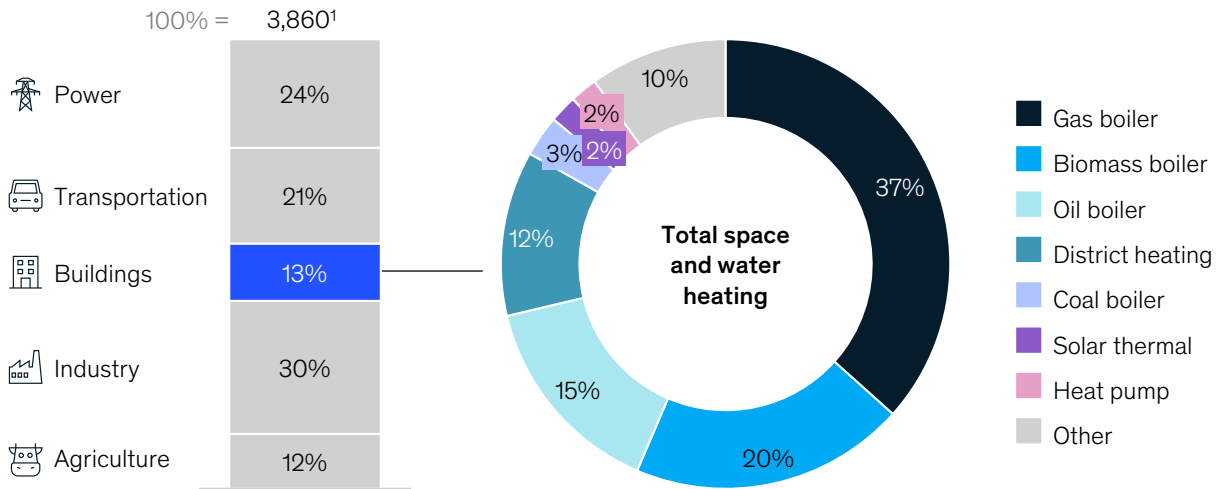
³⁷ In the past 30 years, energy use for appliances in residential buildings has grown by nearly 1 percent per year, mainly because of rising purchases of large appliances such as dishwashers, washing machines, and dryers. From 2010 to 2015, this usage dipped, likely because consumers made fewer household purchases during the 2011–2013 recession. After 2015, we assume energy use continues growing in line with pre-2010 figures because of increasing demand for small appliances and electrical devices. We assume this trend will be partly offset by efficiency gains in large appliances.

³⁸ Coal, oil, and gas boilers and 50 percent of district heating

³⁹ In a district heating system, heat is distributed from a central location through a network of insulated pipes fed by various heat sources. Today, most networks use heat from combined heat and power plants, excess heat from industries, and heat produced by fossil combustion. In the future, district heating can be fueled by combined heat and power plants that run on sustainably-sourced biomass, excess heat from industries, and a combination of other renewable energy such as solar, geothermal, or heat pumps.

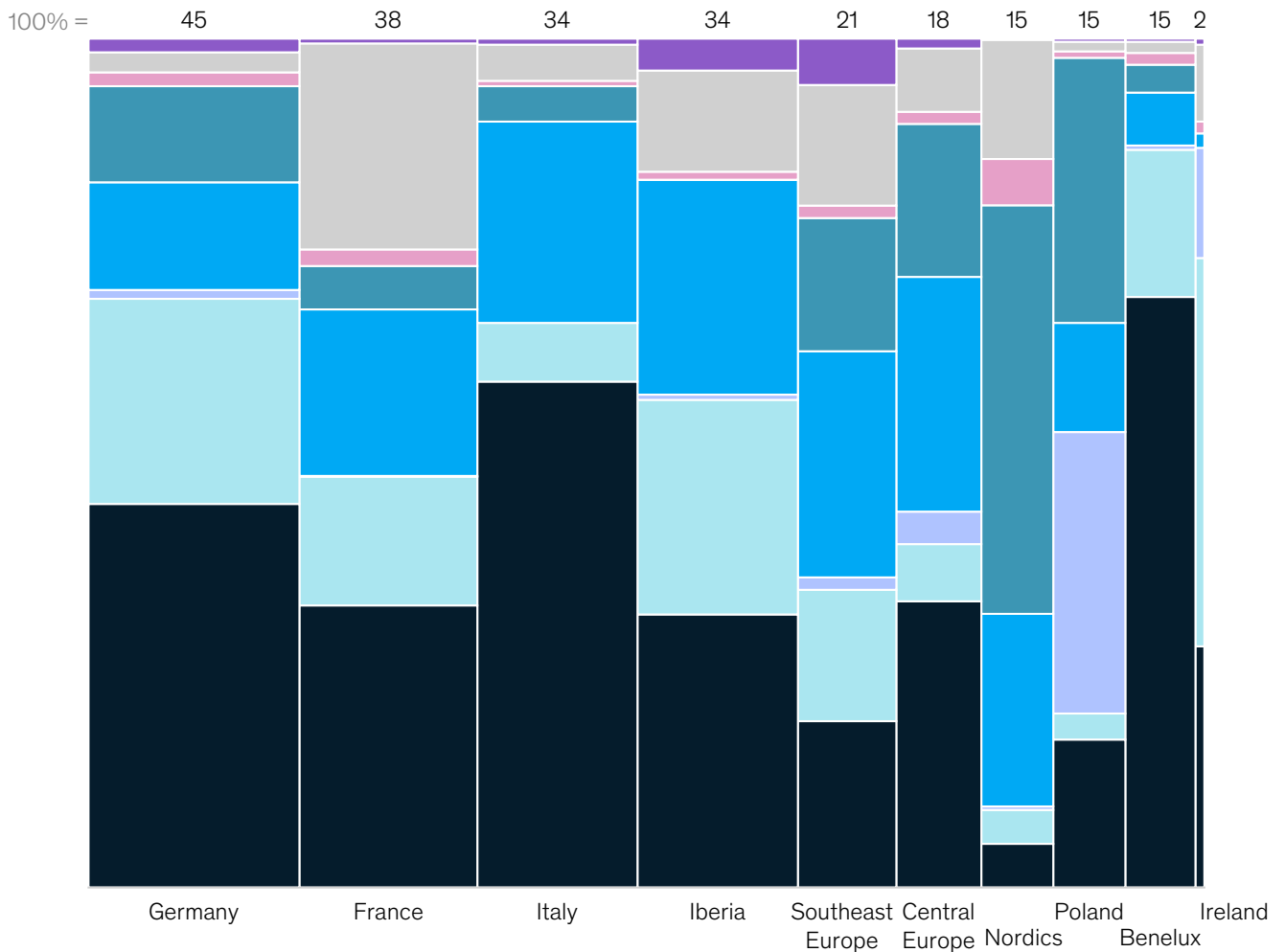
Approximately two-thirds of EU homes are still heated by burning gas, coal, or oil.

Total space and water heating by source for EU-27, 2017, MtCO₂e



Buildings by heating type and region

Million dwellings in EU-27, 2017



1. Total EU-27 emissions excluding international aviation and marine

Source: Building Statistics Observatory – EU, Enerdata, Eurostat, Inspire, Hotmaps

- 23 percent of residential and commercial buildings would use district heating by 2030, reaching 33 percent by 2050 (compared to 12 percent now).
- 15 percent of residential and commercial buildings would be heated by biogas or hydrogen boilers by 2050 (compared to 0 percent now).
- 7 percent of heating would be provided by solar thermal as an add-on technology by 2030, growing to 10 percent by 2050 (compared to 2 percent now).

Improve energy efficiency through insulation

Improving energy efficiency by upgrading building insulation is the most cost-effective way to reduce direct emissions in this sector. The average investment in retrofitting a poorly insulated home actually saves money. It saves €35 per tCO₂ and €5 per tCO₂ to retrofit a poorly insulated building with medium and high insulation, respectively. Better insulation reduces the amount of heat lost through walls, roofs, floors, and windows which, over time, decreases the cost of heating a home or building beyond the initial investment of upgrading the insulation.

By 2030, improving building insulation would reduce emissions by 7 percent (32 MtCO₂e a year). By 2050, it would reduce emissions by 22 percent (99 MtCO₂e a year). For the European Union to achieve these reductions, all new buildings must be highly insulated, and 55 percent of existing buildings must be retrofitted by 2050. In our cost-optimal pathway, the number of retrofits varies per region. In colder regions with higher demands for heat, such as Poland, Central Europe, and Benelux, a higher proportion of homes will need to be upgraded. At the same time, only 20 percent and 40 percent of the houses in Iberia and Southeast Europe will need retrofitting.

The level of insulation also varies across regions. More than 80 percent of homes in the Nordics, the coldest EU region, would need to be upgraded to high levels of insulation, compared with 40 percent of EU homes overall. In Southeast Europe and Iberia, where homes require heating only a few months per year, we don't see an uptake of high insulation at all (medium insulation only).

Switch to renewable energy for heating and cooking

To decarbonize the remaining emissions from space heating, buildings will need to switch to heating systems that use renewable energy instead of fossil fuels. The cost of this initial investment ranges from €1,500 for a biogas or hydrogen boiler to €20,000 for a ground-sourced heat pump, which is why governments will need to offer incentives to encourage widespread adoption. The total abatement cost is an average of €60 per tCO₂e per year.

Switching to renewable technologies for heating would reduce building emissions by 21 percent (95 MtCO₂e a year) by 2030 and by 73 percent (334 MtCO₂e a year) by 2050. Achieving these reductions will require a mix of heat pumps, district heating, and boilers that run on biogas or hydrogen, with solar thermal as an add-on technology. The preferred solution will vary across regions and building types, based on the region's climate, building density, retrofitting possibilities, existing heating system infrastructure, and access to renewable energy sources. For example, air-to-water heat pumps may be more cost-effective for houses with central heating systems using water, which homes in southeast Europe and Iberia often don't have. In these regions, air-to-air heat pumps may be the more affordable solution, particularly since they can provide space cooling during the summer.

Heat pumps will play a significant role in decarbonizing the building sector, growing its share from 2 percent today to 40 percent of the total heating

technology mix by 2050. Although they are expensive, the total cost of heat pumps is lower for building owners than other renewable solutions, such as biogas and hydrogen, with high fuel prices (Exhibit 48).

District heating will also play a significant role in decarbonizing the EU buildings sector, growing its share from 12 percent today to 33 percent of the total heating technology mix by 2050. In areas with high building density and homes that are difficult to retrofit, district heating appears to be the best replacement for existing fossil fuel-based heating systems. Alternative green gas solutions, such as boilers that run on a blend of hydrogen and biogas, are expensive and have limited availability.⁴⁰ Renewable energy sources for district heating systems are available. In fact, the total amount of excess heat generated in the European Union matches the total energy that would be required to heat buildings throughout Europe. The challenge is connecting that excess heat to district heating networks, which isn't always possible. In places where the local waste heat supply is insufficient, other renewable sources could fill the gap, such as large-scale heat pumps, geothermal, or using sustainably sourced biomass.

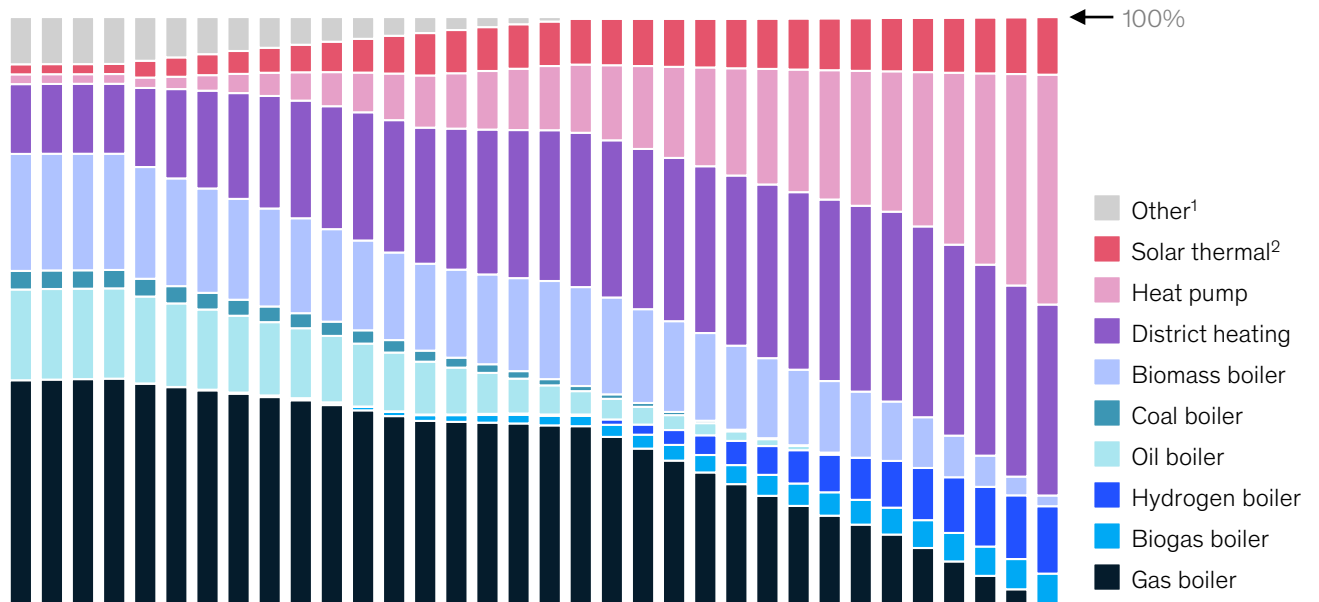
For cooking, shifting to renewable technologies would reduce building emissions by 1 percent (4 MtCO₂e each year) by 2030 and 5 percent (25 MtCO₂e per year) by 2050. The pathways for reducing those GHG emissions will look similar across regions and building types. For example, homes that use electricity for cooking will shift to more efficient induction technology in places like Germany, France, and Iberia. Then after 2030, building owners that still use gas for cooking would need to transition to biogas. Overall, reducing emissions from cooking will cost an average of €150 per tCO₂e.

⁴⁰ Increasing the demand for biogas and hydrogen could also stress the limited supply and drive up already high hydrogen prices.

Heat pumps could play a vital role in the decarbonization of the EU building sector.

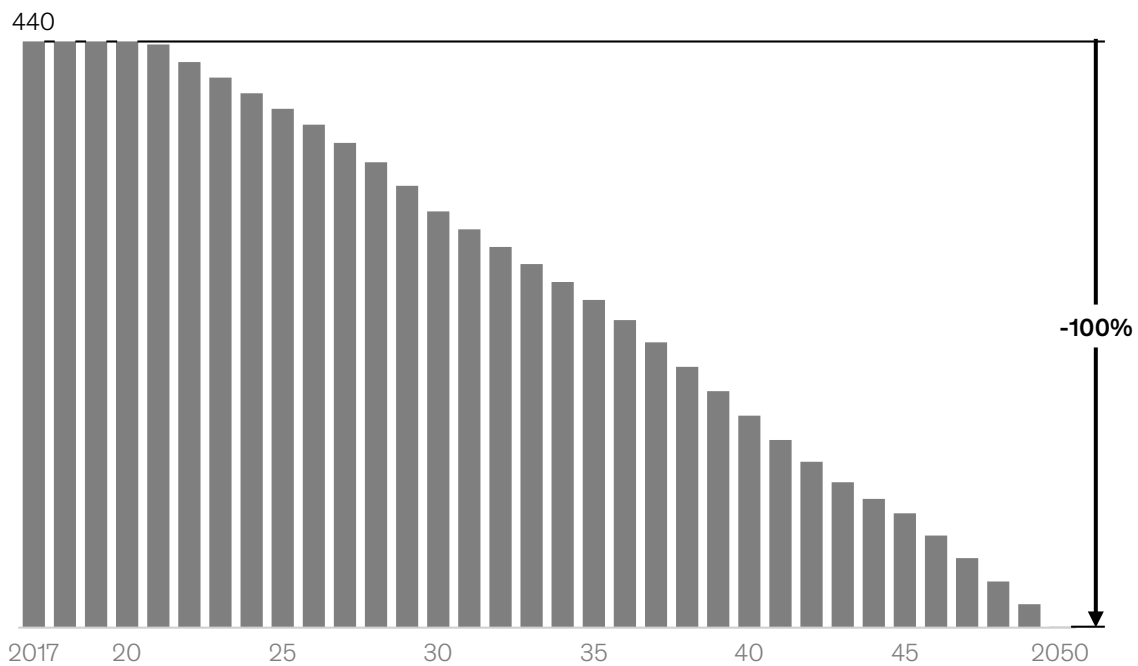
Space and water heating technology mix

Penetration level in %



CO₂ emissions for space and water heating

MtCO₂e



1. Direct electric heaters and electric boilers

2. A share of the total heat demand is provided by solar thermal; no stand-alone solution

Source: McKinsey

3.4.3 Key uncertainties and enablers

Key uncertainties: Prices, policy

developments, and human behavior

Many factors we don't know yet could delay or accelerate GHG reduction and change what now appears to be the most cost-effective pathway for buildings, including:

- **Limited availability or higher prices for biomass and other renewable energy sources for district heating.** It could prove more challenging to connect excess heat sources to district heating networks or be more expensive to run district heating networks on renewable sources. District heating requires extensive stakeholder alignment and sufficient capital for initial investments. This could lead to lower adoption of district heating networks, which would mean that heat pumps and green gas networks such as biogas and hydrogen would need to play a larger role in reducing building emissions.
- **Lower gas and oil prices** could delay the adoption of renewable technologies without regulation that forces building owners to switch.
- **Lower hydrogen prices** could give hydrogen boilers a more significant role in the final heating technology mix. If hydrogen prices drop below €25 per gigajoule, hydrogen could become an attractive alternative solution compared to heat pumps and district heating. If hydrogen prices drop below biogas prices, boilers that run on hydrogen could become cost-competitive with boilers fueled by biogas.
- **Differences in the size, location, design, and construction of buildings** throughout the EU could lead owners to choose other decarbonization solutions than the mix we've proposed. Almost no home or building is identical, and therefore, retrofitting will require tailored solutions. For example, some houses have pitched roofs, while others have flat roofs. Some have walls made of wood, and others have walls made of bricks. Because of these variations, the pathway we've recommended as the cheapest option for the average building might not be the most economical for all of them.
- **National policies that favor one solution over another** could also change the attractiveness of the mix we propose in our pathway. For example, if national officials decided that district heating was the best solution for all urban areas in the country, they could mandate or offer incentives for urban building owners to choose this option, making district heating more prevalent.
- **Greater public awareness** about the need for sustainable practices could lower energy consumption faster than we've projected. This awareness could inspire more building owners to upgrade their insulation, lower their thermostats, and unplug appliances they aren't using. It could also motivate homeowners to choose self-sustainable heating solutions, such as solar thermal and geothermal heat pumps, and become willing to pay a premium for them.
- **Greater digitization** could lower energy demand beyond our projections because technologies such as smart meters and smart appliances that provide users with real-time data on energy consumption can inspire them to make adjustments.

Key enablers: Government policies and incentives

Our pathway assumes that all new buildings in the European Union will be well insulated because of the European Union's current Energy Performance of Buildings Directive (EPBD). We also expect that more new buildings will be constructed with renewable technologies because of stricter regulations in individual countries, such as the Netherlands' law that prohibits new natural gas connections. Beyond these directives, several things must happen to make our buildings pathway cost-effective, including:

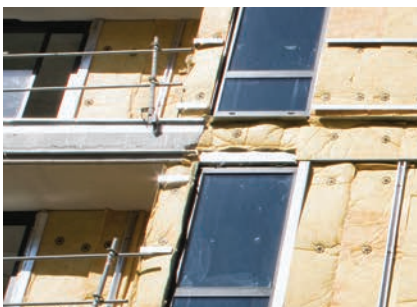
- **Policies to reinforce adaptation.** For the buildings sector to reach net-zero GHG emissions by 2050, governments will need to mandate or offer incentives for homeowners to upgrade to renewable heating systems and install higher levels of insulation. This can include bans on new gas boilers after 2030 that would force homeowners to replace their current boilers with renewable heating systems when they break down. Governments can also regulate insulation levels and dictate which buildings must use district heating.
- **Financially attractive solutions.** Today, building owners invest on

average €280 a year for insulation and in their heating systems. This would need to increase by more than 50 percent to roll out new insulation and heating technologies. These costs will vary by region because of price differences for labor and materials, which will make these projects more expensive in places like Germany and the Nordics and cheaper in southeast Europe and Poland. To make these investments attractive, governments and financial institutions will need to offer homeowners a combination of grants, loans, and subsidies. Lawmakers can also create incentives for banks to create new financial instruments that link the loans to the building rather than the owner.

- **Significant public investment.** For homeowners to switch to renewable heating and cooking technologies by 2050, current electric and district heating networks will need a major overhaul. Just installing new district heating networks will cost €500 to €700 billion. To facilitate the transition, governments would need to make sure that building owners have the prerequisite infrastructure to switch to renewable technologies. Making the

changes we propose in our pathway would also increase the demand for insulation materials and labor by 30 to 50 percent. Meeting these demands would require government initiatives that help expand supply chain capacity.

- **Standards and incentives for building owners.** Homeowners who live in their properties are likely to be more motivated to pay for new insulation and heating technologies because they will lower their utility bills. Landlords may be less willing to do so without government incentives or regulation on minimal required insulation standards.
- **Greater public acceptance.** The changes we propose require the widespread adoption of higher building insulation and renewable heating systems. Marketing campaigns sponsored by public and private agencies that explain the need for change and the cost benefits of taking actions such as installing floor heating and roof insulation could inspire greater willingness among building owners to make these renovations.



3.5 Agriculture

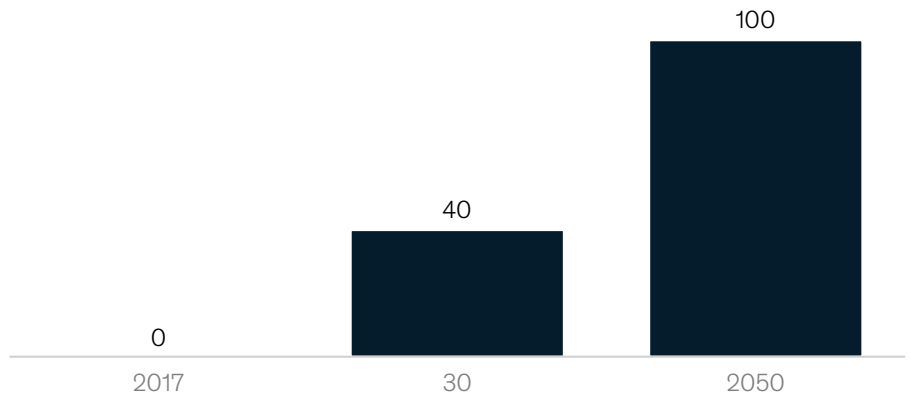


Agriculture pathway in brief

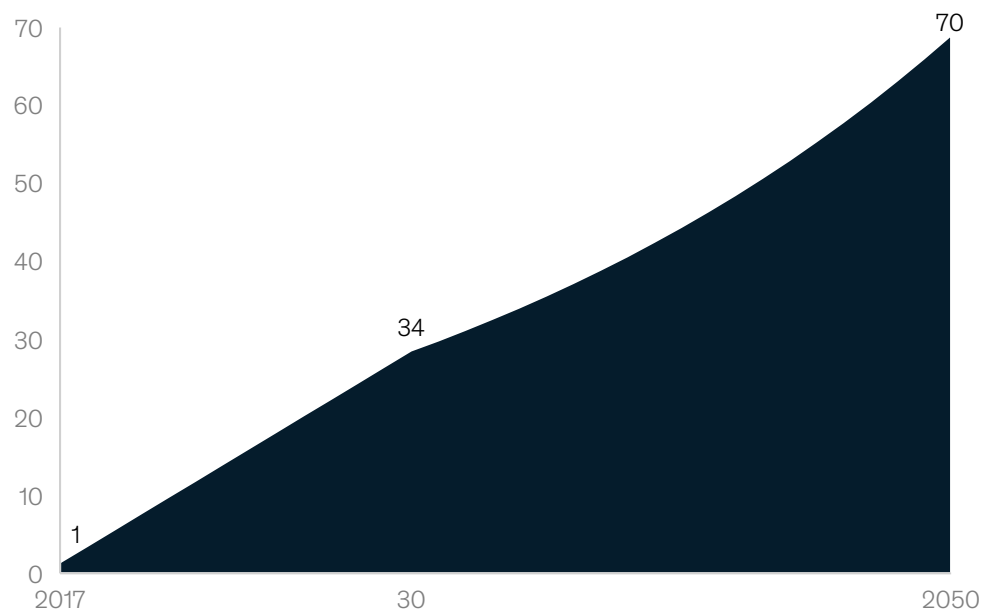


The agriculture sector can decarbonize by electrifying farm machinery, turning manure into biogas, and breeding animals that produce fewer GHG emissions.

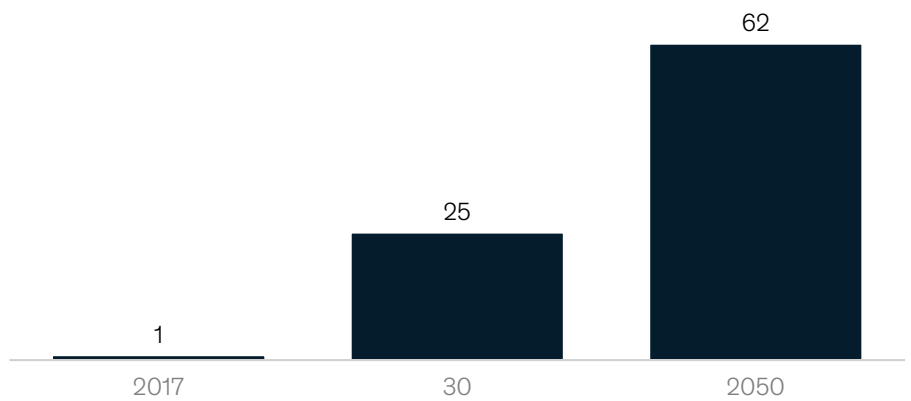
Carbon neutral energy in equipment
% of total



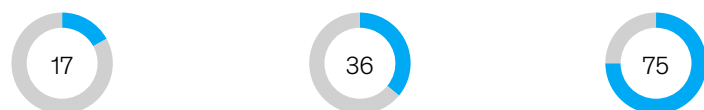
Anaerobic digestion systems
% of captured manure



GHG-focused genetic selection and breeding programs
% of total herd



Variable rate fertilization
% of total hectares



Source: McKinsey

3.5.1 Agriculture emissions today

Half of agriculture emissions are from cattle and other livestock.

In 2017, the agriculture sector produced 470 MtCO₂e, accounting for 12 percent of EU emissions. Raising animals for food generated 55 percent of these emissions, followed by crop production with 30 percent and energy used for farming activities with 15 percent. In animal protein production, 65 percent of GHG emissions come from enteric fermentation, a natural part of animal digestive processes that produce methane, and from manure management, which also emits nitrous oxide. Nearly 90 percent of emissions from animal protein production comes from dairy and non-dairy cattle.

In crop production, 50 percent of GHGs come from synthetic fertilizers because crops cannot absorb all that is applied, and the excess nitrogen is released into the atmosphere as nitrous oxide. Other significant GHG emissions come from the cultivation of organic soils and from crop residues (Exhibit 50).

Agriculture emissions are distributed among EU member states, with the profile in each affected by its relative shares of livestock and crop production. For example, 75 percent of GHG emissions in Ireland are from animal protein production. In Central Europe, where cereal and oil crops are plentiful, and the Nordic countries that grow the European Union's largest

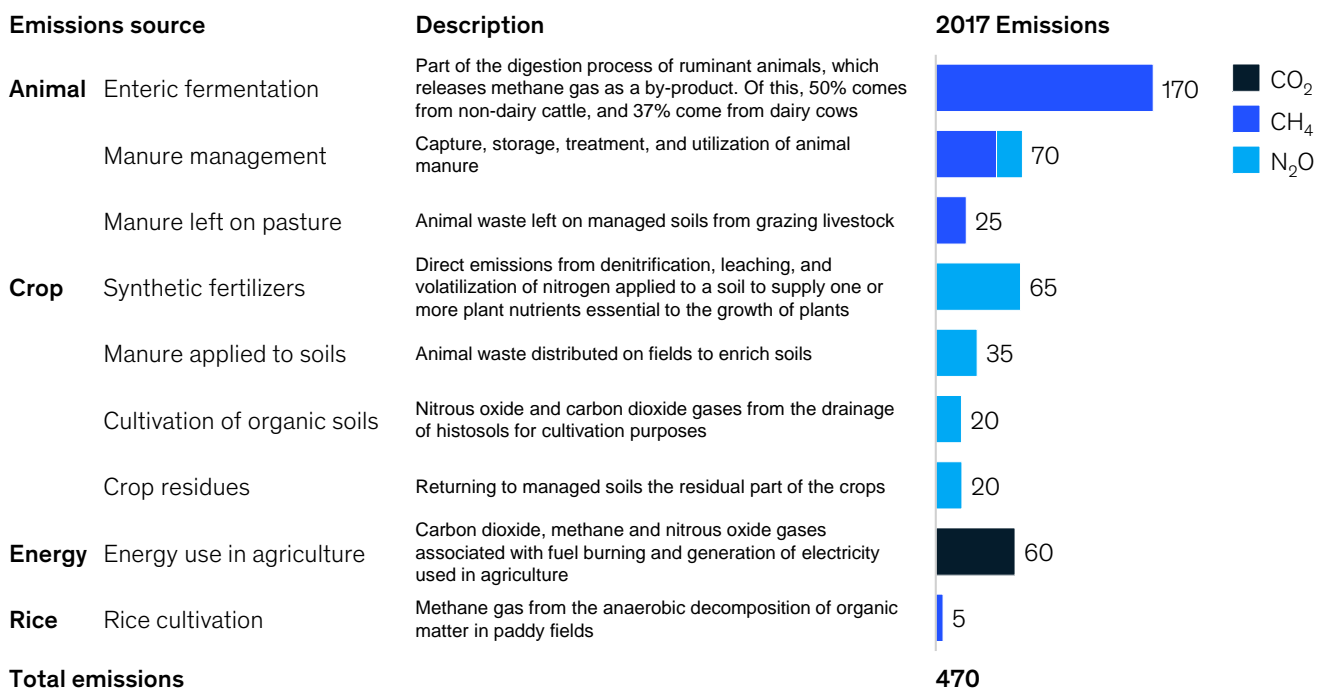
share of beans, nearly 40 percent of agricultural emissions come from crop production. Because of the high energy consumption in greenhouses in the Netherlands, energy use accounts for 30 percent of agricultural GHG emissions in Benelux.

Without intervention, European Union agriculture emissions are projected to drop only 3 percent by 2050, according to the United Nation's Food and Agriculture Organization.

Exhibit 50

Animal digestion processes and manure are responsible for most agricultural GHG emissions across the EU-27.

MtCO₂e, EU-27



Source: McKinsey, FAO 2019, PNAS: Schlesinger et al 2017: Natural Climate Solutions, Eurostat 2020

Global warming potential in 20 vs. 100 years

For the purposes of policy discussion and target setting, greenhouse gases are generally measured by their global warming potential (GWP)—how much energy the emissions of one ton of gas will absorb during a given period compared to the emissions of one ton of carbon dioxide. GWP is calculated for a specific timeframe, typically 100 years.

But the lifetimes of greenhouse gases differ, which affects their GWPs. Because methane stays in the atmosphere for only 12 years, its GWP varies depending on the timeframe. For example, one ton of methane has 28 times the effect of one ton of carbon dioxide when measured over 100 years, but 84 times the effect over 20 years.

To be consistent with other sectors and policy documents, our analysis is based on 100-year GWP values. However, many researchers have argued that the impact of agriculture emissions should be measured over shorter timeframes to reflect their more immediate impact and the urgency of curbing emissions.

3.5.2 The role of agriculture on the path to climate neutrality

Reducing agricultural emissions is particularly challenging for three reasons. First, most emissions come from natural processes that technology today can't fully abate. For example, there is currently no technology that can fully stop enteric methane emissions from cows. The most advanced feed additives are expected to reduce methane emissions only by up to 40 percent. Second, change needs to happen at a very distributed level, there being more than 10 million farms that would need to change their practices. Changing the practices of millions of farmers takes time given the need to create the right incentives and to build new capabilities or know-how. Third, agriculture has to balance a range of goals including production (to both fulfill nutritional needs and ensure food security), rural welfare, biodiversity, and sociocultural and landscape heritage. Consequently, the EU likely cannot reach net-zero agriculture emissions by 2050, but CO₂ emissions can be eliminated while nitrous oxide and biogenic methane can be significantly reduced in line with the pathways identified in the Intergovernmental Panel on Climate Change (IPCC)

2018 report. The interquartile ranges of these pathways suggest that limiting warming to 1.5°C requires reducing methane emissions by 24 to 47 percent and reducing nitrous oxide by 1 to 21 percent (versus a 2010 baseline).⁴¹

Our analysis shows that to achieve climate neutrality, the European Union could reduce emissions from agriculture by one-third, that is, 160 MtCO₂e a year. This reduction would be achieved by eliminating emissions from farm energy use and reducing animal protein production emissions by 26 percent and crop production emissions by 27 percent. Reduced consumer demand for beef and dairy products could reduce these emissions further. For example, if 50% of EU citizens were to adopt a flexitarian diet, emissions would fall by 16 percent (73 MtCO₂e).

Crop levers and feed improvements would contribute to reduced emissions immediately. On-farm machinery and GHG-focused breeding require further advancements in technology before they can contribute to reduced emissions, delaying their deployment and the majority of their benefits into the 2030s and 2040s.

⁴¹ ["Special report: Global warming of 1.5°C. summary for policymakers."](#) IPCC, January 2019.

Key agriculture levers

1. *Switch to zero-emissions on-farm machinery.*

100 percent of on-farm equipment and machinery would use alternative fuels by 2050 to abate 61 MtCO₂e.

2. *Implement anaerobic digestion systems.*

70 percent of dairy and swine manure produced annually would be converted into biogas by 2050 to achieve 21 MtCO₂e abatement annually.

3. *Improve animal feed*

Increased utilization of animal feed

additives to 38 percent of beef, dairy, and sheep animals and 75 percent of feed mix optimized by increasing dry matter percentage of fats would abate 19 MtCO₂e annually by 2050.

4. *Adopt GHG-focused genetic selection and breeding programs.*

62 percent of animals bred to emit 15 percent less methane during enteric fermentation by 2050 would deliver a reduction of 17 MtCO₂e annually.

5. *Use enhanced efficiency fertilizers.*

Exclusive use of N-inhibitors by 2050 would abate 15 MtCO₂e

annually. As nitrification inhibitors aren't applicable to all types of fertilizers, this would apply to 40 percent of synthetic fertilizers used today.

6. *Use of variable rate fertilization*

Utilizing variable rate nitrogen application on all applicable acres (75 percent of total nitrogen fertilizer use) would abate 8 MtCO₂e annually through reduced application rates and improved nitrogen-use efficiency.

In agriculture, there are no silver-bullet technologies that could reduce the majority of emissions. The following levers have the greatest abatement potential, yet each reduces total emissions by less than 12 percent.

Switch to zero-emissions on-farm machinery

The key to eliminating CO₂ emissions in the agriculture sector is to transition farm equipment now dependent on fossil fuels to alternative energy solutions. Although machines using these alternative fuels—such as electricity, ammonia, and biomethane compressed natural gas (CNG)—aren't yet widely available, there are prototypes that will likely be developed into marketable models in the upcoming years. Emerging market dynamics, such as increasing interest in the electrification of road transportation by governments and consumers, also suggest that internal combustion engines will be ripe for mass displacement by 2050. And as businesses in the power sector work toward reducing their emissions, the electricity that farmers use for livestock and crop production will become zero-emissions. Switching to alternative

fuels, along with the decarbonization of electricity, would reduce the European Union's agriculture energy use emissions by 100 percent (61 Mt a year).

Moving away from fossil fuels will also reduce costs for farmers. As battery prices continue to fall, the purchase price and operating costs of electric machines will drop.

Implement anaerobic manure-digestion systems

Capturing methane using anaerobic digesters could reduce GHG emissions from dairy cow and hog manure systems by up to 85 percent. These devices, which promote the decomposition of manure to simple organics and biogases, are primarily applicable to animals maintained indoors. Germany already has an advanced system of anaerobic digestion plants that generate biogas that can be used on farms or sold back to the grid. But other regions such as France and Iberia have untapped potential that could abate up to 4.5 percent of agricultural emissions (21 MtCO₂e per year).

Reaching this potential would require the utilization of all collectible manure

(about 70 percent)⁴² from dairy animals and swine. It would also require large upfront investments of up to €1,000 a head of livestock, depending on the country and species.⁴³

Improve animal feed

Increasing the dry matter percentage of fats from whole seeds, plant oils, or dietary supplements by 2 to 3 percent in cattle diets reduces methane production proportionally. Due to potential health issues and practical aspects, there is a limit of 6 percent of total fat content. There are also some feed additives that have been shown to inhibit methane production in the rumen. Propionate precursors—a class of free acids or salts including sodium acrylate and sodium fumarate—will likely be widely applicable, as they directly inhibit methane emissions from cattle without affecting animal growth. Implementing these measures could abate 18 MtCO₂e emissions, equivalent to 4 percent of 2017 agriculture emissions.

Adopt GHG-focused genetic selection and breeding programs

About 20 percent of the methane a cow or sheep emits during digestion is determined by genetics, according to animal experts. Using genetic

⁴² Nicolae Scarlat Fernando Fahl, Jean-François Dallemand, Fabio Monforti, Vincenzo Motola, "A spatial analysis of biogas potential from manure in Europe." *Renewable and Sustainable Energy Reviews*, 2018, Volume 94, pp. 915–30.

⁴³ "Bioenergy in Germany: facts and figures 2019." Fachagentur Nachwachsende Rohstoffe e.V. (FNR), 2019.

selection that focuses on breeding animals that emit less GHG could reduce EU agriculture emissions by 3.5 percent (17 MtCO₂e) by 2050. However, achieving this reduction would require 50 percent of beef and sheep breeders and 70 percent of dairy and swine breeders to adopt this practice. Today, a major obstacle to investing in genetic selection and breeding programs is a lack of economic incentive and the low maturity of breeding systems. Incorporating emissions-reduction traits into these animals is time intensive and often has a limited financial return, as governments don't currently support those investments with market payments or credits for methane reduction. New breeding techniques, such as those using CRISPR-Cas9,⁴⁴ could lower the barriers to entry. Targeted investments by major animal genetics companies could also accelerate this kind of innovation.

Use enhanced efficiency fertilizers
Using enhanced efficiency fertilizers such as N-inhibitors could reduce nitrous oxide emissions by 15 MtCO₂e by 2050 (2 percent agricultural emissions). Because the nutrient requirements of crops vary as they mature, slow- or controlled-release stabilized fertilizers can ensure that plants receive nitrogen when they need it most. This means less nitrogen will be released into the environment. N-inhibitors instead protect and slow down synthetic fertilizers from breaking down into smaller chemical compounds, leaving more nitrogen available to crops and less nitrogen to create other harmful gases. Although slow- or controlled-release fertilizers are often cost-prohibitive for farmers who don't grow specialty crops, N-inhibitors are more affordable. Yet current adoption is low, as potential cost savings can be highly variable, are not applicable to all

fertilizers (such as urea), and farmers are hesitant to adopt new products without a long history of margin improvements.

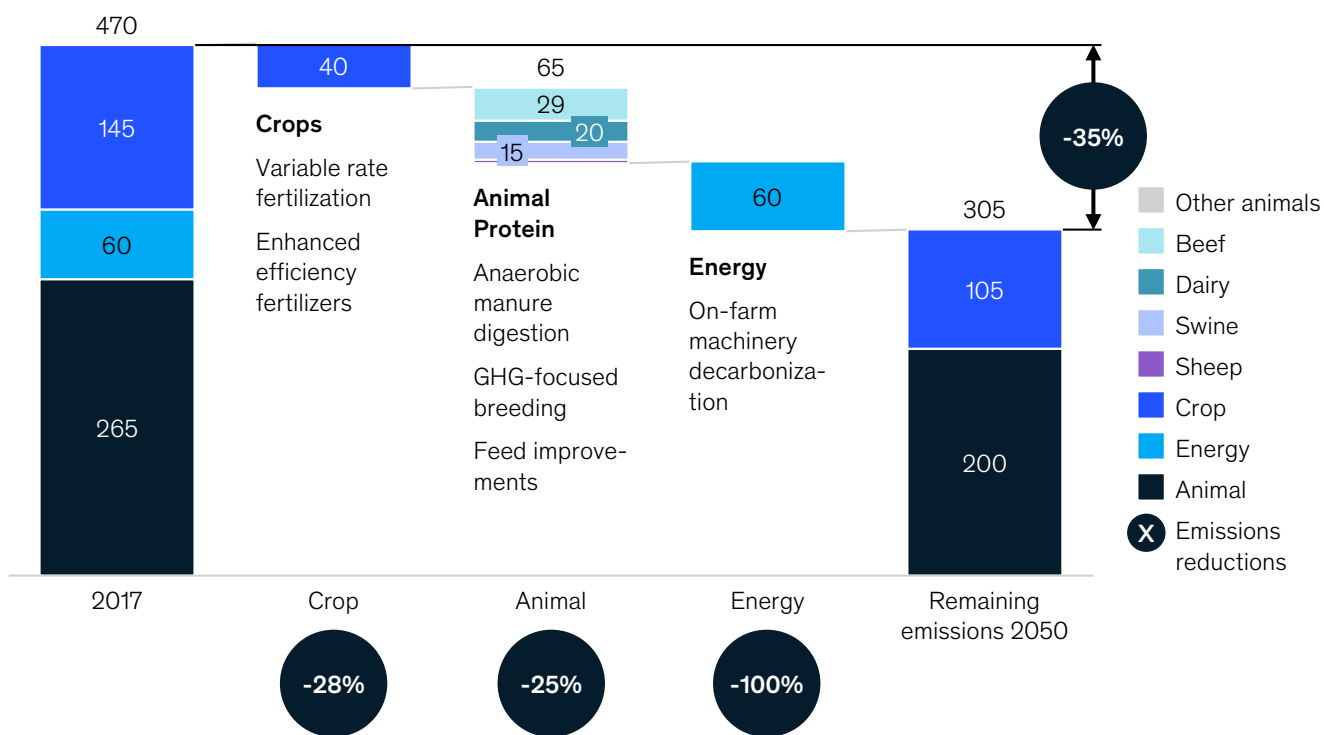
Use variable rate fertilization
Variable rate (VR) nitrogen application on all applicable acres (75 percent of total nitrogen use) can abate 8 MtCO₂e annually. VR nitrogen application can drive down emissions through improved nitrogen-use efficiency and reduce overall nitrogen application. VR fertilization adjusts application to real-time crop or soil needs. This practice relies on the use of VR equipment for application and sensors to monitor in-field nitrogen rates and crop health. This VR rate is based on the 4Rs of fertilizer management: right timing, right product, right amount, and right placement of nitrogen on the field.

⁴⁴ Clustered regularly interspaced short palindromic repeats (CRISPR); CRISPR associated protein 9 (Cas9).

Exhibit 51

On the cost-optimal pathway to climate neutrality, the European Union would achieve a 35 percent reduction in GHG emissions by 2050.

MtCO₂ equivalent, EU-27



Source: McKinsey

3.5.3 Key uncertainties and enablers

Key uncertainties: Consumer demand, food waste, and technology

Many factors we don't yet know could delay or accelerate GHG reduction in agriculture and change what now appears to be the most cost-effective pathway. Those factors include:

- **The current impact of climate change.** The global warming we've already experienced is expected to change many aspects of agriculture over the next 30 years, including crop yields and the types of crops that can grow in certain regions. For example, by 2050, Europe could face a 15% reduction in yields from maize in 20 percent of growing seasons versus 6 percent of seasons currently.⁴⁵ At the same time, the chance of a 10 percent higher than average wheat yield will likely increase by 30 percentage points, from 5 percent to 35 percent by 2050. Whether these predictions come to pass will impact farming-related GHG emissions because it will affect the amount of land that's needed to grow the same amount of food and the quantities of fertilizer required.
 - **Consumer demand for meat and dairy products.** Because the methane emitted by cows and sheep during enteric fermentation accounts for nearly half of agriculture's GHGs, reducing meat and dairy consumption would have the most significant impact on lowering agriculture emissions. Europeans
- are already reducing their meat consumption, as is illustrated by the increasing numbers of vegetarians and vegans.⁴⁶
- **Advancements in farm-related technology.** It's difficult to predict future advancements in technologies that could reduce agricultural emissions. However, they could prove to be highly effective. For example, DSM's next-generation feed additives are expected to reduce enteric fermentation emissions by 30 percent.⁴⁷ Other future advancements that could make a difference include gene editing for disease resistance, enhanced carbon sequestration, plant and soil microbiome technology, vaccines that reduce methane emissions from enteric fermentation, direct methane capture from beef and dairy cattle, and perennial row crops.
 - **Impact on competitiveness.** Given advancing technologies and changing consumer demand, it remains uncertain what impact emissions reduction will have on the competitiveness of the European Union's agriculture sector. Delivering emissions reduction without negatively impacting competitiveness will require the policy, consumer, and technology enablers set out below.

⁴⁵ McKinsey Global Institute, "[Climate risk and response: physical hazards and socioeconomic impacts](#)," MGI analysis.

⁴⁶ Emily Scott, "[Germany is leading a vevaluation—vegan revolution—in Europe](#)," US Department of Agriculture, Foreign Agricultural Service, January 13, 2020.

⁴⁷ DSM website: <https://www.dsm.com/corporate/solutions/climate-energy/minimizing-methane-from-cattle.html>; accessed 08/07/2020

Key enablers: Policy, consumer education, and new equipment and business models

Several things must happen to make this pathway feasible and cost-effective, including:

- **Policies that support environmentally friendly farming practices.** Most climate-change policies don't focus on reducing agricultural emissions. Commitments made under the Paris Agreement cover only 38 percent of current global agriculture emissions.⁴⁸ Policy shifts are vital to speed up technology development and the adoption of environmentally friendly farming practices. For example, financing mechanisms for new technologies, such as anaerobic digestion plants,

could help farmers make these changes. In the European Union, it is particularly important that all EU departments and executive agencies (including Agriculture and Rural Development, Climate Action, and Environment) take an integrated and coordinated approach to supporting a climate neutral agriculture sector.

- **Consumer education to shift the demand for meat and dairy.** If half of the EU population ate healthier, more balanced diets (e.g., flexitarian diet) by 2050, this change alone would reduce agricultural emissions by 16 percent (73 MtCO₂e) while also decreasing premature deaths by 9 to 11 percent.⁴⁹ Although dietary decisions are ultimately up to consumers, governments and

businesses can encourage them to make healthier choices through marketing campaigns and policy changes, such as national food pyramids endorsed by individual EU member states.

- **Development of new farming products and business models.** Emerging technologies at various stages of development could significantly reduce GHGs in the agriculture sector. Considering the European Union's increased focus on the environment, developing these technologies should become more attractive. Companies in the agriculture sector could be offered incentives to contribute to R&D efforts and redesign their business models to prioritize environmentally friendly outcomes.



⁴⁸ Rita Strohmaier, et al., "The agriculture sectors in the intended nationally determined contributions: Analysis," Food and Agriculture Organization of the United Nations, 2016.

⁴⁹ Marco Springmann, Keith Wiebe, Daniel Mason-D'Croz, Timothy Sulser, Mike Rayner, Peter Scarborough, "Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail," *Lancet Planet Health*, October 2018, Volume 2, Number 10, pp. e451–61.

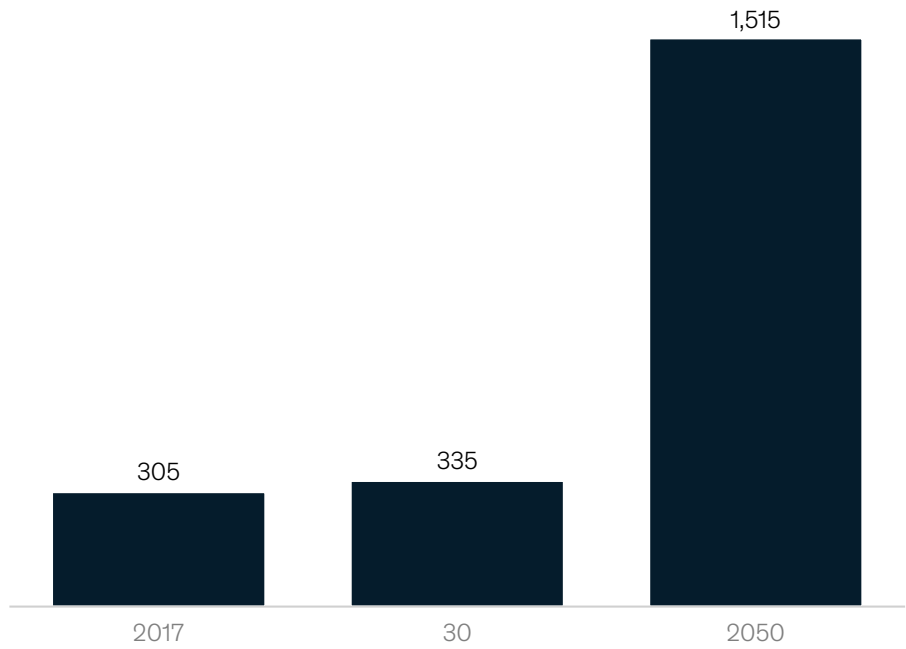


Hydrogen pathway in brief

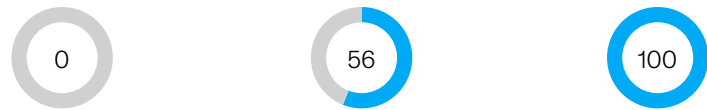


As hydrogen demand increases, green hydrogen production costs should fall 70 percent by 2050

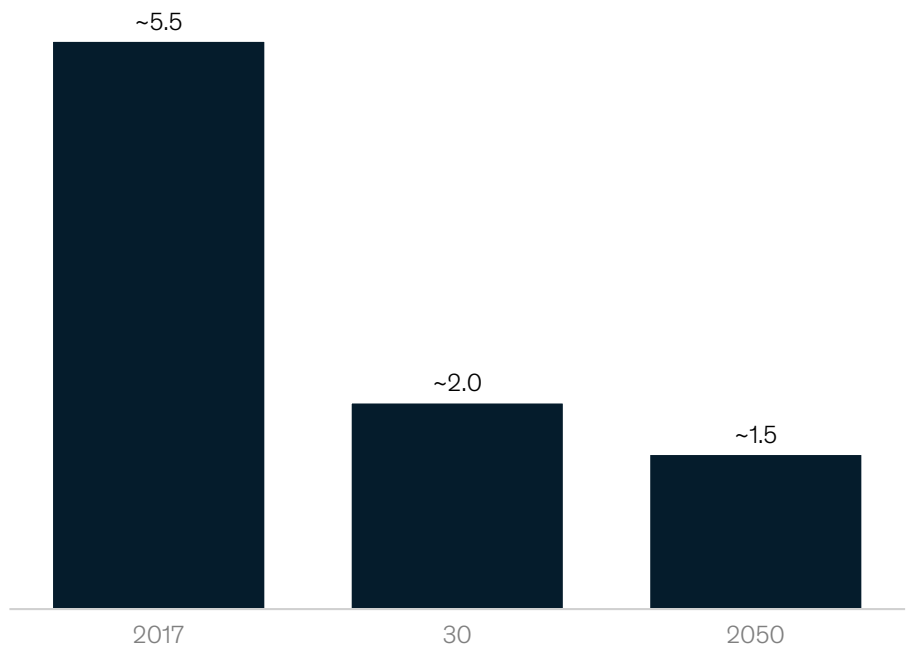
Hydrogen demand Total TWh



Percent of which is low-carbon (blue or green) %



Cost of low-carbon (blue or green) hydrogen production EUR/kg



Source: McKinsey

3.6.1 Hydrogen use today

Hydrogen can fill many roles in the net-zero transition, including enabling renewable power to be integrated at scale, providing flexible power generation, distributing energy between sectors and regions, and decarbonizing end uses. Today, hydrogen mainly is used as a feedstock for ammonia production and oil refining. The European Union produces more than 300 TWh a year of captured hydrogen for chemical sites (mainly ammonia) and refineries. This hydrogen is made by reforming natural gas, a process that emits 81 MtCO₂e a year. New technologies are emerging that can make hydrogen production cheaper and less carbon-intensive (Exhibit 53).

Lower-carbon hydrogen could be supplied using various production processes. Green hydrogen is made by separating the hydrogen molecules from the oxygen molecules in water using electrolysis powered by renewable electricity. It tends to be expensive because of the investment cost of electrolysis, storage, and the operating costs of generating renewable power.

However, green hydrogen prices are expected to drop across the European Union, from a high of €5 per kilogram today to €2 per kilogram by 2030 and €1.5 per kilogram by 2050. As the production of green hydrogen ramps up, it should become less expensive as renewable power also becomes

cheaper. Regions with a healthy supply of renewable power would see even bigger price drops.

Blue hydrogen is usually made from natural gas through steam methane reforming (SMR) and mitigating the CO₂ emitted with CCS. Blue hydrogen can be produced by retrofitting existing gas refineries or building new SMR and auto-thermal reformer (ATR) plants. Production costs include the initial investment in retrofitting refineries for CCS and the operating costs of the natural gas, electricity, and transportation and storage of CO₂. ATR technology is more effective than SMR because it captures 90 to 95 percent of CO₂ emissions versus 70 percent for SMR. ATR could also

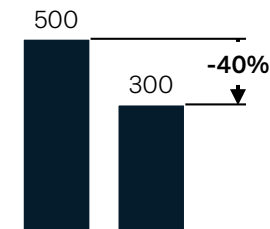
Exhibit 53

Falling renewable power and electrolysis capital expenditure costs should make it much less expensive to produce green hydrogen.

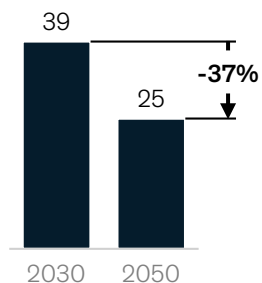
Green H₂ production cost evolution

Cost drivers

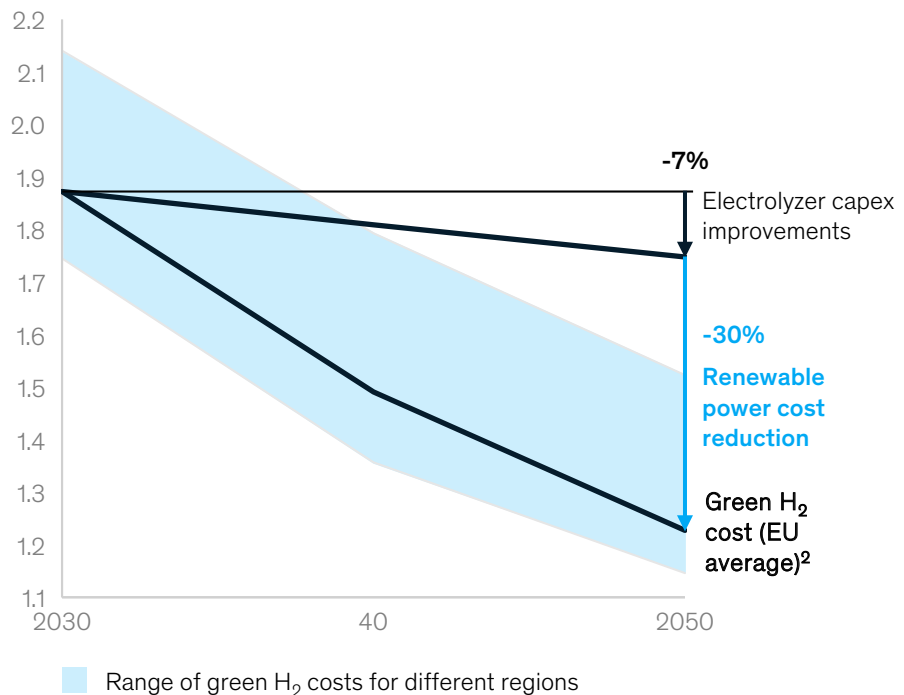
Electrolysis capex EUR/kW



Renewable electricity cost¹ EUR/MWh



H₂ production costs EUR/kg



1. Weighted average LCOEs of solar, onshore and offshore generation in EU-27

2. Renewable LCOE-based costs for green H₂ production, which does not cover the real capture price and flexibility value of H₂ in avoiding alternative flexibility investments. Assuming a utilization factor 50%, lifetime 20 years, 5% WACC

Source: McKinsey

be more affordable than brownfield SMR technology over the long-term as emissions trading scheme (ETS) carbon prices rise.

Both green and blue hydrogen can be produced domestically or imported into the European Union. The landed cost of imported hydrogen would include transportation and conversion. In our pathway, we assume that any imports would come from regions with low renewable energy costs.

3.6.2 The role of hydrogen on the path to net-zero

Hydrogen usage could reduce emissions by 470 MtCO₂e per year by 2050 and satisfy 1,400 TWh of new demand.

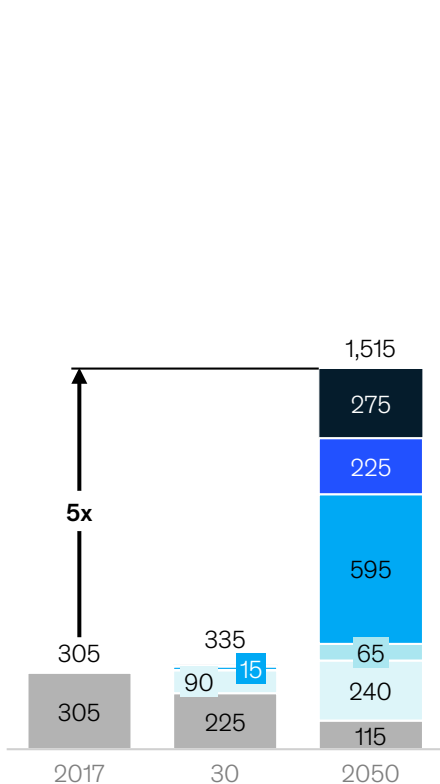
Switching from fossil fuels to green and blue hydrogen is critical to achieving net-zero, potentially reducing the European Union’s annual emissions 13 percent by 2050. As production costs fall, this could create 1,400 TWh of new demand for hydrogen by 2050 for a total demand of 1,515 TWh per year—a five-fold increase over today’s consumption, and equivalent to 10 percent of final energy demand. In the hydrogen breakthrough scenario, 15 percent of final energy demand is met by hydrogen (Exhibit 54).

Exhibit 54

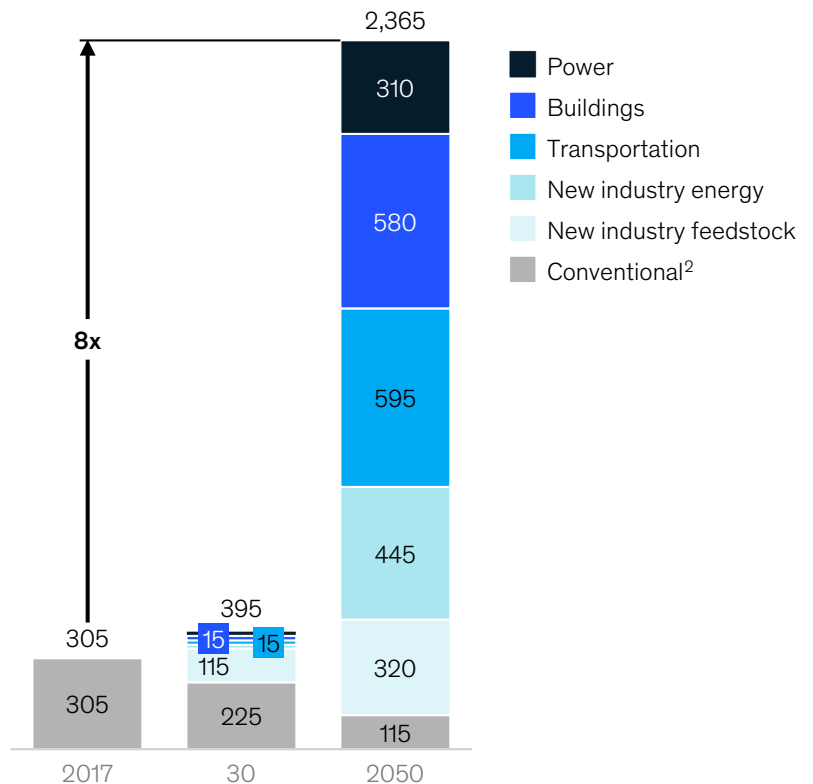
By 2050, hydrogen demand may be five-times to eight-times higher than today, depending on how quickly costs fall.

Hydrogen demand, TWh, EU-27

Cost-optimal pathway



Hydrogen breakthrough scenario¹



1. Assuming hydrogen production cost is 30% lower by 2050 than in cost-optimal pathway

2. Captive hydrogen, e.g., hydrogen used in refining and ammonia production

Source: McKinsey

New consumption in multiple sectors would drive the growth in hydrogen demand, including seasonal power generation, residential heating, long-haul transportation, iron and steel manufacturing, chemical production, and high-temperature heating (Exhibit 55). Also, processes that now use gray hydrogen, such as ammonia production and oil refining, would switch to blue or green hydrogen.

Although most of the European Union's power generation would come from solar and wind by 2050, hydrogen could be used to meet demand during times of the year when solar and wind outputs vary. For example, solar production can drop to 20 percent of its potential during the darker winter months, so the power grid needs an alternative source of renewable energy to bridge the gap.

In the transportation sector, hydrogen would help reduce emissions by serving as an alternative fuel for larger vehicles such as long-haul buses and heavy-duty trucks.

In the industry sector, hydrogen would be the most economical alternative in the metals segment, where it could reduce those emissions by 80 percent of abatement. By 2040, hydrogen could be used to decarbonize steel production at an additional cost of €40 per tCO₂e.

In the buildings sector, hydrogen uptake would begin after 2030, and its adoption would vary by building type and region. For example, we expect some apartment buildings to switch from gas to hydrogen boilers after 2030 when there's a sufficient supply of hydrogen and it becomes cheaper than biogas.

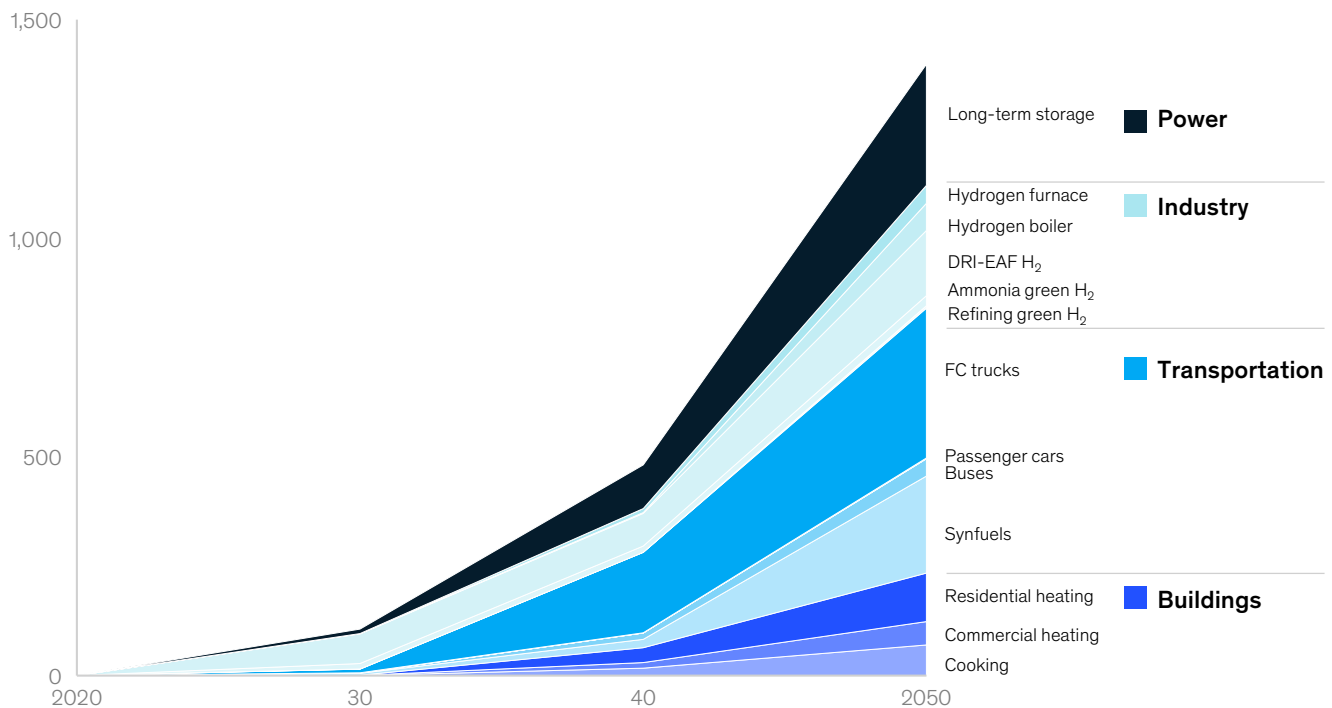
By 2050, 11 percent of building heating in the European Union would come from hydrogen boilers, compared to 70 percent generated by heat pumps and district heating, with an average abatement cost of €100 per tCO₂e.

Most hydrogen technologies would become viable options after 2030 when the cost of fuel cell technology comes down and hydrogen production prices fall below €2 per kilogram. We forecast the investment cost of electrolyzers to decrease 40 percent, from €500 per kilowatt in 2030 to €300 per kilowatt by 2050. This, along with a 37 percent decrease in renewable energy costs during this period, would cause a significant drop in green hydrogen prices.

Exhibit 55

On the cost-optimal pathway, much of the growth in hydrogen demand would come from fuel-cell trucks, synthetic fuel production, and long-term power storage.

Additional demand on top of existing hydrogen use¹, PJ, EU-27



1. Existing hydrogen uses include refining, ammonia, and other chemicals.

Source: McKinsey

In the near term, brownfield SMR and new-build ATR would be the most cost-competitive sources of hydrogen. However, green hydrogen would approach total cost parity by 2040 or earlier in regions with plentiful renewable resources. Realized green hydrogen costs could be even lower if electrolyzer operators could monetize their ability to balance variable renewables on the power grid.

On the cost-optimal pathway, 335 TWh of total hydrogen demand would be satisfied by 20 percent green hydrogen, 35 percent blue hydrogen, and less than 1 percent imported hydrogen by 2030. Approaching 2050, 85 percent of the 1,515 TWh of total hydrogen demand would be fulfilled by green hydrogen.

Blue hydrogen costs from brownfield SMR would increase slightly if ETS carbon prices rise because SMR with CCS only captures about 70 percent of the CO₂ emissions. Although carbon pricing is not a factor for ATR because of its higher CO₂ capture capacity, its uptake in the near term could be limited by access to CCS infrastructure.

Over the long term, given the constraints on blue, green hydrogen would account for the lion's share of the production mix. The cost-optimized pathway assumes a steep increase in electrolysis capacity to 18 GW in 2030 and 385 GW in 2050.

However, the development of hydrogen production capacity could go faster. Today, the European Union's hydrogen strategy already calls for the accelerated introduction of electrolysis, with a total capacity of 40 GW by 2030. Supported by incentives, this level of deployment would reduce the cost of hydrogen faster than in our modeled scenarios and lead to faster and higher uptake of hydrogen.

This domestic supply would be complemented by 4 percent imported hydrogen for seasonal balancing in the winter when local renewable power generation is low. The estimated cost of imported hydrogen makes it a last resort to satisfy new demand. Shipping, trucking, and other associated costs are more than double local EU hydrogen production costs and are not expected to decline over time.

If green hydrogen costs come down faster, total hydrogen demand could grow to over 2300 TWh of demand by 2050.

In addition to the cost-optimal pathway, we also analyzed the impact of a "hydrogen breakthrough" scenario that assumes a faster decline in the cost of green hydrogen production. If electrolyzer costs fall to €180 per kilowatt by 2050 rather than the €300 in our pathway, an additional 850 TWh of demand could be satisfied in the buildings and industry sectors.

The production mix would be the same in this accelerated scenario. More than 85 percent of the additional demand would be met by green hydrogen by 2050. However, this would require an additional 15 percent in renewables generation per year—800 TWh from solar and 140 TWh from onshore and offshore wind.

3.6.3 Key uncertainties and enablers

Key uncertainties: Price developments, technology, and activism

Several unknown factors could affect the uptake of hydrogen, including:

- *Price developments for bioenergy and commodities.* Low gas or biomass prices could shift the cost-optimal production mix to more blue hydrogen than green hydrogen. It could also delay the adoption of hydrogen for some applications entirely. It's also unclear how much the learning rate for electrolyzers could increase to further reduce green hydrogen capital costs.
- *Technology breakthroughs.* Innovations in CCS could alter the mix of gas with CCS versus hydrogen.
- *Public and activist concerns.* Public concerns about the risk of leaks from underground CO₂ storage could hinder CCS adoption. This would limit the use of blue hydrogen to meet anticipated demand.
- *Renewable power capacity in the European Union.* The ability to satisfy an increase in green hydrogen demand would depend on the ability to scale up renewable power capacity.



Key enablers: Funding, policies, and market design

Several things must happen to make hydrogen a feasible and cost-effective part of the cost-optimal pathway, including:

- **Funding to bridge the economic gap.** Transportation and production costs would account for most hydrogen capital expenditures through 2050. But its use in the industry sector would face the biggest challenges. For instance, in steelmaking, hydrogen would be more expensive than conventional technology because of high fuel and feedstock costs and the site rebuilding required. Policy and investment support would need to bridge the gap until hydrogen use reaches the break-even point. We estimate it would cost €60 billion to bridge the gap for hydrogen consumption in the transportation, industry, and buildings sector through 2050. Although the business case for hydrogen in these sectors is negative today, scale effects could rapidly reduce

costs similarly to the significant drop in solar PV prices in recent years. Scaling renewable power in many EU member states would also require funding through a combination of feed-in tariffs, direct subsidies, and capital expenditure support to boost hydrogen uptake and make it cost-competitive. Likewise, further development of CCS for the conventional production of hydrogen from natural gas could enable faster adoption in the near-term.

- **Market creation.** The long-term success of hydrogen depends on reducing the uncertainty of future demand. This could be achieved with hydrogen vehicle targets, feed-in tariffs, and long-term offtake agreements. Leveraging local economies of scale could also significantly reduce the cost of a hydrogen rollout. Although installing hydrogen infrastructure in a single chemical plant is expensive, the costs go down when costs can be shared across more applications, for example with the use for heating and

trucking. So, creating clusters of demand would be critical for making a hydrogen rollout cost-effective. Setting EU-wide standards and creating cross-border trade opportunities would also ensure that new and foreign players can enter and invest in the hydrogen market.

- **Policy alignment across countries.** Hydrogen adoption would require a streamlined policy across EU member states. The climate strategies of EU member states would need to align with the international objectives and approaches. Governments could support this process by creating and aligning national and international standards and regulations, such as those related to hydrogen pressure levels at truck refueling stations. Governments could also work together to develop standard hydrogen infrastructure. For example, creating common policies to allow gas pipelines to be reused for hydrogen distribution could help create an EU-wide market for local players.

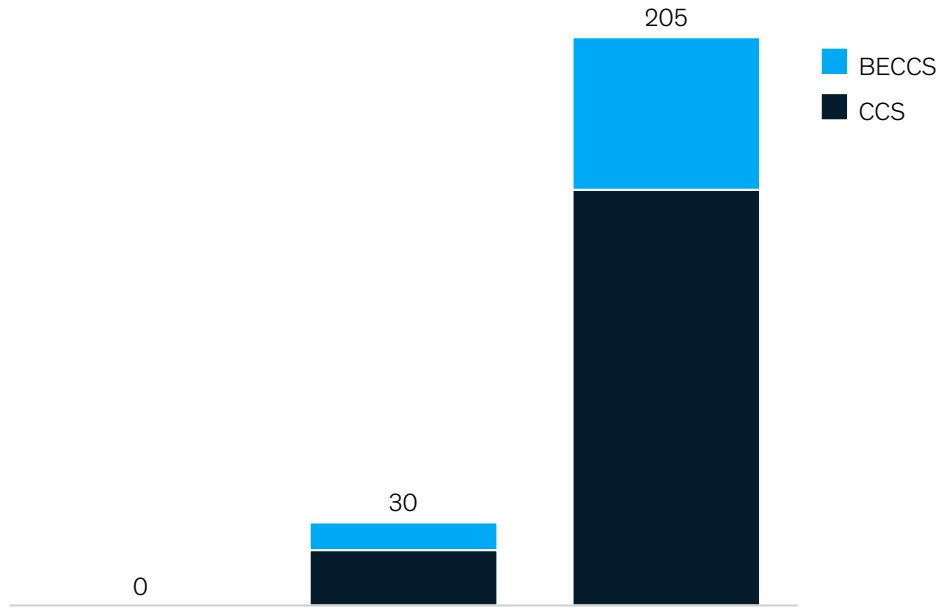


CCS pathway in brief

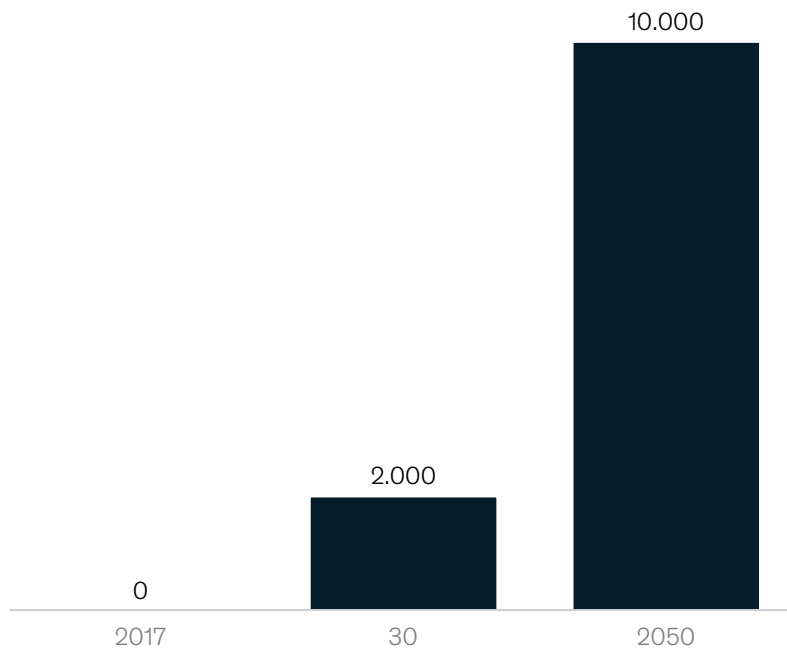


As CCS projects come online, they could capture and store more than 200 million tons of CO₂ per year by 2050

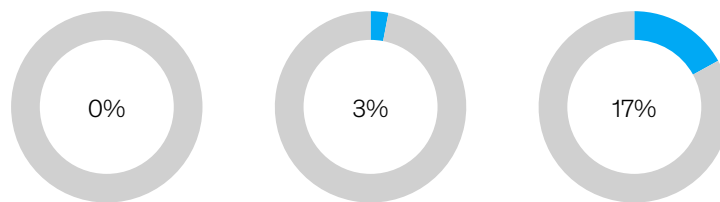
Carbon capture¹
MtCO₂ per annum



Amount of storage capacity reserved²
MtCO₂e



Share of total North Sea CCS capacity



1. Technologies include CCS, BECCS and other carbon sinks. Demand includes power.

2. Amount of capacity needed to be reserved to store 50 years worth of CO₂ from CCS installations

Source: McKinsey

3.7.1 CCS installations today

Today, most CCS projects have business models based on “Enhanced Oil Recovery”—injecting CO₂ into a gas reservoir to extract more oil or gas from a well. This has allowed CCS technology to be demonstrated in many parts of the world, particularly the US and Middle East. Partly because of this, various CCS technologies are already tested and proven today, yet their use has so far remained local in scope and focused on oil and gas. To contribute to the decarbonization challenge in Europe, CCS would need to scale up and be deployed at larger scales beyond the oil and gas sector.

In Europe, only the Northern Lights project in Norway is operational today at scale, although several larger CCS projects are under development. Across Europe, and particularly around the North Sea basin, numerous ‘clusters’ of companies and carbon-intensive assets are coming together to spread the cost of infrastructure and enable CCS at acceptable costs.

There are clusters formed in most EU countries, with some, particularly in the UK and Benelux region, having multiple clusters centered on existing industrial heartlands.

In addition, two CCS regional networks are pursuing a common system for transporting and storing carbon dioxide: the North Sea Basin Task Force composed of the UK, Netherlands, Norway, Germany, and Belgium; and the Baltic Sea Region CCS network, which includes Estonia, Germany, Finland, Norway, and Sweden.

3.7.2 The role of CCS on the path to net-zero

The European Union would by 2050 need to capture 205 MtCO₂ per year to reach and sustain net-zero.

Until 2030 in the cost-optimal pathway, CCS would be used primarily to produce carbon-neutral hydrogen for the chemicals sector. After that, the cement, power, chemicals and other industrial sectors would ramp up CCS deployment too. Cement would grow to become the biggest CCS user because it has few alternatives for abating the CO₂ emitted during cement production (Exhibit 57). The cement industry is more geographically fragmented than others, with many plants a long way from

other industries. Hence it's unlikely that all the cement plants in Europe could be grouped into industrial clusters connected by pipelines. This means that other transport solutions for CO₂ from the plants outside the clusters may be needed. Under an alternative pathway where renewable power is more scarce, there would likely be a greater need for CCS for power generation, additional blue hydrogen production and iron & steel.

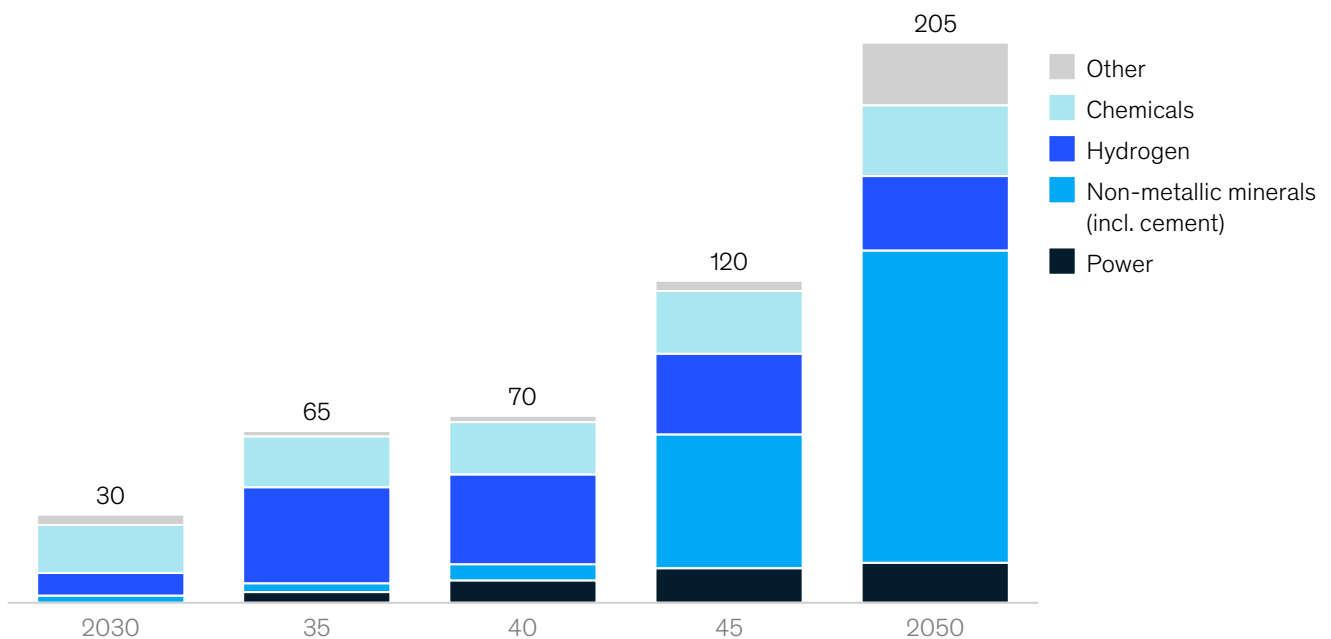
CCS is critical for generating negative emissions that enable the EU to achieve net-zero emissions by 2050. In the cost-optimal pathway, at least 55 MtCO₂ of negative emissions would need to be created annually by 2050 to

offset residual emissions from hard-to-abate processes such as industrial waste management and raising livestock for food. Because our pathway already calls for the cement industry to install CCS infrastructure, a low-cost way to create negative emissions is to start blending biomass into cement kiln fuels to produce carbon-negative cement. Similarly, the pathway includes negative emissions coming from blue hydrogen production with biomethane. Other options pursued in the pathway are negative emissions from biomass-fueled power or heat generation with CCS.

Exhibit 57

Until 2030, CCS would be deployed mostly in the chemicals sector, but the cement sector would become the major user by 2050.

Annual CO₂ capture and storage in EU-27, MtCO₂ p.a.



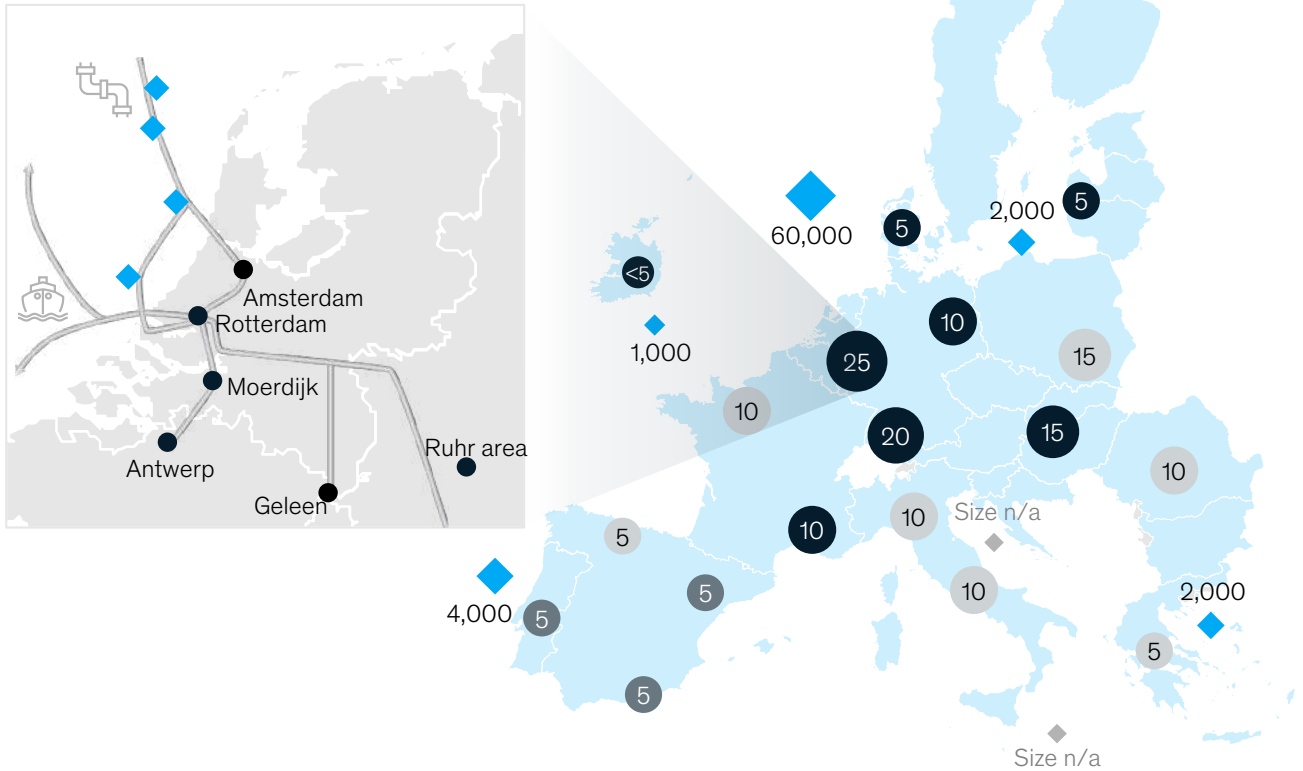
Source: McKinsey

CCS would likely spring up around existing industry clusters close to storage locations in the North Sea. Because of the extensive need for carbon capture in the industry sector, CCS clusters are expected to spring up in regions with existing industry clusters, such as the Benelux (Exhibit 58). Because of public resistance to onshore CO₂ storage, offshore storage locations would likely be preferred, and thus countries close to the North Sea would be able to transport and store carbon dioxide at a lower cost than for those in the middle of the continent. This could change if onshore storage options, mostly aquifers in France, Germany, Poland, and the Baltics, could be used. For example, Poland has an onshore storage capacity of more than 14 Gt, which is equal to one-quarter of the North Sea's storage potential.

CCS infrastructure would develop around existing industry clusters and in regions with easy access to offshore storage locations in the North Sea.

Example of possible clusters for CCS

Example of potential CCS cluster, Benelux and Ruhr Area



◆ Offshore storage location, conservative estimate of total MtCO₂ storage available

● Region with CCS demand, estimated 2050 CCS demand in MtCO₂ per year²

Robustness of 2050 CCS demand by region¹

● Low ● Light ● High

1. Based on robustness across pathways and proximity to storage

2. Using 2014 emissions data. These include emissions for production of cement, fertilizer, plastics, iron & steel and power

Source: McKinsey, EEA, Global CCS Institute, EU GeoCapacity, CO2StoP, country-level geological studies

3.7.3 Key uncertainties and enablers

Key uncertainties: Technology, transportation infrastructure, and fuel prices

Several unknown factors could affect the uptake of CCS, including:

- *The trajectory of technologies under development* would impact the demand for CCS. For example, if electric furnaces or hydrogen-based steel production don't take off, it would create a much greater need for CCS to meet reduction targets. To achieve the 2030 targets, decisions will need to be made in the next 12 to 24 months on the emissions-reduction pathways for many important industrial assets such as steel and chemicals plants. If alternatives are not credible by that

time, CCS could become the default “back stop” technology. On the other hand, if the cost of alternative decarbonization options decreases more quickly, or if new technologies become available, there will be less need for CCS.

- *The timely roll out of a dedicated transportation infrastructure* to carry CO₂ from the point of generation to the point of sequestration. In a decarbonized Europe, methane will be displaced by CO₂ and hydrogen as the main gasses being transported long distances. There will be opportunities to re-use both existing gas pipelines and also existing pipeline routings to lay new pipes, if the projects can be phased correctly.

- *Prices of zero-emission fuels* could further increase or limit CCS uptake. CCS will always be needed to capture emissions that cannot otherwise be avoided, such as those from the chemical reactions during cement production. However, there are those areas where there is a choice between e.g., biofuels, hydrogen and CCS. If hydrogen or biomass end up costing some 20 to 30 percent more than we estimate, CCS would become the lowest-cost decarbonization technology for more industries.



Key enablers: Economic incentives, regulations, and stakeholder alignment
Although CCS is a proven technology, it hasn't yet been implemented at large scale. Whilst Europe has enough offshore storage space to store the required volume of CO₂ from CCS beyond 2100, primarily in the North Sea⁵⁰, three challenges must be addressed first:

- **Economic incentives.** Implementing CCS will be an added cost because it normally requires installing a CO₂ capturing plant at an industrial site. That investment won't reduce operating costs like for some other decarbonization measures, such as the lower heating bills that homeowners enjoy after upgrading their building insulation. In fact, CCS raises operating costs through both operation of the plant and downstream transportation and storage of CO₂. The lifecycle cost of carbon capture ranges from €30 per tCO₂ for a pure CO₂ waste stream to €90 per tCO₂ for heavily contaminated streams. Transport and storage costs ranging from €10 to €60 per tCO₂, depending on location, come on top of this. The current EU ETS price of less than €30 doesn't adequately support the CCS business case, requiring €40 to €150 to break even.⁵¹
- **Reporting and liability regulations.** Many governments have legislative restrictions on CO₂ storage, particularly onshore. There is also no existing national or EU wide regulator to set standards, ensure safety and determine how liabilities should work

in the event of CO₂ storage leaks. Issues of accounting will also need to be addressed, for example, whether the country of origin or country of end sequestration would be able to count the ultimate CCS effects, and how these would flow into, e.g., NDC commitments.

- **Stakeholder alignment.** The most cost-effective way to implement CCS is to form clusters of industrial sites to maximize the amount of CO₂ captured and minimize the cost of transporting it to storage facilities. In Europe today, we see multiple clusters emerging, particularly around the North Sea, with diverse memberships that are keen to come together to build shared infrastructure to manage both cost and risk to the benefit of all. These projects could be challenging to orchestrate and will need innovative funding solutions to access appropriate capital.

The following steps can help stakeholders overcome these challenges:

- **Raise carbon prices to close the gap with CCS costs.** If consumers aren't willing to pay more for decarbonized products, it may be necessary to raise the current EU ETS carbon price or introduce additional carbon incentives to increase the attractiveness of CCS to industrial manufacturers. Governments would need to kick-start projects with new regulations, direct funding, subsidies, and tax incentives.⁵²

- **Develop the rules and oversight for a formal CCS market.** To reduce CCS investment risk, lawmakers could outline the market design, define safety standards, assign CO₂ storage liability, and set carbon accounting rules. A CCS regulator, potentially at the EU level, could be appointed to oversee cross-border CCS supply chains. It would also be helpful to create a task force that could resolve project-specific regulatory issues on short notice. It may also make sense for one body to form a comprehensive picture of EU carbon sinks and stores and ensure that these are licensed and utilised in an effective, transparent and fair way, given the inherent local monopoly risks associated with this type of infrastructure.
- **Local orchestrators for industrial clusters.** Each industrial cluster's orchestrator could be responsible for creating the master plan that lays out how the CCS system will operate. Each master plan needs to evaluate its transportation options, such as whether it's more cost-effective to transport captured CO₂ to storage sites through pipelines or ship it.
- **Develop a master plan for each industrial CCS cluster.** Each industrial cluster's orchestrator could be responsible for creating the master plan that lays out how the CCS system will operate. Each master plan needs to evaluate its transportation options, such as whether it's more cost-effective to transport captured CO₂ to storage sites through pipelines or ship it.

⁵⁰ Based on conservative estimates using available geospatial data, including the United Kingdom and Norway. Estimates of storage space in the Adriatic and Mediterranean are limited.

⁵¹ Depending on CO₂ stream purity and distance to storage

⁵² As applied by the United States, known as the 45Q Tax Credit

3.8 Cross-sector: Bioenergy

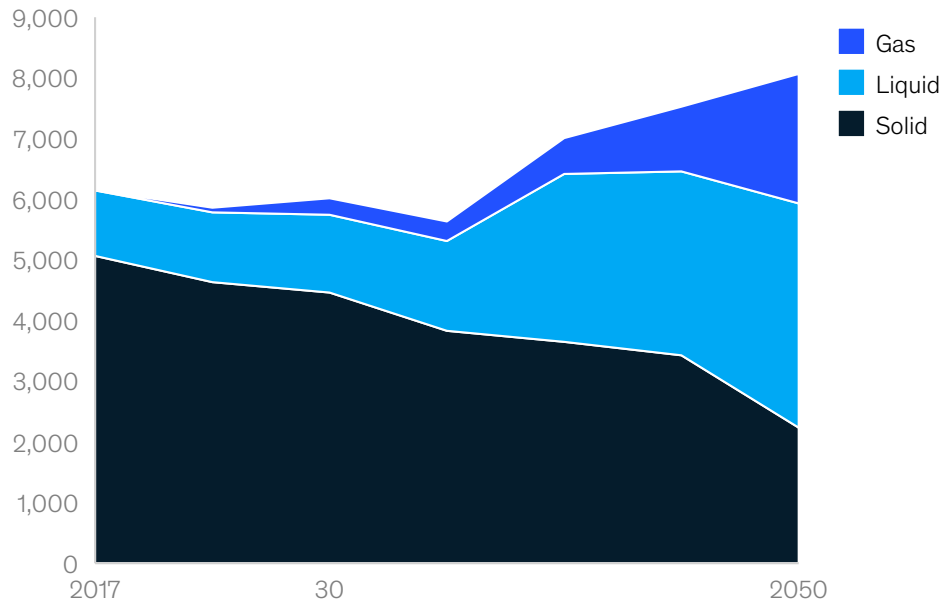


Bioenergy pathway in brief

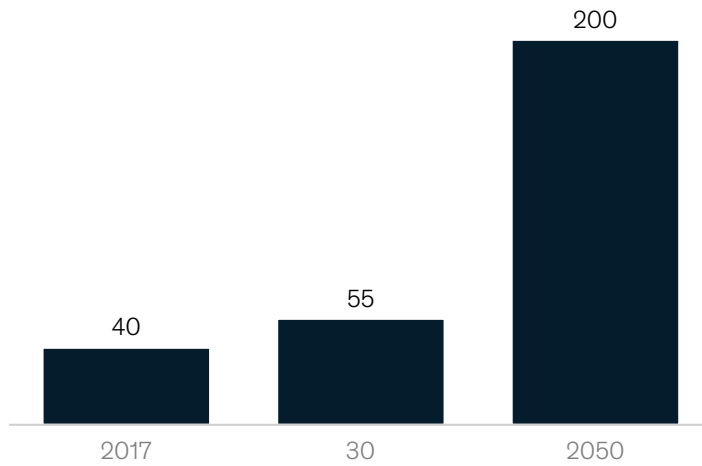


The pathway demand for sustainably produced bioenergy will rise significantly after 2030

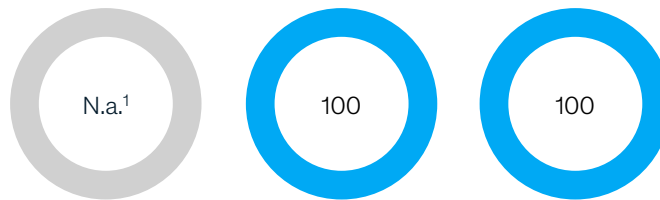
Primary biomass demand
PJ p.a.



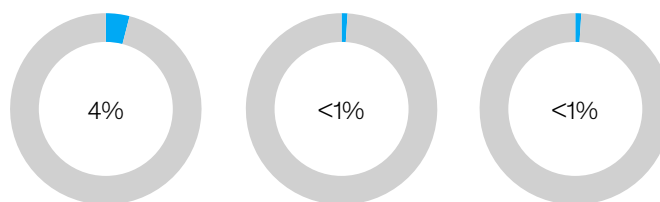
Liquification and gasification capacity
GW



Sustainably produced
% of total



Imported
% of total



1. There is currently no unified EU system to track and trace sustainably produced biomass

Source: McKinsey

3.8.1 Bioenergy use today

People have long used biomass as a fuel source, such as firewood for heating and cooking, and corn and barley for feeding livestock. The EU's demand for biomass is 6.2 EJ a year, primarily for heating in buildings and industrial applications (60 percent), electricity generation (21 percent), and transportation (18 percent); see Exhibit 60. Eighty-five percent of biomass is used in its solid form, and 15 percent as liquid biomass and biogas. Ninety-six percent of this biomass is sourced from within the EU.

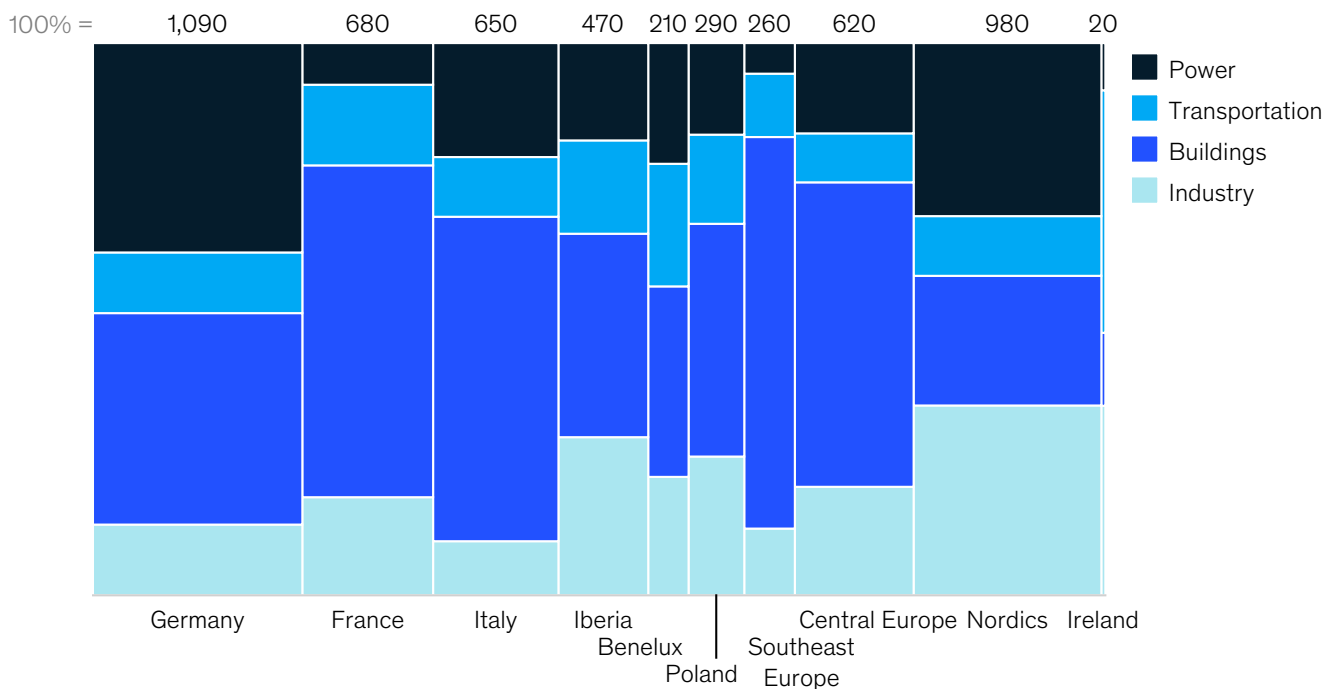
3.8.2 The role of bioenergy on the path to net-zero

Increasing the use of biomass is critical to reaching net-zero GHG emissions in the European Union, particularly in hard-to-abate sectors. The European Union could generate 9.1 EJ of unprocessed biomass annually, about half of which would come from energy crops on unused and abandoned lands. Potential biomass production would vary by region. For example, coastal areas and Southern Europe have much less suitable land available than North and Central Europe (Exhibit 61).

Exhibit 60

Buildings and industry account for 65% of EU bioenergy demand.

Bioenergy demand by sector and region
PJ, 2017, EU-27

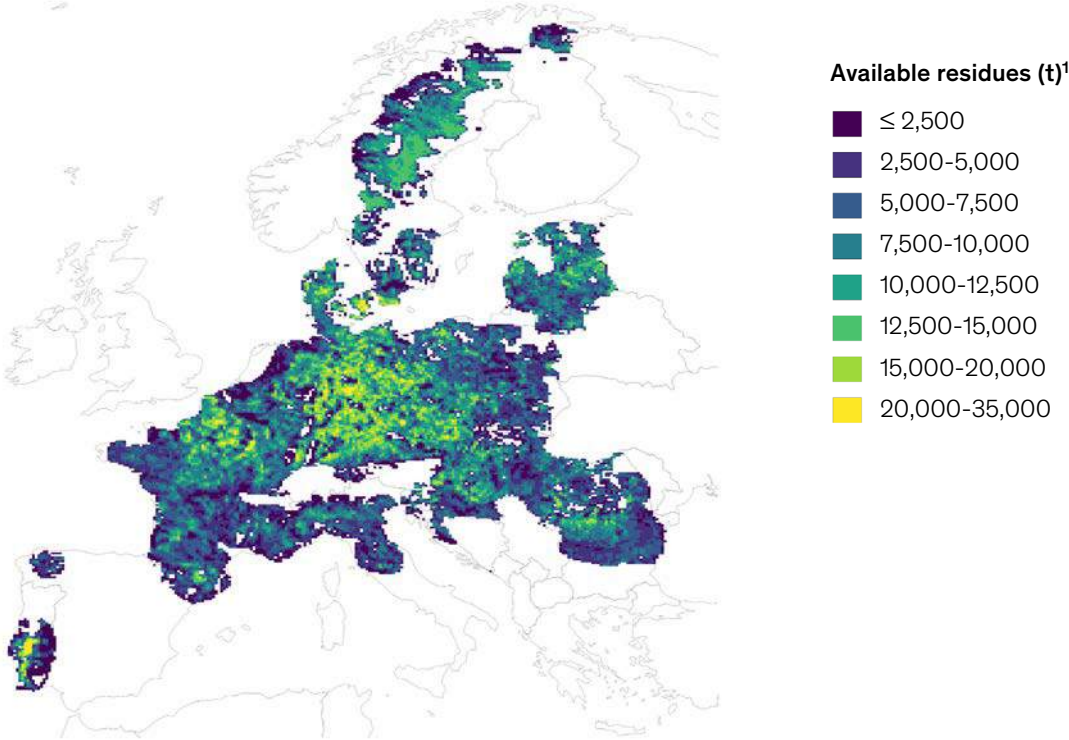


Source: McKinsey, IEA

Exhibit 61

North and central Europe have the highest potential for biomass production.

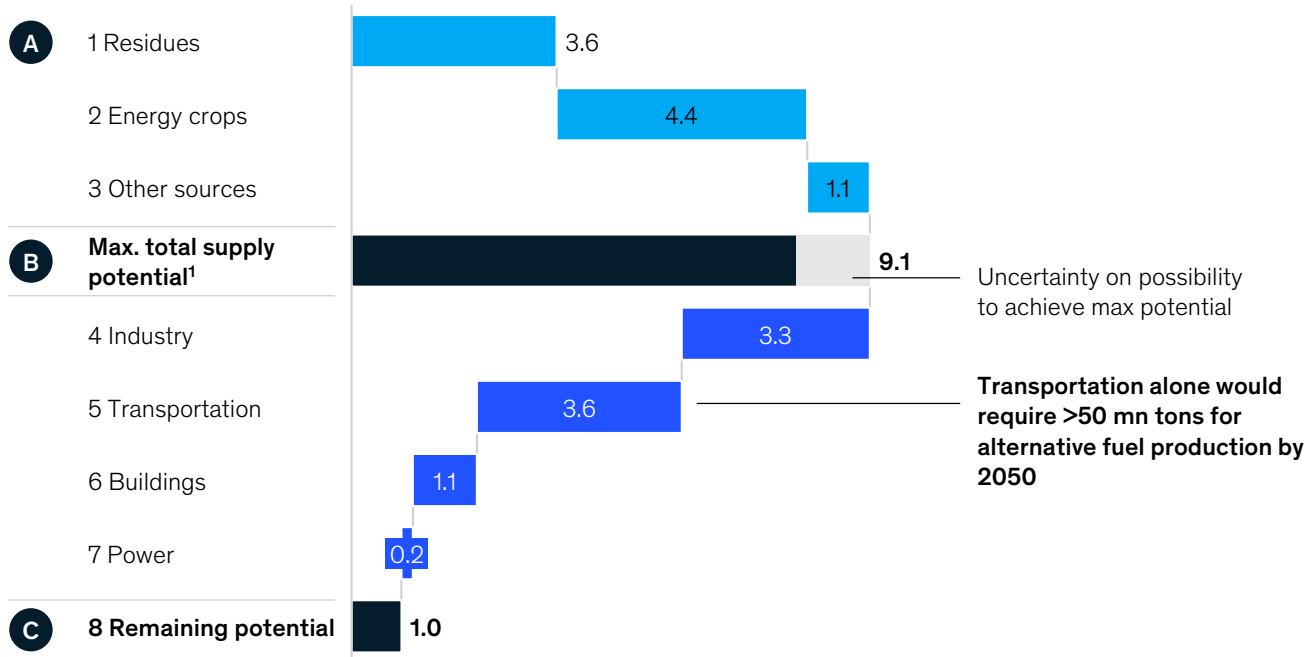
Agriculture and forestry residues, t



1. Potential in Finland not assessed as some of our global sustainability filters (e.g., presence of peatlands and biodiversity) were not adapted to local conditions
Source: McKinsey

Increased demand for bioenergy in industry and transportation would be met primarily from residues and energy crops.

Biomass supply potential and demand in EU-27, 2050, EJ



A Biomass sources²

1 Existing agricultural and wood product residues	3.6
Forestry residues	1.1
Agricultural residues	2.5
2 Potential from unused and abandoned lands	4.4
Currently grown energy crops	1.4
Additional energy crops on marginal lands	3.0
3 Biogas/biomethane from anaerobic digestion	1.1
Manure	0.5
Organic MSW ³	0.6

B Demand from key sectors⁴

4 Biomass for furnaces and boilers	3.3
5 Biofuels for aviation and marine	3.6
Domestic	0.3
International	3.3
6 District heating and biomass boilers	1.1
7 CHP and BECCS	0.2

C Max. potential available for other sectors

8 Sectors like oleo-chemicals and bioplastics	1.0
---	-----

1. Supply from EU forest and agricultural residues (cereals, maize) that is deemed to be economically feasible

2. Highly dependent on production pathways, feedstock use and collection density

3. Assumes MSW (municipal solid waste) from cities with more than 300,000 inhabitants can be economically collected

4. Demand converted from end-use state (e.g., liquid) to biomass

Source: McKinsey, Biomass Futures, Bioenergy Statistical Report 2018, EU Agricultural Outlook 2019-30, Betsen & Felby 2012, Gerwin et al. 2018

In our sector pathways, the demand for primary biomass in its solid, liquid, and gaseous forms remains unchanged. However, there would be a substantial increase in demand for liquid biomass in transportation and biogas in industry (Exhibits 62 and 63). Although biomass use in buildings would decline, the form in which it is used would change from mostly solid to more than 50 percent gas by 2050. Converting biomass to a liquid or gas is essential for the intended end uses but leads to transformation losses. The demand for unprocessed biomass would rise to 8.2 EJ by 2050.

Using bioenergy to decarbonize the industry sector would be essential to achieving cross-sector net-zero by 2050. One of the primary examples is ammonia production. Early on, biogas could directly replace natural gas without any capital investments. Later, the conventional production

system could be retrofitted with carbon-capture installations to create a carbon sink. (CO₂ is first absorbed when plants used to make biogas are growing and then a second time when fuel combustion emissions are captured.) Although the total cost of these systems would be higher than producing ammonia with hydrogen using electrolysis, using CCS technology would produce negative emissions. These negative emissions would be essential for offsetting emissions from agriculture that can't be decarbonized or are very expensive to abate, such as landfill emissions that could only be abated by direct air-capture over large stretches of land. In addition, biofuel could be one of the lower-cost options to reduce emissions in aviation and marine transportation. The production process also yields a significant share of road biofuels that can be used for applications that are harder to electrify.

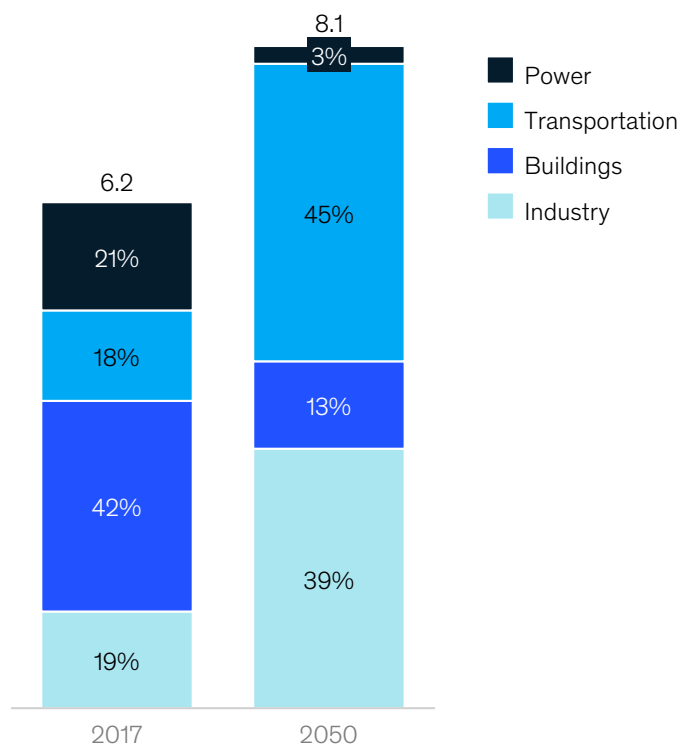
Scaling bioenergy introduces risks that need to be carefully managed. To make it sustainable, it will be essential to maintain carbon cycles, protect biodiversity, and minimize indirect land-use changes. The biomass should also be sourced from within the European Union to avoid increasing the decarbonization challenges of other regions.

To keep the process net-zero, the entire supply chain for bioenergy, from production to consumption, would need to be decarbonized. And because biofuel combustion emits gases such as sulfur dioxide and nitrogen oxides that impair local air quality, businesses would need to implement other measures to mitigate them. An EU-wide certification system could be established to track and trace the sustainability of biomass.

Exhibit 63

The demand for bioenergy will increase substantially in industry and transportation.

EU-27, EJ primary demand



Source: McKinsey

It's also important to consider the proximity of biomass to possible users. In places where the biomass sources are close, local manufacturers could more easily use it as a feedstock. High-temperature demand in industry is typically concentrated, while heating needs are more distributed. For example, in Central Europe, local industry sectors could use the abundant supply of crop residues to fuel its high-temperature furnaces and boilers. When the supply of biomass is far from demand, it could be converted to liquid fuel to replace heavy fuel oil in peak district heating boilers or transportation. However, this would be expensive.

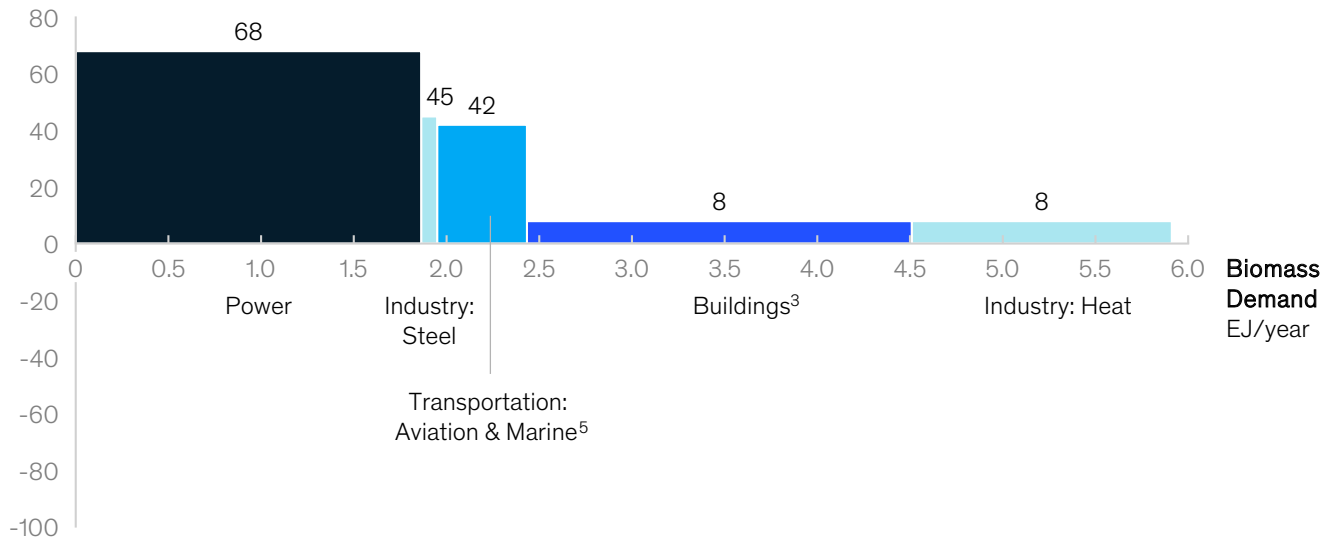
Another factor to consider when determining where and when to use biomass is the cost of alternative decarbonization options. Biomass should be prioritized for situations where the other options are too expensive, especially in hard-to-abate sectors like power, to help provide much-needed flexibility in the power grid. However, the supply and demand for biomass are highly local because of high logistics costs for residues. In some areas, there are cheaper decarbonization alternatives for industry and heating, and using biomass to create biofuels for use in the transportation sector would be more effective.

From 2030, bioenergy is significantly less expensive than the next best option in power, steel and transportation.

Average abatement cost for 2030 and 2050 for EU-27

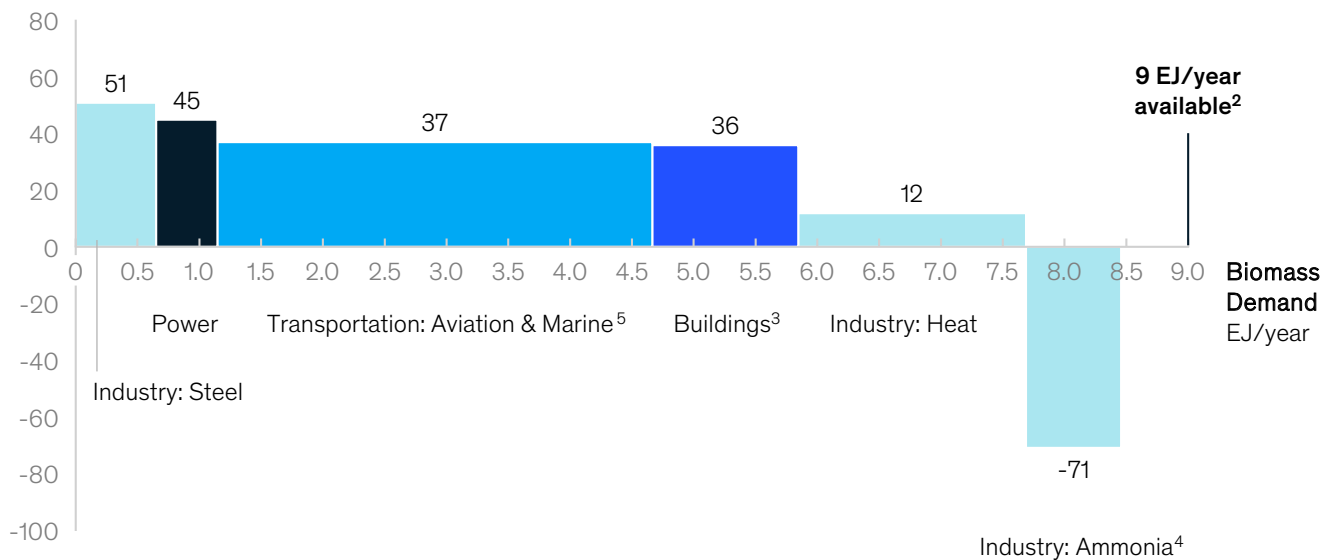
2030

Delta decarbonization cost of next-cheapest option compared to biomass
EUR/tCO₂e¹



2050

Delta decarbonization cost of next-cheapest option compared to biomass
EUR/tCO₂e¹



1. Decarbonization cost of next-cheapest option that brings segment to 80% decarbonization relative to conventional/carbon-intensive production method
 2. Estimate based on practical availability in Europe of sustainable feedstocks: energy crops, cover crops, agricultural residues, primary and secondary forest residues
 3. Including NO_x and CH₄ emissions from incomplete combustion in buildings segment
 4. Biomass option chosen due to negative emissions through BECCS, even though electrolyzer is cheaper
 5. Biofuel production routes for aviation/marine also create a share road biofuels, which should be used for the hardest to abate road sectors like remote areas.

Source: McKinsey

3.8.3 Key uncertainties and enablers

Key uncertainties

Two unknown factors could affect the feasibility of bioenergy in our net-zero pathways, including:

- *Lower-than-expected availability* of biomass could increase the need for more expensive alternative technologies or fuels.
- *Lower-than-expected cost of other decarbonization options* would reduce the demand for bioenergy. In transportation, the price of hydrogen-based fuels would determine whether using biofuels would be the most cost-effective.



Key enablers

Scaling sustainable bioenergy would require significant investments in the biogas, bioliquid, and solid biomass value chains. Making this happen would require numerous actions, including:

- ***Establish regulatory certainty to create supply and demand for bioenergy.*** Bioenergy production is unlikely to scale organically due to a “chicken-and-egg” problem. There’s a restricted market due to limited production, and investment in production is constrained by low demand. Given this problem, some policy direction would be needed to clarify a 10- to 20-year horizon for investors, land-owners, and other stakeholders. Policy direction would need to be supplemented with bioenergy share targets or blending

mandates, feed-in-tariffs, taxation, and pricing mechanisms.

- ***Scale bioenergy supply chains.*** Creating feedstock collection and storage infrastructures in high-density agricultural and forestry residue areas and near large cities for municipal solid waste would make biomass collection less expensive. It would also help to scale preprocessing and conversion technologies. Since this would require many geographically dispersed plants, taking early action is critical. Because accommodating other feedstocks would require many different technologies, it will be essential to invest in existing technologies, such as lipid conversion, and new ones, such as alcohol-to-jet. Making limited

changes to existing fossil fuel distribution networks would also help accommodate liquid biofuels.

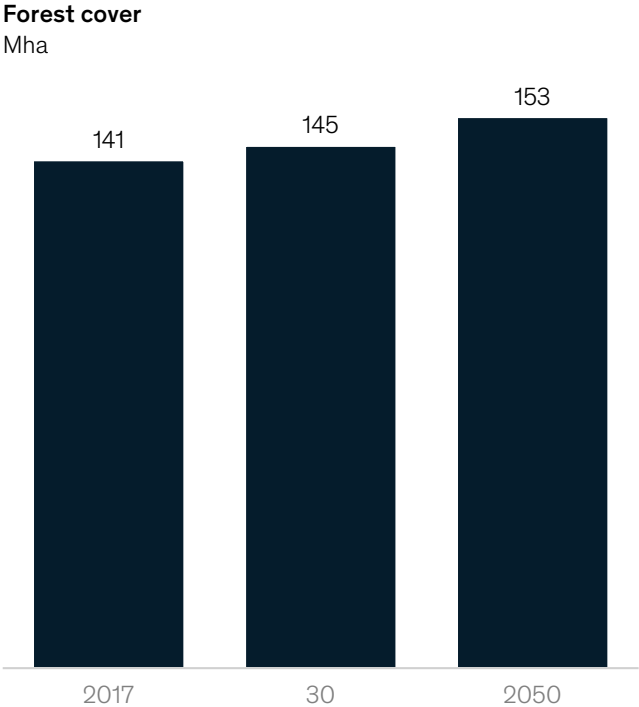
- ***Ensure the sustainability of bioenergy.*** Making sure bioenergy is a viable renewable option would require considering land-use competition, biodiversity, and carbon cycles. It would also require decarbonizing the bioenergy supply chain, from farming to transportation and consumption. This could be achieved with building standards and verification and traceability mechanisms for supply chain emissions and end-product usage.

3.9 Cross-sector: Nature-based carbon sequestration



Nature-based carbon sequestration pathway in brief

Nature-based carbon sequestration will be increasingly critical to cost-optimal achievement of EU climate targets



Source: McKinsey

3.9.1 Nature-based carbon sequestration today

Today, the European Union's forests and soils store a total of 524 GtCO₂e of carbon, almost 150 times the EU-27 net 2017 emissions of 3.6 GtCO₂e (Exhibit 66).

3.9.2 The role of nature-based carbon sequestration on the path to net-zero

There is potential to increase carbon storage in the European Union by about 38 GtCO₂e through reforestation, maintenance, and management. Despite this potential, biomass growth rates and land availability limit how much carbon can be added each year.

Exhibit 66

The biomass of the EU's forests and soils currently stores more than 500 Gt of CO₂e.

Current carbon stored in biomass

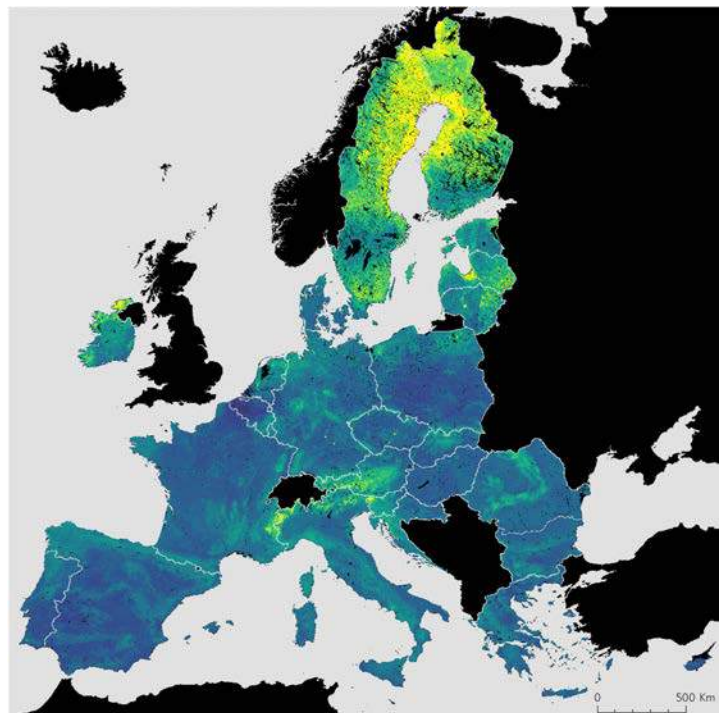
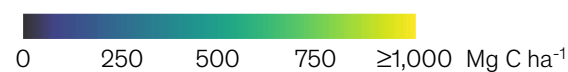
524 GtCO₂e

is currently stored in EU's forests and soils

Equal to almost

150 years

of EU-27 net emissions in 2017
(~3.6 GtCO₂e p.a.)



Source: Walker et al. (In Review) – Map of EU Current Carbon Storage

For example, about 248 MtCO₂e was sequestered in 2018, comprising 345 MtCO₂e from forests minus the emissions from agriculture and wetlands. To achieve net-zero, the European Union would need to increase its annual carbon storage to 353 MtCO₂e by 2050, which would require converting 12 Mha of agricultural land to forest. This is significantly more ambitious than current projections, which foresee annual sequestration declining to 172 MtCO₂e a year by 2035 without intervention.

Exhibit 67

Using reforestation plus forest maintenance and management, the European Union could increase natural carbon sequestration by 38 GtCO₂e.

Unrealized potential to store carbon in biomass

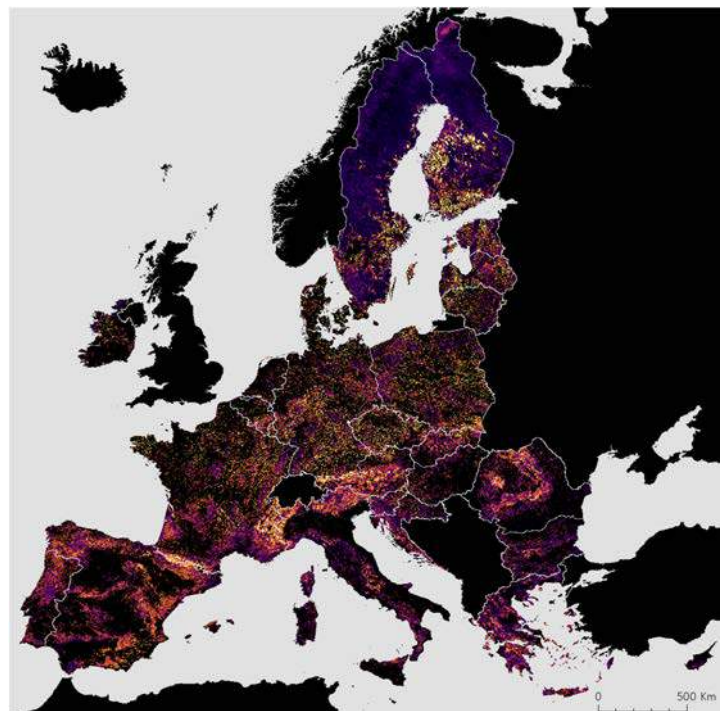
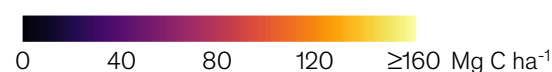
38 GtCO₂e

potential to increase store of carbon across EU while safeguarding food production. Split across: reforestation, maintenance,¹ and management²

Equal to

~10 years

of EU-27 net emissions in 2017 (~3.6 GtCO₂e p.a.)



1. Maintenance category refers to places where current stocks are at or near their potential (specifically within 10%) so there is little active management required beyond avoiding losses
 2. Management category includes places where trees are present but current carbon stocks are below their potential, suggesting the prevalence of degraded forests. Here it is important to maintain current stocks while improving management practices for increased carbon sequestration

Source: Walker et al. (In Review) – EU Unrealized Potential Carbon Constrained

There are four levers for increasing annual sequestration (Exhibit 68):

- **Reforestation:** This involves converting non-forest to forest in locations that historically supported forestry or where forests are ecologically appropriate or desirable. Reforestation can sequester carbon in the long and short term because forests capture carbon and convert it into biomass. Reforestation projects are most successful in temperate regions where the availability of native trees for replanting is high and where replanting is a well-established practice.
- **Natural forest management:** This is the manipulation of naturally occurring forests to manage species composition, age distribution, fires, or pests, plus tree cutting and extraction. Natural forest management can alter the carbon stored in natural forests by, for instance, favoring species with dense wood or delaying harvesting.

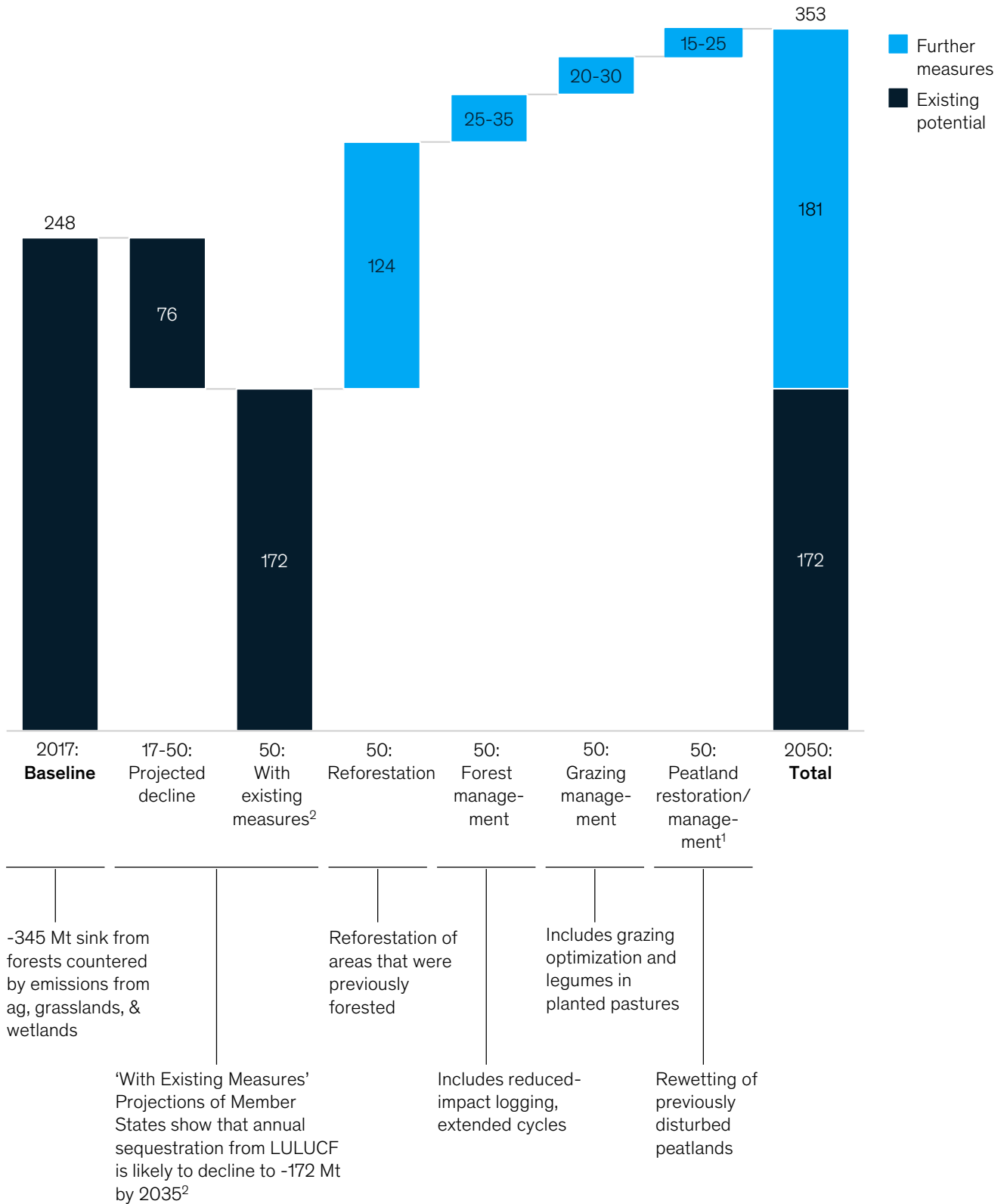
There are extensive forest areas that could be managed to sequester additional carbon.

- **Grazing management:** This involves controlling pasture forage plants, animal stocking rates on pastures, animal food sources, and livestock breeds. Grazing management can sequester large volumes of carbon by changing the timescale of livestock feeding cycles, especially in wetter regions with high forage growth rates.
- **Peatland restoration and management:** This is the restoration of peatlands that have degraded, including through water-table management and re-vegetation.

In addition to providing greater carbon sequestration, these changes to forests and soils can deliver other benefits, such as improved water quality, better-regulated water supply, higher soil quality, and biodiversity protection.

Reforestation would be the most powerful lever for increasing natural carbon sequestration in the European Union.

Negative emissions in EU-27, MtCO₂e p. a.



1. Walker et al. (In Review) – EU Unrealized Potential Carbon Constrained

2. European Environment Agency emissions projections; Griscom, B. et al. PNAS October 31, 2017 114 (44) 11645-11650; Ceccherini et al. (2020)

Source: McKinsey, National Inventory Reports for UNFCCC

3.9.3 Key uncertainties and enablers

Key uncertainties: Climate change, forest management, and agricultural efficiency

Three unknowns could impact the level of natural carbon sequestration, including:

- *Climate change* has increased the frequency of drought and weakened the natural defenses of trees in some parts of the world. This creates risks for Europe's forests. For example, the bark beetle outbreak across Central Europe in 2018 infested five times as many trees as the average from 2012 to 2016.⁵³ As much as 80 percent of spruce forests in the Czech Republic may be at risk.⁵⁴ The continuation or acceleration of such climate-related risks could impact the amount of carbon sequestration possible in Europe's forests.
- *Increased harvesting* with poor forest management leads to a loss of biomass and carbon sequestration. From 2016 to 2018, the amount of harvested forest area in Europe increased 49 percent and biomass loss rose 69 percent compared with 2011 to 2015, particularly in the Iberian Peninsula and the Nordic and Baltic countries, according to a recent analysis.⁵⁵ This does not change the potential for natural carbon sequestration, but it does raise questions about whether existing forest management approaches are compatible with more carbon storage in the future.
- *Increased agriculture efficiency* is critical to ensuring continued food production while freeing up at least 12 Mha of agricultural land, about 7 percent of the current area, for reforestation. This aligns with past trends in which agricultural land in EU countries shrank by 6 percent (9 Mha) from 2009 to 2015, while forest land increased by 2 percent (2.5 Mha). However, the potential for agricultural efficiency improvements to make land available for reforestation is uncertain.

⁵³ ["Bark beetle ravages central Europe's forests." Reuters Graphics, April 26, 2019.](#)

⁵⁴ Jan Lopatka, ["Climate change to blame as bark beetles ravage central Europe's forests." Reuters, April 26, 2019.](#)

⁵⁵ Guido Ceccherini, et al., ["Abrupt increase in harvested forest area over Europe after 2015." Nature, July 2020, Volume 583, Issue 7814, pp. 72-77.](#)

Key enablers: Climate targets, the CAP, and carbon markets

Achieving increased levels of carbon sequestration would require supporting regulatory frameworks and compensation mechanisms, including:

- ***Incorporate natural sequestration into member states' targets.***

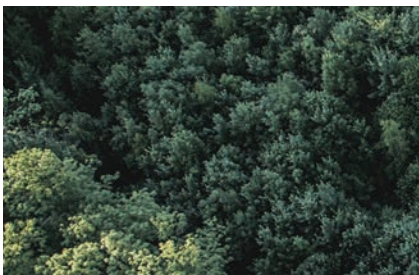
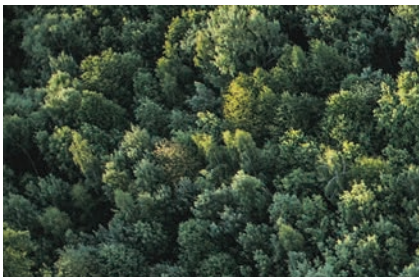
Following recent regulation, the European Union's climate targets will include CO₂ removal through land use. Until now, emissions and

removals related to land use and forestry were excluded.

- ***Use the Common Agricultural Policy (CAP) to support farmers through the transition.***

Improvements to natural sequestration would only be possible if they are coordinated with other policy mechanisms, of which CAP is the most important.

- ***Consider the role of carbon pricing and markets in supporting natural sequestration.*** Farmers and other landowners would need to change how they use their land to contribute to a climate-neutral European Union. Private markets can support them. For example, the United Kingdom's Woodland Carbon Code validates carbon sequestration and compensates farmers and landowners.



4. The socioeconomic implications of decarbonizing Europe

For most citizens, the European Union's transition to climate neutrality won't significantly change their everyday lives. They might see more solar PV farms in the countryside, their cars would have better acceleration, and their homes might be better insulated. But most things would seem the same. However, the structure and metabolism of the economy would change, in some respects substantially. New sectors and technologies would emerge, while others would shift their focus or become obsolete. As a result, there would also be some job displacement. Managing these changes will require Europe's leaders to address the socioeconomic impact of decarbonization, as well as the financial investments and other actions it will take to achieve it.





4.1 Financing the transition

4.1.1 The capital investments required

On our pathway, reaching net-zero would require investing a total of €28 trillion in clean technologies and techniques over the next three decades (Exhibit 69). This would comprise €23 trillion (an average of €800 billion per year) of funds that would otherwise be invested in incumbent technologies and €5.4 trillion (an average of €180 billion per year) of additional capital outlay (Exhibit 70). In 2018, the total investments made in the entire EU-27 economy were about €2.7 trillion.⁵⁶ Decarbonization would require redirecting roughly a quarter of those annual investments, or about 4 percent of current EU GDP. It would also require increasing that investment pool by 7 percent, the equivalent of 1 percent of the European Union's current GDP.

Nearly half of the total capital would go to transportation (€11.8 trillion), followed by 30 percent to buildings (€8.4 trillion), 9 percent to power (€2.5 trillion), 3 percent to agriculture (€935 billion), and 1 percent to industry (€350 billion). About 14 percent (€3.4 trillion) of the total investment would fund infrastructure that improves energy transmission and distribution.

Of the additional €5.4 trillion in capital expenditures, €1.5 trillion (29 percent of the total) would be invested in the buildings sector, €1.8 trillion (33 percent) in the power sector, €410 billion (8 percent) in industry, €76 billion (1 percent) in agriculture, and €32 billion (1 percent) in transportation, which would begin to experience net savings from emissions-reduction measures in the 2040s. Cross-sector infrastructure would absorb an additional 28 percent of the investment,

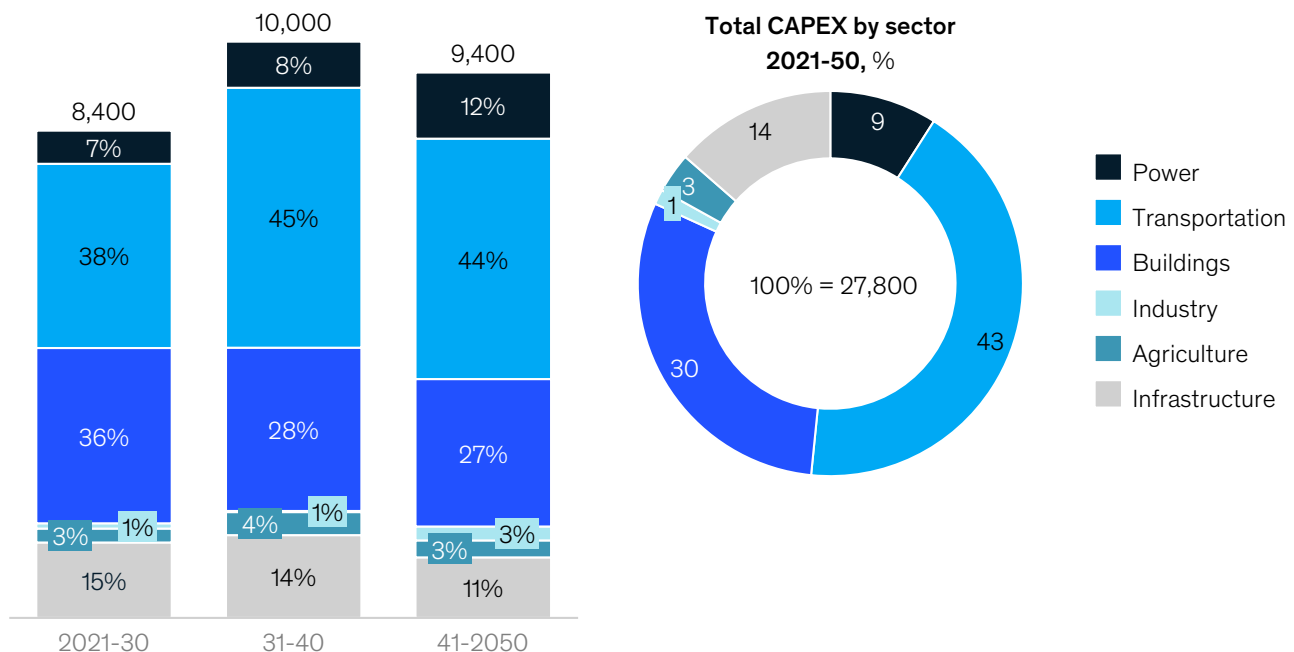
most of which would be used to upgrade the power grid (€1.4 trillion). The remaining €500 billion would be used to invest in pipeline networks.

⁵⁶ This includes all investments made by the public and private sector in 2018 in the EU-27, source: Eurostat.

Exhibit 69

Reaching net-zero GHG emissions in the EU by 2050 would require €28 trillion of investment in clean technologies and techniques.

Total CAPEX in EU-27, bn EUR (total within time bracket)



Source: McKinsey

4.1.2 Operating cost reductions

The transition to net-zero would create significant operational cost savings, such as lower heating bills from improved building insulation. As a result, at the societal level, net-zero emissions could be achieved at net-zero cost because the €5.4 trillion in additional investment would be recuperated through operating cost savings. So, the net cost of reaching the abatement targets would be €0 per tCO₂e.

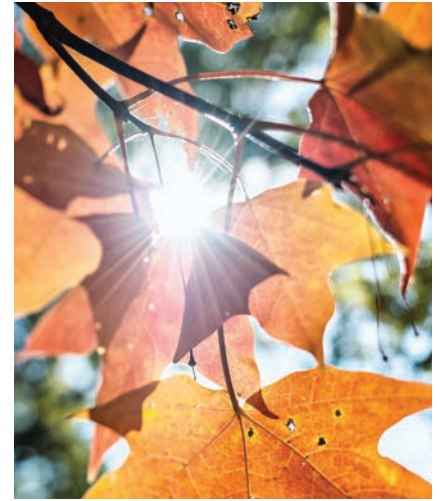
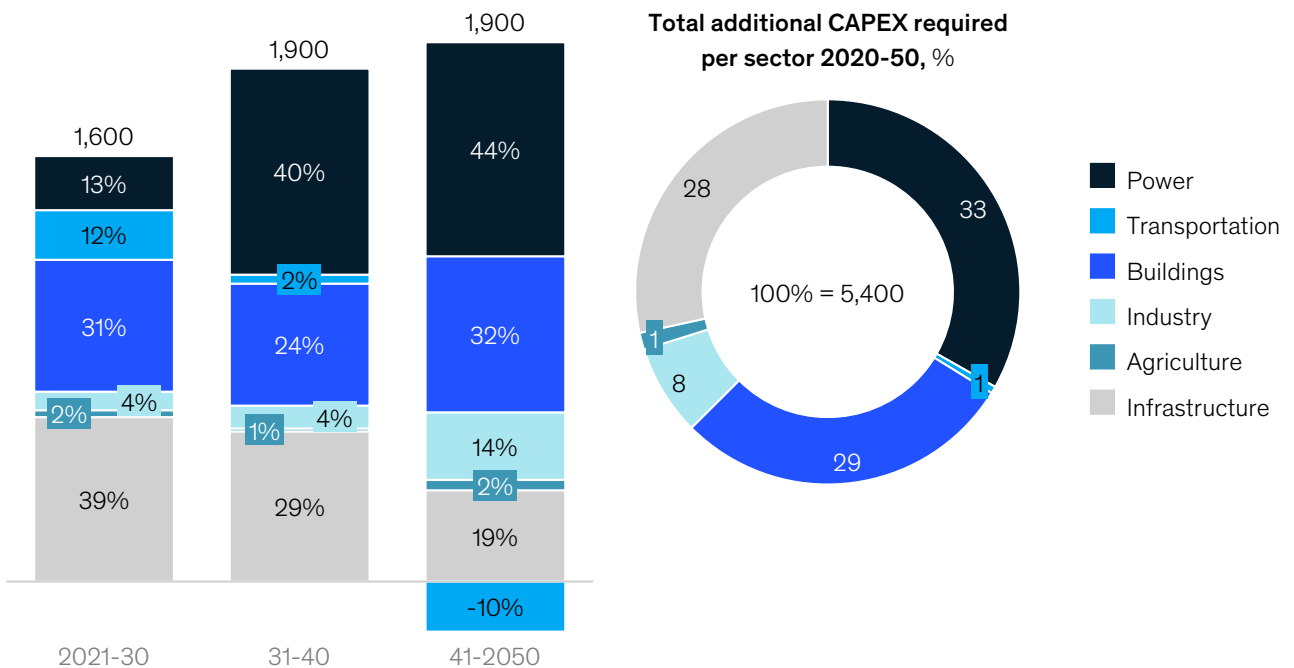


Exhibit 70

Capital expenditure on the cost-optimal pathway is €5.4 trillion more than if the EU took no climate action at all.

Additional CAPEX in EU-27, Bn EUR (total within time bracket)



Source: McKinsey

From now until 2050, operating costs would drop an average of €130 billion per year, offsetting 70 percent of the capital investments over the same period at a macro level (Exhibit 71). As a result, €3.9 trillion of the €5.4 trillion in additional investment would be recovered by 2050. The remaining €1.5 trillion would be recovered soon after, as operating costs continue to outpace capital investments by at least €65 billion a year. Taken together, the average TCO across all newly adopted technologies and techniques would be cost-neutral.

However, this would not be the case for each sector or individual measure. Domestic transportation would derive most of the operating cost savings, while sectors like international aviation and industry would see an increase in operating costs, in addition to the initial investments.

4.1.3 Bridging the financing gap

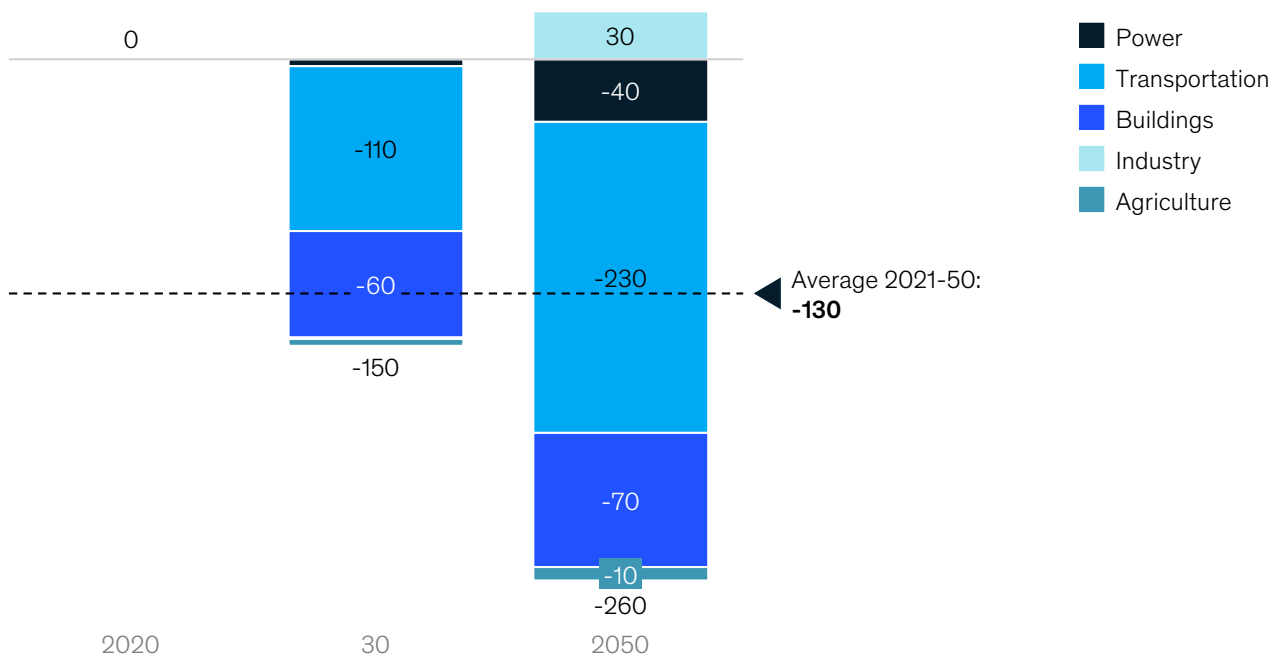
The pathway we lay out optimizes net-system-level costs under a societal discount rate. However, individual stakeholders usually make capital allocation decisions based on their own cost of capital and payback period expectations. So, the decisions that individual actors would make without targeted interventions would likely differ from those laid out in our pathway. From the perspective of the relevant stakeholder in each case, we estimate that half of the required €28 trillion capital outlay would not appear to have a positive investment case. This may be due to differences in cost of capital, shorter payback period expectations, or the benefits not directly benefitting the stakeholder making the investment. For example, car buyers usually give more weight to the upfront purchase price than the total ownership cost.

The volume of investments without a business case varies by decade. From now to 2030, 60 percent of the investment would not have a business case. But from 2030 to 2040, that share drops to 36 percent as renewable technologies mature and prices decline. From 2040 to 2050, about 45 percent of the investment would lack a business case for individual stakeholders because hard-to-abate sectors require more expensive measures to decarbonize (Exhibit 72).

Exhibit 71

From now to 2050, the transition to net-zero GHG emissions would save the EU an average of €130 billion per year, offsetting 70 percent of capital investments

Total OPEX^{1,2} in EU-27, Bn EUR p.a.



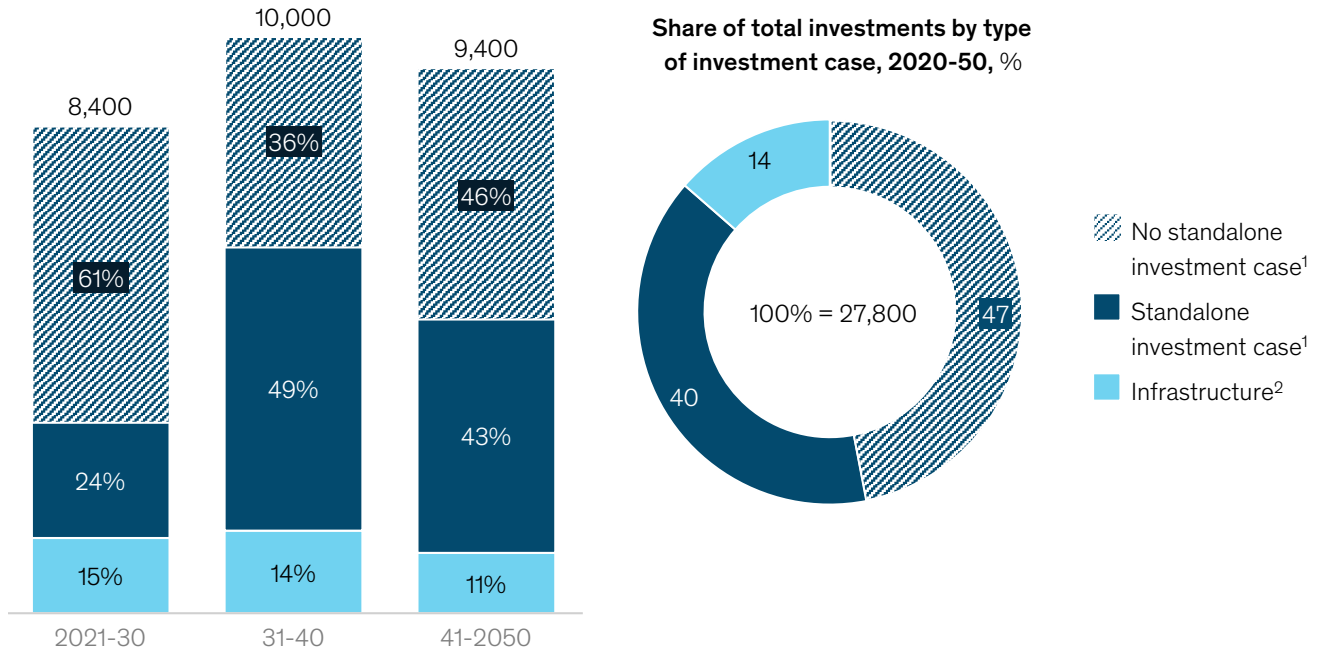
1. Fuel and feedstock OPEX

2. Excluding OPEX reduction in refining sector (which is mainly due to reduction of the refining activity)

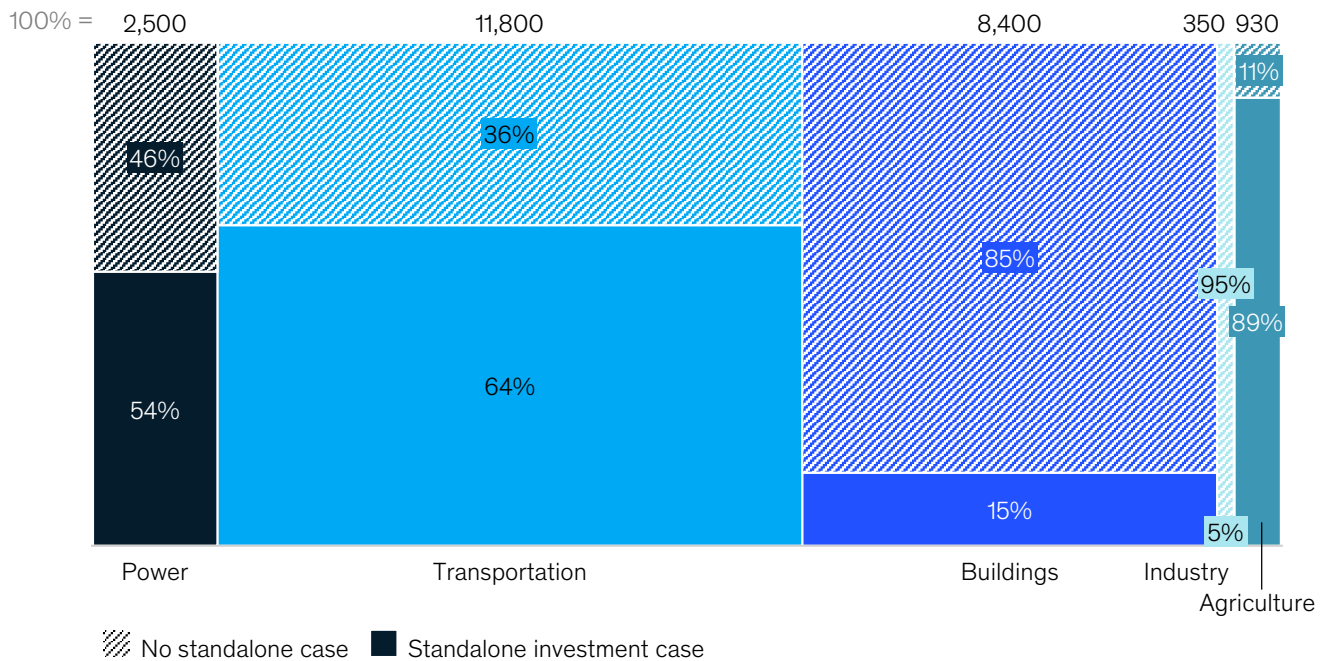
Source: McKinsey

About half the required investments do not have positive standalone investment cases for their stakeholders.

Emissions-reduction investments by type of investment case for individual stakeholders
 Total CAPEX in EU-27, Bn EUR (total within time bracket)



Emissions-reduction investments by type of investment case for individual stakeholders by sector
 Total CAPEX¹ in EU-27, total for 2020-50, Bn EUR



1. Investment cases that are NPV positive. For assumptions (including WACC and lifetime expectancy) see technical appendix
 2. Profitability of infrastructure investments are not modelled as business model is often unclear and asset base is often regulated
 Source: McKinsey

The share of investments with a positive investment case for individual stakeholders also varies by sector (Exhibit 73). Although most of the transportation, agriculture, and power sector investments have standalone business cases, only 15 percent of those in the buildings sector and 5 percent in industry would eventually pay for themselves. In agriculture, more than half of emissions could only be abated with behavioral changes, such as reducing meat consumption. But of the emissions that can be reduced through technological interventions, almost 90 percent have standalone business cases. Because of these differences, sectors will require differing levels of financial support or innovative finance solutions to switch to green technologies.

There are multiple ways to mobilize capital, including:

- **Direct financing interventions.** Direct government investment is usually most appropriate for projects that lack a revenue stream reliable enough to interest the private sector or suitable for outright public ownership, such as grid upgrades or CCS systems. Tax credits and subsidies tend to work best for accelerating an active market, such as increasing building insulation and industry efficiency efforts. Grants are often required for funding R&D projects that generate no short-term revenues. Loans and loan guarantees tend to work best when they target a few beneficiaries because of their higher administrative costs. As shown in Exhibit 73, applying direct financing to close the gap in each stakeholder's business case would require committing about €4.9 trillion over the next three decades.

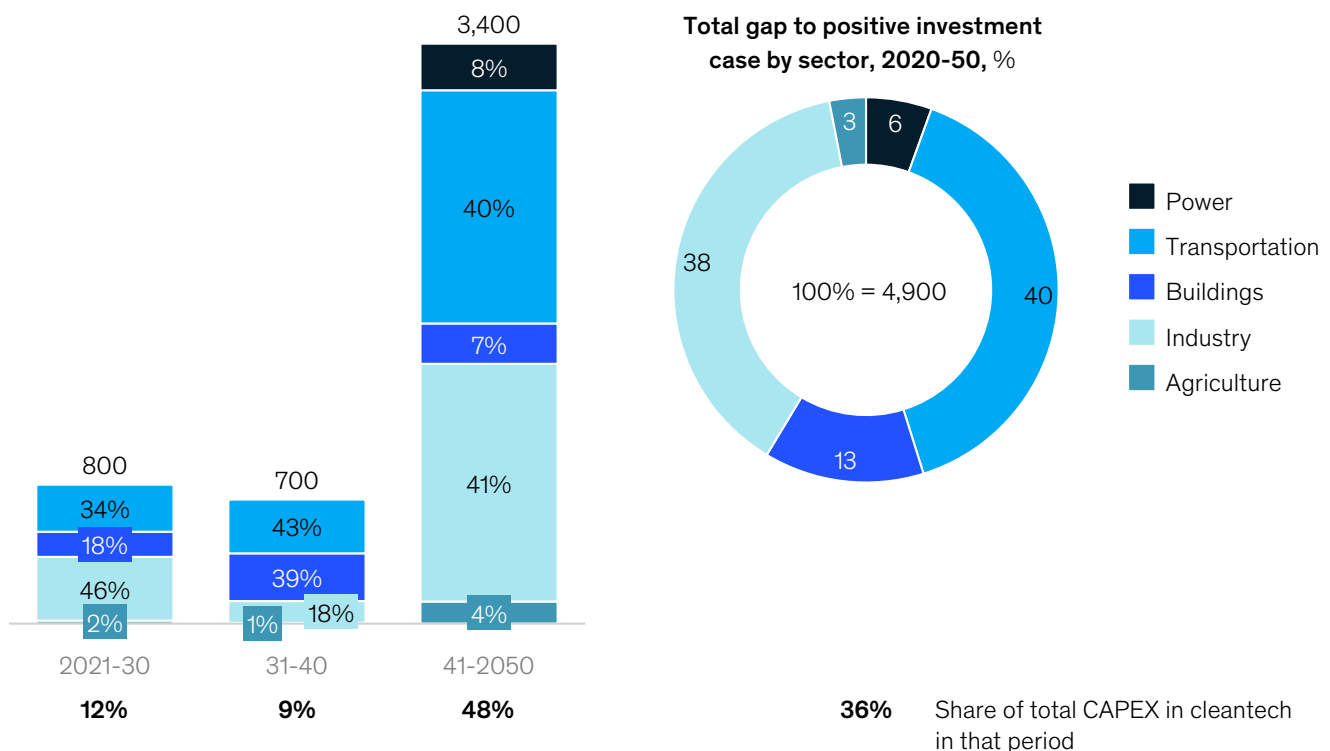
- **Price measures such as carbon prices or cap-and-trade systems.**

Carbon prices could increase the mobilization of private capital, as increasing the carbon price would make more investment cases positive. We estimate that at a carbon price of €50 per tCO₂e, an additional 21 percent of capital required through 2050 could be unlocked on top of the 40 percent that already has a positive investment case. A carbon price of €100 per tCO₂e could unlock another 10 percent of capital requirements, giving more than 85 percent of the required capital a standalone business case. The remainder would require carbon prices of over €100 per tCO₂e. See Exhibit 74 for the impact of carbon prices on the total investable capital.

Exhibit 73

Government intervention may be needed to encourage individual stakeholders to make clean technology investments in the absence of compelling investment cases.

Additional CAPEX and OPEX in EU-27 required, Bn EUR (total gap created within time bracket)



Source: McKinsey

— *Commercial derisking and involving long term investors.* Capital could be mobilized by reducing investment risks, such as establishing an ETS price floor, providing loss guarantees, or using models such as public-private partnerships and blended finance. New financing models and products, such as adding insulation costs to house mortgages or creating leasing schemes for technologies with high upfront costs, could bring more long-term investors into markets dominated by short-term decisions. For example, if the applied weighted average cost of capital (WACC) dropped to 4 percent and short payback expectations were relaxed, the share of investments with a positive business case, even without a carbon price, would increase from 40 percent to almost 50 percent of the total €28 trillion. Combined with carbon prices of €50 to €100 per tCO₂e, the proportion of investable business cases would increase to 65 percent and 89 percent, respectively.

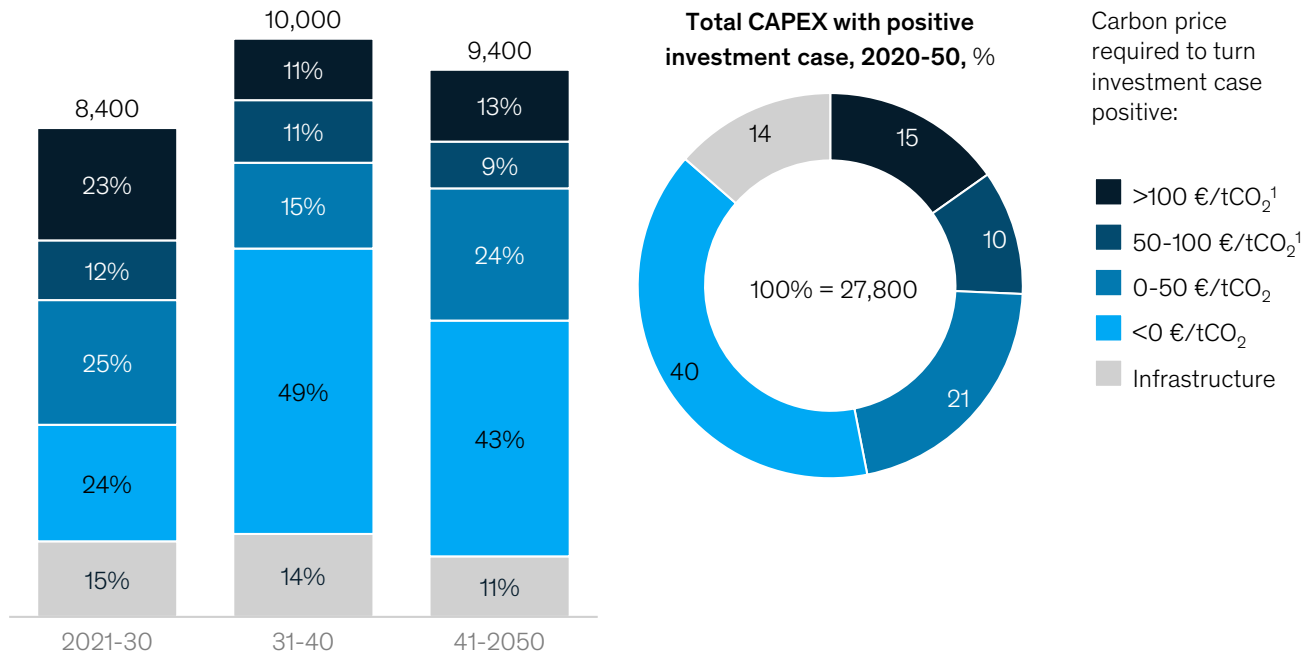
The sustained low-cost capital available from capital markets today may be an opportunity to lower the overall cost of the transition. Capital markets innovations—such as asset-backed securities, utility and corporate power purchase agreements, and risk guarantees—could accelerate the rate of decarbonization.

Of course, increased costs could also be passed on to end customers through regulatory backstops such as banning gas boiler installations after a specific date and establishing portfolio standards that require a minimum share of investment in the renewable power sector.

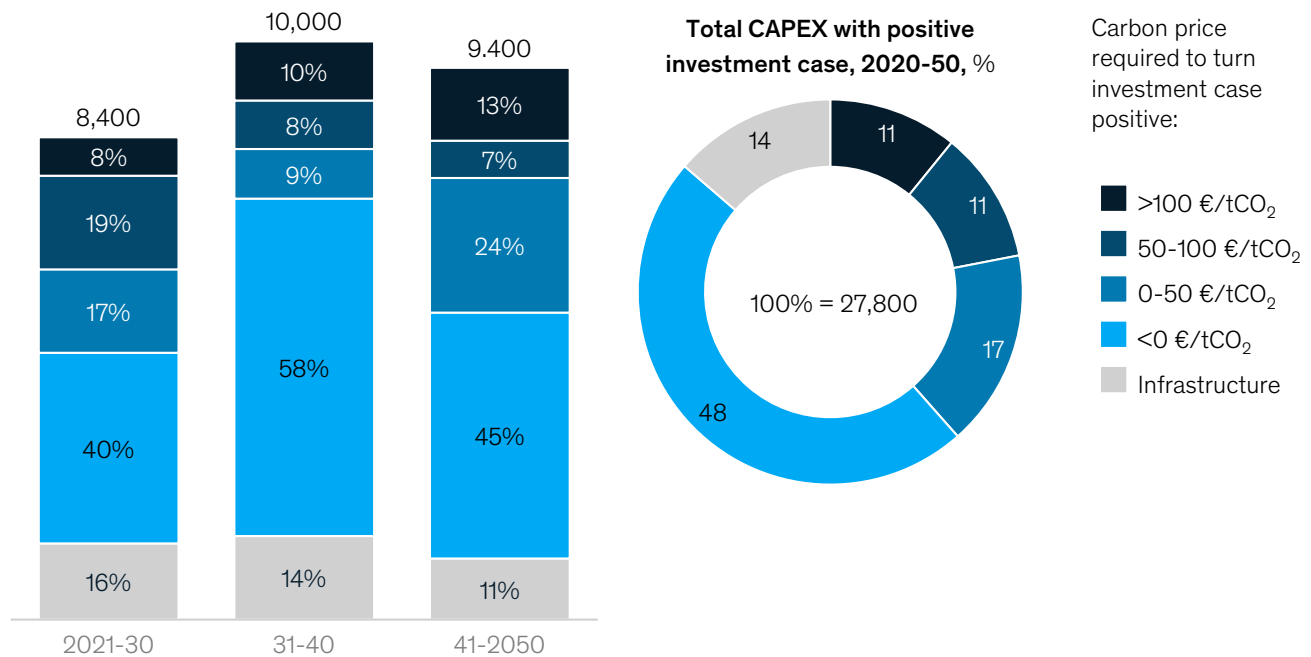


Carbon prices and other pricing measures could increase mobilization of private capital where there may not be a standalone investment case.

Share of CAPEX with positive investment case from perspective of individual stakeholders
 Total CAPEX in EU-27, Bn EUR (total within time period)



Long-term investor perspective on share of investments with positive investment case
 Total CAPEX in EU-27, Bn EUR (total within time period)



1. Profitability of infrastructure investments are not modeled, as business model is often unclear and asset base is often regulated
 Source: McKinsey

Overcoming the infrastructure deployment challenge

For consumers and companies to switch to low-carbon technologies, they will need access to the right types of infrastructure. For example, a trucking company can only change its business to green hydrogen trucks if the enabling infrastructure—hydrogen refueling stations, a hydrogen distribution network, and renewable power to electrolyzers—is all in place. And the absence of infrastructure affects upstream technology development and deployment. Commercial vehicle original equipment manufacturers (OEMs) would likely invest in developing hydrogen trucks only if they are confident that the lack of infrastructure wouldn't reduce future demand. So, a delay in ramping up sufficient infrastructure could stall the transition to net-zero, whereas early deployment could accelerate it.

However, the fact that infrastructure deployment usually needs to precede technology deployment creates two challenges: it could prematurely conclude the technology race and make it harder to mobilize the required capital.

On the first point, in instances where there isn't a clear leading zero-emissions technology choice, deploying infrastructure can influence what becomes the most attractive decarbonization option. For example, for industrial players for which CCS or electrification have similar

decarbonization costs, connecting an industrial cluster to CO₂ pipelines could lead members of the cluster to choose CCS to reduce emissions. This could create lock-in effects and higher-cost outcomes. As discussed in Section 2.4, there are two or more equally cost-optimal abatement technologies for reducing 20 percent of total EU emissions. In these cases, the type of infrastructure that's deployed could impact which technology gets chosen.

On the second point, the total investment needed for infrastructure from 2020 to 2050 is about €4 trillion. Three quarters of this, some €3 trillion, would go to upgrading the power grid. Nearly €500 billion would go toward installing new district heating networks for 45 million households. Another €500 billion would be spent on CO₂ and hydrogen pipelines, EV charging infrastructure, hydrogen refueling stations, and other smaller infrastructure projects. Seventy-five percent of the total investment for infrastructure would need to be mobilized before 2040.

This may not be trivial. The challenge stems from the fact that infrastructure typically needs to be in place before the roll-out of technologies. Sometimes, market development is uncertain, even with the required infrastructure in place. This creates risks and uncertainties for investors, who consequently are often hesitant to deploy the capital required.

For these reasons, interventions would be necessary to ensure that the proper infrastructure is put in place. The private or public sector could lead these interventions. For example, private sector players could form joint ventures to build the required infrastructure, much like the European automotive OEMs have joined together to install EV charging infrastructure along EU highways. Public sector leaders also have various mechanisms at their disposal, ranging from direct public ownership, such as road or rail networks in most places; to including a certain infrastructure type in the regulated asset base, similar to power grids; to targeted subsidies aimed at derisking investment cases. Each type of infrastructure would need a different approach, depending on the characteristics of the capital-expenditure profile, market development and viable market mechanisms, and the complexity of the stakeholder ecosystem.

Because of these factors, decision makers need to think carefully about infrastructure. If left unattended, it could become a critical barrier to the transition or lead to suboptimal outcomes. But done right, it becomes a crucial part of enabling change and creating business opportunities and new markets.

4.1.4 Impact on households

Another critical consideration is the impact the net-zero transition would have on households (Exhibit 75). Changes in the cost of living would depend on the details of local regulatory interventions and taxes. In this section, we assess the impact on household expenses, assuming consumption patterns remain the same and the cost increases and savings of decarbonization are directly passed through to consumers.

In this scenario, the aggregate cost of living for an average household in a climate-neutral European Union would

be roughly the same as today, albeit with variations in the following spending categories:

— **Power and heating/cooling bills:**

The short-term investment in improving energy efficiency in residential buildings could produce long-term savings. However, the amount of those savings will depend on the type of technology the homeowner chooses, the location and age of the house, and how agency issues are resolved, such as whether landlords raise rent prices to pay for the investment.

— **Mobility:** Transportation costs would drop over time because of lower operational costs and lower capital investments in EVs as technology and production costs fall.

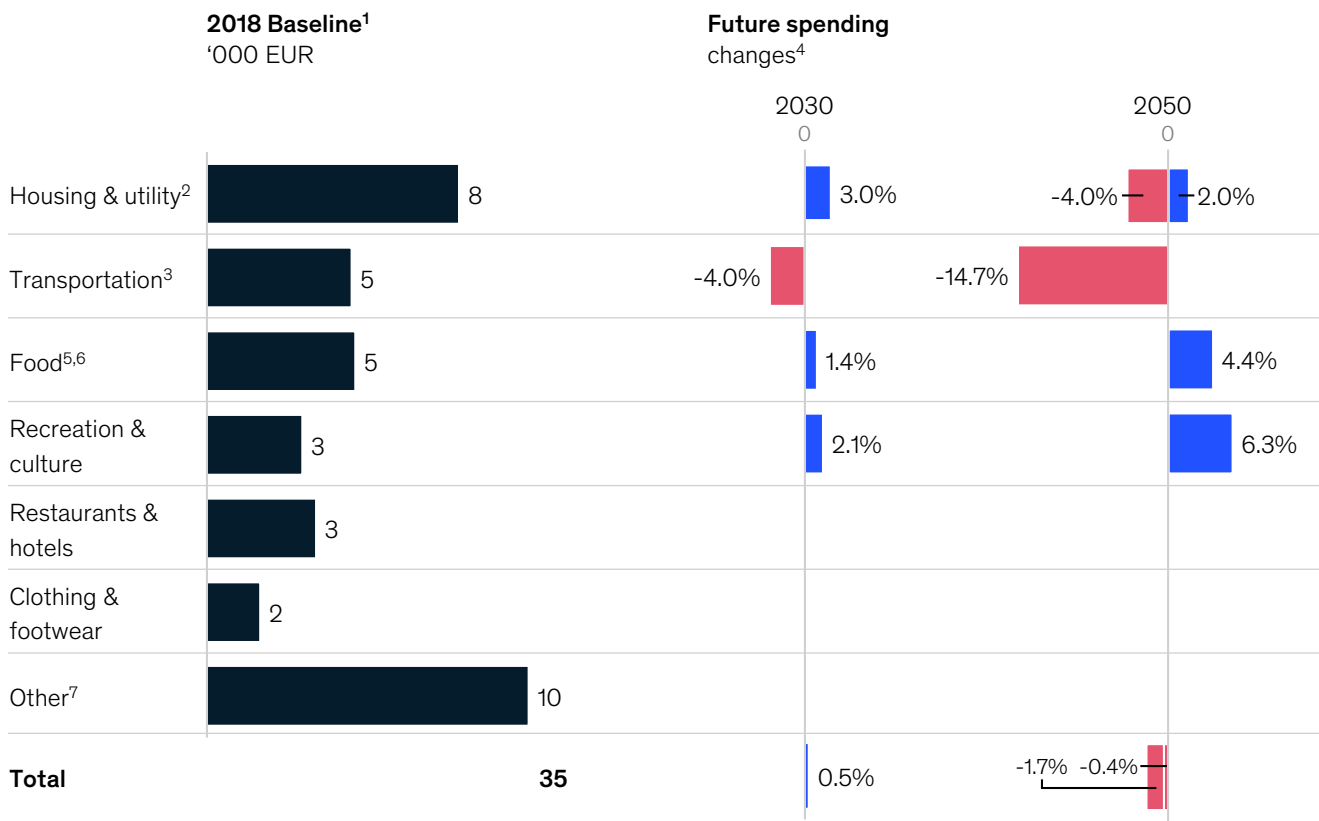
— **Food:** The cost of food would rise as the agriculture sector takes steps to decarbonize, although switching to a plant-based diet could offset the cost increases.

— **Recreation:** The cost of things like international flights would rise as airlines switch to more expensive alternative fuels.

Exhibit 75

On the cost-optimal pathway to a climate-neutral EU, the average household would spend less on transportation and somewhat more on food and recreation.

Average household annual spending in EU-27



1. Excludes Greece due to data availability

2. Based on 2017 data, excluding ~5% spending in water

3. Only for passenger cars (i.e. no bus / rail) and exclude the price for green steel production

4. Assuming only the true costs are passed on to consumer, i.e. there is no additional mark up from the decarbonization costs

5. Only ~35% of food spending goes to the farmers and assuming 60% of food spending is for animal based products

6. Excludes the impact of electrification of tractors

7. Other includes health, communications, education, alcoholic beverages, tobacco, narcotics, furnishings, household equipment, routine household maintenance and miscellaneous goods and services

Source: McKinsey, Eurostat

Based on our analysis of a sample of households across income levels, we found that middle-income households in middle-income countries such as Italy, Germany, and France would save the most over the short and long-term (Exhibit 76). Low-income households in lower-income countries like Romania, Hungary, and Poland would also financially benefit from decarbonization (Exhibit 77). However, high-income households from high-income countries such as Luxembourg, Ireland, and Denmark would see no real change because of their higher share of spending on recreation and other items that would see cost increases.

During the transition to climate-neutrality, it's typically the cost of intermediate goods and services that rises, whereas the cost of the final goods doesn't change much. For example, a ton of zero-emissions steel is 25 percent more expensive to produce than its high-carbon counterpart. But the price of a typical passenger vehicle increases by less than 1 percent if the manufacturer uses zero-emissions steel.⁵⁷ And while zero-emissions container shipping would be twice as expensive, it would increase the price of a pair of jeans produced in Southeast Asia and sold in Europe by less than 2 percent.

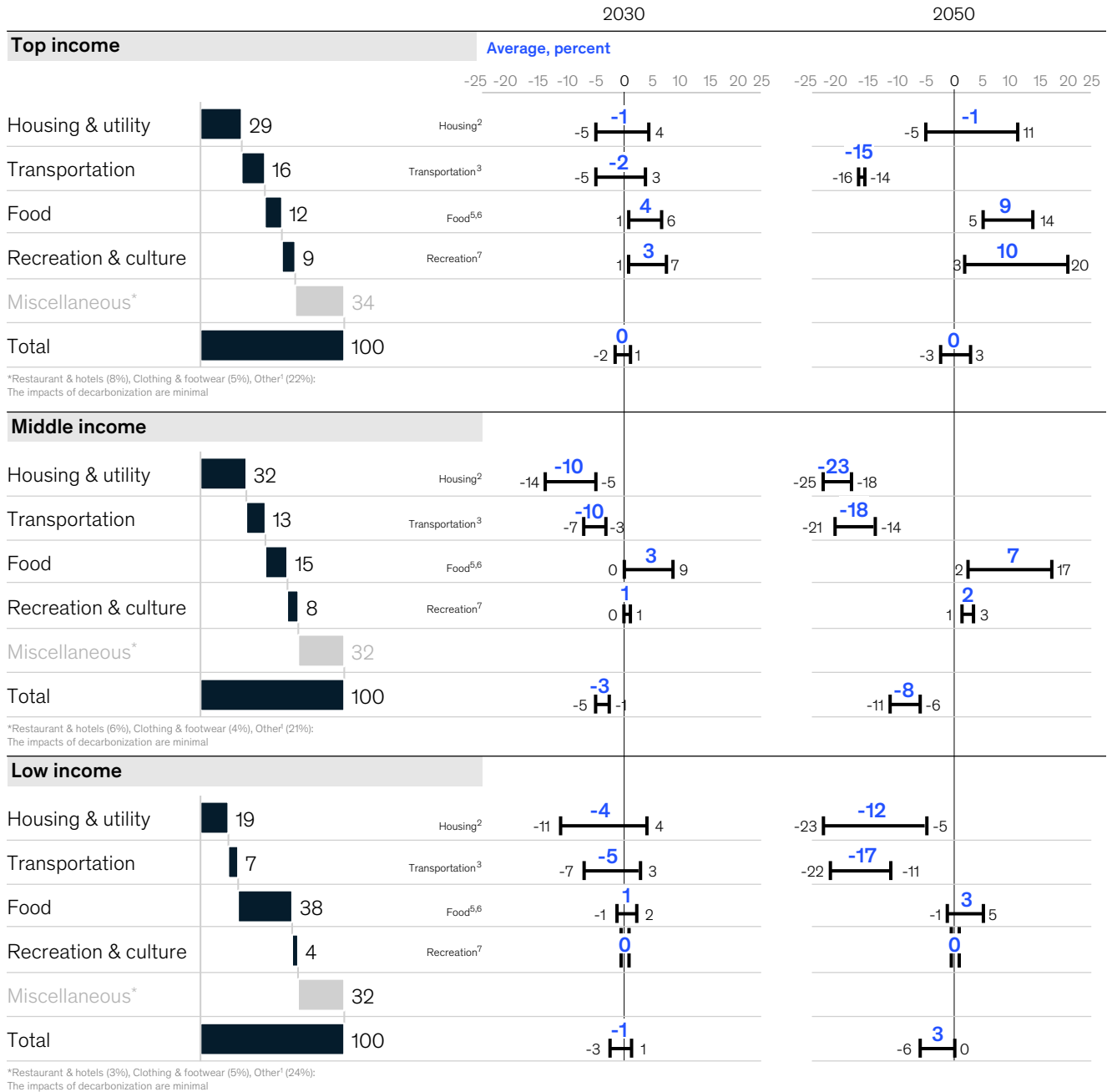


⁵⁷ Eric Hannon, Tomas Nauclér, Anders Suneson, and Fehmi Yüksel, ["The zero-carbon car: Abating material emissions is next on the agenda," McKinsey, September 18, 2020.](#)

Middle-income households would see the most economic benefits on the cost-optimal pathway to EU climate-neutrality.

Household expenditure breakdown
%, 2017

Decarbonization impacts¹
% changes to baseline year

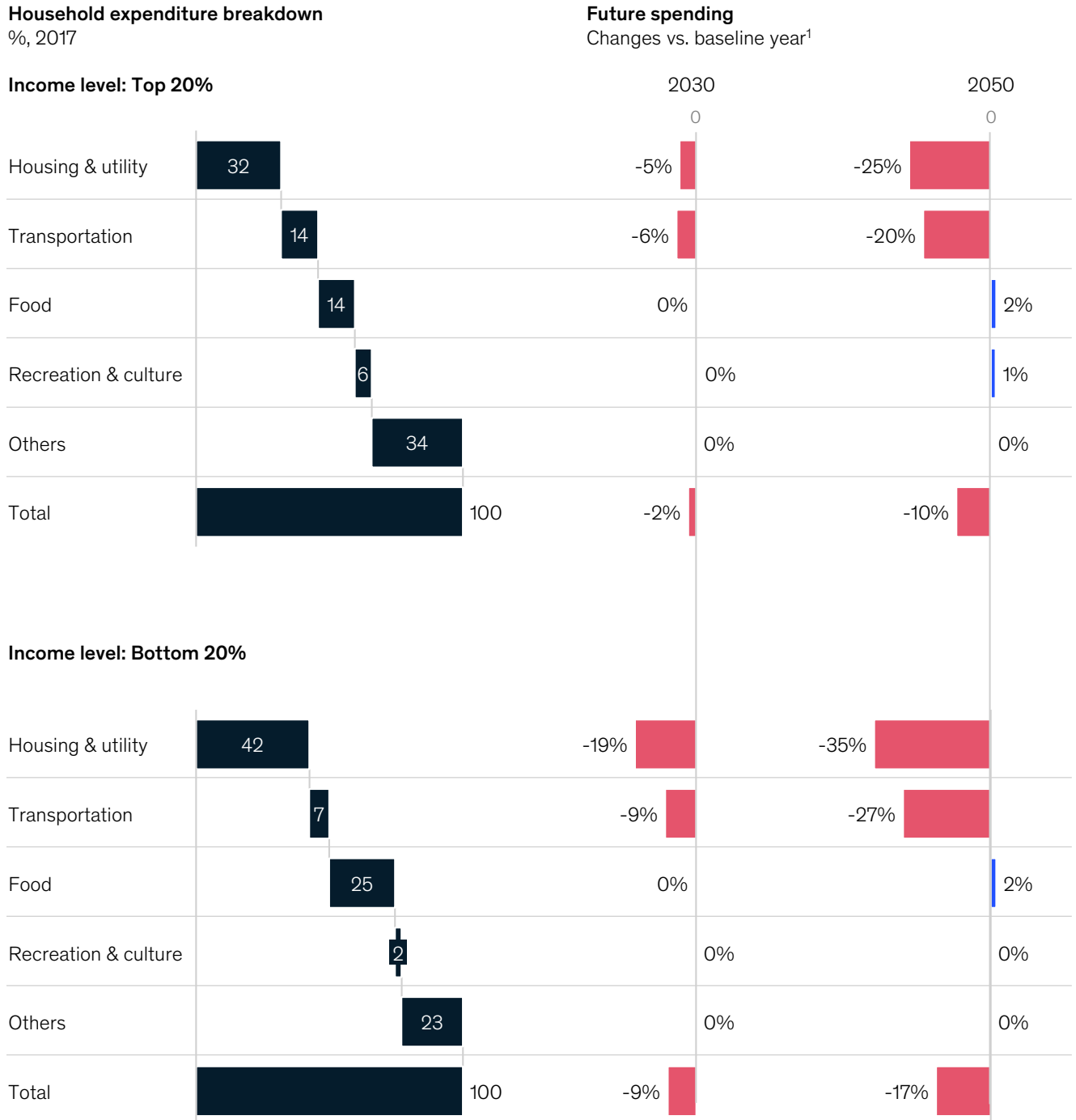


1. Assuming only the true costs are passed on to consumer, i.e. there is no additional mark up from the decarbonization costs
 2. Based on 2017 data, excluding ~5% spending in water
 3. For first decile bracket, transportation is only public transportations for countries with low or medium car ownership and 50/50 public transportation/car for high car ownership countries; for fifth decile, only public transportations for countries with low car ownership, 50/50 public transportation/car for medium ownership, and only passenger cars for high ownership countries; and for top decile, only passenger cars for countries with high or medium car ownership and 50/50 public transportation/car for low car ownership countries
 4. Based on data for Hungary, Poland, and Romania for first decile; Italy, Germany, and France for fifth decile; and Luxembourg, Ireland, and Denmark for top decile
 5. Only ~35% of food spending goes to the farmers and assuming 60% of food spending is for animal based products
 6. Excludes the impact of electrification of tractors
 7. For top income bracket, only international aviation (road transportation not included to avoid double counting); assume 50% of middle income bracket will also be affected and 0% for bottom income bracket
 8. For first decile and for France (data available for tenants),

Source: McKinsey, Eurostat

In certain countries, low-income households would see even greater economic benefits along the cost-optimal path to climate-neutrality.

Example country: Italy



1. Assuming only the true costs are passed on to consumer, i.e. there is no additional mark up from the decarbonization costs

Source: McKinsey, Eurostat

4.1.5 Stranded assets

One of the concerns about a net-zero transition is the risk of stranded assets, the forced retiring of assets like blast furnaces and coal plants before the end of their lifecycle.

However, our analysis shows that the risk of stranded assets in Europe's net-zero transition may be smaller than expected, with a total stranded asset value of €215 billion⁵⁸ (Exhibit 78).

Most of these stranded assets would be in the industry sector, amounting to €80 billion in assets in the iron and steel industries and €45 billion in oil refining. A large portion of asset stranding in iron and steel would happen before 2030 as manufacturers switch to hydrogen-based steelmaking to meet the 55 percent emissions-reduction target.

Towards 2040, changes to ethylene and ammonia production would result in additional stranded assets as conventional ethylene crackers and ammonia production facilities that rely on CCS are abandoned.

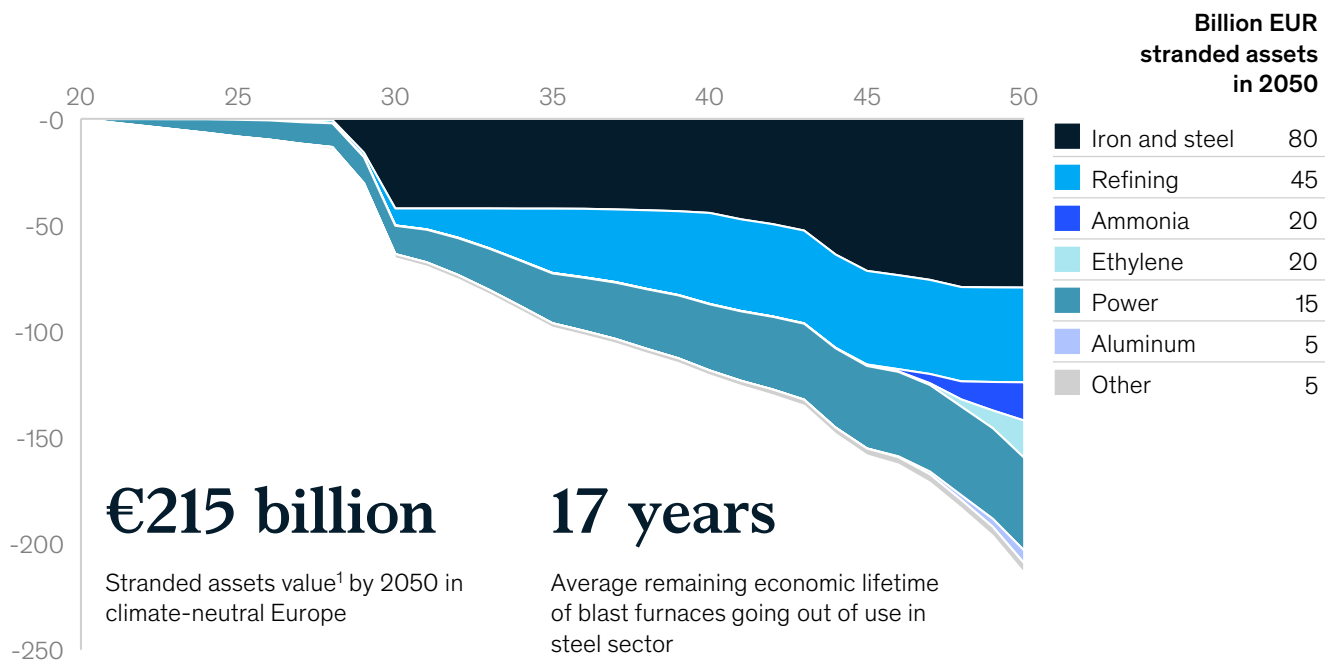
In the power sector, the early phase-out of coal power plants would result in €13.7 billion of stranded assets, equivalent to half a percent of total power investments over the next three decades.

⁵⁸ We calculate the 'stranded' value of prematurely retired assets by multiplying the share of remaining useful life at the point of retirement with the initial capital investment. For example, retiring an asset after 30 years that cost €50 million to build and would have a useful life of 50 years produces a stranded asset value of €50 million x (20 years/50 years) = €20 million.

Exhibit 78

The total value of stranded assets retired before the end of their lifecycle would reach €215 billion, mainly in the iron and steel and oil refining industries.

Cumulative stranded asset value in EU-27, Bn EUR



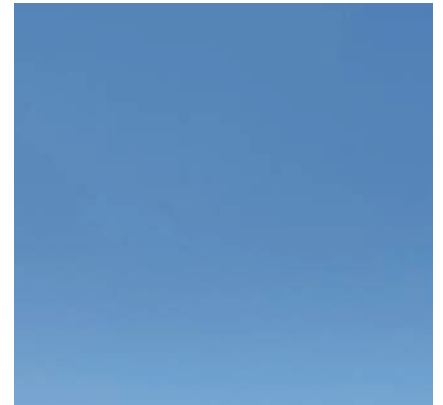
1. We calculate the "stranded" value of prematurely retired assets by multiplying the share of remaining useful life at the point of retirement with the initial capital investment. Stranded assets included in the analysis are production assets that are retired at some time prior to the end of their economic life

Source: McKinsey

4.2 Job gains and job losses

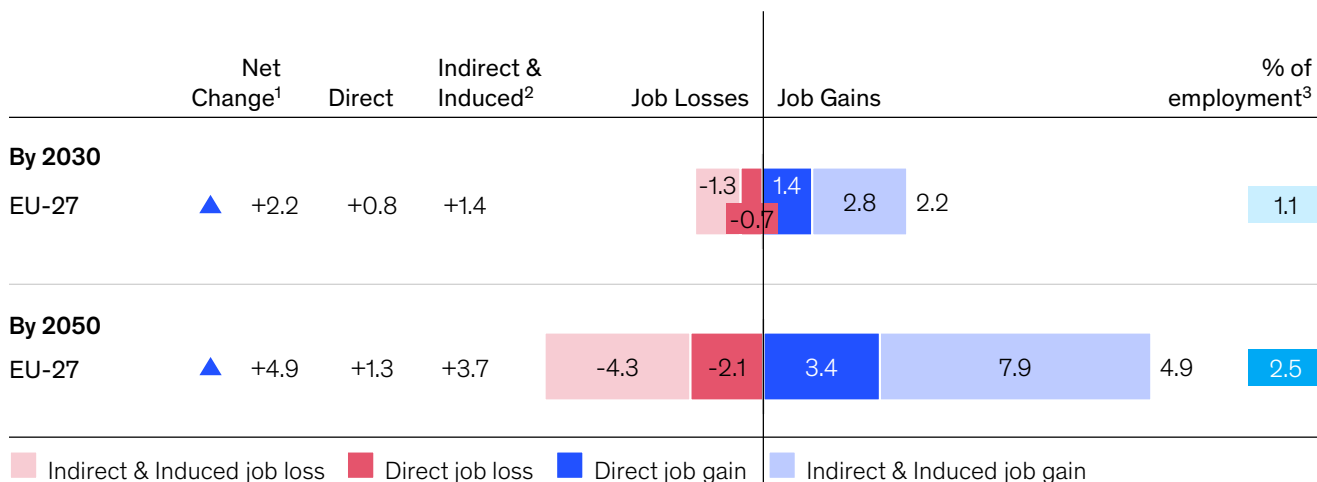
4.2.1 Emissions reductions would lead to 5 million more jobs

We estimate that the transition to net-zero emissions can create net job growth of 2.2 million by 2030, reaching 4.9 million by 2050, which represents a 1 percent increase in EU employment by 2030 and a 2.5 percent increase by 2050.

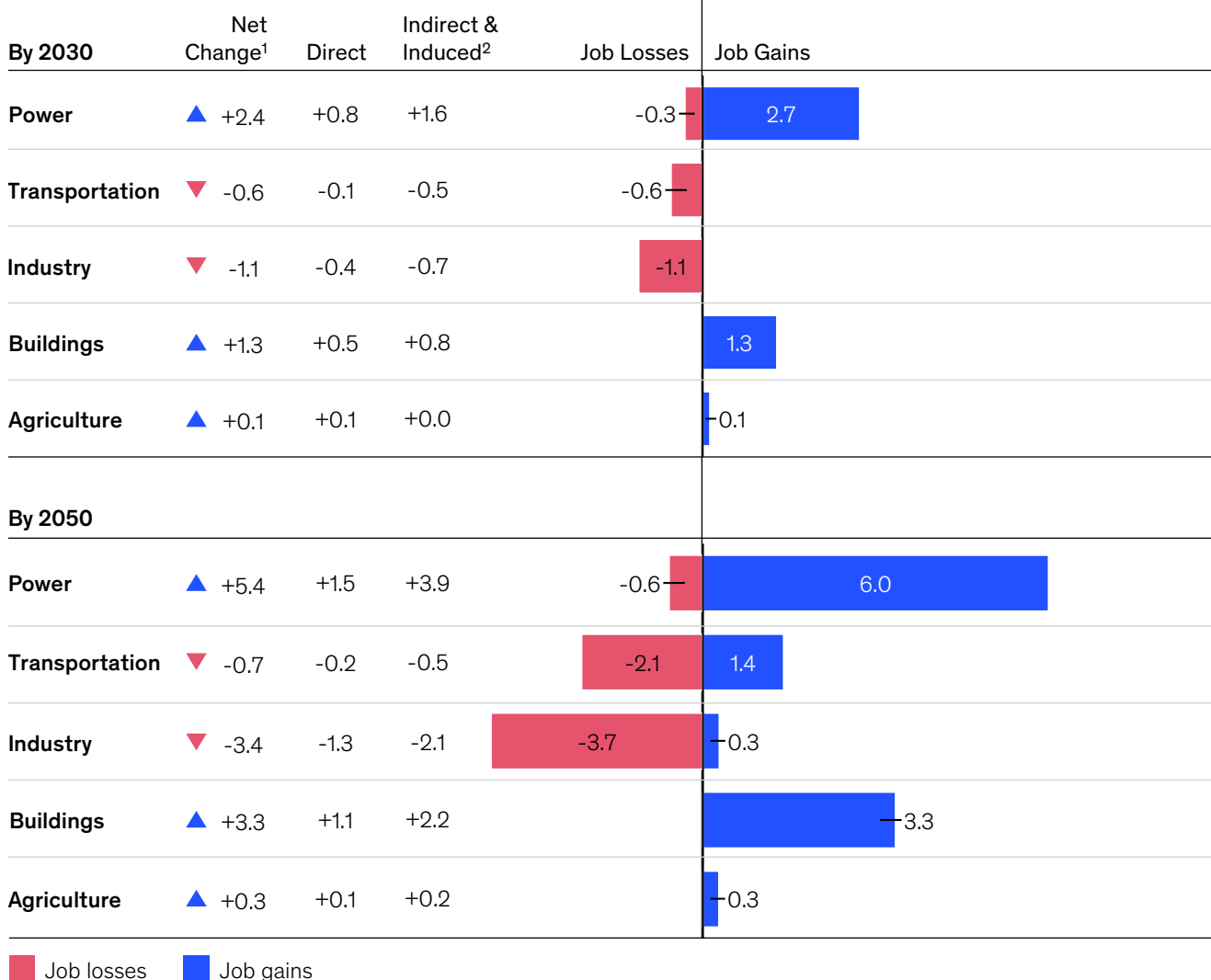


Net-zero emissions can create 2.2 million net jobs by 2030, and 4.9 million by 2050.

Millions of jobs, EU-27



Job gains and losses by sector



1. May not sum due to rounding. Numbers given in millions of jobs.

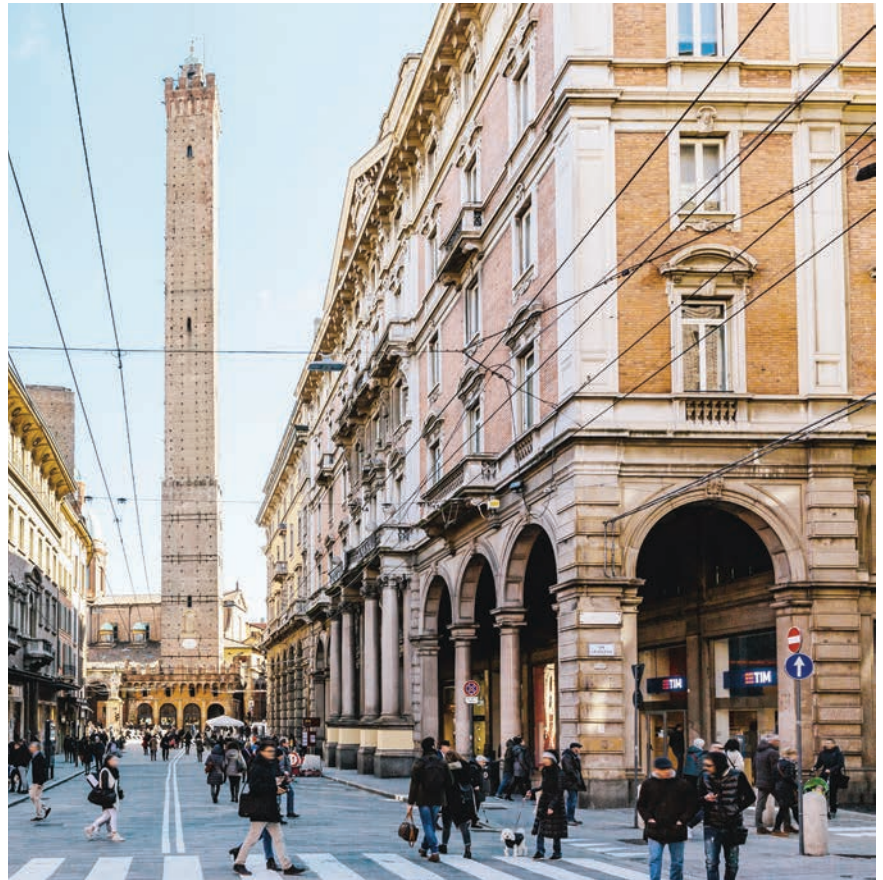
2. Indirect and induced jobs are mapped to the sectors that cause the indirect and induced jobs shifts but occur outside these sectors in the wider economy

3. Net change in direct, indirect, and induced jobs over total employment in 2019

Source: McKinsey

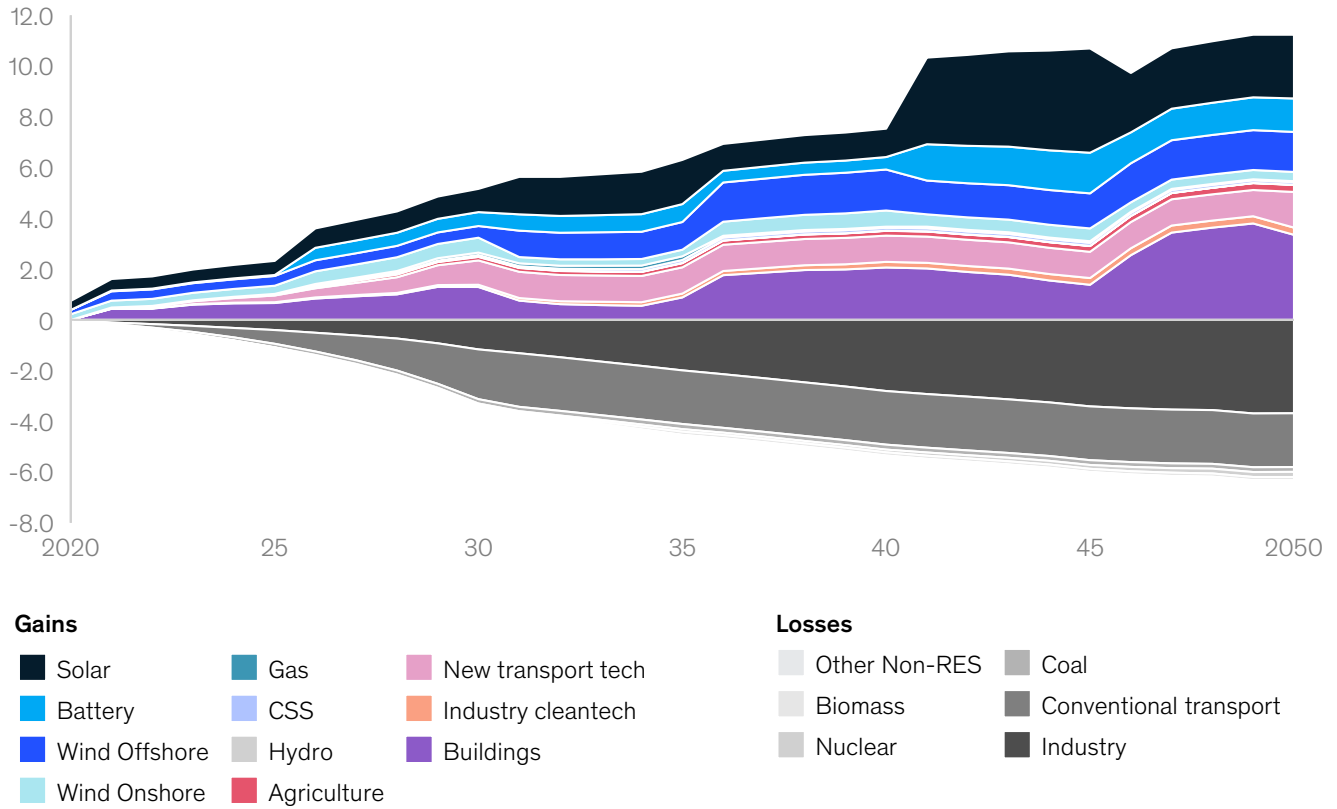
In the power sector, we estimate that 1.5 million new jobs would be added by 2050, including almost 700,000 jobs in solar power and 450,000 in wind power (Exhibit 79). About 70 percent of these new power jobs would involve manufacturing and installing green infrastructure, which could be considered temporary employment. However, these jobs would actually be de facto permanent, considering the steady increase in renewable-generation capacity over the next 30 years and the fact that most infrastructure must be replaced every 20 years.

Beyond the power sector, we expect to see 100,000 new jobs in the agricultural sector as farmers adopt new technologies such as anaerobic digesters, feed mix optimization, and greenhouse-gas-focused breeding. Retrofitting homes and commercial buildings with new green heating and cooking systems would create 1.1 million jobs in the buildings sector. In the automotive sector, we estimate a net loss of roughly 150,000 as manufacturing activity shifts away from current practices (Exhibit 80).

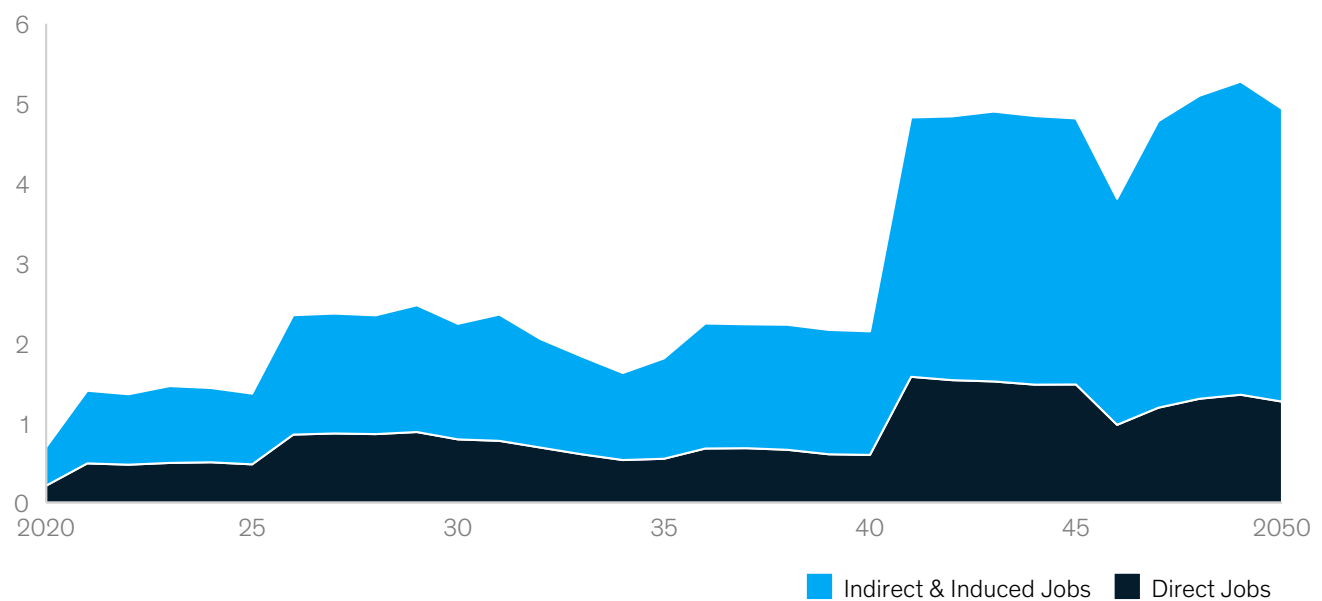


The EU would create approximately 11 million new jobs on the cost-optimal pathway to net-zero GHG emissions, but certain industries would experience job losses.

Total¹ job gains and losses by sector in EU-27
Millions



Net direct and indirect job change in EU-27
Millions



1. Direct and indirect jobs, with indirect jobs mapped to the sectors that cause the indirect jobs shifts, but occurring outside these sectors in the wider economy
Source: McKinsey

Regions may experience different levels of job displacement, but most would see net employment gains.

New job gains would be spread across and within countries, because many of the new jobs would be dispersed, such as those in building renovation and agriculture. However, some regions may experience some job losses, and there would be bigger shifts in areas with high concentrations of jobs in affected sectors. For example, many oil and gas jobs are concentrated in Benelux. Automotive manufacturing is prevalent in some parts of Germany but not others, and coal mining is prominent in Poland. These geographically concentrated job shifts are important to consider when addressing the socioeconomic impact of the transition.

Although the transition to net-zero would lead to some job loss, it would happen over 30 years, providing time to prepare. And some subsectors, such as mining, have older workforces that would be nearing retirement over this period. For example, we found that in Poland, the drawdown of the coal industry could be achieved without significant layoffs. Because of the coal workforce's advanced age structure, the workforce would naturally shrink faster due to retirements than because of decarbonization. So, the transition—if carefully managed—could be smoother than the numbers suggest. At the same time, it is important to look beyond the statistics and recognize that every job displacement may cause worry and hardship for those affected, no matter their number. Care needs to be taken to offer them support and create new opportunities.

Our analysis assumes that no production will shift outside the European Union's borders. Although it is possible that EU companies may fall behind overseas competitors during the course of the transition and thus lose domestic market share, this may not lead to significant job losses to overseas locations as production of most of the products and services in question would likely remain in the EU regardless of which company is producing them. That said, shifting jobs from incumbents to new entrants could lead to more extensive socioeconomic disruptions than workforce transformations occurring within organizations. On the other hand, value creation and employment could rise if products now imported began to be produced within the European Union.

4.2.2 Reskilling the workforce
Reaching net-zero could require skills training for up to 18 million EU workers.

Across the European Union, we expect to see 3.4 million new jobs by 2050 and 2.1 million job losses in the sectors directly impacted by the transition. For these new and lost jobs, workers will likely need reskilling or upskilling to obtain or maintain employment.

The European Union would see another 7.9 million in gains and 4.3 million in losses in sectors indirectly impacted by the transition. Those include suppliers to impacted sectors and more distant economic activities, such as restaurants that benefit from the patronage of employees in those impacted sectors. Although not all workers affected indirectly by the transition would require new training to

find employment, some, such as those working with new products and supply chains, would likely require additional education. In this context, the number of people needing reskilling could be larger than 5.5 million for those jobs directly impacted by the transition, and up to 17.7 million if we include new jobs and workers indirectly affected.

Although the projected job losses and reskilling requirements are significant, they are substantially smaller than those expected due to other trends such as automation, which we estimate would require reskilling more than 100 million workers by 2030.⁵⁹

The new green jobs would generally be higher-skilled positions such as installing solar panels, developing hydrogen fuel cell technology, and growing genetically modified organism (GMO) crops to feed livestock.⁶⁰ As a result, reaching the EU's decarbonization goals would require a more educated and higher-skilled workforce. To meet this demand, workers throughout the European Union will need greater access to training opportunities. When providing this skills training, governments and companies could take advantage of skills overlaps between different sectors, such as oil and gas engineers who can switch to developing offshore energy infrastructure. In industries where jobs require new skills, such as in green agriculture, governments may need to create dedicated training programs.

⁵⁹ Sven Smit, Tilman Tacke, Susan Lund, James Manyika, and Lea Thiel, "[The future of work in Europe.](#)" McKinsey Global Institute, June 10, 2020.

⁶⁰ Hauke Engel, Alastair Hamilton, Solveigh Hieronimus, and Tomas Naclér, with David Fine, Dickon Pinner, Matt Rogers, Sophie Bertreau, Peter Cooper, and Sebastien Leger, "[How a post-pandemic stimulus can both create jobs and help the climate.](#)" McKinsey, May 27, 2020.

4.3 Risks and opportunities in trade and production

4.3.1 The impact on fossil fuel trade balance and energy dependency

A potential shift away from fossil-fuel imports to zero-emissions technologies and raw materials

Between 2020 and 2050, oil, gas, and coal demand would decline more than 90 percent from 43 EJ to 3 EJ (Exhibit 81). It would remain primarily as feedstock in chemical manufacturing and reducing the fossil fuel trade deficit by two-thirds, from €180 billion a year today to about €65 billion a year by 2050.

Since current fossil fuel value chains and infrastructure are set up for ten times the volume needed in 2050, single-source supplier dependencies would likely be eliminated. For instance, natural gas demand would drop from roughly 400 billion cubic meters (bcm) now to 30 bcm in 2050. The current

import infrastructure has a capacity of over 700 bcm⁶¹, and domestic production from Norway is more than 100 bcm.

4.3.2 A potential shift in import dependencies from fossil fuels to zero-emission technologies and materials

While decarbonization would enable the European Union to move away from its dependence on fossil fuel imports, it could develop new dependencies on technology and raw materials imports that are vital to a zero-emissions economy.

By 2050, about 75 percent of the primary energy supply would consist of renewables, with electricity representing over 50 percent of the secondary energy supply. This could lead to a new type of import dependency. Today, more than 75 percent of all solar cells installed in

Europe are imported from China and other Asia Pacific countries.

Also, there are limited raw material supplies of the critical minerals for battery cell production, such as graphite, 70 percent of which comes from China. And iridium, which is required to produce hydrogen electrolyzers, currently has such a small volume on the world market that its price and availability could be volatile.

Solar PVs, Li-ion batteries, and electrolyzers are only three components that may be crucial to the energy transition. The availability of critical parts and materials would need to be monitored, and action would need to be taken when it's at risk.

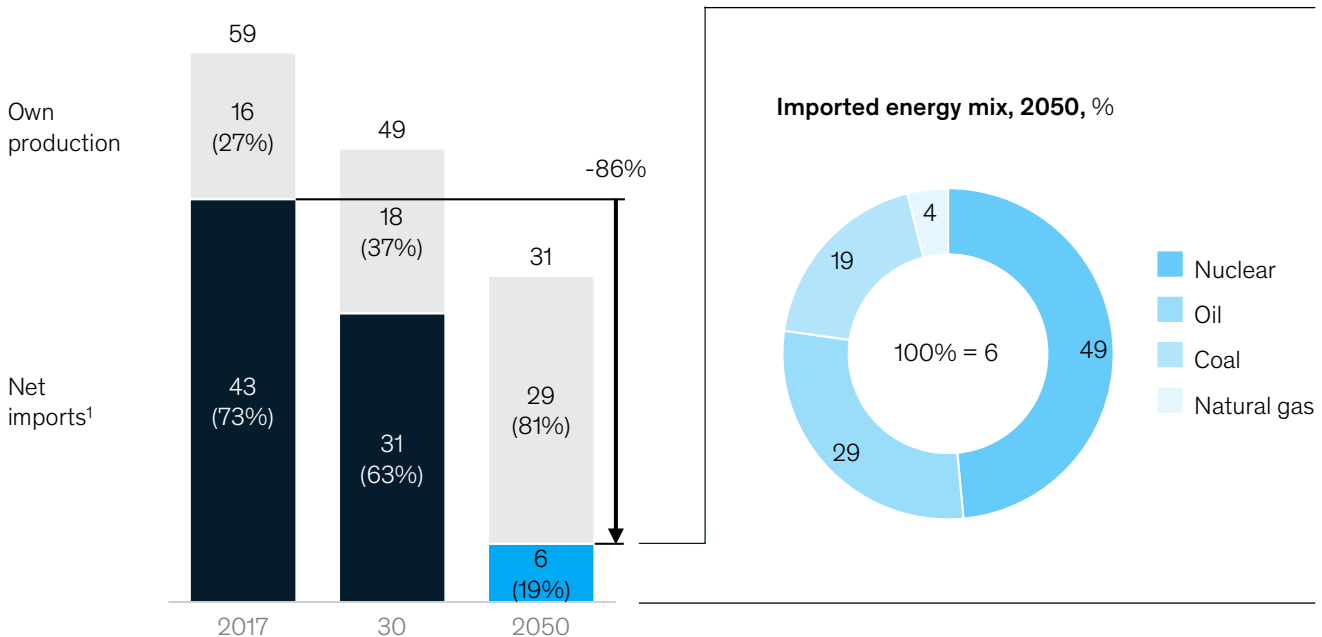
⁶¹ IEA: <https://www.iea.org/data-and-statistics/charts/average-capacity-utilisation-of-eu-natural-gas-import-capacity-2018>

Exhibit 81

On the cost-optimal pathway, the EU would import much less energy than it does now.

Million TJ

Trade balance of fossil fuels in 2017 and evolution under cost-optimal pathway in EU-27



1. Assumption: 85% of fossil fuels are imported by 2030; 100% by 2050. All nuclear remains imported

Source: McKinsey, UN Comtrade (2016)

4.3.3 EU production and exports

The transition to zero-emissions technologies could influence competitive dynamics and shift the EU import-export landscape. The rate of global innovation on decarbonization continues to accelerate, and the innovators are taking market share from those that fall behind. Navigating the transition and making the strategic and operational adjustments to thrive in a zero-emissions world is no easy task for many incumbents. This poses a risk for core pillars of European prosperity, such as the automotive sector. This risk is particularly relevant for markets of globally traded products in which the products or value chains are likely to be fundamentally transformed and where overseas competitors have a head start or structural advantages like low-cost labor.

At the same time, the European Union has an opportunity to accelerate R&D across sectors, become a leader in zero-emission technologies, and open new export segments. If the European Union takes a leadership position in decarbonization, it could give EU companies an advantage since they would have a large home market for zero-emissions products.

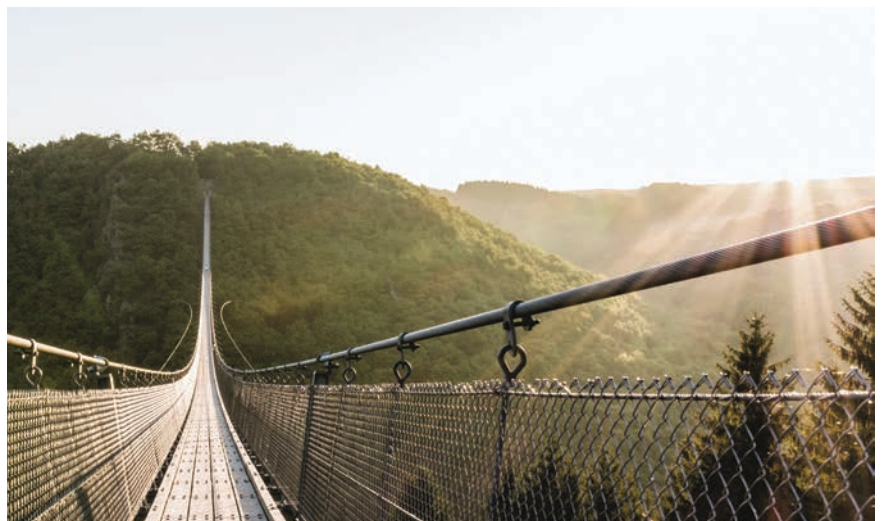
This could enable them to become global leaders in these products and, in turn, safeguard market shares in the European Union and important export sectors while unlocking new export opportunities. For example, we estimate that heat pumps, electric furnaces, electrolyzers, and zero-emission agriculture technologies could account for over €50 billion of exports by 2050. The following enablers are critical to sustaining and advancing Europe's competitiveness in zero-emissions products and services:

- *Extensive R&D spending*, including flagship research programs and specific financing schemes for a range of zero-emissions technologies.
- *A considerable pool of highly skilled employees* to enable the large-scale manufacturing of zero-emissions products. Examples include clean technology education and manufacturer-led apprenticeships supported by subsidized education.
- *Significant investments in automation and digital innovations* to maintain a cost-competitive technological advantage. This would require cross-sector learning to combine knowledge from different industries. For example, setting up open innovation labs where automation and digital players could co-develop solutions with manufacturers.

4.3.4 EU industrial topography

Local industrial clusters and ecosystems often emerge because of factors like lower transportation costs, the pooling of skilled labor markets, and the location of resources. For many subsectors, future energy and materials inputs will be different, particularly as hydrogen and renewable electricity replace fossil fuels. As the industrial metabolism shifts from fossil fuels to renewables, the European Union's industrial topography could also change.

For example, the locations of ammonia, steel, and ethylene production could change to take advantage of where hydrogen, CCS, or green electricity cost the least. We estimate that the total cost difference between the current location and that of lowest-cost inputs could be 2 percent for steel and up to 20 percent for ammonia production. However, other factors may inhibit relocation, such as the rest of the supply chain's aggregation or a historical affinity with a specific region or community.



5. Charting a way forward

Although 2050 seems far away, many of the decisions that consumers, business leaders, and policy makers make now will stay with us for years to come. Vehicles are driven for 10 to 15 years. Steel plants have lifetimes of 50 years or more. And the development and maturation of new technologies take time, as does building up and scaling new supply chains.

The European Union's decarbonization targets are ambitious, but as our analysis shows, they should be achievable and affordable. Success will depend on everyone taking decisive action while recognizing that time is of the essence. Five forces would help galvanize the kind of widespread action required to meet the decarbonization targets:

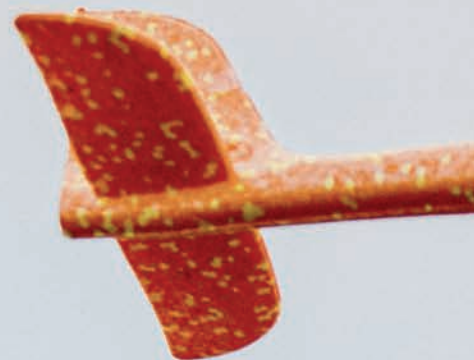
- **Shift social norms and consumer and investor expectations to zero-carbon as the new normal.** Consumers and business leaders would need to make decisions in the expectation and in support of a shift to net-zero instead of business-as-usual as the public and business default.
- **Create secure and stable policy frameworks and regulatory environments.** Successful decarbonization depends on public sector leaders who adopt robust regulatory frameworks proportionate to the emission-reduction goals rather than incremental policies. This would provide stable planning and investment signals that would provide incentives for low-carbon technologies and business models.

- **Encourage constructive industry dynamics.** Business leaders that lean into the transition and demonstrate a commitment to overcoming transition hurdles through collective action rather than worrying about first-mover disadvantages will be critical.

- **Mobilize green capital and investment.** Much more public and private money would need to be invested in precommercial technologies and rapidly deploying commercially mature infrastructure. Investors that provide ESG-aligned funding mandates that require businesses to quantify their exposure to climate risks and emissions could also play an important role.

- **Accelerate net-zero technologies along their learning curves.** Achieving the necessary technological breakthroughs to reduce emissions in hard-to-abate sectors and accelerating their progress to market would require consistent public and private investment. It would also require greater willingness among business leaders and policy makers to adopt new technologies.

The good news about creating an environment driven by these transition forces is that they build on and strengthen each other. For example, providing long-term regulatory signals would reduce the cost of capital for low-carbon investments and increase their competitiveness with fossil fuels. When consumers vote with their wallets and purchase low-carbon products such as electric cars and CLT, it accelerates their development. Overall, public support for green energy efforts speeds up political decision-making and the redeployment of business capital.

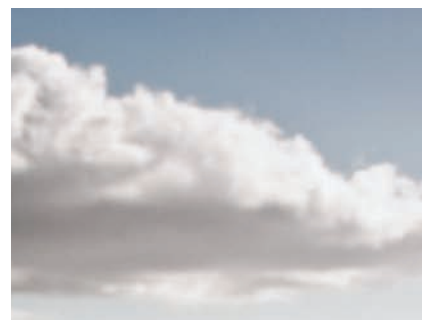




5.1 The time is now

In subsectors such as consumer electronics, technology cycles are fast, and development costs are typically relatively lower. But most new clean technologies require a substantial lead time and significant development investment. For example, large commercial aircraft designs can take 15 years from concept to certification.

The journey for any one technology from early-stage R&D and proof-of-concept to early deployment and commercial competitiveness requires a complex interplay of support models and stakeholders. The phase between government-supported R&D and commercial maturity, often called “the valley of death,” can be particularly challenging to navigate. The societal benefits of the new technology often cannot be fully captured by the innovator, who consequently cannot fully fund the scale-up.



Achieving net-zero emissions by 2050 hinges on the willingness of policy makers and business leaders to take the following actions now:

1. **Rapidly scale cost-competitive technologies and business models to reduce near-term emissions.**

Achieving near-term emission-reduction targets requires accelerating the scale-up of available mature and early-adoption zero-emission technologies. These include solar and wind power, EVs and charging infrastructure, better building insulation, and district heating systems.

2. **Accelerate next-generation technologies and invest in enabling infrastructure to allow emission reductions after 2030.**

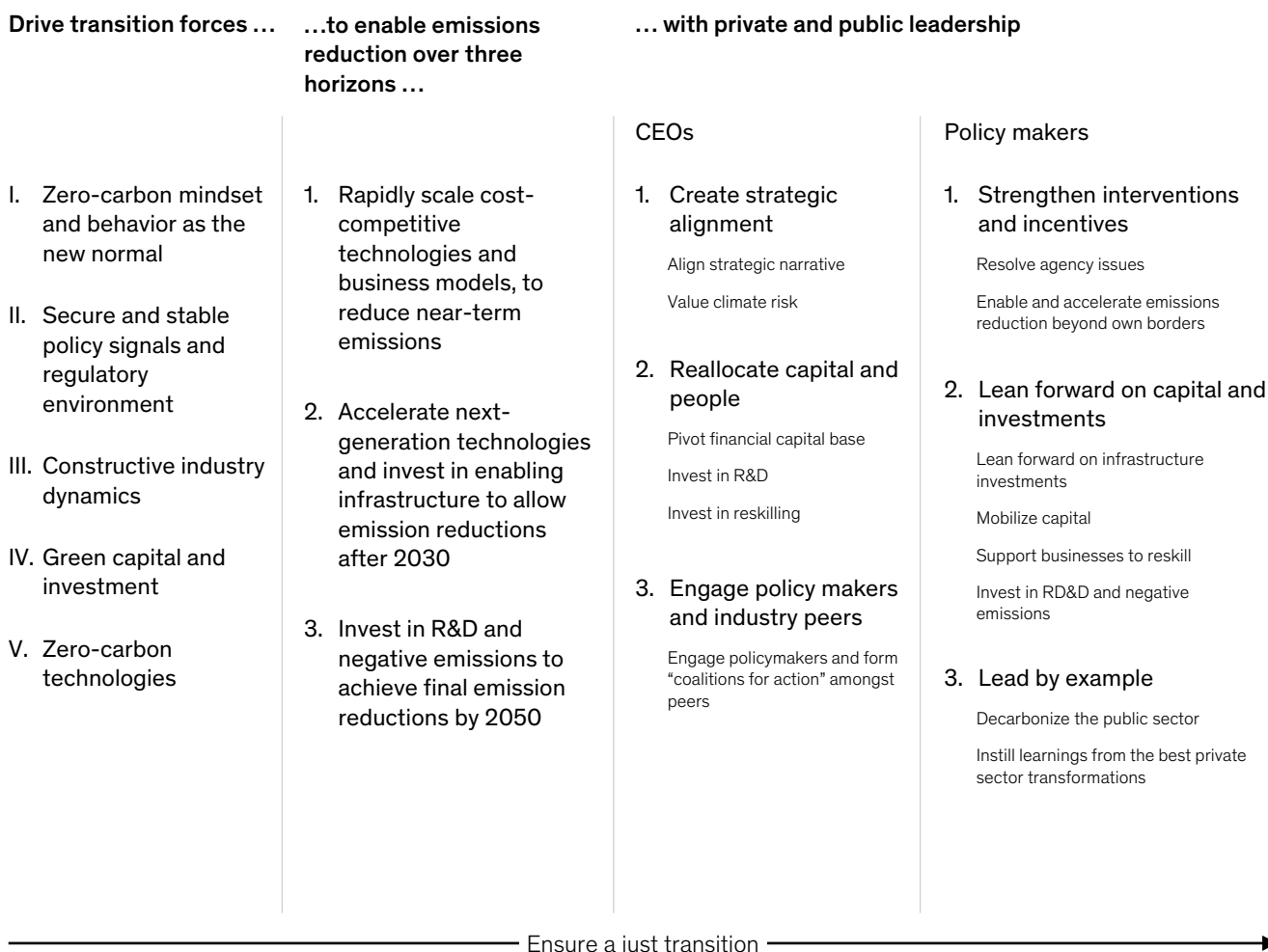
To boost industry-wide innovation, funding mechanisms for deploying early technology should encourage collaboration. Policy makers could create regulatory certainty, such as CO₂ and hydrogen price floors, to mobilize capital for essential infrastructure such as carbon and hydrogen pipelines.

3. **Invest in R&D and negative emissions to achieve final emission reductions by 2050.**

Increasing public and private investments in R&D will be critical to address the long-term needs for achieving net-zero, such as finding a way to drive down the costs of direct air capture technologies. It would also be essential to invest in reorganizing land use to generate negative emissions through reforestation. Lawmakers can also start passing legislation to make it easier for each sector to reach net-zero emissions, such as the automotive emissions standards now in effect in transportation.

Exhibit 82

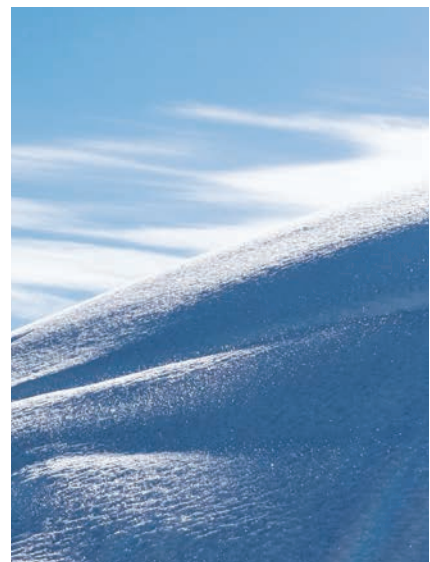
Meeting the EU's decarbonization targets would require decisive action from business leaders and policymakers.



Source: McKinsey

5.2 Critical players and actions to make change possible

Achieving net-zero within 30 years will require governments to set a clear direction and business to be the engine of innovation and delivery. In this section, we discuss the actions that private and public sector leaders could take to support reaching climate neutrality.



5.2.1 The role of CEOs

To thrive during the transition and shape it, CEOs could focus on three areas: creating strategic alignment, reallocating capital and people, and engaging with policy makers and industry peers.

1. *Create strategic alignment.*

Businesses face many uncertainties as they try to understand what the transition to net-zero would require of them. Although incumbents would need to drive most of the movement toward decarbonization, it's not easy to keep the legacy business running while also building a new business model. For example, profit margins for new products are often initially lower than legacy products. But leaders can embrace this as a challenge and make calculated bets on innovative product substitutes while building a strong narrative to bring employees, investors, and customers on board.

As leaders prepare to discuss green transformation with their boards and investors, it may help to quantify the potential costs of not addressing climate risks. These can be categorized into physical and transition costs and liability climate risks, which will differ in relevance under different macro scenarios. Leaders can analyze the physical impacts of climate change using tools that provide a geographic understanding of the likelihood that climate change could result in physical damage to the business. The transition risks are the stricter consequences that companies could face if they don't take action, such as regulators imposing more drastic measures to meet carbon budgets. This is sometimes referred to as "crash decarbonization," a scenario of more invasive regulation that results in much higher job losses and stranded assets. Another transition risk is that investors may sell their stakes to reinvest elsewhere, causing a rapid

devaluation of the business. Liability risks include litigation for climate change inaction.

2. *Reallocate capital and people.*

Investors may see lower value in capital stock and business models that aren't aligned with science-based carbon budgets, and most companies are not quick to reallocate capital.⁶² For companies that are slow to do it, the gap between management expectations and market valuation may grow. To keep this from happening, leaders can deploy proven strategies, including:

- Review the business from a zero-emissions budget perspective, determining where each ton of emissions adds the most business value ("Return on Carbon").
- Invest in gray-to-green transformations or greenfield capital formation.
- Scale new business models rather than focus on existing product lines and capabilities.
- Derisk capital investments through commercial, technical, and policy innovation, such as investments in electrolyzers combined with renewables to improve the price certainty for clean power.

To thrive in a zero-emissions world, companies would also need to build competitive positions in zero-emission technologies instead of focusing on prolonging their lead in traditional ones. This would involve investing in both midterm research, such as in lithium-air batteries, floating offshore wind, and perovskite tandem solar cells, as well as long-term research, such as direct air capture and storage and BECCS. In these endeavors, it would be vital to collaborate with the public sector through joint research agenda-setting and funding.

As for talent, the existing workforce may be well-suited to the zero-emissions transition. However, CEOs would need to reskill and redeploy this talent quickly. For example, they could shift capital project engineers to low-carbon projects now. They could also:

- Conduct workforce planning with long-term horizons driven by top management that considers reskilling, outsourcing, and replacing talent where necessary.
- Consider collaborating with others on reskilling, forming groups such as the UK's FutureNow program, a coalition of companies, educators, and charities that work together to develop digital talent.

3. *Engage policy makers and industry peers.*

Business leaders could consult with policy makers to determine what's required to accelerate decarbonization and how they can help meet climate targets. For example, transmission players could shape the investment environment to accelerate interconnector or offshore grid build-out to improve renewable power integration. And they can influence how environmental performance is measured and reported while setting the bar on reporting and disclosures. For example, leading banks have been defining what it means for financial institutions to align their investment portfolios with science-based targets and what data they need to measure this.

⁶² Yuval Atsmon, "[How nimble resource allocation can double your company's value.](#)" McKinsey, August 30, 2016.

4. To make their efforts and investments go further, business leaders can also form coalitions with peers at the industry- and value-chain level (“coalitions for action”) to take the following actions:

- Industry-level: Create critical mass demand for a decarbonized product such as green steel in the automotive industry, jointly shape regulation, agree on product standards to accelerate the industrial learning curve, and share information to track supply chain decarbonization.
- Value-chain level: Accelerate innovation and scale-up by encouraging value-chain partnerships and supporting global standards for things like hydrogen production and transport. This would help drive costs down the learning curve, provide the coordination required to stabilize and scale supply and demand together, while derisking infrastructure investments.

5.2.2 The role of policy makers

To reach net-zero, policy makers would need to create a business environment conducive to transitioning quickly to green energy. Shaping and managing the transition would likely require more policy intervention and stronger international cooperation than usual. Government officials could focus on the following three areas:

1. **Strengthen interventions and incentives.** Policy makers can influence the behavior of companies and consumers to reduce the overall cost of the transition. For example, switching to EVs and improving building energy efficiency is much more cost-effective than other decarbonization options. Policy makers could help accelerate their adoption through actions like extending subsidies, enacting stricter emission standards, and creating regulatory backstops such as banning sales of ICEs after a specific date.

In each sector, policy makers can set targets that are aligned at a granular level to meet the interim targets per year. These targets could complement the traded carbon markets; although these carbon markets already provide some encouragement, carbon prices can provide insufficient incentives to mobilize investments in hard-to-abate sectors. Carbon price volatility also does not give assurance to making capital investments over decades.

For example, policy makers could set volumetric targets for consumption of hydrogen in steel, chemicals, and power sectors. These volumetric targets would be directionally consistent with the lowest cost pathway. Alternatively, government could procure low-carbon hydrogen at reverse auctions and create the marketplace for this supply within prioritized hydrogen hubs. This “clearinghouse” matches supply and demand for industries, and the competition for clean hydrogen volumes supports a market price for long-term (~10 years) hydrogen contracts. The gap between the reverse auction costs and revenues in the clearinghouse equals the subsidy that is required that year. Similar to the impact of feed-in tariffs and reverse auctions in the renewable power sector, as technology costs come down, the subsidy requirements reduce. We estimate €60 billion will be required to bridge the economic gap for hydrogen consumption in transport, industry, and buildings through 2050.

While providing certainty through such volumetric targets per subsector, policy makers can still check and adjust to create an agile policy as technology costs change and the preferred pathways per subsector become more certain over time.

It’s also essential for policy makers to strengthen international cooperation to decarbonize the aviation and shipping industries with measures such as harmonized technology standards and refueling infrastructure at airports and harbors. This cooperation would also be necessary for accelerating decarbonization beyond the EU’s borders in other sectors. The potential for international friction through policies such as carbon border adjustment mechanisms could be reduced by approaching climate issues collaboratively, such as forming working groups of importers and exporters.

Along the way, policy makers would need to monitor technological development and adjust industrial policy accordingly. The stakes of intervention would be higher than ever, and these interventions require greater collaboration with the private sector.

Throughout this process, policy makers would need to address any agency issues that slow decision-making. For example, landlords may not invest in making their buildings more energy-efficient if they can’t share the resulting cost savings with tenants.

2. **Lean forward on capital and investments.** Infrastructure will be critical for decarbonization, whether it’s creating new power interconnectors or developing ways to capture and sequester CO₂. Having the right infrastructure in place is a common challenge among businesses that is often too risky for private investors to tackle. In the next decade, policy makers can remove these hurdles by forming public-private partnerships to build the necessary energy transition infrastructure.

Policy makers can also help mobilize capital for these kinds of initiatives by removing process barriers that introduce costs, standardizing contracts, providing carbon price floors, providing public guarantees, and offering tax incentives. Banks, regulators, and supervisors can play a role in creating stable and favorable frameworks for green financing.

Policy makers could provide transparency through midterm (2030) and long-term (2040+) infrastructure master plans for energy-transition infrastructure and appoint a central orchestrator to organize and oversee industrial clusters. To accelerate the implementation of these master plans, policy makers could support regulated infrastructure returns for new energy transition infrastructure such as feedstock collection, storage infrastructure, or new hydrogen and CO₂ pipelines.

Policy makers can also support businesses in reskilling their workforces. For example, the Austrian government funds nearly 70 percent of skills training for employees at smaller companies that form cooperatives of at least three companies for training. Similarly, the Netherlands provides tax credits equal to the amount for companies to spend on reskilling.

Policy makers can also play a role in increasing public investment in R&D to pursue breakthrough technologies that could reduce the cost of decarbonization. They would need to help reorganize land use to generate negative emissions at scale and create legislation to make it easier for sectors to reach net-zero.

3. **Lead by example.** Government leaders can spark change in the broader economy by modeling the necessary changes while creating a steady demand for sustainable solutions for the government's own use. For example, the Irish government backed its ambitious 10-year decarbonization plan by setting two targets for itself: to reduce its emissions by at least 30 percent and improve its energy efficiency 50 percent by 2030.⁶³ The actions for achieving these goals include retrofitting school buildings built before 2008, providing behavioral change training to its workforce, increasing afforestation rates to an average of 8,000 hectares per year, and evaluating suppliers against sustainability criteria.⁶⁴

Like Ireland, national governments throughout the European Union can develop detailed climate plans with clear timelines and targets. To establish accountability, the entire government would align around these goals. For example, prime ministers and cabinet ministers can work together to lead the day-to-day implementation of the plans. Delivering this kind of societal transformation will only be possible if the public sector accounts for the interconnections between its infrastructure, employment, environment, and economy in the design.

5.2.3 No one left behind

Although the transition to net-zero could be cost neutral at an aggregate level, it would impact some people more than others. For example, energy tax hikes would create more hardship for low-income households than those with higher incomes. Reskilling efforts would involve front-line workers much more than white-collar colleagues. These socioeconomic disparities would need careful management.

The opportunity to make decarbonization easier and more affordable for everyone extends beyond EU borders. The European Union could help other countries transition to net-zero and make development support contingent on it being used for zero-emission objectives. At the same time, EU leaders can work with the rest of the world to ensure that the transition benefits everyone while reducing global emissions.

□ □ □

Climate change is a critical global challenge. As this report has shown, the European Union has an opportunity to take a leadership position and achieve net-zero emissions without compromising prosperity. Advances over the last decades have put climate neutrality within reach. Laying the foundation in the next decade will be critical to achieving this goal.

⁶³ ["Climate Action Plan 2019 Annex of Actions," Government of Ireland, July 2019.](#)

⁶⁴ ["Climate Action Plan 2019 Annex of Actions," Government of Ireland, July 2019.](#)

6. Technical appendix

Modeling methodology

To determine our cost-optimal pathway to net-zero emissions, we used two McKinsey optimization tools: the Decarbonization Pathway Optimizer (DPO), which models industry, transportation, buildings, and agriculture, and the McKinsey Power Model (MPM), which models power and new fuels, particularly hydrogen. Both represent the possible combinations of technologies in each of their respective sectors and assume continued economic activity and growth, for example, in tons of steel produced or passenger kilometers traveled. Then they optimize for the lowest system cost while achieving the EU emissions reduction targets. The resulting pathways thus represent the minimal cost route to climate neutrality. No co-optimization was done, for instance, on GDP. Nor were any benefits of decarbonization, such as reduced physical hazards, included in the optimization.

We included more than 600 different business cases for technologies and techniques in the modeling. These range from conventional technologies, such as ICE long-haul trucks and natural gas furnaces for industrial heating, to technologies still under development, such as hydrogen trucks and electric furnaces. For new technologies, uptake rates were constrained by when products should first come to market and how fast their chains could reasonably ramp up. The resulting pathway provides a technology-by-technology outlook of

how the European Union could achieve climate neutrality.

Various cost outlooks for commodities and technologies were defined. For fossil fuels, we assumed prices to remain close to current levels going forward. No price impacts of supply shocks due to rapidly falling oil demand were included. Power and hydrogen prices were dynamically modeled in the MPM and used as input for the demand sectors in the DPO. The capital cost reductions for some critical technologies such as electrolyzers and batteries were defined based on the learning rate; the faster electrolyzers are rolled out at scale, the faster they can decline in cost. Our cost outlooks for such technologies assumed that the rest of the world scales up their decarbonization efforts, helping drive adoption and the associated downward pressure on costs.

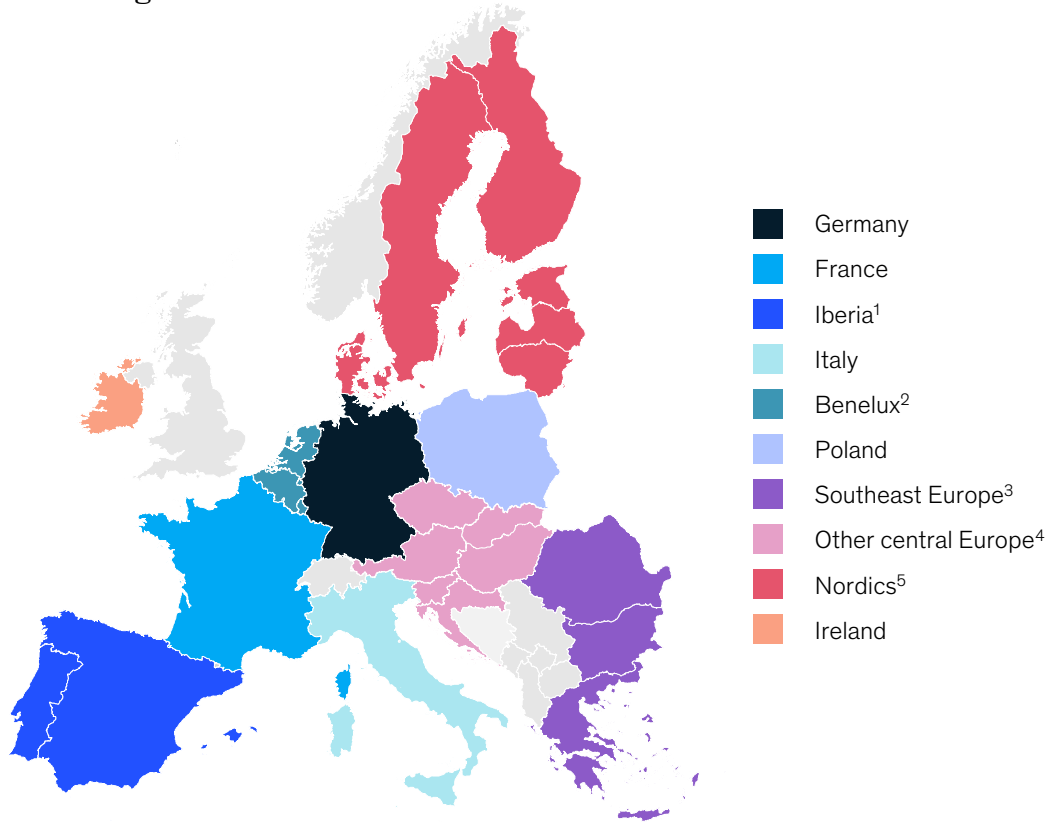
The optimization minimizes the societal cost of the transition. Therefore, cost calculations do not include money transfers between EU actors. For instance, we did not include profit margins that one EU player, such as a large hydrogen producer, may charge a trucking company. Such transfers are zero-sum in the European Union and not a net cost to society. Similarly, we did not use different costs of capital for sectors or technologies, as capital returns are also money transfers, not net costs. The cost optimization was done at a societal discount rate of 4 percent. Cost data in this report, unless otherwise indicated, is shown using the same 4 percent discount rate.

To express volumes of different greenhouse gases using a common metric, we used metric of tons of CO₂ equivalent (CO₂e). Different greenhouse gases have different impacts on global warming. CO₂ can remain in the atmosphere for decades, while methane has a much stronger warming effect but a half-life of only 12 years. It is not obvious how much methane abatement is equal to abating a gram of CO₂, since the average global warming potential of methane is much higher over a 20-year period than over a 100-year period. To translate methane and other GHG emissions to CO₂, therefore, requires setting a common timescale. The European Union uses the 100-year global warming potential for all greenhouse gases, and so we adopted this to aid comparability.

EU regions in the report

For this report's modeling effort, we split the EU-27 into 10 regions (Exhibit 83). Region splits were informed by how geographic differences could impact local pathways. For instance, different climates can lead to different costs of wind or solar power, or heat demand in buildings, which are key to pathway choices.

We modelled ten regions in the EU-27.



1. Spain & Portugal
2. Belgium, Luxembourg, Netherlands

3. Bulgaria, Greece, Romania
4. Austria, Croatia, Czech Republic, Hungary, Slovakia, Slovenia

5. Denmark, Estonia, Finland, Latvia, Lithuania, Sweden

Source: McKinsey

Financing analysis methodology

The cost-optimized decarbonization pathway takes a societal perspective, as reflected in our societal discount rate of 4 percent. This is in the middle of the range used by different economists and organizations. For example, The Stern Review on the Economics of Climate Change published in 2006, argues that discounting should incorporate an ethical aspect and uses a rate of 1.4 percent while suggesting that even a zero rate may be appropriate.⁶⁵ On the other hand, some think tanks suggest rates up to 7 percent.⁶⁶ However, recent studies suggest that economists are increasingly comfortable using low discount rates for climate change analyses.⁶⁷

The low discount rate, which may be the right one from a societal perspective, favors options with high capital investments. But the cost of capital for individuals can be higher and they may expect shorter payback periods, leading to higher effective discount rates. For example, under a TCO perspective, to switch to a medium-size electric car in the next few years is economically reasonable. However, many individuals are more focused on upfront cost, and thus the effective discount rate can be higher and delay the decision to switch by many years.

We have reflected the limitations of the societal discount rate for individual decision-making in our modeling. For the analysis of financing needs, we recalculate the business case using an individual's discount rate for each sector and segment. We then split technology switches based on their abatement cost. Technologies with a cost below zero are considered standalone. That is, if a decision-maker is entirely rational, the switch to this technology should happen without intervention. For example, a fleet owner switches to hydrogen-fueled trucks as soon as it becomes profitable. Technologies with an abatement cost above zero do not have a standalone business case, for example, replacing an affordable gas furnace with an expensive heat pump. These technologies require some form of regulatory or financial intervention. The financing needed for these interventions is calculated as the total financing to bring the abatement cost to zero over the lifetime of the technology.

Household spending methodology

The income analysis model provides an overview of the potential impact of the EU decarbonization pathway on consumer prices by region, income bracket, and purchase sector for the years 2030 and 2050. The main inputs for the model are:

- Capital and operating expenditures for the main household spending categories from the decarbonization pathway model
- Household spending per country by spending category from Eurostat
- Household spending per country by income bracket and spending category from national statistics agencies
- Categorization of car ownership, used to divide transport costs between cars and buses, from the European Environment Agency

The analysis does not take into account potential costs such as road taxes or increased costs for companies' branding or marketing.

The splits between low-, medium- and high-income groups are based on income deciles for groups of countries with similar average incomes. The low-income first decile is based on data for Hungary, Poland, and Romania; the medium-income fifth decile is based on Italy, Germany, and France, and the high-income top decile is based on Luxembourg, Ireland, and Denmark.

⁶⁵ Simon Evans, Roz Pidcock, and Sophie Yeo, "[The social cost of carbon](#)," Carbon Brief, February 14, 2017.

⁶⁶ David Kreutzer, "[Discounting climate costs](#)," The Heritage Foundation, June 16, 2016.

⁶⁷ The results of a survey of economists published in 2015 indicate that more than three-quarters of the 200 experts were comfortable with a median discount rate of 2 percent.

While different income brackets would see different distributions of household spending between categories, some of the largest differences can be expected in transport. Therefore, for the first decile, transport is assumed to be exclusively public in countries with low or medium car ownership and 50-50 public versus car for countries with a high proportion of car ownership. For the fifth decile, we assume solely public transport for countries with low car ownership, 50-50 public versus car for medium ownership, and solely passenger cars for high ownership countries. For the top decile, we assume solely passenger cars for countries with high or medium car ownership, and 50-50 for low car ownership countries.

Jobs analysis methodology

The direct and total job impacts are derived by applying regional, industry, and process-specific jobs multipliers to: 1) the additional supply (and the technologies of supplying) different goods and services in a decarbonization scenario relative to the baseline in McKinsey's DPO model, and 2) forecasts of the installed capacity of different energy-generation technologies in a decarbonization scenario relative to the baseline from the MPM.

Forecast volumes of goods and services across 10 regions of the EU-27 from 2017 to 2050 are generated by the DPO model. To estimate the jobs impact of decarbonization, industry and country-specific multipliers from McKinsey's Economics Analytics Platform (EAP) are applied to the difference in gross output supply for each good and service. Ratios of the differential impact on jobs of creating a green or brown good or service via a specific production method are estimated for each good. These "green multiplier ratios" are applied to the EAP multipliers and the differences in gross output supply to yield the impact of decarbonization on jobs.

For the power sector, the DPO power model provides forecasts of the installed capacity by energy source across 10 regions of the EU-27 from 2017 to 2050. Jobs multipliers, in terms of direct jobs per megawatt (MW), are derived from a literature review. Multipliers for operations and maintenance and fuel are applied to the annual changes in installed capacity to calculate the effect on permanent jobs. To calculate the effect on temporary jobs, multipliers for commercial and industrial and manufacturing are applied to the changes if they are positive. If negative, decommissioning multipliers are applied. To calculate the indirect and induced employment impacts, ratios between direct and total multipliers from McKinsey's EAP are applied to every industry and region. These direct effects are translated to estimated indirect and induced effects using historical ratios for each industry.

7. Acronyms


ATR	Auto-thermal reformer	GWP	Global warming potential
BECCS	Bioenergy with Carbon Capture and Storage	HEV	Hybrid electric vehicle
BEV	Battery electric vehicle	HVDC	High voltage direct current
bcm	Billion cubic meters	IATA	International Air Transport Association
CAP	Common Agricultural Policy	ICE	Internal combustion engine
CAPEX	Capital expenditure	IMO	International Marine Organization
CCS	Carbon capture and storage	IoT	Internet of Things
CCU	Carbon capture and utilization	IPCC	Intergovernmental Panel on Climate Change
CLT	Cross-laminated timber	kW	Kilowatt
CNG	Compressed natural gas	kWh	Kilowatt-hour
CO ₂	Carbon dioxide	Li-ion	Lithium-ion
CO ₂ e	Carbon dioxide equivalent	LNG	Liquid natural gas
COVID-19	Coronavirus disease 2019	LULUCF	Land use, land-use change, and forestry
CRISPR - Cas9	A gene-editing technique	MaaS	Mobility as a shared service
DERMS	Distributed energy resource management systems	Mha	Megahectares
DPO	McKinsey Decarbonization Pathway Optimizer	MPM	McKinsey Power Model
DRI-EAF	Direct reduced iron in the electric arc furnace	Mt	Megaton
EAP	McKinsey's Economics Analytics Platform	MtCO ₂ e	Megaton of carbon dioxide equivalent
EC	European Commission	MW	Megawatts
EJ	Exajoules	NECP	National energy and climate plans
ENTSO-E	European Network of Transmission System Operators for Electricity	OEM	Original equipment manufacturer
EPBD	Energy Performance of Buildings Directive	OPEX	Operating expense
ESG	Environmental, social, and corporate governance	PHEV	Plug-in hybrid electric vehicles
ETS	Emissions Trading Scheme	PV	Photovoltaic
EU	European Union	SMR	Steam methane reformer
EV	Electric vehicle	T	Ton
FCEV	Fuel cell electric vehicle	tCO ₂ e	Ton of carbon dioxide equivalent
GDP	Gross domestic product	TCO	Total cost of ownership
GHG	Greenhouse gas	TJ	Terajoules
GMO	Genetically modified organism	TSO	Transmission system operators
Gt	Gigaton	TW	Terawatt
GtCO ₂ e	Gigaton of carbon dioxide equivalent	TWh	Terawatt-hour
GW	Gigawatt	VR	Variable rate
GWh	Gigawatt-hour	WACC	Weighted average cost of capital

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