Carbon-neutral Poland 2050

Turning a challenge into an opportunity

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Turning a challenge into an opportunity

By Hauke Engel, Marcin Purta, Eveline Speelman,
Gustaw Szarek, and Pol van der Pluijm

Preface

Over the past decades, Poland has taken steps toward one of the most profound changes in its history: the transformation of the energy system. Poland, with average GDP growth of around 4 percent a year[1] over the past three decades, has successfully decoupled economic growth from emissions.[2]

However, the transition path will be challenging. The country is not blessed with rivers that could support extensive hydro generation, and it has only 1,400 to 1,900[3] sunny hours a year (half of what California enjoys). Natural gas is scarce, and geopolitical factors make it difficult to import it at a sustainable scale. The Baltic Sea provides an opportunity for offshore wind generation in the north, but high-consumption areas are located in the south of the country. Also, Poland does not have a single nuclear-power reactor (in contrast to other post–Eastern Bloc EU members such as Bulgaria, Czech Republic, Hungary, Romania, and Slovakia). What Poland does have are coal-fired power stations progressively depleting coal reserves, and a huge agricultural sector.

However, the path to decarbonization is more urgent than ever as the window to keep global warming below 2°C narrows. To become a net-zero-emissions economy by 2050, the year of EU emissions targets and the primary reference year in the Paris Agreement, Poland will have to triple its rate of decarbonization over the next decade compared with the previous 30 years. It must then further accelerate from 2030 to 2050.

Although subject to uncertainty, the transition to carbon neutrality is estimated to require additional investments of €10 billion to €13 billion a year, or 1–2 percent of GDP, for the next 30 years. Raising and investing that amount of capital in a highly coordinated fashion would be a considerable challenge for the country's government and business leaders.

At the time of publication, global attention is focused on countering the spread of COVID-19, and on blunting the force of slowdown that is likely to follow. The exact short-term impact of the crisis is as yet unknown. However, it is not expected to change the fundamental structure of the Polish economy or the available decarbonization technologies. Therefore, in this report, it is reasonable to still base our decarbonization scenario on pre-COVID-19 business activity and growth dynamics.

This report does not aim to predict the future. Rather, it outlines a pathway for the Polish economy to decarbonize in the most cost-efficient way. We investigate the actions and investments required and identify opportunities for the economy to benefit from. We hope our work will serve as a fact base for an informed debate on how to make decarbonization a reality—within and outside of Poland, where the pathway could serve as an inspiration for other countries facing significant decarbonization challenges.

This pro bono effort reflects McKinsey's deep commitment to the development of Poland's economy and its success in the international arena. The study develops the arguments presented in our earlier reports, including *Poland 2030: A chance to join the economic big league*, *Developing offshore wind power in Poland: Outlook and assessment of local economic impact*, and *Poland 2025: Europe's new growth engine*.

In the development of this report and its insights, we have worked extensively with, among others, McKinsey's sustainability insights, global energy perspective, sustainability practice, automotive practice, and the McKinsey Global Institute. In particular, we want to thank Dickon Pinner and Thomas Vahlenkamp for their leadership and insights.

In addition, this report would never have been possible without the input and expertise drawn from a broad spectrum of stakeholders, including leaders from public institutions, academia, nongovernmental organizations, conservation organizations, and industry players. In particular, The Woods Hole Research Center (WHRC), in collaboration with The Nature Conservancy, evaluated the carbon sequestration potential of Poland's forests and soils for this report.

We would like to take this opportunity to thank all of them for their invaluable input.

Hauke Engel, Marcin Purta,
Eveline Speelman, Gustaw Szarek,
and Pol van der Pluijm

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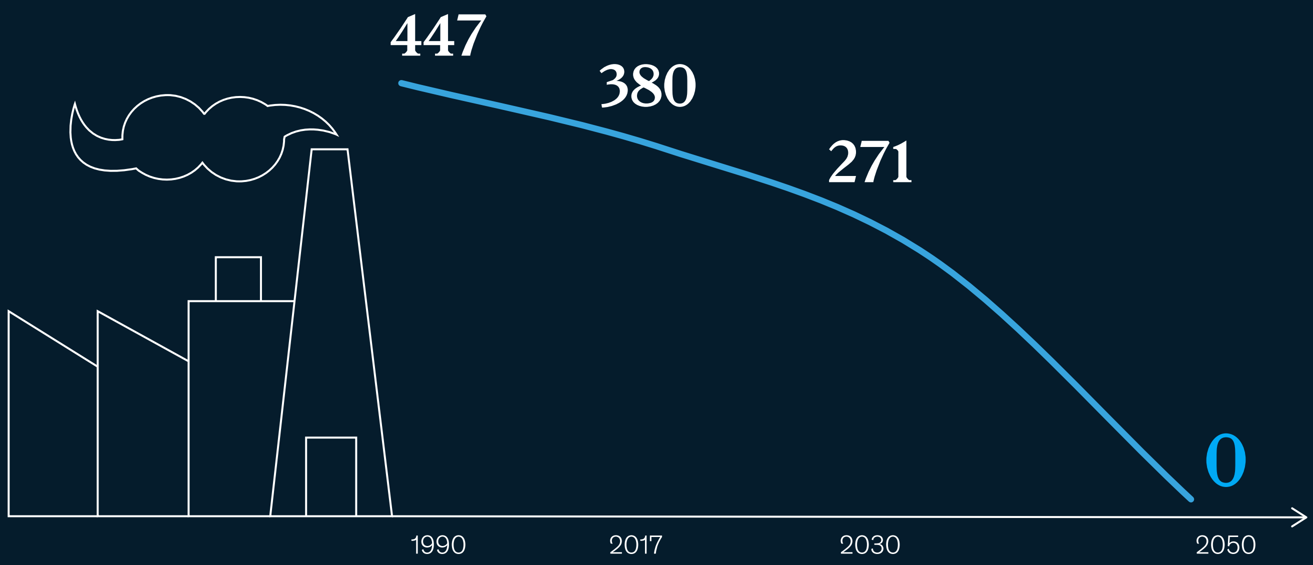
Key findings

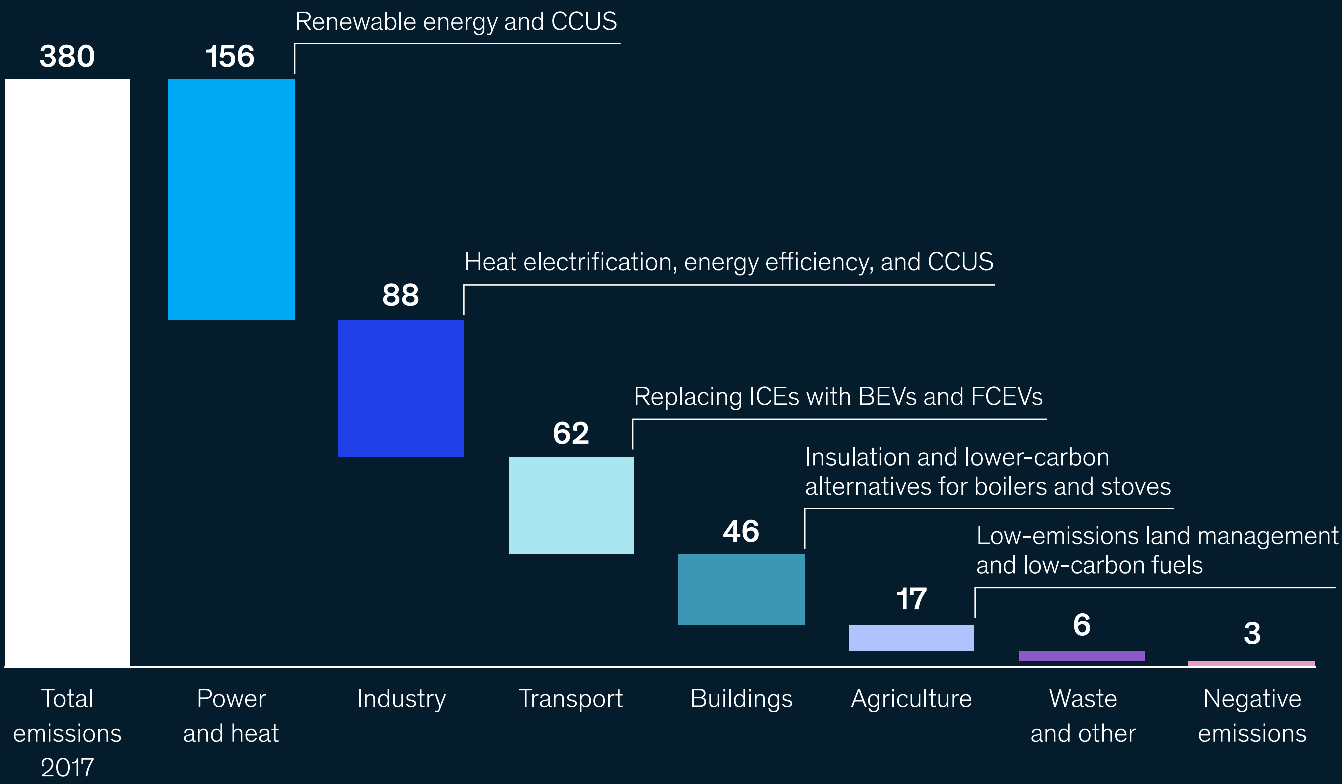
Poland’s emissions levels and potential targets

$MtCO_2e$



Main decarbonization levers

$MtCO_2e$

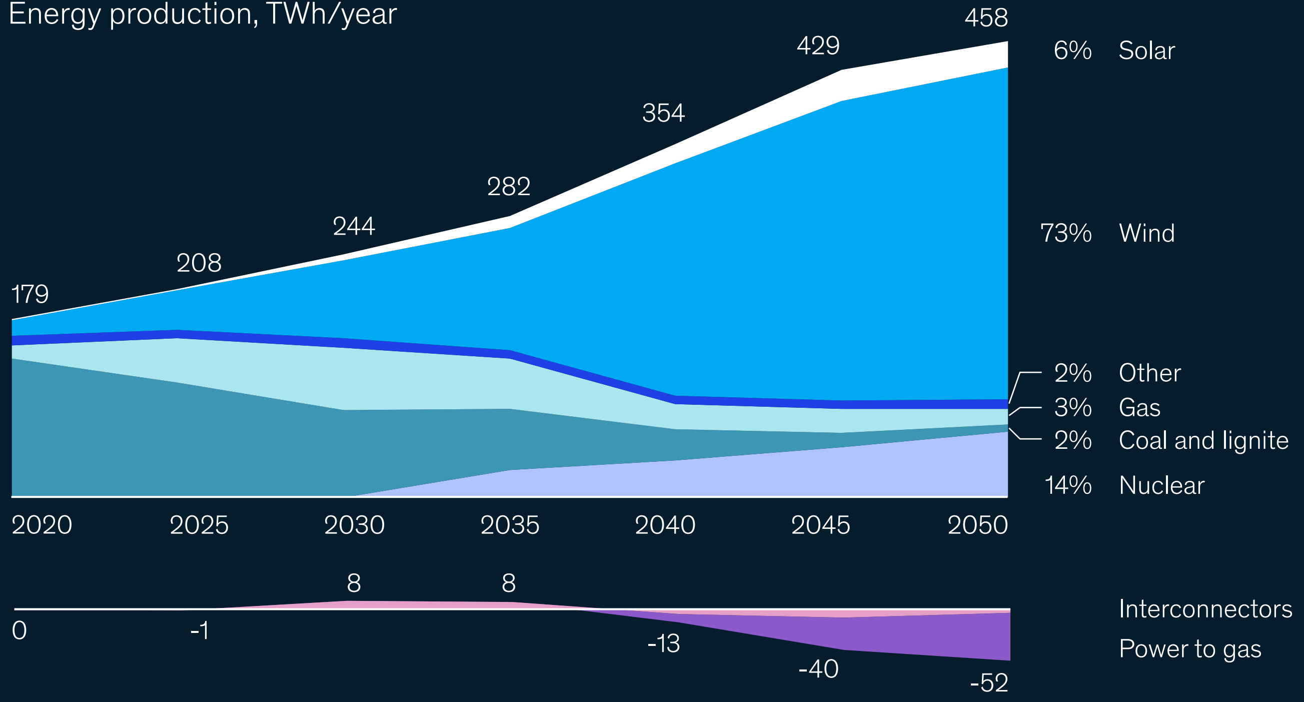


Source: Statistics Poland; KASHUE; Eurostat; EIU; KOBiZE; McKinsey & Company analyses

Potential changes in Poland's energy up to 2050

Energy production, TWh/year

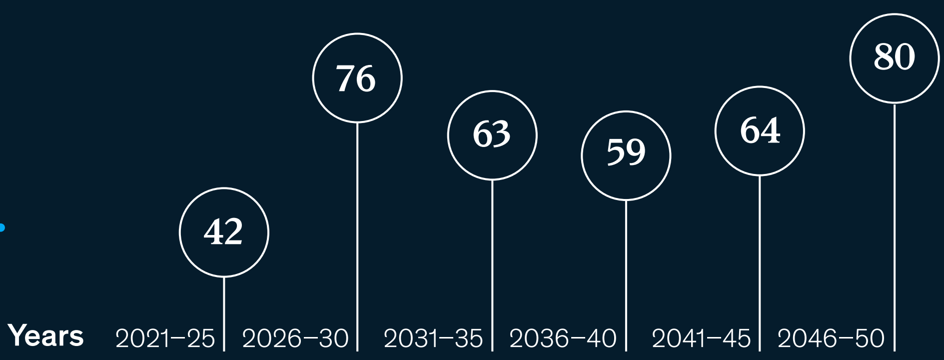
~2.5x higher energy production in 2050 than now



Potential additional investment needed

€ billion

€380 bn or
1–2% GDP p.a.



Potential decarbonization benefits

Savings

€75 bn

savings in operational costs

Energy security

80%

reduction of energy commodities imports in the carbon-neutral scenario

New industries developed

1–2%

boost in GDP

250–300K

jobs created

Executive summary

When the Paris Agreement went into force in 2016, countries around the world signed on to reduce their greenhouse gas (GHG) emissions by 2050 to help limit global warming to 2°C, with the aspiration of slowing its growth even more, to 1.5°C. As such, the European Union has begun exploring the necessary actions to significantly reduce emissions by 2030 and to achieve carbon neutrality by 2050.

Poland's GHG emissions have dropped from 447 $MtCO_2e$ (megatons of carbon dioxide equivalent)[4] in 1990 to 380 $MtCO_2e$ in 2017. This decline was possible due to a shift from an industrial planned economy to a more service-focused economy, improved industrial energy efficiency, a reduction in the use of coal and lignite, and a rising share of renewable energy sources (RES).

Despite this progress, in 2017 Poland remained the European Union's third-most carbon-intensive economy, emitting more than 800g of CO_2e per euro of GDP. In total, Poland produced 414 $MtCO_2e$ in 2017, of which 34 $MtCO_2e$ was offset by carbon sinks in forests from the land use, land-use change, and forestry (LULUCF) sector.

380 $MtCO_2e$

Poland's GHG emissions in 2017

Decarbonizing the economy

While there are multiple paths to achieving carbon neutrality by 2050, this report lays out a possible cost-effective economic pathway that Poland could adopt to reach this goal. This economically driven decarbonization scenario is for the time period from 2020 to 2050, a period relevant for current investment decisions and staying on track to meet the Paris Agreement targets.

We assume that by cutting GHG emissions levels by 91 percent from 2017 to 2050 and increasing carbon sinks to abate the remaining 9 percent of emissions, Poland could reach carbon neutrality by 2050.

Five sectors—industry, transport, buildings (predominantly heating), agriculture, and power—are primarily responsible for greenhouse gas emissions in Poland, and most of these sectors use coal as the primary fuel. Employing energy efficiency and switching from carbon-based fuels to zero-emissions energy sources (including electric power, hydrogen, and ammonia) across all sectors will be needed to achieve carbon neutrality by 2050. A decarbonized economy would require much more green power and therefore in this report we define a potential power mix to supply the required energy.

In this report we take a through-cycle, long-term perspective on Poland's economy, without the effects of various short-term shocks that are bound to occur in the upcoming 30 years. At the time of writing, the countries around the world, including Poland, are focused on containing the spread of COVID-19 and safeguarding their economies against the slowdown caused by the outbreak. However, the available decarbonization options and therefore the solutions space is not expected to change significantly.

Addressing climate change in a post-pandemic world

As a result the COVID-19 pandemic, resident movement is restricted, economic activity is curtailed and governments are putting in place extraordinary measures.

Given the scope and magnitude of this global crisis, and the longest-term impact, many are asking if the world can afford to pay attention to climate change and the broader sustainability agenda at this time? As we laid out in an article "Addressing climate change in a post-pandemic world," the evidence is compelling that we simply cannot afford to do otherwise.[5] Not only does climate action remain important over the next decade, but investments in climate-resilient infrastructure and the transition to a lower-carbon future are likely to drive significant near-term job creation while increasing economic and environmental resilience.

Climate change—a risk multiplier—can contribute to pandemics, according to researchers at Stanford University and other recognized research organizations.[6] For example, rising temperatures can create favorable conditions for the spread of certain infectious, mosquito-borne diseases, such as malaria and dengue fever, while disappearing habitats may force various animal species to migrate, increasing the chances of spill over pathogens between them. Conversely, the same factors that mitigate environmental risks—reducing the demands we place on nature by optimizing consumption, shortening and localizing supply chains, adding plant proteins to our diets and decreasing pollution—are likely to help mitigate the risk of pandemics.

The COVID-19 pandemic transformed the way we live and interact but also offered us an opportunity to find a balance between what worked before

and what needs to happen in the next normal. Some new practices will likely endure long after the lockdown ends. Among factors that could support and accelerate climate action are teleworking and greater reliance on digital channels that may help to reduce transportation demand and emissions. Second, supply chains may be repatriated to increase supply security, reducing some emissions. Moreover, lower interest rates may help accelerate the deployment of new sustainable infrastructure, as well as the adaptation and resilience of infrastructure—investments that would support near-term job creation.

Decarbonization pathways for each sector

Industry

In 2017, the industry sector was responsible for 22 percent of Poland's emissions (91 $MtCO_2e$), primarily concentrated in fuel production, cement, chemicals, and steel. According to our analysis, from 2017 to 2050, Polish industry growth is expected to drive a 19 percent emissions increase if no action is taken. This industrial expansion can be used as an opportunity install lower-emissions equipment in greenfield facilities.

Our analysis shows that the industry sector could potentially reduce emissions by 97 percent. This reduction can be achieved by implementing several decarbonization levers: improvements in energy efficiency, electrification of heat, and carbon capture, utilization, and storage (CCUS) technology.

Transport

In 2017, Poland's transport sector emitted 63 $MtCO_2e$ and was responsible for 15 percent of Poland's emissions. Road transportation represented 98 percent of emissions, while rail and domestic aviation together accounted for 2 percent. Our analysis suggests that the transport sector would need to almost fully decarbonize (with a 99 percent reduction, or 62 Mt of CO_2e) by 2050 for Poland to achieve climate neutrality.

Technology options for moving the transport sector toward carbon neutrality require replacing internal-combustion-engine (ICE) vehicles across road-transportation subsegments with battery electric vehicles (BEVs) and—in the case of trucks and buses—hydrogen-based alternatives such as fuel-cell electric vehicles (FCEVs). A further reduction of transportation demand might result from behavioral changes and the rise of new modes of transport, such as electric scooters, which were not considered in this report.

Buildings

In 2017, buildings accounted for 11 percent of Poland's emissions (46 $MtCO_2e$), of which 84 percent came from the residential sector and 16

Decarbonization of the entire Polish economy within 30 years is an ambitious and highly complex endeavor

percent from the commercial sector. Efforts to decrease emissions in buildings fall into two main categories. First, the energy efficiency of structures could be improved by actions such as retrofitting buildings with better insulation to reduce energy consumption for both heating and cooling. Second, high-emitting fuel sources could be reduced by replacing boilers and stoves that currently use coal, natural gas, and oil with lower-carbon alternatives.

Agriculture

In 2017, agriculture accounted for 11 percent of the country's emissions (44 $MtCO_2e$). Methane and nitrous oxide generated 75 percent of this total, primarily from the application of inorganic fertilizers to land, the cultivation of organic soils, and enteric fermentation from dairy and beef cattle. Carbon dioxide, mainly caused by the fuel consumption of agricultural equipment, contributes the remaining 25 percent. Decarbonization options for the agricultural sector include low-emissions land management (for example, optimizing fertilization and reducing tillage), switching to low-carbon fuels (mostly ammonia) for farm equipment, and reducing enteric fermentation (for instance, by optimizing feed and improving animal health and breeding).

Power

Switching power-generation technology from fossil fuels to renewable energy will be a major challenge for Poland. Currently, coal dominates Poland's power sector (with a 77 percent share in electricity production in 2018), where it is the largest source of GHG emissions. Gas accounted for 7 percent of energy production; wind, solar and other RES accounted for 13 percent; and the remaining sources for approximately 3 percent.[7]

~75%

of total power supply potentially will come from wind by 2050

Moreover, according to our analysis, electricity demand is expected to grow by more than 50 percent by 2050 because of increased economic activity, mainly GDP growth. The electrification of processes (such as the rapid adoption of electric vehicles, heat pumps in buildings, and electric furnaces in industry) adds another 50 percent to this growth. Therefore, compared with today, electricity demand in our decarbonization scenario is expected to double.

Poland's power-generation stock is aging: about two-thirds of Poland's installed coal capacity is older than 30 years. With a possible life span of up to 60 years, these assets would need to be replaced by 2050. Moreover, investment in new power-generation capacity is urgently needed to meet the expected increase in electricity consumption. This creates an opportunity to replace fossil-based power generation with zero-emissions generation capacity.

Three fundamental changes will likely be necessary to move toward full decarbonization of the power supply by 2050. First, coal-fired generation would have to decrease by almost 95 percent from 2020 to 2050 (with a corresponding 80 percent reduction of capacity). Second, renewable generation would have to feature more heavily in Poland's power mix, with wind and solar accounting for about 80 percent of the total power supply in 2050. Third, gas would need to play a prominent role in the transition period, covering up to 20 to 25 percent of the demand from 2025 to 2030 and playing an important system-balancing role thereafter.

Our detailed analysis of renewable power generation's potential suggests that wind power could become the single largest power source after 2030 and account for about 75 percent of the total power supply by 2050. Offshore wind capacity could potentially increase to 45 GW and could provide around 53 percent of the total power supply in 2050. Onshore power could grow to 35 gigawatts (GW) by 2050 and contribute 20 percent of the total power supply. And by 2050, solar power could account for approximately 6 percent of total supply.

Our economically driven decarbonization scenario assumes the commissioning of nuclear capacity in line with the latest Energy Policy of Poland, with 6 to 9 GW of nuclear-power capacity to be constructed from 2033 to 2043.[8] This capacity could supply about 14 percent of the power demand by 2050. Biomass and hydropower sources, as well as coal-fired plants retrofitted with CCUS, could largely supply the remaining generation in 2050.

Decarbonization's cost and impact

Decarbonizing Poland's economy could potentially have profound effects on the country's economic structure. In this report, we outline three main macroeconomic implications of our decarbonization scenario.

Increased capital expenditures
We estimate that in a business-as-usual (BAU) scenario (with no decarbonization measures), Poland would need to spend €1,200 billion to €1,300 billion for the five sectors in our analysis (power, buildings, transport, industry, and agriculture) to replace infrastructure and add new assets. Full decarbonization will require additional capital expenditures for mobility transformation and upgrading energy infrastructure and building stock. To achieve it, total investments in the Polish economy from 2020 to 2050 would need to increase by €380 billion, an average of around €13 billion a year. At the same time, operational costs are expected to decrease by €75 billion.

These additional annual investments equal roughly 1-2 percent of Polish GDP and 10 to 12 percent of Poland's current annual investments in the economy. Such an increase in

spending would bring Poland in line with the EU average for investments of around 22 percent of GDP.[9]

Improved trade balance
The Polish trade balance is expected to structurally improve as the country reduces its imports of fossil fuels by €15 billion each year. This pattern would likely decrease the country's import balance, as virtually all other economic activities retain more domestic value.

Higher economic growth
Our analysis indicates that a portfolio of five low-carbon economic activities can bring economic benefits to the country. Such a portfolio could involve developing a set of industries: BEV-components manufacturing, Baltic offshore wind development, industrial-scale production of electric heat pumps, electrified agriculture-equipment manufacturing, and R&D and deployment of (BE)CCUS technology. The combination of these activities could boost Poland's GDP by 1 to 2 percent and create 250,000 to 300,000 jobs.

It is possible because the slowdown started while the pandemic was still going on, governments and citizens will reprioritize climate change behind the pressing needs of economic recovery. This could set back planned investments, previous commitments, and regulatory approaches. Investments in carbon-neutral infrastructure could drive significant job creation and accelerate the rebuilding of the economy.

A pathway forward

To transition to a carbon-neutral economy, a wide set of activities must occur in a coordinated fashion. Across most of the sectors in this report, technology is available to launch the transition and start renewing stock in the early 2020s as well as to enable full decarbonization by 2050. The only exception is the industry sector, as the CCUS technologies required for decarbonization are not yet available for industry-wide deployment.

By 2030, decarbonization efforts would need to be well under way in sectors with available cost-effective, low-carbon technologies, such as building-insulation upgrades, electrified urban transport, and offshore wind.

From 2030 to 2040, our road map assumes scaling up of the already-launched initiatives and adopting additional low-carbon technologies—for example, the introduction of negative emissions through bioenergy carbon capture, utilization, and storage (BE)CCUS, and fueling switches in industry toward hydrogen power and biogas. To close the gap to full decarbonization in 2050, action will also be needed in the hardest-to-abate economic activities. Examples include deployment of carbon capture, utilization, and storage (CCUS) across the industry sector at scale or green district heating in Poland.

Potential actions to enable the decarbonization transition Include:

- Laying out a comprehensive road map to guide industries in the transition as well as to give investors confidence and thus unlock capital for the required investments.
- Developing financing frameworks to ensure sufficient capital availability. The required financing could be provided by energy companies, industrials, the agriculture sector, consumers, and the state government. In certain sectors of the economy (such as renewable generation), private investors could be attracted with the right regulatory initiatives.

Infrastructural investments and the transition to lower-carbon solutions will likely drive job creation and boost economic growth

- Existing infrastructure would need to be strengthened, expanded, and built to enable certain technology switches.
- Regulatory and other interventions aimed at reducing any transition barriers (such as ensuring a sufficiently qualified labor force and support for technology development and deployment) could help keep decarbonization plans on track. These efforts could be put in place while ensuring a supportive business environment.

Decarbonization of the entire Polish economy within 30 years is an ambitious and highly complex endeavor. A transformation of this scale would require consideration of any regulatory, environmental, and supply-chain constraints. The global COVID-19 crisis could make this more challenging. At the same time, decarbonization could create opportunities for the development of new industries in Poland and for building a knowledge-based and forward-looking economy for future generations.

Chapter 1

Defining the decarbonization challenge

In Poland and around the world, there is an increased understanding that action to prevent further climate change is needed. More and more, businesses are considering sustainability when making decisions and pursuing long-term growth. In addition, investors and financial institutions have begun accounting for climate risks in decision making, and many are taking steps to reduce the carbon intensity of their portfolios. Awareness is also growing at the consumer level: more than two-thirds of Polish consumers consider sustainability when making purchasing decisions.[10]

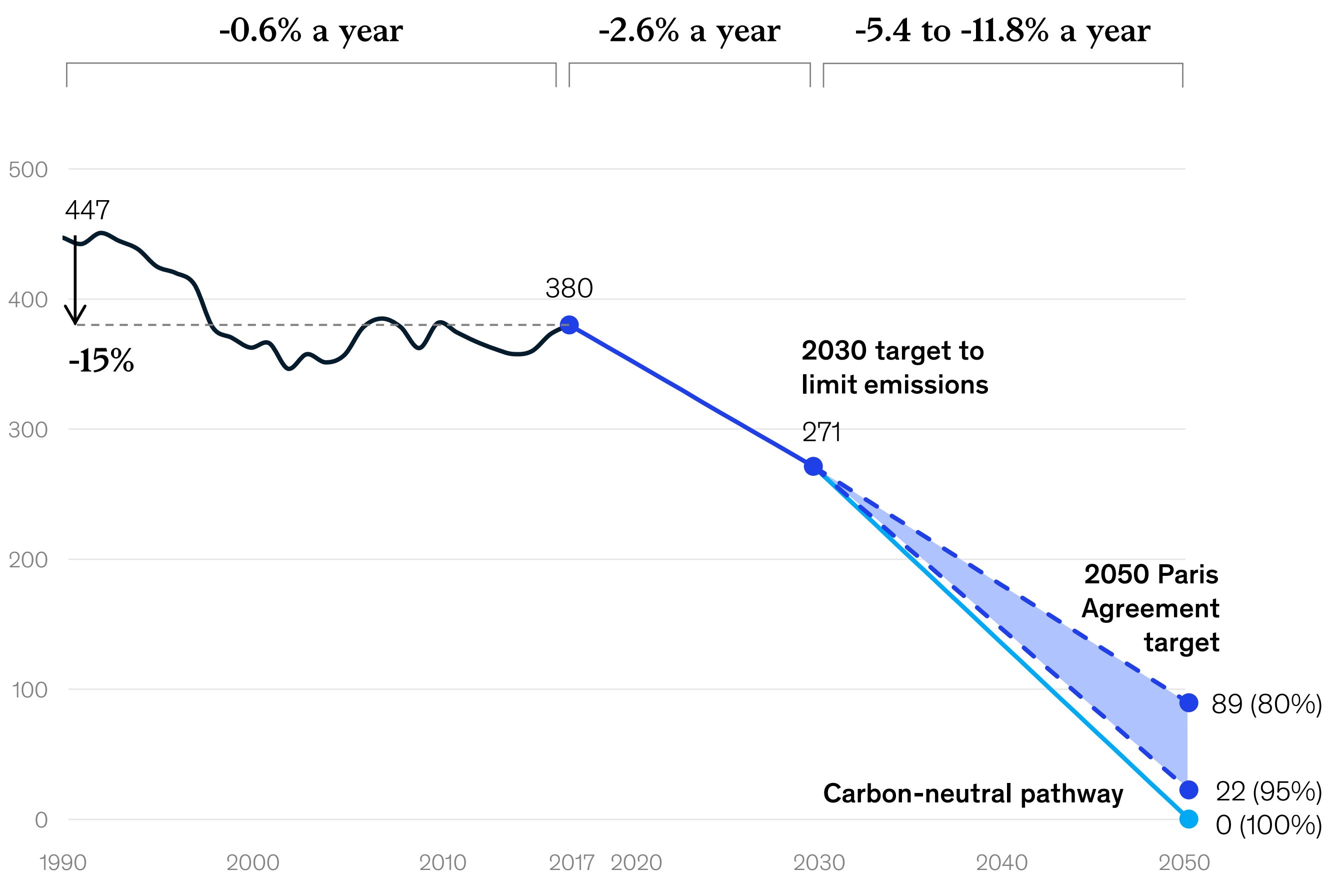
The Paris Agreement was adopted in December 2015 to reduce greenhouse gas (GHG) emissions by 2050 and help limit global warming to a maximum of 2°C with the ambition to limit it to 1.5°C. Poland ratified the agreement in October 2016.[11] But the window is closing if the world wants to meet the 2°C target. Due to the time sensitivity,[12] the European Union—including Poland—has begun exploring the actions necessary to significantly reduce GHG emissions by 2030 and to achieve carbon neutrality on the European continent by 2050.

Carbon neutrality (or net-zero emissions) refers to an economy that, within national borders, does not emit more GHGs than are captured. In practice, carbon neutrality means that any remaining emissions are offset by negative emissions—for example, by forests extracting CO_2 from the atmosphere. New investments, technologies, and changes in the energy mix could help EU countries reach their goals. However, each country faces challenges and

Exhibit 1

Poland's emissions levels and targets

$MtCO_2e$



Source: GUS; KASHUE; Eurostat; EIU; UNFCCC 2019 National Inventory Report; IOŚ-PIB, *Climate for Poland, Poland for Climate*

opportunities unique to its historical, economic, and social contexts.

Poland embarked on its free-market journey 30 years ago, and since that time its GDP has almost tripled.[13] Modernization has occurred by shifting from an industrial planned economy to a service economy. At the same time, the country experienced improved industrial energy efficiency, higher consumption of petroleum-based fuels, a reduction in the use of coal and lignite, and a rising share of renewable energy sources (RES). These developments led to a decrease in GHG emissions from 447 $MtCO_2e$ (megatons of carbon dioxide equivalent) in 1990 to 380 $MtCO_2e$ in 2017 (Exhibit 1).[14]

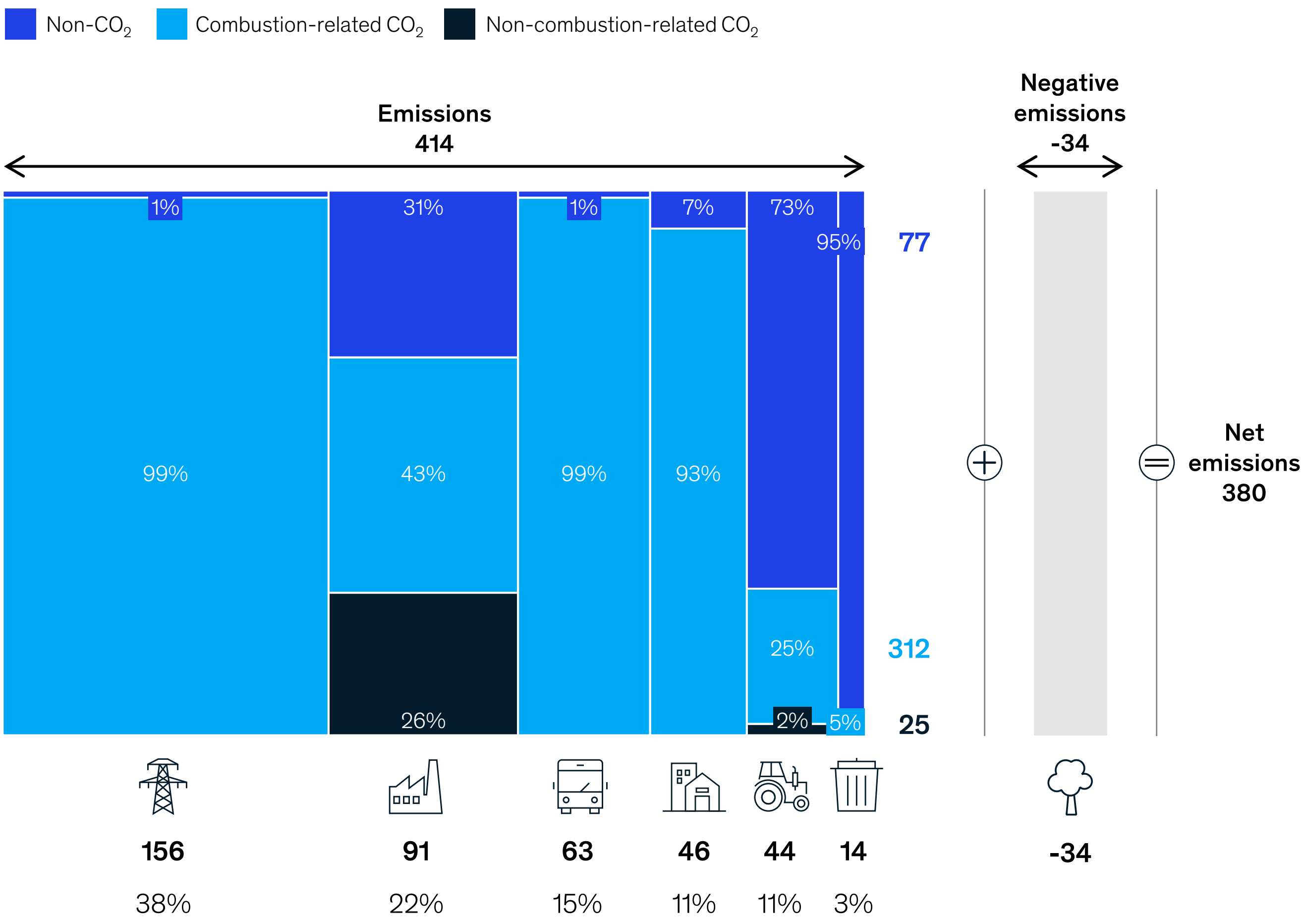
Despite this progress, in 2017 Poland remained the European Union's third-most carbon-intensive economy, emitting more than 800g of CO_2e per euro of GDP. Economic activity in Poland produced 414 $MtCO_2e$ in 2017, of which 34 $MtCO_2e$ was offset by negative emissions in land use, land-use change, and forestry (LULUCF) and carbon sinks (Exhibit 2). Five sectors—power and heat, industry, transport, buildings, and agriculture—contribute the most emissions in Poland, and a substantial number of them use a lot of fossil fuels.

To achieve net-zero emissions by 2050, Poland's rate of decarbonization should accelerate by a factor of four over the

Exhibit 2

Profile of Polish GHG emissions in 2017

$MtCO_2e$



Power and heat

Power and heat account for 38% (156 $MtCO_2e$) of total emissions—primarily driven by coal- and lignite-fired electricity generation (~82%) and coal-fired CHP plants

Industry

Industry accounts for 22% (91 $MtCO_2e$) of total emissions—subsectors contributing most emissions are fuel manufacturing (36%), non-metallic minerals (22%), chemicals (13%), and steel (9%)

Transport

Transport accounts for 15% (63 $MtCO_2e$) of total emissions—54% driven by passenger cars, 44% by trucks and buses, remaining 2% by aviation, marine, and rails

Buildings

Buildings account for 11% (46 $MtCO_2e$) of total emissions—coming from coal- and natural gas–based space and water heating in residential and commercial buildings

Agriculture

Agriculture accounts for 11% (44 $MtCO_2e$) of total emissions—45% from non-CO_2, mainly from enteric fermentation and manure management; 25% of energy-related CO_2 emissions from diesel; and 30% related to liming and urea application

Negative emissions

Poland has negative emissions of -34 $MtCO_2e$; most carbon removal in the Polish LULUCF sector comes from biomass growth in existing forests (-33.6 $MtCO_2e$) and from an increase in forest coverage (-3.3 $MtCO_2e$)

Not considered for abatement potential:

Waste and others

Waste and other categories account for 3% (14 $MtCO_2e$) of total emissions next decade compared with the past three decades. From 2030 to 2050, efforts would need to escalate by at least an additional factor of two. In some ways, Poland is well positioned to tackle GHG emissions. For example, a significant part of the existing energy infrastructure, regardless of climate change, will need to be renewed in the next 20 to 30 years. More than 50% of the capacity of centrally dispatched generation units will most likely be decommissioned by 2035.[15] At the same time, more than three quarters of the aerial high- and medium-voltage lines that form the basis of the transmission system are now over 25 years old.[16] This reality provides an opportunity to design and build with a zero-carbon mindset instead of retrofitting or prematurely shutting down existing assets. In addition, Poland, with its large forest area, has a net carbon sink (capturing 34 $MtCO_2e$ in 2017)[17] that the country could use to offset emissions from hard-to-abate economic activities such as agriculture.

Poland has multiple paths it can take to achieve carbon neutrality by 2050. This report lays out an economically driven decarbonization pathway, focused on five sectors, that Poland could adopt to reach its decarbonization goal (see sidebar "About the research"). The pathway, however, should not be misconstrued as a policy recommendation. Instead, this report examines different trade-offs to provide data for discussions on the possibilities for the decarbonization of the Polish economy.

Our scenario focuses primarily on 2020 to 2050, a period relevant for current investment decisions and for working toward the targets set out in the Paris Agreement. We identify plausible changes for the short, medium, and long term and discuss the costs and benefits of these changes. Our analysis approaches Poland as a stand-alone entity, although we recognize that, in practice, solutions need to be optimized and embedded internationally. For simplicity, we consider only those technologies that are currently proven or are likely to become workable in the near term. And, while we take feasibility constrained—for example, stock-turnover times—into account, following the economically driven decarbonization scenario would also entail overcoming many practical and societal barriers.

First, we define a plausible pathway, highlighting potential changes for each of the five sectors. Next, we interpret the implications of such changes on the energy system and infrastructure. Then we discuss the necessary investments and resulting impact on the entire economy as well as on specific sectors. We conclude by outlining a high-level road map with midterm, necessary moves and initiatives that can help create longer-term socioeconomic value.

Carbon neutrality, or net-zero emissions, refers to an economy where, within the national borders, no more GHGs are emitted than captured

About the research

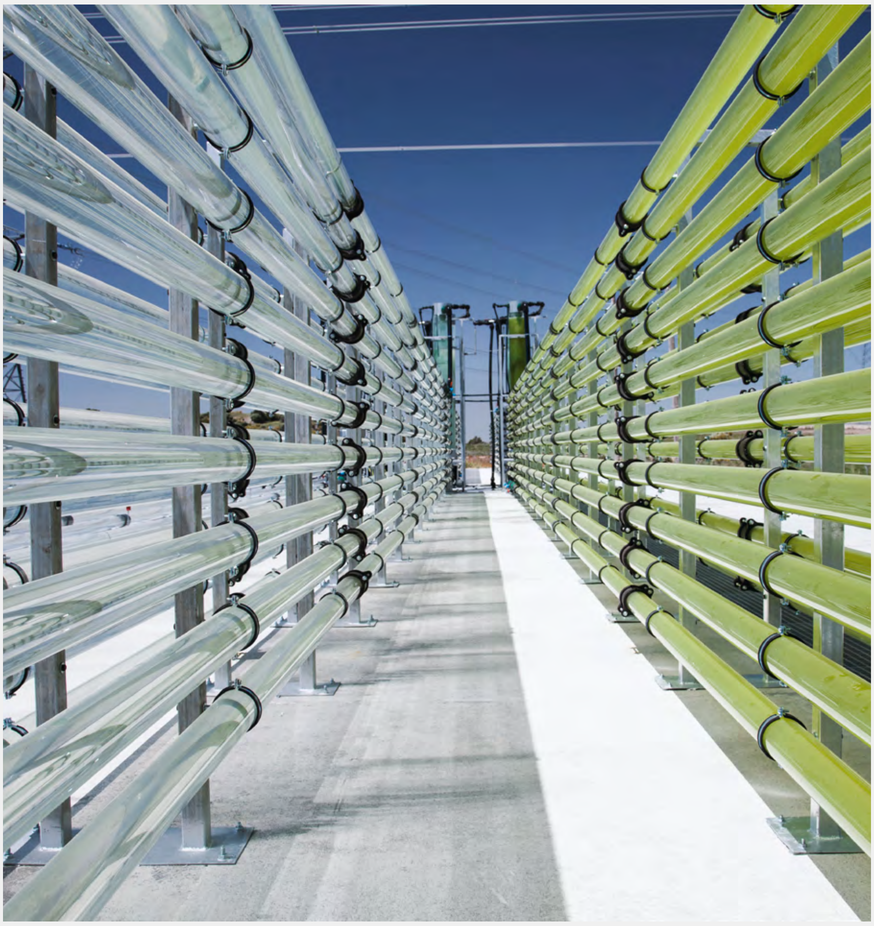
This report seeks to offer a plausible pathway for Poland to achieve carbon neutrality[18] by 2050, while minimizing the total cost of the country's transition to a low-carbon economy. Our model assumes agents are rational economic decision makers and will switch to lower-carbon technologies when the total cost of ownership (TCO) is lower than status-quo solutions. Noneconomic switches are made as late as possible when realistically working to meet emissions reduction targets.

The proposed solutions are tailored to Poland. The model adheres to existing programs and set targets as well as constraints in business (for example, scaling up supply chains), physical inputs (such as resource availability), and technology (for example, cost of solutions).

All major economic activities are included in our model, from passenger transport and cement production to power generation and building insulation. The model also assumes existing behavioral patterns. Further cultural changes related to preferred transport modes (for example, a growing preference for public transport) or demand reduction (such as in a circular economy) could help further reduce the costs of the economically driven decarbonization scenario.

Finally, we used our best available cost outlook. However, we are aware that results may slightly differ in the future as costs evolve.

For more on the report's methodology, see Appendix B.



Chapter 2

Decarbonizing the economy: A pathway to net-zero emissions in Poland

Reaching carbon neutrality in Poland by 2050 will be a substantial undertaking. It will require all major economic activities to decarbonize significantly (reducing 40 to 100 percent of emissions compared with 1990 levels) as well as move toward negative emissions to offset some of the remaining, hardest-to-abate activities.

Summary of sector contributions

Our economically driven decarbonization scenario includes levers that would achieve continual emissions reduction across sectors (Exhibit 3). All sectors are expected to substantially contribute to decarbonization, and approximately 70 percent of measures are expected to be cost effective by 2050. However, the timing of contributions by sector is expected to vary:

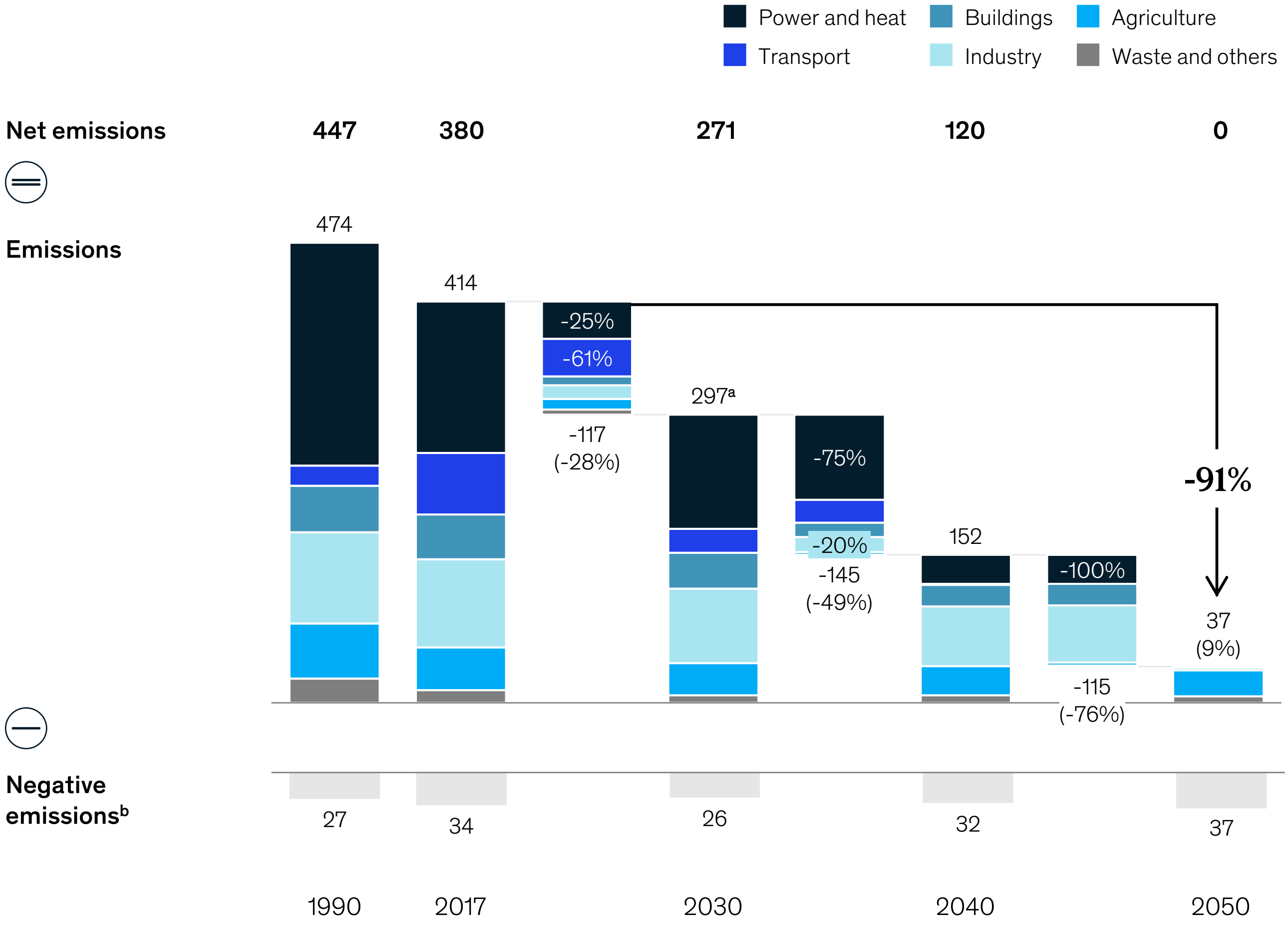
— From 2017 to 2030, the transport sector will likely lead emissions reductions (39 $MtCO_2e$, or a 61 percent decrease from 2017 levels), followed by the power and heat sector (39 $MtCO_2e$, or 25 percent).

— From 2030 to 2040, the decarbonization of the power and heat sector could decrease emissions by an additional 88 $MtCO_2e$ (75 percent), and industry decarbonization could gain momentum with a 15 $MtCO_2e$, or 20 percent, reduction

— From 2040 to 2050, all sectors—except for agriculture—could close the gap to carbon neutrality. Negative emissions would be required to offset the remaining 37 $MtCO_2e$ in 2050

Exhibit 3

Poland's emissions-reduction trajectory in our economically driven decarbonization scenario



Power and heat

Power sector could decarbonize continuously over the next 3 decades by developing renewables (e.g., on- or offshore wind, solar), nuclear energy, and (BE)CCUS

Industry

Industry sector could decarbonize relatively late and by using alternative fuels and feedstocks (e.g., hydrogen, biomass, electricity) and deploying CCUS

Transport

Transport could decarbonize relatively early through BEVs as TCO parity to ICE vehicles is reached for most vehicle types within the next decade

Buildings

Buildings could decarbonize relatively late. There are 3 main levers: insulation, switching from coal to low-carbon energy as heating source, and reducing emissions in district

Agriculture

Agriculture could decarbonize by switching from fossil fuel to low-carbon farm equipment and reducing enteric fermentation emissions though using different animal feeds; however, there is no established technology to eliminate all negative emissions in sector

Negative emissions

Negative emissions can be reached in 2 ways: by increasing carbon-absorption efficiency and by devoting more land (e.g., afforestation, agroforestry)

a. This emissions reduction is in line with the 2030 EU emissions-reduction target.
b. Land use, land-use change, and forestry. LULUCF carbon sink initially decreases (as in with business-as-usual case); however, after 2030 we assume linear increase in total sink potential thanks to additional measures that will be introduced in the economically driven decarbonization scenario.

Source: UNFCCC 2019 National Inventory Reports; Decarbonization Pathway Optimizer McKinsey & Company

By cutting GHG emissions levels by 91 percent from 2017 to 2050 and increasing carbon sinks to abate the remaining 9 percent of emissions, Poland could reach carbon neutrality by 2050.

Decarbonization options

Our analysis indicates that by 2050, more than 70 percent of decarbonization can be done with levers that will be cost neutral, 20 percent will be economically viable when CO_2 is priced at €100 per ton, and the remaining 10 percent will cost an average of €150 per ton CO_2 (Exhibit 5).[19]

Significant action across all sectors will be needed to achieve carbon neutrality by 2050. In this report, we consider ten main decarbonization levers categorized by four themes that could be implemented to bring down emissions (Exhibit 4).

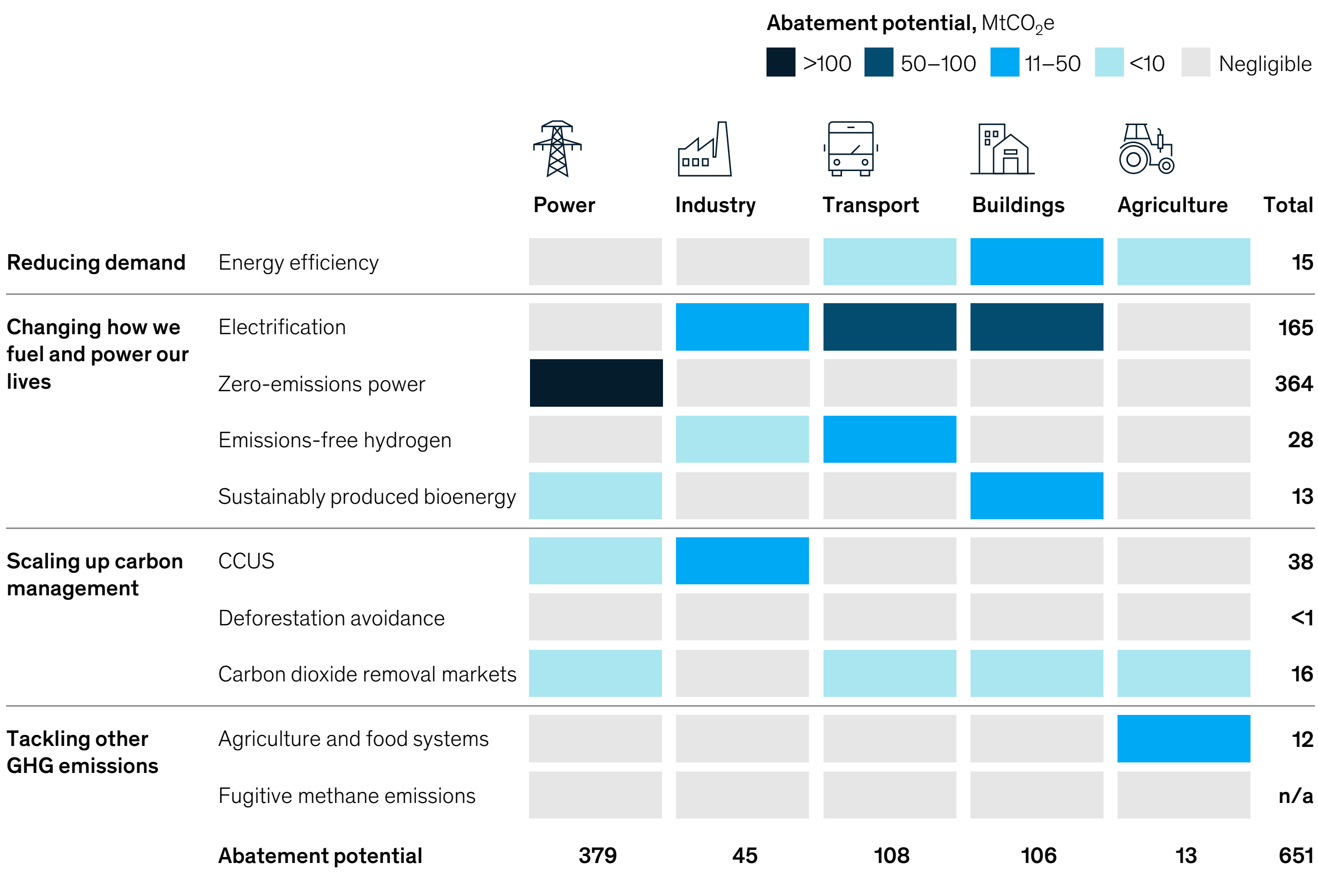
Changing how we fuel and power our lives

Electrification: Switching from technology and fossil energy-based to electricity-based processes—for example, by transitioning from internal-combustion engines (ICEs) to battery electric vehicles (BEVs) and from gas-based mid-temperature heating to electric heating using industrial-scale heat pumps.

Zero-emissions power: Switching power-generation technology from fossil

Exhibit 4

A potential portfolio of abatement measures required to reduce CO_2 emissions



Note: (BE)CCUS in industry is included in CCUS category.
Source: Decarbonization Pathway Optimizer McKinsey & Company

fuels to renewables (for example, on- and offshore wind and large-scale and rooftop solar photovoltaics) and nuclear.

Emissions-free hydrogen: Replacing the production of hydrogen from natural gas by electrolysis powered by renewable power ("green hydrogen") or production of hydrogen in combination with CCUS ("blue hydrogen"). These alternatives can replace existing applications of hydrogen as fuel or feedstock (such as ammonia production) and open new applications of hydrogen—for example, as an alternative fuel for long-distance trucks.

Sustainably produced bioenergy: Switching from fossil-based fuels to zero-emissions bioenergy and feedstocks (for example, biomass as fuel for cement kilns and bio-based plastics production).

Scaling up carbon management

Carbon capture, utilization, and storage (CCUS): Implementing carbon-capture technologies to avoid emissions from selected economic activities for which fossil fuels remain critical is necessary. These integrated technologies capture emissions for further usage[20] (for example, captured CO_2 as an input for methanol production) or storage.

Deforestation avoidance: Implementing regulation and enforcement to avoid loss of forest coverage and preserve forests' emissions-mitigating function. Additional actions include afforesting marginal agricultural land to create further negative emissions.

Carbon dioxide removal markets: Fostering markets to match providers and buyers of CO_2 removal (for example, providers of sequestration options with industrial emitters of CO_2).

Tackling other GHG emissions

Agriculture and food systems: Moving agriculture operations to low-carbon alternatives (such as low-tillage crop production and low-emissions animal feed).

Fugitive methane emissions: Minimizing or eliminating coal-bed methane extraction emissions, which are 25 times[21] more potent than carbon dioxide, and capturing the emissions and using them for power generation would be beneficial.

All sector s are expected to substantially contribute to decarbonization. About 70% of the measures will be cost effective by 2050

Reducing energy demand

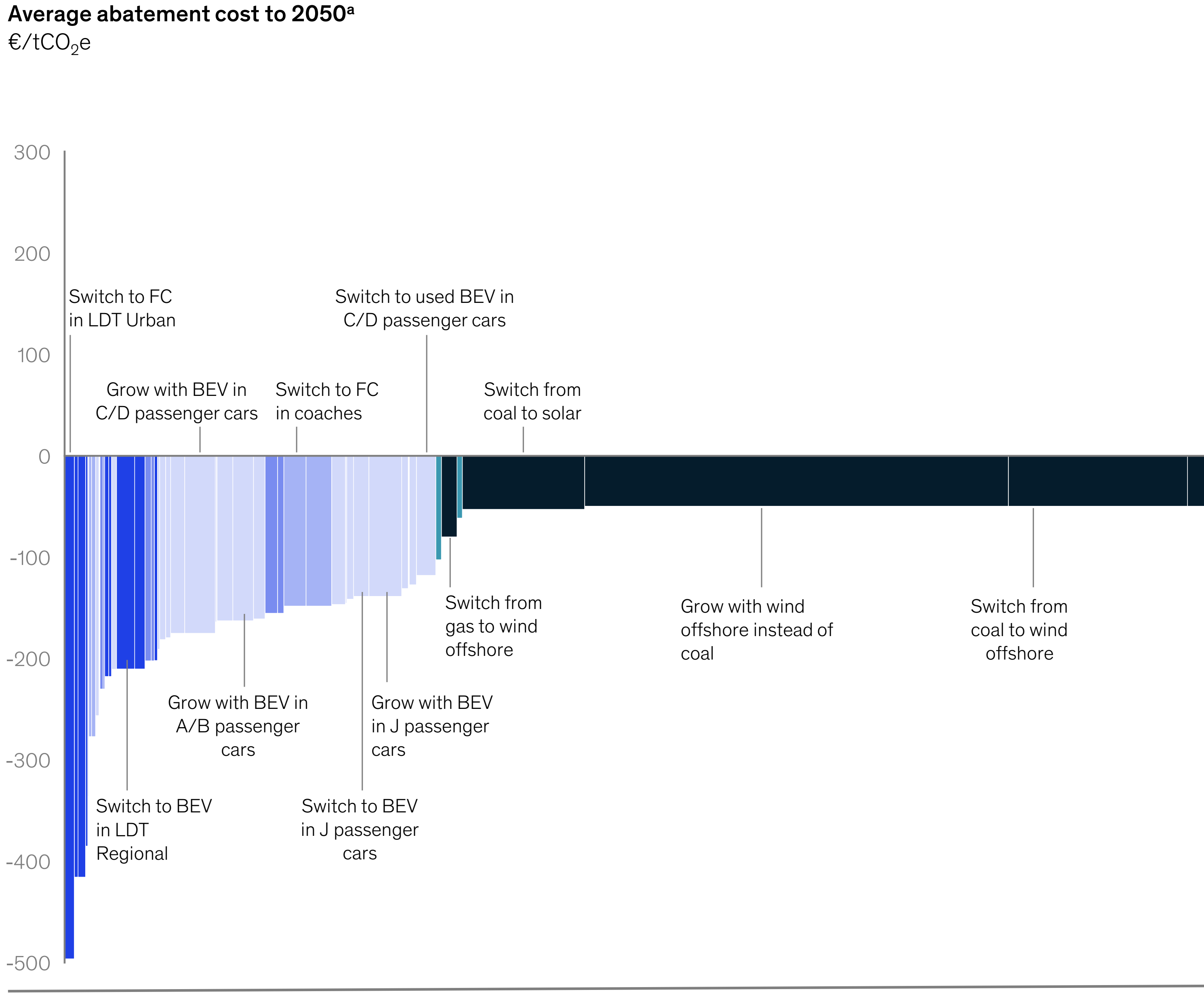
Energy efficiency: Promoting energy-efficiency efforts, such as building insulation and the installation of more efficient equipment, can help reduce energy demand.

Circular economy: Using the same resources more efficiently through asset sharing, reusing, refurbishing and remanufacturing, cascading in other value chains, and recycling can reduce demand. Producing materials based on recycled products generally consumes less energy and feedstock than the production of virgin materials (for example, increased recycling will reduce demand for iron ore). Circular-economy levers are not assessed in this report, though we recognize they could make a significant contribution. Estimates suggest that in the EU, a more circular economy could reduce GHG emissions from four industries (plastics, steel, aluminum, and cement) by as much as 56 percent.[22]

Exhibit 5

Marginal abatement cost curve (MACC) for Poland

(for detailed assumptions, see Appendix B)

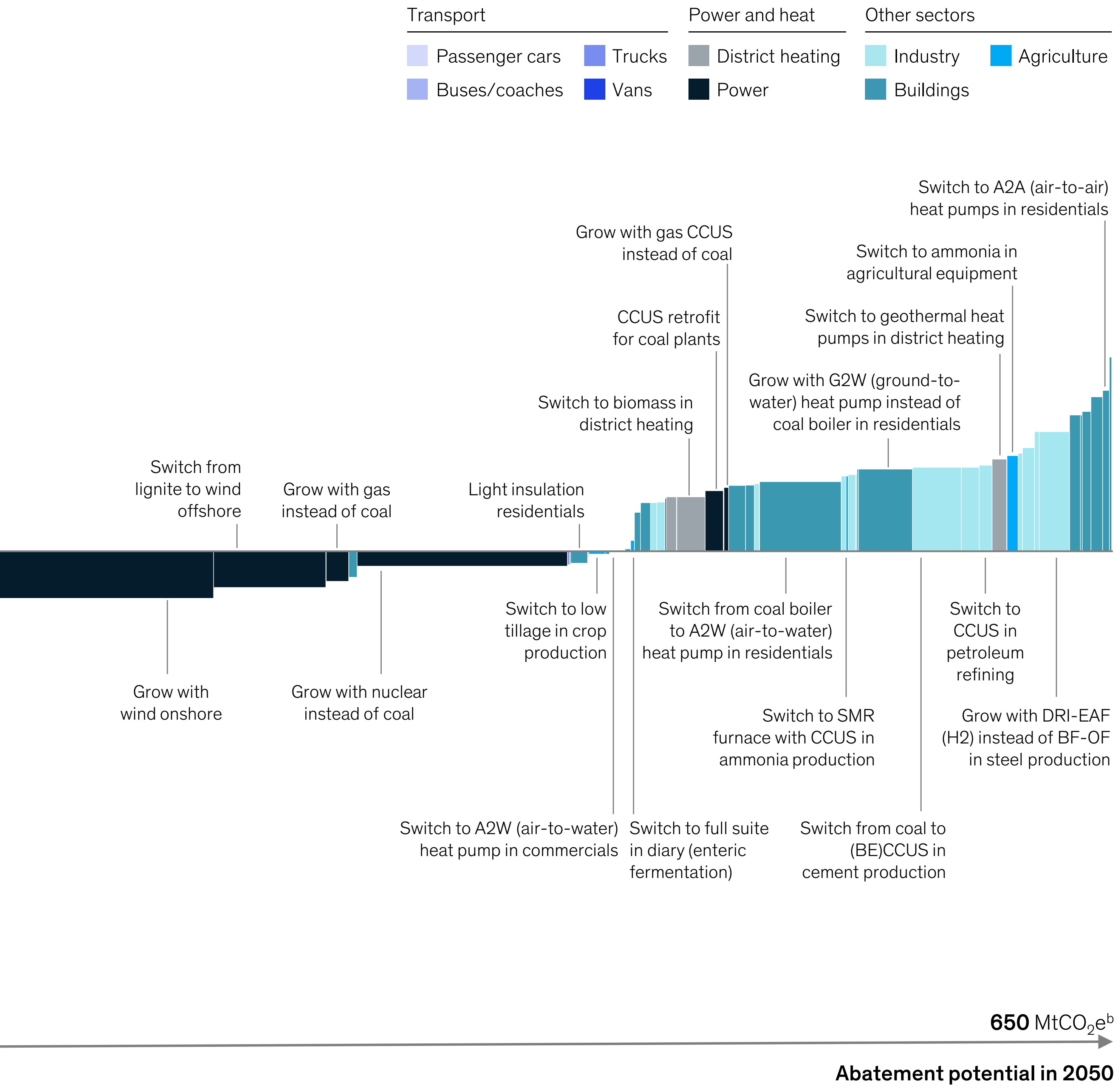


Note: The horizontal axis shows the abatement potential of the technology switches. The vertical axis displays the average abatement cost as €/tCO_2e for each switch.

a. Measures considered exclude LULUCF and biofuels use in energy/heat production. MACC does not include cost of enabling infrastructure (e.g., EV charging network, transmission, and distribution network upgrade).

b. According to our macroeconomic modeling of the Polish economy, economic activity is expected to increase and thereby increase emissions in the business-as-usual case from the current 474 $MtCO_2$e to 650 $MtCO_2$e by 2050. For full decarbonization, the current and expected growth of emissions needs to be mitigated.

Source: Decarbonization Pathway Optimizer McKinsey & Company; Global Energy Perspective; Sustainability Practice McKinsey & Company


Transport
Passenger cars
Trucks
Buses/coaches
Vans
Power and heat
District heating
Power
Other sectors
Industry
Agriculture
Buildings
Switch to A2A (air-to-air) heat pumps in residentials
Grow with gas CCUS instead of coal
Switch to ammonia in agricultural equipment
CCUS retrofit for coal plants
Switch to geothermal heat pumps in district heating
Switch to biomass in district heating
Grow with G2W (ground-to-water) heat pump instead of coal boiler in residentials
Switch from lignite to wind offshore
Grow with gas instead of coal
Light insulation residentials
Switch to low tillage in crop production
Switch from coal boiler to A2W (air-to-water) heat pump in residentials
Switch to CCUS in petroleum refining
Grow with wind onshore
Grow with nuclear instead of coal
Switch to SMR furnace with CCUS in ammonia production
Grow with DRI-EAF (H2) instead of BF-OF in steel production
Switch to A2W (air-to-water) heat pump in commercials
Switch to full suite in diary (enteric fermentation)
Switch from coal to (BE)CCUS in cement production
650 $MtCO_2e^b$
Abatement potential in 2050

Behavioral changes and demand[23]

The decarbonization scenario described in this report assumes a number of technological and business changes leading to a reduction in emissions. A similar or even greater impact on the reduction of emissions may also result from changes in consumers' lifestyles and behavior, or the development of the circular economy.

Long-term climate strategies should also take into account the potential for behavioral change in areas with a strong impact on the environment and energy consumption:

— Transportation: A reduction in the carbon footprint can be achieved by stopping or reducing vehicle usage, developing public transit (railroads, urban transportation), increased popularization of cycling, widespread use of electric personal transportation devices (for example, electric scooters), carpooling and ride-sharing, increased investment in low-carbon infrastructure (e.g., more cycle paths, development of urban transportation), and introduction of congestion charges and tolls to enter city centers

— Diet: The prevailing diet in a society has a strong environmental impact. A person whose diet is dominated by meat contributes more than twice the quantity of greenhouse gases as a vegan. According to the Food and Agriculture Organization of the United Nations (FAO), animal husbandry accounts for 18 percent of global GHG emissions.[24] By contrast, plant production causes 20 to 30 times fewer emissions than meat and dairy products

— Food production and logistics: When assessing the environmental impact of the food products chosen by consumers, the entire chain should be taken into account—plant and animal production, transportation, processing and storage of products, and delivery to wholesalers and retail stores, shopping by consumers, transportation to their homes, processing and storage at home, and food-related waste products. Food wastage is also important, both at a production and at a consumption level. According to the FAO, around 1.3 billion tons of food are thrown away each year, or one-third of all food produced for human consumption.[25] Poland ranks fifth in Europe the amount of food wastage

— Goods and services: Other important factors in climate protection are reducing the use of plastic, regulating for the circular economy and zero waste, reducing demand for new products, and using previously

owned items such as apparel, electronics, books, toys, and even furniture. At present, 38 percent of people in Poland admit that they buy more than they need. A significant section of society says that instead of buying new products they repair old ones (45 percent), rent products (34 percent), or exchange products with others (32 percent). However, only one-quarter of the population sees the need to limit consumption. When buying food or cosmetics, price is the deciding factor, overshadowing environmental impact. The key reason for not buying “green” products is price (72 percent of respondents)[26]

— Housing: Where we live, what household appliances we own, how we use electricity and water at home, and how we heat our homes also influence environmental impact. For details, please refer to the section on buildings in in Chapter 3

The fashion for sustainable consumption and respect for natural resources could reverse the trends in consumerism. This mainly relates to growing environmental awareness and a whole range of increasingly popular behavior patterns, such as preferring local, regional and seasonal products, limiting consumption, and stressing corporate social responsibility.

Table

Three types of Polish consumers[27] and their impact on the global climate[28]

Area of assessment	Non-green person	Average green person	Proactively green person
Housing[29]	Poor insulation; 100 m^2 housing space; 3-person household; heating to 25°C; no effort to save power; prolonged ventilation; 0% renewable energy	Average insulation; 80 m^2 housing space; 3-person household; heating to 23°C; frequent ventilation; 0% renewable energy	Excellent insulation; 60 m^2 housing space; 3-person household; heating to 19°C; careful and quick ventilation; 20% renewable energy
Hot water[30], air conditioning	7 showers/week; 5 baths/week; air conditioning used continuously in summer to reach 25°C	5 showers/week; 2 baths/week; air conditioning used in very hot weather, in the evening, at night, and on weekends to reach 25°C	7 showers/week; air conditioning on in exceptional circumstances; only in the evening and at night to reach 27°C
Private transportation	Large SUV running on diesel (200 km/week); very occasionally used by 2-persons or more; air conditioning used	Medium-sized vehicle running on gasoline (150 km/week); sometimes used by 2-persons or more; air conditioning used	Bicycle
Public transportation	Taxi used 4 times/week; business-class flights: short-haul 30 hours/year; long-haul 40 hours/year	City bus 100 km/week; streetcar/subway 50 km/week; taxi used 2 times/week; economy-class flights: short-haul 18 hours/year; long-haul 20 hours/year	City bus 30 km/week; intercity bus 5 km/week; streetcar/subway 30 km/ week; suburban rail 20 km/week; long-distance rail 10 km/week; economy-class flights: short-haul 6 hours/year
Food	Very large quantities; exotic and non-seasonal products; meat every day; frozen food 2–3 times/week; refrigerator efficiency class A; separate freezer	Average quantities; does not pay attention to where produce is from and whether it is in season or not; meat 3–6 times/week; frozen food 2–3 times/week; refrigerator efficiency class A	Rather small quantities; local; seasonal produce; no meat; frozen food once a week; highly energy-efficient refrigerator
Other consumption	No recycling; new, fashionable apparel; beautifully packaged products; new, fashionable possessions; tech-based leisure activities (e.g.; quads); power usage not considered; use of clothes dryer; 0% renewable energy	Some trash recycled; some new clothes if old are worn out; packaging unimportant; only some possessions new; leisure activities such as movie theater and bars/restaurants; use of clothes dryer; tries not to waste electricity; 0% renewable energy	Most items recycled; mainly secondhand clothes; minimal packaging; generally secondhand possessions; outdoor leisure activities; reduced energy use; 20% renewable energy
Carbon footprint	**57.2 tons of CO_2 per year**	**22.6 tons of CO_2 per year**	**8.0 tons of CO_2 per year**

Chapter 3

Plausible decarbonization pathways for each sector

This chapter looks closely at what decarbonization would mean for all major sectors of Poland's economy, highlighting the challenges and opportunities. Decarbonization of the power and heating sector is addressed separately in the next chapter, as it plays an enabling role in the transition of the sectors described here.

Industry

The challenge

In 2017, the industry sector was responsible for 22 percent of total economy emissions (91 $MtCO_2e$). Of those, fuel production contributed 36 percent, cement 22 percent, chemicals 13 percent, and steel 9 percent, while other industries including food production totaled 20 percent.

The commodities produced in these industries—cement, steel, ammonia, and ethylene—generate 26 percent of GHG emissions through the processing of feedstocks. Heat generation is responsible for the remaining emissions across three temperatures: low (less than 100°C), medium (100–500°C), and high (more than 500°C). In some industries, such as cement, iron, and steel production, high-temperature needs can represent over 80 percent of energy consumption.[31]

Four technical reasons inhibit the reduction of GHG emissions in the industry sector.

— First, reducing emissions from feedstocks typically requires changing production processes rather than simply lowering the carbon content of fuels.

— Second, the technology for emissions-free high-temperature heat is, in some cases, not yet commercially available. For example, in cement production where kilns operate above approximately 1,400°C, their electric counterparts are not (yet) available at scale.

— Third, processes can rarely be changed in isolation, as industrial processes are deeply integrated.

— Fourth, few natural opportunities exist for large capital-intensive rebuilds or retrofits, as asset lifetimes often exceed 50 years with regular maintenance.

Economic factors may compound inhibitions. Adopting costly low-carbon processes may be seen by industrial producers as a competitive disadvantage if others do not implement similar changes. Furthermore, many manufacturing products in Poland are commodities competing for price in an international market, where increased production costs are absorbed by the business and not passed onto customers.

97%

of emissions can be reduced in industry; CCUS technology plays a major role in securing this emissions reduction

Decarbonization options

Six decarbonization levers could be applied to the industry sector to reduce emissions over the next 30 years in Poland.

— First, demand-side measures could prevent emissions for industrial commodities. For example, construction recycling and light-weighting can reduce steel consumption, and wood alternatives could replace cement.

— Second, energy-efficiency improvements, such as lower-energy appliances, could help decrease fuel consumption by as much as 20 percent.

— Third, electrification of heat could be introduced by switching to electric furnaces, boilers, and heat pumps powered by zero-carbon electricity.

— Fourth, hydrogen produced from zero-carbon electricity could replace hydrogen from steam methane reforming (SMR) and open the door to new steel production processes using direct reduced iron (DRI) coupled with electric arc furnaces (EAF).

— Fifth, liquid or solid biomass such as bionaphtha could replace fuel and feedstock.

— Sixth, and finally, CCUS could capture and productively reuse emissions at industrial facilities.

A plausible decarbonization pathway

Determining which decarbonization solution is most suitable for each plant depends largely on local conditions such as the availability of infrastructure for storage capacity and affordable, carbon-free electricity and hydrogen. In general, our current technology cost projections suggest industry's decarbonization pathway will likely require the development of alternative fuels (hydrogen, biomass, and electricity) and CSS (as a last-resort option) at scale. Overall, this combination of measures could bring industry emissions down 97 percent by abating a total of 88.4 $MtCO_2e$, with negative emissions from LULUCF compensating for the remaining 2.6 $MtCO_2e$. According to our estimates, the cost of decarbonization options would reach an average of €85 per tCO_2e.

— In cement and lime production, advances in bioenergy carbon capture, utilization, and storage would have to facilitate the shift away from coal, thereby abating approximately 24.8 $MtCO_2e$ per year. These measures could average €85 per tCO_2e.

— In the steel sector, the total reduction and sequestration potential of decarbonization options by 2050 could exceed 15.6 $MtCO_2e$ per year, coming from alternative fuels such as electrification and the switch to hydrogen-based steelmaking (DRI + EAF) and CCUS. These measures could average €120 per tCO_2e.

- In the chemicals sector, the emissions reduction potential would have to reach 6.2 $MtCO_2e$ by 2050. In total, 27 percent of these reductions could originate from ethylene production, where CCUS would be implemented at steam crackers in the late 2030s while also continuously pushing energy efficiency to the limits. The other 73 percent could be achieved from decarbonizing ammonia production through CCUS with current and future SMR capacity as well as zero-emissions hydrogen feedstock. Of this portion, 22 percent of this ammonia would be used for urea production, which suggests biogas may be a viable alternative for natural gas. These measures could average €70 per tCO_2e.

- Refineries would have to abate direct emissions by 5.2 Mt of CO_2e by 2050 under a BAU case for demand of oil and oil products. These emissions would decline significantly if production were scaled down when demand develops in line with net-zero scenarios across Europe and the world. The remaining emissions reductions would be achieved through continuous efficiency improvements and changes to technology processes (for example, electrification of heat or biomass and other alternative feedstocks). To abate the remaining emissions, CCUS would need to be introduced in the late 2030s. These measures could average €90 per tCO_2e.

- Reduction across other industry subsectors would need to reach 39.1 $MtCO_2e$ by 2050. The main sources would be decreased coal-mining emissions due to lower demand and energy efficiency and the decarbonization of low- and medium-temperature heat.

Implications for the energy system
To support the implementation of industrial decarbonization solutions, existing infrastructure must be extended or enhanced and new infrastructure should be developed. The enabling infrastructure could help ensure access to sustainably produced biomass and energy, waste, decarbonized hydrogen, natural gas, and power. For CCUS, carbon dioxide transmission (for example, via pipelines or shipping) and storage solutions need to be piloted, tested, and built, potentially harnessing Poland's geological conditions (Exhibit 6).

Transport

The challenge
In 2017, Poland's transport sector emitted 63 $MtCO_2e$. Road transportation represented 98 percent of emissions, while rail and domestic aviation together contributed 2 percent. Passenger vehicles alone generate 53 percent of transport emissions, and heavy- and light-duty trucks produce 35 and 10 percent of CO_2 emissions, respectively.[32]

The Polish vehicle fleet consists almost entirely of internal-combustion-engine (ICE) vehicles. Based on the number of registered vehicles, Poland is one of the most motorized countries in Europe: its population of 38 million has nearly 30 million registered ICE vehicles. Over two-thirds of new vehicle registrations in Poland are pre-owned, making the country the largest secondhand vehicle importer in Europe.[33] Providing owners of secondhand cars with an affordable, cleaner alternative to meet their transportation needs is a primary challenge to decarbonizing the Polish transportation system.

Decarbonization options
Technology options for transitioning the transport sector toward carbon neutrality require replacing ICE vehicles across road transportation subsegments with battery electric vehicles (BEVs) and—in the case of trucks and buses—hydrogen-based alternatives such as fuel-cell electric vehicles (FCEVs). In addition, alternatives for the "classic" passenger car model (including car sharing and modal shifts to electric scooters, particularly in urban areas) may continue to gain popularity.

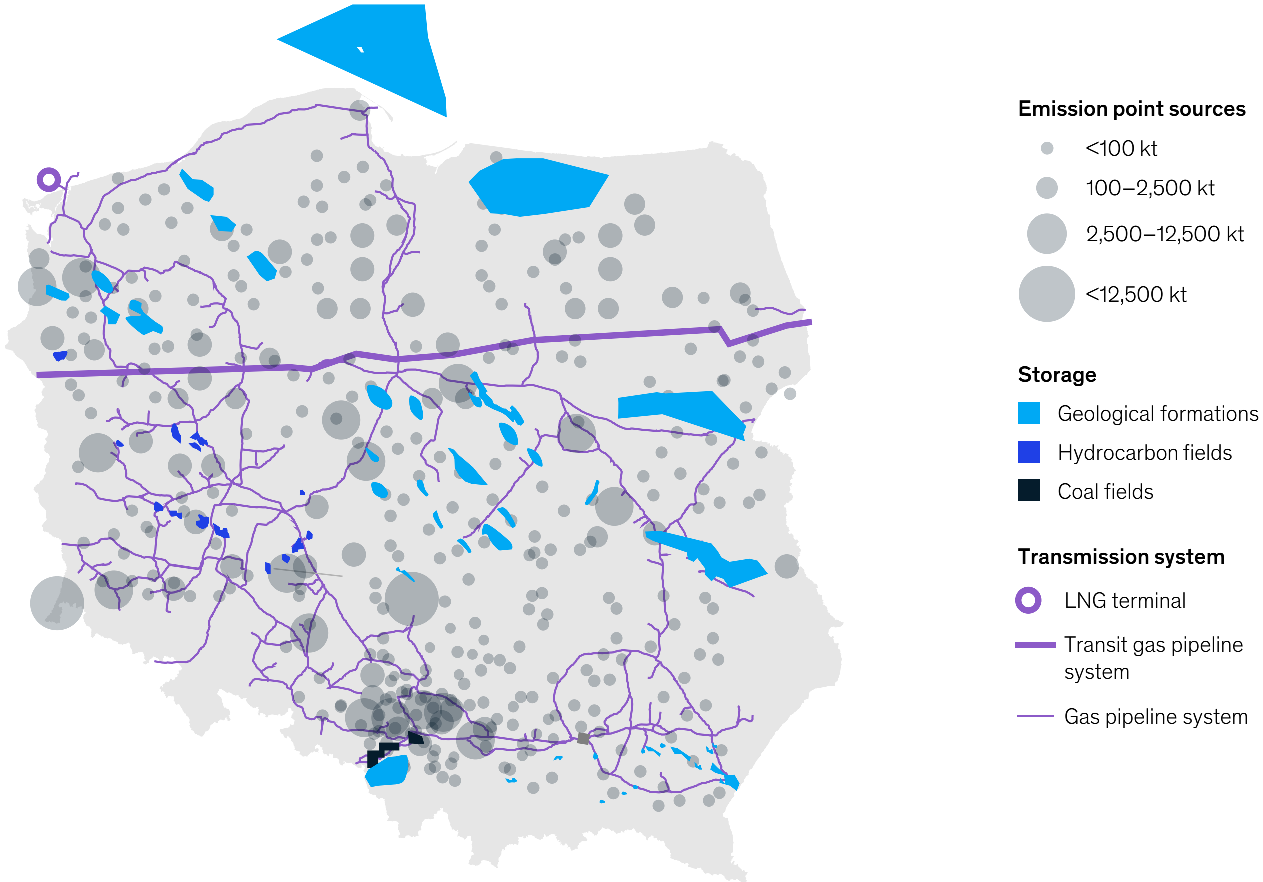
A plausible decarbonization pathway
Our analysis suggests the transport sector would need to almost fully decarbonize (with a 99 percent reduction, or 62 $MtCO_2e$) by 2050 for Poland to achieve climate neutrality. Though the reduction is substantial, current cost estimates suggest this reduction can be reached at a net savings from an individual user point of view; the average savings for the measures is €180 per tCO_2e.

The uptake of BEVs will likely accelerate when cost parity with ICE vehicles is achieved, with large-scale adoption beginning in 2020 until 2030 depending on the car type, starting with small passenger vehicles. By 2037, BEVs would need to represent 100 percent of passenger cars for Poland to reach its emissions-reduction goals.

Adoption of BEVs could be enabled by a decline in battery cost, as projected in our analysis, to less than €50/kWh by 2050. However, the initial capital investments remain relatively high, as they increase the cost of renewing the vehicle fleet. At current cost projections, passenger BEVs could become more affordable than ICE alternatives between 2022 and 2024 on a TCO basis. However, the higher relative cost for new BEVs may prevent customers from switching. We estimate that a similar dynamic would hold true for the secondhand market. Pre-owned BEVs may see a price premium of €5,000 or more compared with ICE vehicles, resulting mostly from battery replacement or refurbishment costs. Typically, this investment has a payback time of less than ten years due to operational cost savings (per kilometer, electricity costs are three to four times lower than gasoline).

Exhibit 6

Opportunities for carbon storage in Poland



Poland's estimated storage potential is 15 Gt of CO_2:

14.3 Gt storage in geological formations

1.0 Gt storage in hydrocarbon fields

0.1 Gt storage in old coal fields

Estimate storage capacity is enough to store 600 years of emissions at post-2050 levels

Source: Adapted from Państwowy Instytut Geologiczny (Polish Geological Institute), "Interactive atlas presenting possibilities of CO_2 geological storage in Poland"

In trucking, hydrogen is predicted to eventually become more cost effective for long-distance transport than battery electric trucks. Long-haul hydrogen trucks could enter the market before the second half of this century. FCEVs would need to mitigate 26 $MtCO_2e$ emissions in the trucks segment by 2050.

Implications for the energy system

Three enablers would need to be in place to achieve the desired transport abatement opportunity. First, EV charging infrastructure in public areas, businesses, and homes needs to be rolled out. Second, the electrification of transport would increase electricity demand by 68 TWh a year by 2050. The viability of BEVs as a low-carbon alternative to ICE vehicles is contingent on decreasing the emissions of the Polish power mix while adding more low-carbon capacity to accommodate rising demand. Third, to facilitate the required adoption of hydrogen-based transport, the supporting hydrogen value chain would need to be established. Demand for hydrogen

80%

of houses would need to have been retrofitted to reduce energy demand and make them suited for zero-carbon heating technology

in the transport sector could rise by 2.1 Mt a year —a sizeable amount compared with the current annual production of the approximately one million tons used in industry.[34] In addition, the supporting hydrogen-distribution infrastructure would need to be developed, including pipelines and a sufficiently dense network of fueling stations.

Buildings

The challenge
In 2017, buildings accounted for 70 $MtCO_2e$ of emissions, of which 84 percent came from the residential sector and 16 percent from the commercial sector. Two-thirds (66 percent, or 46 $MtCO_2e$) of emissions were generated by space and water heating for 13 million households and 400 million square meters of commercial space. Of these emissions, 61 percent originate from coal-fired stoves, common in Polish houses.[35]

The remaining one-third of emissions (accounted for in the power and heat bucket) was generated by district heating (24 Mt): Poland operates one of the largest district-heating networks in the world, with more than 20,000 kilometers of district heating pipes. Coal contributes 35 percent of district-heating emissions through combined heat and power (CHP) coal-fired plants. Most district heating is consumed in apartments and commercial buildings, while houses often rely on coal and natural-gas boilers.[36]

Poland's building stock varies in energy efficiency: half of all buildings were built before 1970 that have a relatively high final-energy demand of 270 kWh per square meter, per year.[37] By contrast, newly built facilities are three times more efficient.

Decarbonization options
Efforts to decrease emissions in buildings fall into two main categories. First, the energy efficiency of structures could be improved through actions such as retrofitting buildings with better insulation in order to reduce fuel consumption. Solutions can target the most inefficient housing segments (for example, buildings with heating demand above 200 kWh per square meter, per year) and address the least-insulated element of a given building (such as its attic, walls, windows, and floor).

Second, high-emitting fuel sources could be reduced by replacing the fuel for boilers and stoves currently fueled by coal, natural gas, and oil with lower-carbon alternative fuels. Some viable, affordable solutions may include:

Sustainably produced biomass. This can function as fuel for boilers. Wood pellets, for example, are particularly suited to houses where larger units and space allow for wood-based boilers.

Electrification of heating. Electrifying heating through several technologies such as electric resistance (or boilers) and various types of heat pumps can be a viable emissions-reducing measure.

The most appropriate technology will largely depend on the building type (such as apartments and stand-alone houses), density of neighborhoods, in-house space constraints for installing equipment, distance to and suitability of natural-gas and power infrastructure, the owner's willingness to retrofit, and the current energy efficiency of the structure.

A plausible decarbonization pathway
Our current estimates suggest the building sector would have to abate 46 $MtCO_2e$ by 2050 and hit a target of about half (53 percent) before 2040. This path would cost an average of €70 per Mt of CO_2e. Although upgrading the building stock will take a while, progress can be made over the next few years by focusing action on both energy-efficiency retrofits and efforts to replace retiring CHPs with lower-carbon options.

To meet Poland's emissions goals by 2050, 80 percent of houses would need to have been retrofitted to reduce energy demand and make them suited for zero-carbon heating technology. Light (25 percent energy reduction) and deep (50 percent energy reduction) insulation would have to be implemented in the near term across commercial buildings, houses, and apartments.

Replacing coal and gas as fuel sources could materially contribute to decarbonizing the building sector by both building heating systems and district heating. In heating systems for houses, pellet stoves may be installed in the near term as an interim solution while converting to heat pumps. For heating systems in both houses and commercial buildings, the 2030s would need to see the adoption of air-to-water heat pumps and, by the late 2040s, the complete phase-out of natural-gas boilers. Current cost outlooks suggest coal stoves and boilers will likely remain cost-competitive, thereby creating disincentives for homeowners to transition to lower-carbon alternatives.

District heating would need to be decarbonized through a mix of two-thirds biomass and waste CHP and one-third geothermal heat pumps. In addition, low-temperature (50°C or less) district heating could also be explored as energy demand per square meter of building stock gradually decreases.

Our analysis suggests multiple types of heat pumps can contribute to decarbonizing the buildings sector. In general, the suitability of heat pumps as a solution will vary by building, as conditions such as heat demand, existing insulation levels, existing natural-gas and electricity infrastructure, and access to fuel sources must be met.

Implications for the energy system
Improving insulation, installing heat pumps, and scaling biomass have further implications for the energy system. While total energy demand for buildings will likely decrease substantially, the demand for electricity in buildings is likely to increase for two reasons. First, the electrification of heat in buildings and the conversion of CHP to biomass and heat pumps means the power-producing capacity of CHP would need to be replaced by alternative power generation. Second, to accommodate these changes, additional low-carbon power would need to be generated, coupled with grid expansion and improved power infrastructure in buildings.

Rapidly deploying decarbonization retrofits and equipment installations requires further developing the nece-ssary value chain—including equipment suppliers, installers, and transportation and logistics—to support this initiative.

The scaling of biomass-based solutions, such as wood pellets and biogas boilers, is contingent on the availability of biomass, storage facilities, and distribution infrastructure as well as on the logistics of reusing waste as fuel in existing CHP.

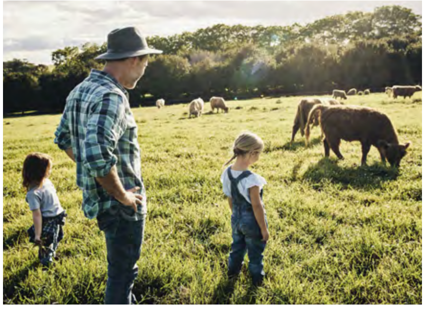
Agriculture

The challenge
In 2017, agriculture accounted for 44 MtCO_2e emissions from several sources. Methane and nitrous oxide generated 75 percent of this total, primarily from the application of inorganic fertilizers to land, the cultivation of organic soils, and enteric fermentation from dairy and beef cattle. CO_2, mainly caused by the fuel consumption of agricultural equipment, contributed the remaining 25 percent.[38]

Implementing emissions-reduction solutions at scale is complicated by the fact that Poland's agriculture sector is highly fragmented. About 750,000 farms—53 percent of total farms—are smaller than five hectares.[39]

Decarbonization options
Decarbonization options for the agri-culture sector fall into three categories.

Adopt low-emissions land management. Reducing emissions in land management can be achieved by optimizing fertilization and reducing tillage. In the first category, traditional synthetic fertilizers could be traded for low-emissions fertilizers (for example, slow- or controlled-release fertilizers) or nitrogen stabilizers (for example,



nitrification inhibitors). Making this switch decreases nitrous oxide emissions, as it lowers the required amount of nitrogen.

Switch to low-carbon fuels for farm equipment. Using lower-carbon fuels for existing farm equipment—for example, by blending ammonia into diesel—as well as employing electrification could reduce emissions from farm equipment.

Reduce enteric fermentation. Enteric fermentation is a natural part of ruminant animals' (such as cows) digestive processes that results in methane emissions. Currently, few technology options exist to address these emissions, and technologies in development may only reduce a small portion of the impact. For example, one potential solution involves introducing animal feed additives and promoting feed changes that improve digestibility and decrease methane emissions directly. Another solution being explored is to introduce GHG-focused breeding and selection, as well as to improve animal health monitoring.[40] More research is needed in this area, including any effects on animals.

A plausible decarbonization pathway
Emissions from agricultural production are expected to fall 5 percent (from 44 $MtCO_2e$ to 42 $MtCO_2e$) from 2017 to 2050 because of a decline in both dairy production and the total area of cultivated land. An additional 39 percent reduction of agricultural emissions would be required for Poland to meet its decarbonization target. This reduction could be achieved by implementing low-emissions land management (24 percent reduction), switching fuels for farm equipment (10 percent reduction) and reducing enteric fermentation (5 percent reduction).

~40%

of agricultural emissions will need to be eliminated by 2050

However, even when all decarbonization levers are pulled, the agriculture sector's emissions would still not be reduced to zero: in our scenario, 25 $MtCO_2e$ would still be emitted in 2050.

Two primary trends (in addition to the aforementioned actions) could further reduce agricultural emissions in 2050. The first is a shift in consumer diets away from animal to plant-based proteins, which could result in reduced meat production and reduce the emissions associated with meat production. The second is negative emissions—capturing emissions on behalf of the agriculture sector (for example, through (BE)CCUS in industry and power and heat) and using nature-based solutions such as carbon sinks to reduce emissions.

Implications for the energy system
An agricultural knowledge network is needed to promote the productivity and benefits of operational expenditure for specific decarbonization methods.

Transitioning from fossil fuels to low-carbon alternatives would require capital investment in new equipment and accelerating the development and availability of alternative fuel sources, with a focus on electrification and the use of ammonia as fuel blended into diesel.

Negative emissions

The challenge
GHG emissions mitigation is the main action that countries plan to take to reduce global warming. In addition, negative emissions that offset the hardest-to-abate emissions would have to play a meaningful role in order to achieve carbon neutrality. Poland's current negative emissions from carbon sinks are estimated at 34 $MtCO_2e$.[41] However, these are expected to decline to 10 $MtCO_2e$ by 2050 due to aging forests (see sidebar "Carbon sinks and their potential for Poland").

While the theoretical potential of different negative emissions technologies is substantial, the actual achievable carbon sink is uncertain, as no current models can accurately predict the development of these complex ecosystems.

Decarbonization options
Negative emissions include nature-based and technology-based solutions. To ensure that carbon sinks achieve the actual additional required carbon abatement, explicit targets should be set and coupled with incentives.

Nature-based solutions
Each of the following measures differs in its carbon sink intensity (how much carbon can be absorbed per hectare) and the amount of land required (size of the area where activities are applied). Among the natural solutions, there are four measures.

Extend forest-management practices throughout the country. This strategy could potentially be applied to up to one million hectares by 2050.

Afforest 600,000 hectares of low-quality agricultural land (category V and VI).[42] Incentives could be considered for private landowners would be needed to take up or support new afforestation.

Introduce land-use-management systems based on a combination of agriculture and forestry (agroforestry). This strategy involves integrating trees into croplands at levels that do not reduce crop yields (for example, through windbreaks, alley cropping, and farmer-managed natural regeneration). The total land area in Poland that has faced different environmental challenges (such as soil erosion and poor water quality), which is estimated to be 129,600 hectares, could benefit from agroforestry.

Restore the wetlands that have been drained for farmland, estimated to be 132,000 hectares. Enabling this restoration process would require both financing and legislation; what was once a single wetland might now be multiple small farms with several owners.

Technology-based solutions

The following technology-based solutions can be pursued to augment nature-based solutions and increase the capacity of carbon sinks.

Implement bioenergy carbon capture, utilization, and storage. (BE)CCUS captures the carbon released from biomass energy production (for example, in cement and lime production) and buries it underground instead of releasing it into the air.

Convert biomass and waste through pyrolysis into stable biochar products. Biochar is a lever with the highest theoretical carbon-storage potential—it can be applied to all croplands. Biochar products can be plowed on agricultural land to enhance its fertility and stability and to store CO_2.

Deploy direct-air capture (DAC) at the current state of development. As CO_2 in the atmosphere is present at a much lower concentration than in flue gases in the industry or power and heat sectors, the DAC process is usually energy-intensive and expensive. Therefore, this likely would be one of the last steps to offset the most difficult emissions required to be reduced to achieve net-zero emissions.

The expected decarbonization pathway

In Poland, our analysis suggests the remaining 37 $MtCO_2e$ emissions in 2050 would need to be compensated by at least an equal amount of negative emissions.

Current cost projections suggest that nature-based solutions could contribute to the reductions of 23 $MtCO_2e$ in 2050 to close the gap. At least 10 $MtCO_2e$ could be derived from forests in existence today. Technology-based solutions would need to address the remaining 14 $MtCO_2e$ in 2050.

Implications for Poland's energy system
Technology-based solutions are typically power intensive. As such, the implementation of solutions such as (BE)CCUS and DAC will require increased low-carbon power generation to deploy at scale.

In addition, the scaling of (BE)CCUS is contingent on an established bioenergy supply chain including the availability of biomass, storage facilities, and distribution infrastructure. CCUS infrastructure and technology would also need to be developed for this solution to be successful.

GHG emissions mitigation is the main action that countries plan to take to reduce global warming

Carbon sinks and their potential for Poland

A carbon sink is any environment (such as forest or ocean) or technology that can absorb CO_2 from the atmosphere and store it permanently. In simple terms, the sink is a difference between biomass growth and biomass loss. As trees reach maturity, for example, their growth slows, resulting in lower CO_2 absorption every year.

In 2017, Poland had a net carbon sink of 34 $MtCO_2e$, mostly from its forests[43].

Poland's carbon sink is expected to contract by 2050, as its forests are already relatively mature: 40 percent of the forests are older than 60 years. Planned growth of forest areas (as a percentage of Poland's area) by three percentage points (from 30 percent in 2019 to 33 percent in 2050)[44] is not enough to make up for the forest absorption rate loss. As a result, the total carbon sink is expected to be approximately 10 $MtCO_2e$ in 2050.

Poland has the conditions in place to increase the required biomass and store CO_2 to offset emissions. Over the next 30 years, advancements in managing carbon sinks and increasing their capacity could help unlock the country's massive potential.

Consider that in 2017 Poland had 9.2 million[45] hectares of forest, which could store 4.4 $GtCO_2e$ in standing biomass above and below ground. An additional 23.4 $GtCO_2e$ is stored in organic soil—for example, in agricultural fields and wetlands.

Beyond existing agricultural lands and urban areas, Poland has the potential to increase the amount of CO_2 stored on land in woody biomass by 0.9 Gt. In addition, Poland has significant CO_2 storage potential in low-carbon-density land that could further develop biomass. Together these lands have the capacity to absorb 1.8 $GtCO_2e$ from the atmosphere. With an estimated 20 Mt a year in negative emissions required, this area could offset residual emissions for well more than a century.

Poland has a huge potential for carbon sinks because of its large surface area (Exhibit 7). The regions with the highest carbon-absorption potential are Pomeranian, Greater Poland, Lower Silesian, Silesian, Świętokrzyskie, and Masovian Voivodeships.

To generate at least 23 Mt of carbon storage in terrestrial ecosystems, Poland has a variety of options; however most require either sizeable land areas or significant effort. To maximize the feasibility of creating a sufficiently large carbon sink, the least difficult, lowest-cost methods should be identified. However, assessing these options is relatively challenging, as these decarbonization levers are characterized by diseconomies of scale. For example, the larger the area for reforestation, the harder it is to secure. This is due to the land acquisition cost curve increasing.

Exhibit 7

Current and potential aboveground carbon sinks

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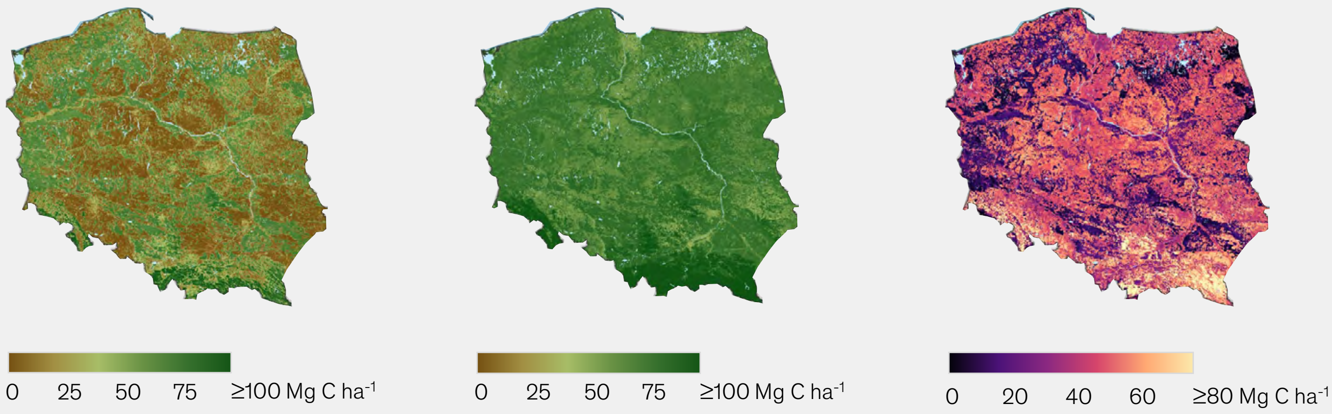
Current aboveground carbon density (ca. 2016) | **Potential aboveground carbon density** | **Unrealized potential aboveground carbon density**



Source: Woods Hole Research Center and The Nature Conservancy, 2019

Chapter 4

Transitioning the energy system

As outlined in the previous chapter, decarbonizing the four sectors of the economy could rely mainly on electrification and changes to the fuel mix, with the remaining emissions to be captured or offset. As a result, the current energy mix in Poland's economy of coal, oil, natural gas, and other energy sources would change, with the demand for electric power rising significantly.

In this chapter, we explore a possible low-carbon mix for power generation that could meet both existing and new demand of the Polish economy. For the other sectors, we explore a lowest-cost pathway based on our current understanding of technology development and cost outlooks. As the energy from renewable sources such as solar and wind is intermittent, we also explore the stability of the system and the sources of flexibility, focusing on storage and power-to-X technologies (methods for converting electrical energy into liquid or gaseous energy sources through electrolysis and further synthesizing processes such as power to hydrogen and power to heat).

Even without the added effort of decarbonization, the Polish transmission and distribution infrastructure is aging and will require significant investments in the next 30 years. Additional demand and increased renewable energy generation can create new challenges to be factored into the build-out of energy infrastructure.

Energy-mix changes

In the economically driven decarbonization scenario, primary energy demand for coal, oil, and natural gas would fall substantially in the long term. According to our analysis, coal demand would decrease by 94 percent from 2020 to 2050, with about 73 percent of this reduction caused by declining coal use in the power sector. The buildings sector accounts for an additional 18 percent of coal demand decline, due to the replacement of coal-fired heating with alternative technologies (including heat pumps and electric space heating). Coal demand in the industry sector would decline mainly due to fuel switches in cement and steel production (for example, biomass, with potential CCUS and electric arc furnaces).

Oil demand would drop 88 percent by 2050 compared with 2020 levels, as the transport sector would switch predominantly to electricity in passenger cars, hydrogen in heavy vehicles, and ammonia blended into fuels in agriculture vehicles.

According to our analysis, demand for natural gas would increase by 33 percent from 2020 to 2030, as natural-gas power generation is the most cost-efficient technology to offset the falling generation of coal-fired power plants. However, it would begin declining after 2030, for two reasons. First, natural-gas power generation would be replaced by renewables as they become more cost competitive. Second, natural gas–based heating in buildings would be replaced by heat pumps after 2040 for economic reasons. As a result, by 2050 demand for natural gas would decrease by approximately 74 percent from 2020 levels.

From 2020 to 2050, electrification across all sectors would increase demand for low-carbon power sources, including renewables, nuclear, and others (mainly bioenergy). The use of bioenergy is expected to increase in the short term due to the rise of biomass-based heating, which could be replaced by electric heating in the long term (Exhibit 8).

Electrification of Poland's economy increases power demand

When we model Poland's energy system without decarbonization, electricity demand is expected to grow by more than 50 percent by 2050 because of increased economic activity.

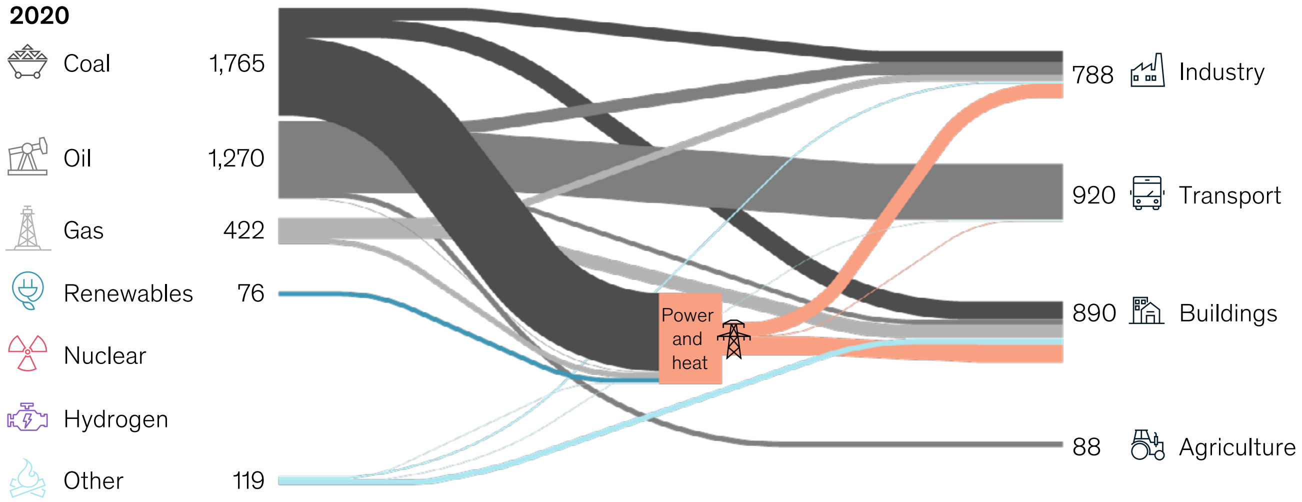
The economically driven decarbonization scenario results in the increased electrification of all sectors, which boosts demand growth by an additional

Changes in the energy system would be profound. The transition away from fossil fuels would increase power demand by a factor of 2.4

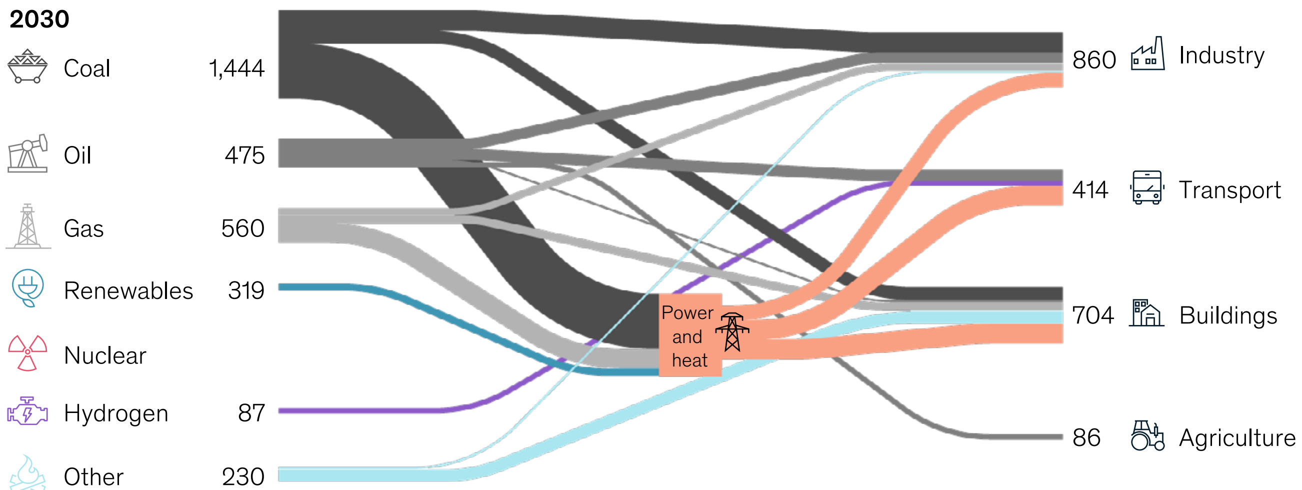
Exhibit 8

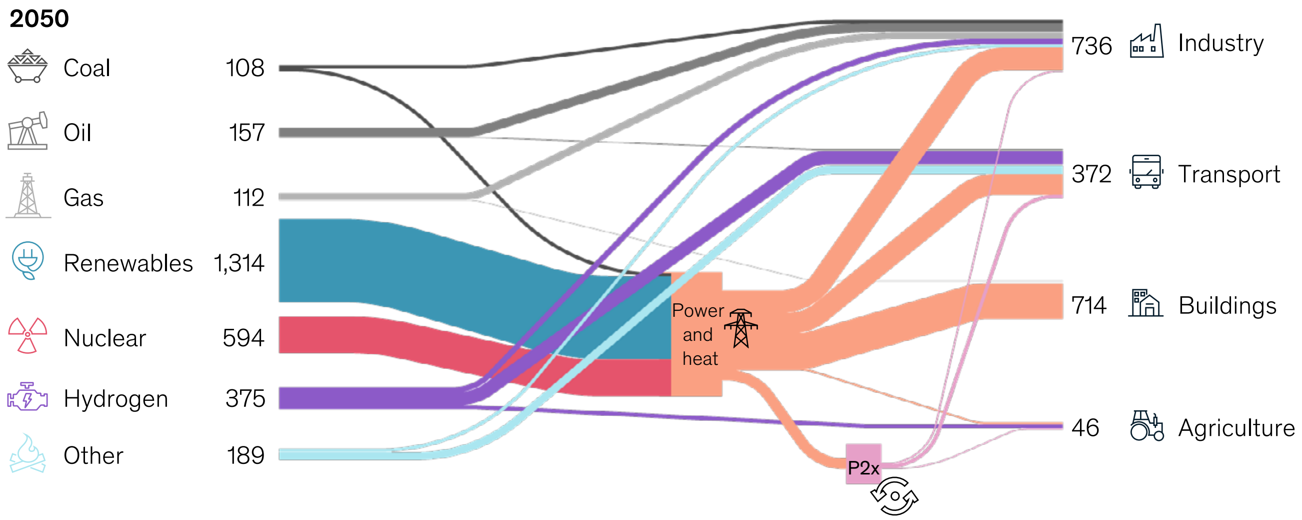
Poland's evolving energy inputs and outputs

PJ



Note: Actual energy flows in Poland in 2020 might look different from to the outlook due to the COVID-19 outbreak's impact on the economy.



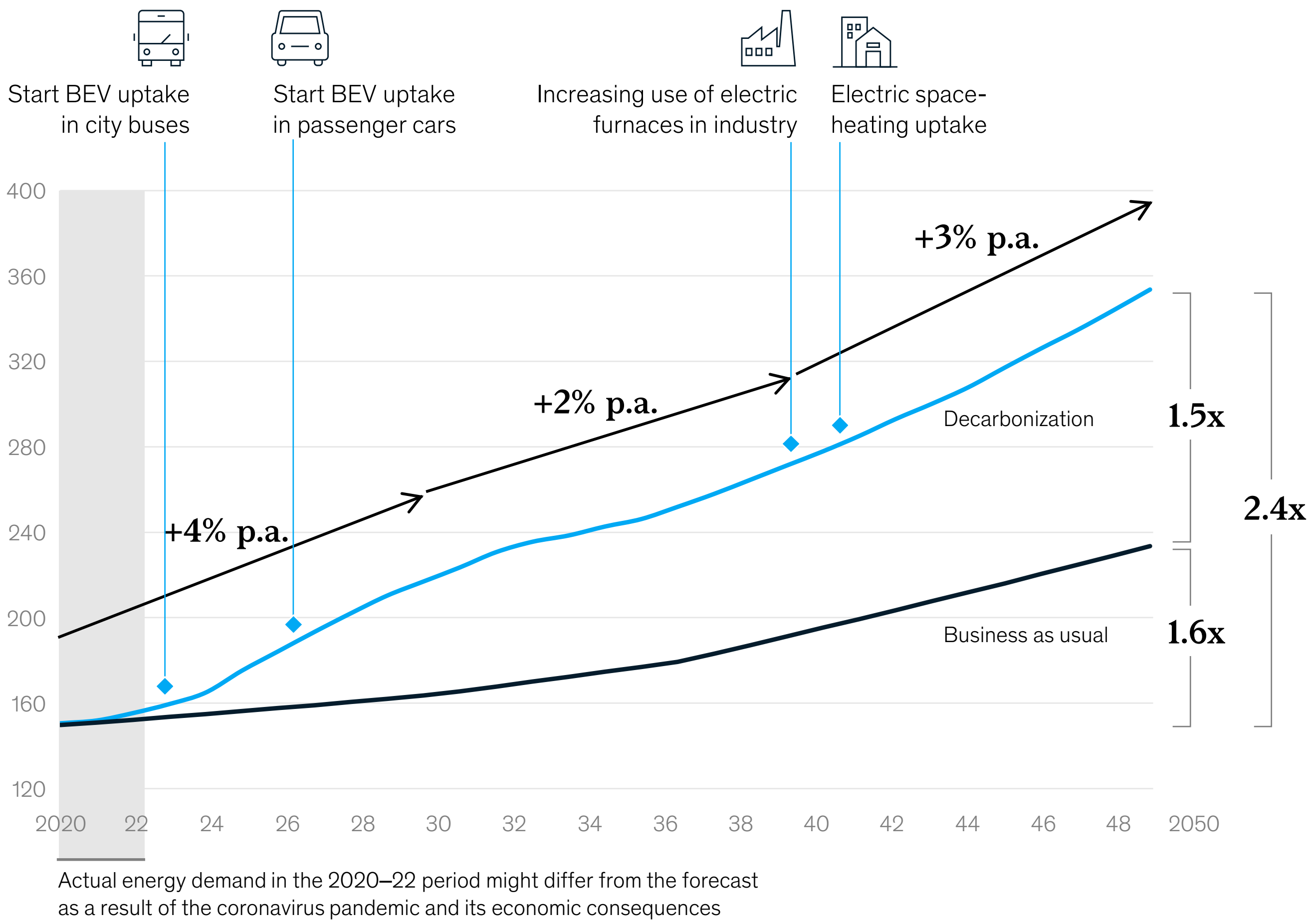


Source: Decarbonization Pathway Optimizer McKinsey & Company; Global Energy Perspective; Sustainability Practice McKinsey & Company

Exhibit 9

A potential increase in electricity demand for the next 30 years

%, annually



Source: Decarbonization Pathway Optimizer McKinsey & Company; Global Energy Perspective Reference Scenario; Sustainability Practice McKinsey & Company, McKinsey Energy Insights.

50 percent compared with the BAU case (Exhibit 9). Therefore, compared with today, electricity demand in our decarbonization scenario is expected to grow by a factor of 2.4.

The transport and buildings sectors make up 80 percent of this total, while electrification in other sectors, such as industry, adds 20 percentage points. As a result, in 2050, transport's share of electricity demand will likely increase to roughly 25 percent (compared with the current 2.4 percent). However, industry's share will decrease to less than 30 percent of the national total in 2050 (compared with about 45 percent today).

In our economically driven decarbonization scenario, electricity demand grows at different rates over time, as each sector has its own electrification starting point. From now until 2030, the growth rate will likely be fast (4 percent each year), mainly spurred by the rapid adoption of EVs in transport (city buses and passenger cars) after 2022. The rate slows slightly after 2030, but acceleration (3 percent each year) is expected from 2040 onward. The latter would occur as electric industrial and building solutions—for example, electric furnaces in industry and heat pumps in buildings—are implemented at scale.

The increase in power demand could be met with a sustainable supply of low-emissions energy. Carefully planning capacity additions would be necessary to enable progressive electrification without negative external side effects, such as price increases or the greater risk of grid instability.

There is potential for a power-supply evolution

Two fundamental changes would be necessary to move toward fully decarbonizing the power supply by 2050. First, coal-fired generation would need to decrease by almost 95 percent from 2020 to 2050 (with a corresponding reduction of capacity by 80 percent). More than 85 percent of existing coal-fired capacity is currently expected to reach the end of its lifespan during this window.[46]

Second, renewable generation is expected to increase in Poland's power mix, with wind and solar accounting for about 80 percent of the total power supply by 2050. The expansion of renewable power is largely enabled by the declining capital costs of technologies and the expected CO_2 prices from the EU Emissions Trading System (ETS), assumed at €29 to €34 per tCO_2 emissions from 2020 to 2050. Our analysis shows that onshore wind power is expected to reach cost parity with existing coal generation before 2025, followed by offshore wind power before 2030 and solar power before 2035.

The shift away from coal would likely have profound implications for the country. Historically, Poland's economy has relied heavily on coal: approximately 80 percent of its power is currently generated by coal-fired power stations. In addition, about 90,000 people are employed in the coal industry, with sources quoting a similar quantity in adjacent industries.[47] The coal industry is an important social and economic topic in Poland, making the transition to RES an important issue for all stakeholders (see sidebar "Poland's history with coal").

These shifts—perhaps surprisingly—would likely have a limited impact on

current employees, at least initially, but may require reskilling efforts in the long term. Production from coal-fired power stations is expected to decrease by approximately 20 percentage points by 2030 under the most recent government plans.[48] In the same time period, a similarly large portion of employees (according to our analysis, approximately 40,000 employees, or 45 percent)[49] is expected to retire for age reasons. Considering that employment in coal mines is largely fixed and Poland imported approximately 10 to 15 percent of its coal consumption in 2017 and 2018,[50] the reduction in coal demand would likely not be matched by a proportional reduction in labor. The industry would likely have to hire new workers by 2030 to at least partially cover the retirement gap (in both the business-as-usual case and the economically driven decarbonization scenario), but the absolute number of employees may be decreased due to automation and increased mining efficiency. Planning ahead with reskilling programs to ease the movement of these workers to low-carbon industries after 2030 would be beneficial for the workforce in Poland. More information on that topic can be found in Chapter 5.

Achieving an optimal, cost-effective mix of energy sources to meet Poland's power demand with low-carbon generation through 2050 would require additional natural-gas and wind capacity (Exhibit 10). These two energy sources account for approximately 15 percent of total power generation in 2020, a share that would rise to approximately 75 percent by 2050. The remaining generation in 2050 could be largely supplied by nuclear, solar, biomass, and hydropower sources, as well as coal-fired plants retrofitted with CCUS.

Natural-gas-power capacity could increase to 18 GW by 2030, which could offset almost all decreases in supply from existing coal power plants. The total natural-gas supply needed for peak power generation is expected to increase to about 9 billion cubic meters (bcm) in 2030. Poland should be able to import and transmit this volume given its recent and planned expansions of natural-gas infrastructure. In the economically driven decarbonization scenario, 5 GW of natural-gas power stations would be decommissioned after 2040. Their lifetime can be extended to provide additional balancing capacity in the system, as detailed in the following part of this chapter. Increased demand would also require a strong infrastructure for natural-gas transmission, storage, and importation. For the latter, one option is to expand Poland's current liquefied natural gas (LNG) infrastructure.

Zero-carbon power sources

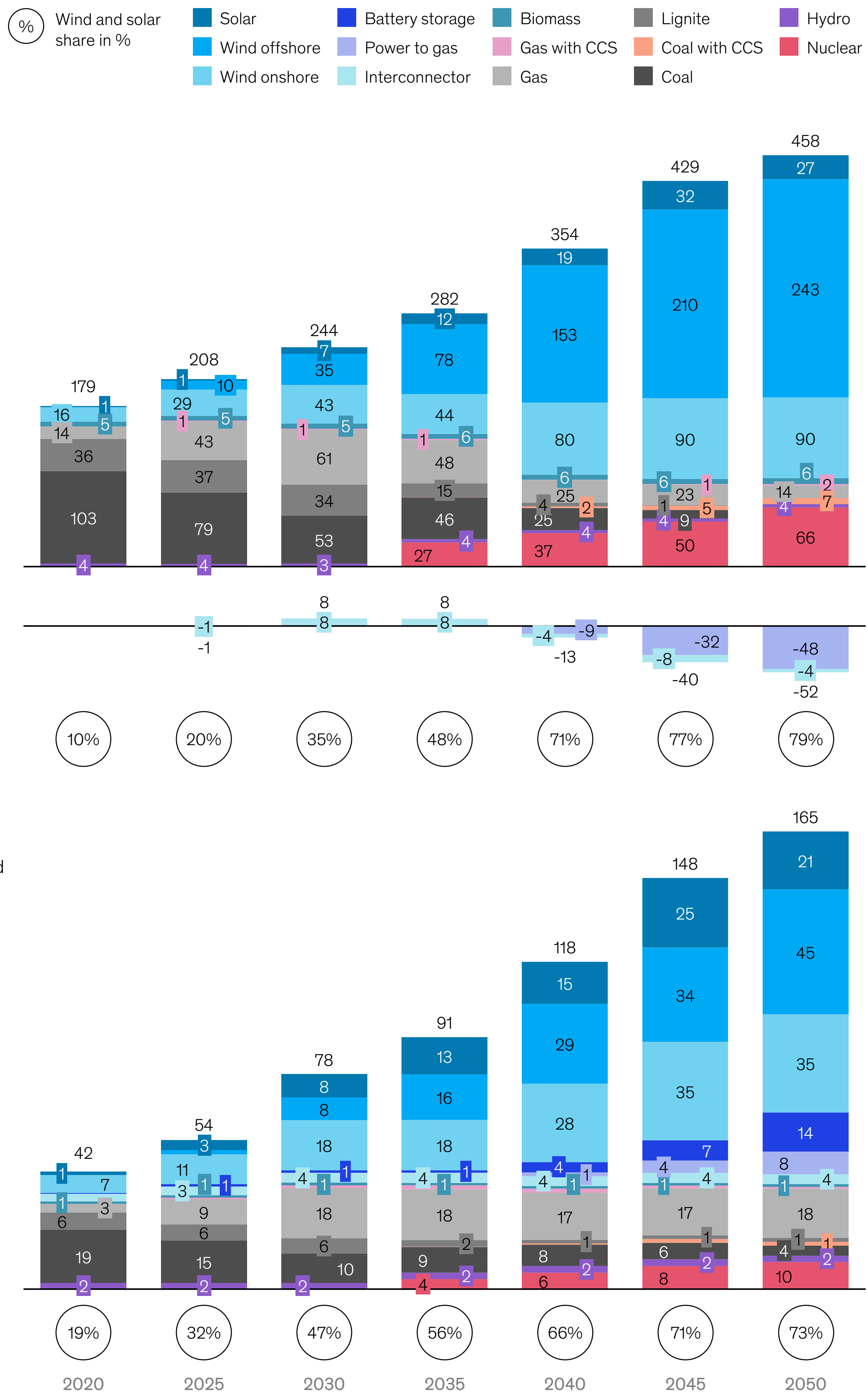
The transition to zero-carbon power depends on accelerating the installation of RES to meet electricity demand.

In our economically driven decarbonization scenario, wind power becomes the single largest power source after 2030 and accounts for approximately 50 percent of the total power capacity by 2050. Offshore wind increases to 45 GW, or about 30 percent of the total power capacity in 2050 (see sidebar "Offshore wind's potential"). Onshore power would grow to 35 GW by 2050 and contribute 21 percent of the total power capacity that year. A construction program of this scale would require solving regulatory, environmental, and supply-chain constraints. However, it could also create opportunities to develop new industries in Poland.

Additional solar-power capacity is assumed to grow at a relatively constant rate and will benefit from ongoing decreases in technology costs and associated expenditures. By 2050, solar power would account for approximately 13 percent of total capacity.

Exhibit 10

Poland's potential energy mix



Source: McKinsey Flexibility Power Model, October 2019

Poland's history with coal

Before Poland's transition to a market-based economy in 1989, coal was its primary source of electricity, accounting for almost 100 percent of the electricity supply. As a result of its reliance on coal, Poland was among the top five global coal producers at the time. Production peaked in 1979 but decreased subsequently because of falling efficiency in coal mines and a lack of access to global markets. Similarly, the coal mining sector's contribution to Poland's economy fell by more than half during the past two decades—from 3.7 percent of GDP in 1995 to 1.8 percent in 2015. Employment declined from 400,000 people in 1990 to fewer than 90,000 in 2018.

Coal is still integral to the country's total primary energy demand, but a few factors are expected to lead to further reductions. First, production costs are expected to increase as easy-to-exploit deposits run out, and Polish labor costs are predicted to rise. Second, decreasing costs of renewable energy sources provide a viable alternative to coal power. Third, coal-fired power generation would become increasingly expensive if zero-emissions targets are introduced (accompanied by increasing carbon taxes, for instance). Finally, the availability and cost of financing new carbon investments such as coal mines and power stations have been decreasing over the past several years, with both commercial and development banks introducing negative screening for high-emissions technologies.

Our scenario assumes the commissioning of nuclear capacity in line with the latest Energy Policy of Poland by the Polish Ministry of Energy, with 6 to 9 GW of nuclear-power planning to be constructed from 2033 to 2043.[51] This capacity can supply about 6 percent of the power demand by 2050. Nuclear projects are typically beset by time and budget challenges, including site selection, start preparation, and securing of the supplier contracts. Poland would have to address these hurdles in the near term to deliver the first unit according to the plan.

Assuming that plans are realized, nuclear would become relatively attractive in our decarbonization scenario. First, capital expenditures for subsequent nuclear plants are expected to be lower than for the first units, as certification, design, and construction experience accrues, reducing the levelized cost of energy. Moreover, coal or natural-gas generation gets more costly because of the purchase of EU ETS credits and CCUS. Assuming already-planned investments, our modeling of Poland's power mix suggests that 1 GW of additional nuclear capacity beyond the government plan will be justified, for 10 GW in total. If the efficiency promise on the nuclear technology is not realized, the additional dispatchable power could be contributed by gas-fired power stations equipped with CCUS technology, for example.

Power-system flexibility and resilience

Integration of more than 80 percent of intermittent renewable power generation into the grid would require new zero-carbon flexibility solutions (flexibility solutions provide additional power-balancing capacity and power quality services). These solutions would provide additional intraday backup with storage, power curtailment for periods of high renewable-energy production, and resilience against extreme weather events, such as prolonged periods of overcast skies and no wind.[52]

The following solutions can help Poland meet its GHG-reduction goals, according to our scenario.

— First, Power-to-X technology (such as renewable electricity-powered electrolyzers) can be used to produce hydrogen, making hydrogen an increasingly important

In our economically driven decarbonization scenario, wind power could become the single largest power source after 2030 and could account for around 50 percent of total power supply by 2050

€75bn

potential investment needed for electricity-grid replacement in Poland regardless of decarbonization by 2050

energy carrier in heavy-duty transport and industry. Our scenario assumes 8 GW of Power-to-X capacity will be used to absorb excessive renewable generation (especially offshore wind in northern Poland) and feed it back into the power system as needed.

- Second, battery storage would increase to 14 GW, mainly serving as intraday backup. The deployment of new storage would be enabled by decreases in the costs of technology, which are assumed to drop from about €260 per kWh in 2019 to approximately €50 per kWh in 2050.[53]
- Third, coal-fired power stations with a generation capacity of 4 GW could be retrofitted with CCUS technology and co-fired with biomass by 2050 to provide additional zero-carbon balancing capacity.
- Last, our scenario estimates a limited contribution from cross-border transmission lines in energy production, mainly because most neighboring countries have renewable supply-and-demand profiles similar to Poland's. These transmission lines will still play an important role for system balancing, however.

There are additional opportunities to further increase the power system's resilience. For instance, the introduction of demand response and distributed generation could provide even more opportunities for peak load reduction. (For more details, see Appendix C).

A reinforced electricity transmission and distribution grid

According to our analysis, over the next three decades—regardless of decarbonization—a total investment of approximately €75 billion will likely be needed for electricity-grid replacement in Poland. The economically driven decarbonization scenario would add €30 billion to €35 billion for its extension and enhancement.

From 2020 to 2050, we estimate that under the BAU case the transmission grid would require investments of approximately €25 billion. To facilitate decarbonization, an additional €20 billion to €25 billion may be required to reinforce and upgrade transmission grids to accommodate the growth of power capacity and demand. About half of this additional investment would be allocated to increasing the power capacity. Significant upgrades would be necessary to take offshore wind power from the Baltic Sea to the south of the country (where large coal and lignite plant retirements will occur). The remaining investment would be allocated to accommodate peak load growth.

From 2020 to 2050, our modeling shows that the distribution grid would require additional investments of approximately €50 billion in the BAU case, as current infrastructure requires end-of-life replacement and electricity demand grows. An additional investment of approximately €10 billion for distribution grids would be needed to accommodate the economically driven decarbonization scenario. The main investment drivers are the electrification of demand (such as electric-powered heat pumps and EV charging) and consumer trends (such as rooftop solar), which account for approximately 80 percent of the incremental investments in the distribution grid, as well as onshore wind, which makes up the remaining 20 percent of investments.

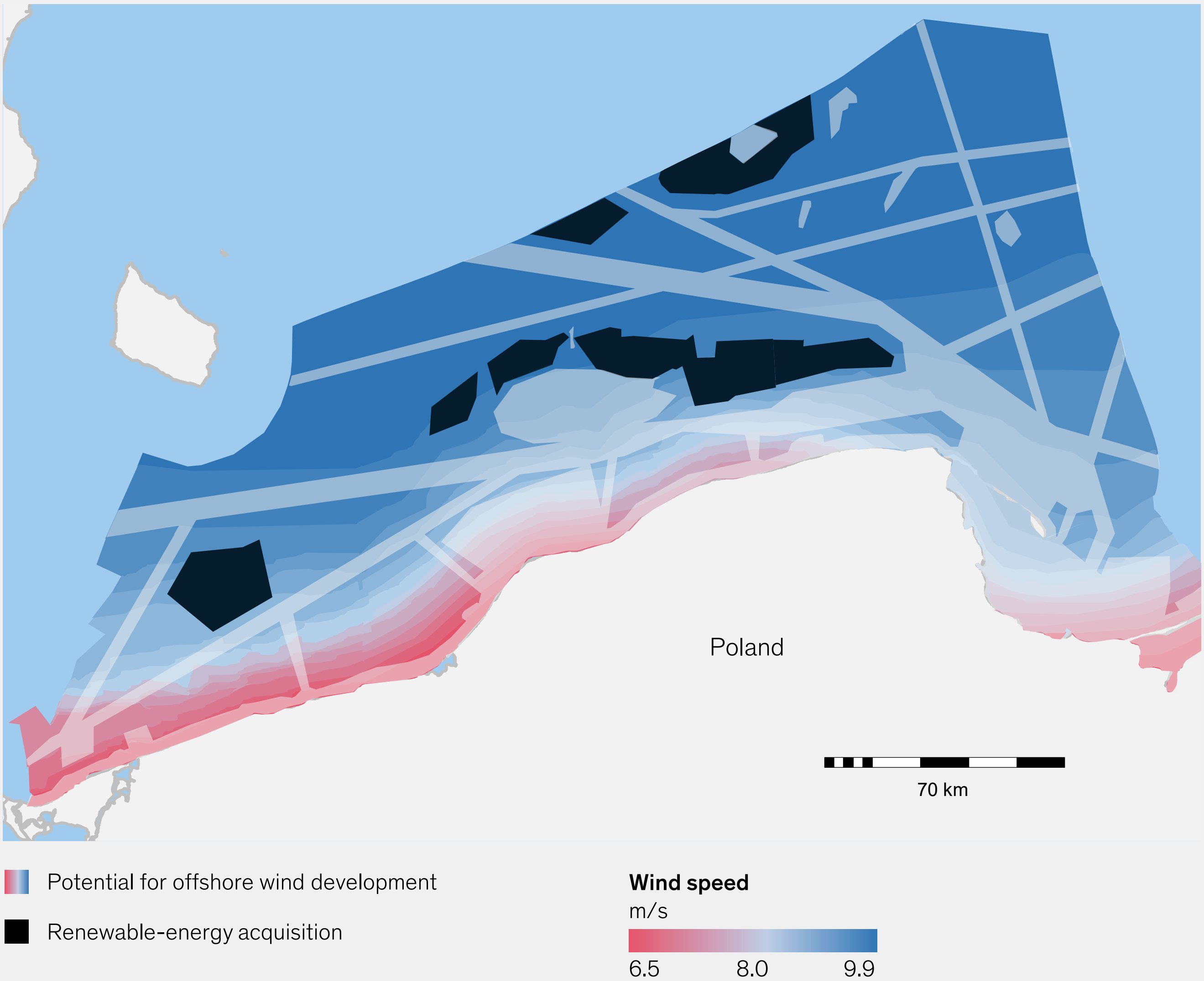
Offshore wind’s potential

In our economically driven decarbonization scenario, offshore wind plays an important role in providing low-carbon electricity. From 2020 to 2040, up to 30 GW of offshore wind power could be constructed. Over the subsequent ten years, an additional 15 GW could come online, bringing the total to 45 GW. This figure is higher that of other market perspectives. Our analysis, based on the availability of unassigned offshore territories, suggests that the potential 30 GW of offshore wind generation would require approximately 25 to 30 percent of the available area. Assigning an additional 15 percent of the available sea area would be sufficient to host a total of 45 GW (Exhibit 11). More details can be found in Appendix C.

The Polish Baltic Sea offers very good conditions for offshore wind. It is not only quite shallow (with an average depth of less than 50 meters) but also has strong winds. Average wind speeds are more than 8 meters per second, and offshore wind projects are potentially viable with wind speeds exceed 7 meters per second.[54]

Exhibit 11

Offshore wind development potential in Poland's exclusive economic zone in the Baltic Sea



Source: Maritime Office in Gdynia (2018); National Marine Fisheries Research Institute (2018); *Bulletin of the Polish Academy of Sciences* (2018)

Chapter 5

Decarbonization's costs and impact

Decarbonizing Poland's economy could have profound implications on the country's economic structure. In this chapter, we outline the three main macroeconomic implications of our scenario. First, decarbonization would require additional initial capital expenditure—for example, to enable the mobility transformation and the upgrade of energy infrastructure and building stock. This increase in capital outlays would be partially offset by operational savings, such as from better-insulated homes or more efficient transport.

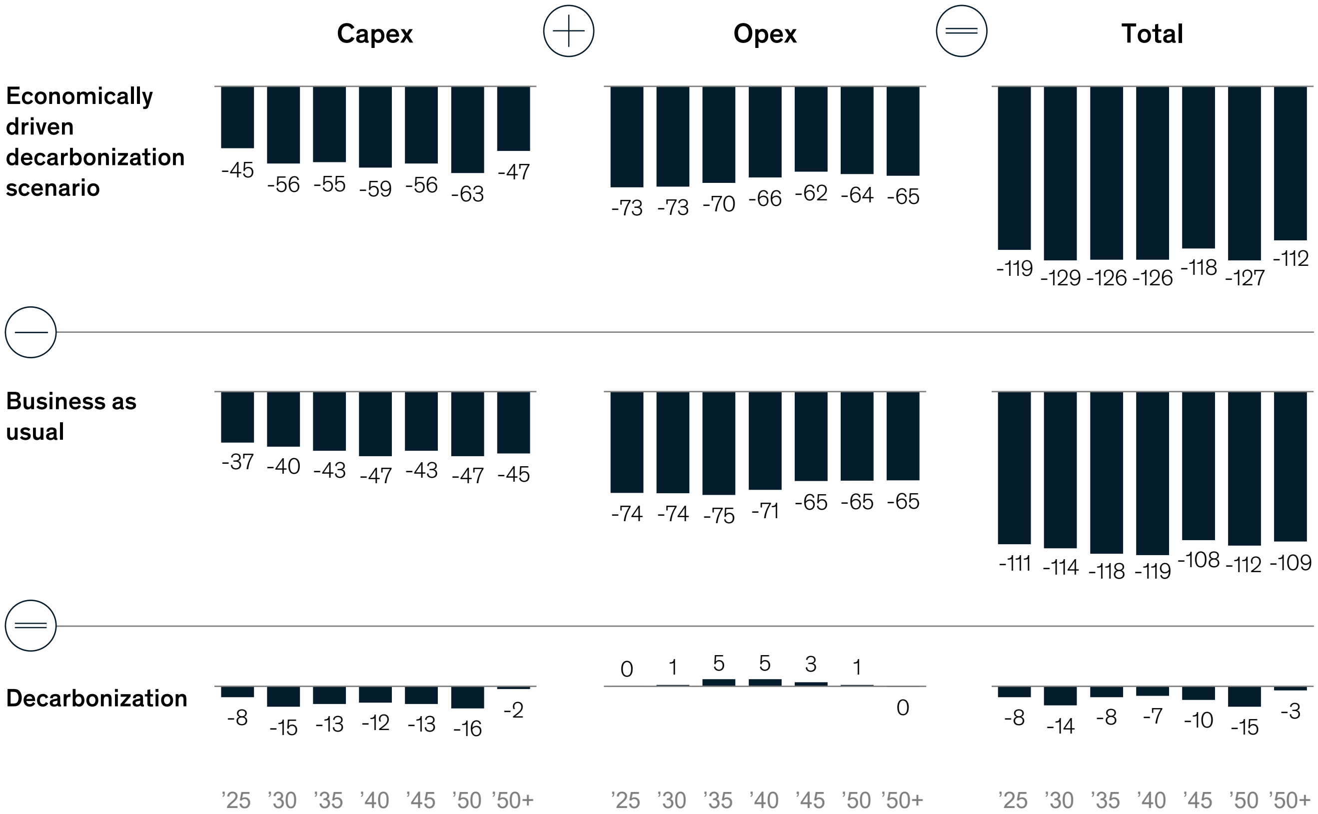
Second, our analysis suggests two fundamental, second-order effects from the decarbonization pathway. The Polish trade balance is expected to structurally improve as the country reduces its fossil fuel imports by approximately €15 billion each year (under current commodity prices). In addition, a decarbonized economy has structurally different economic activities and could thus benefit from tailored taxation redesign. We have performed an illustrative analysis of the role of taxation in transport to outline the role to understand the potential tax implications of a transition to a low-carbon economy.

Last, the decarbonization pathway could present opportunities that can help Poland boost economic growth. Our analysis indicates that a portfolio of five low-carbon economic activities could bring economic benefits to the country: BEV components manufacturing, Baltic Sea offshore wind development, industrial-scale production of electric heat pumps, electrified agriculture equipment manufacturing, and R&D and

Exhibit 12

Financial impact assessment for our decarbonization scenario

€ billion, 5-year averages



Note: Assuming a 4% WACC. For cash-flow assessment beyond 2050, 2050 run rate opex is assumed and capex is based on replacement capex as decarbonization-driven technology switches are assumed to have happened during the 2030–50 time frame.

Source: Sustainability Practice McKinsey & Company

deployment of (BE)CCUS technology. These activities combined could structurally increase Poland's GDP by 1 to 2 percent and create 250,000 to 300,000 jobs.

The economics of our decarbonization pathway

Over the next 30 years, decarbonizing Poland's economy would require additional investments that could pay off in reduced operational costs. In our decarbonization pathway scenario, total investments in the Polish economy from 2020 until 2050 would need to increase by €380 billion. At the same time, operational costs are expected to decrease by €75 billion.

Decarbonization's investment and return profile

Our analysis suggests that to achieve full decarbonization, Poland would need to increase capital expenditures by an average of €13 billion each year through 2050. Almost half of these additional investments would need to be made over the next 15 years, mainly focused on switching to BEVs and upgrading energy and buildings infrastructure. In most situations, economic actors are expected to recoup their decarbonization investments through operational savings (Exhibit 12).

These additional annual investments equal roughly 1-2 percent of Polish GDP and 10 to 12 percent of Poland's current annual investments in the economy. Such an increase in spending would bring Poland in line with the EU average for investments, around 21–22 percent of GDP.[55]

Investment and return profile by sector

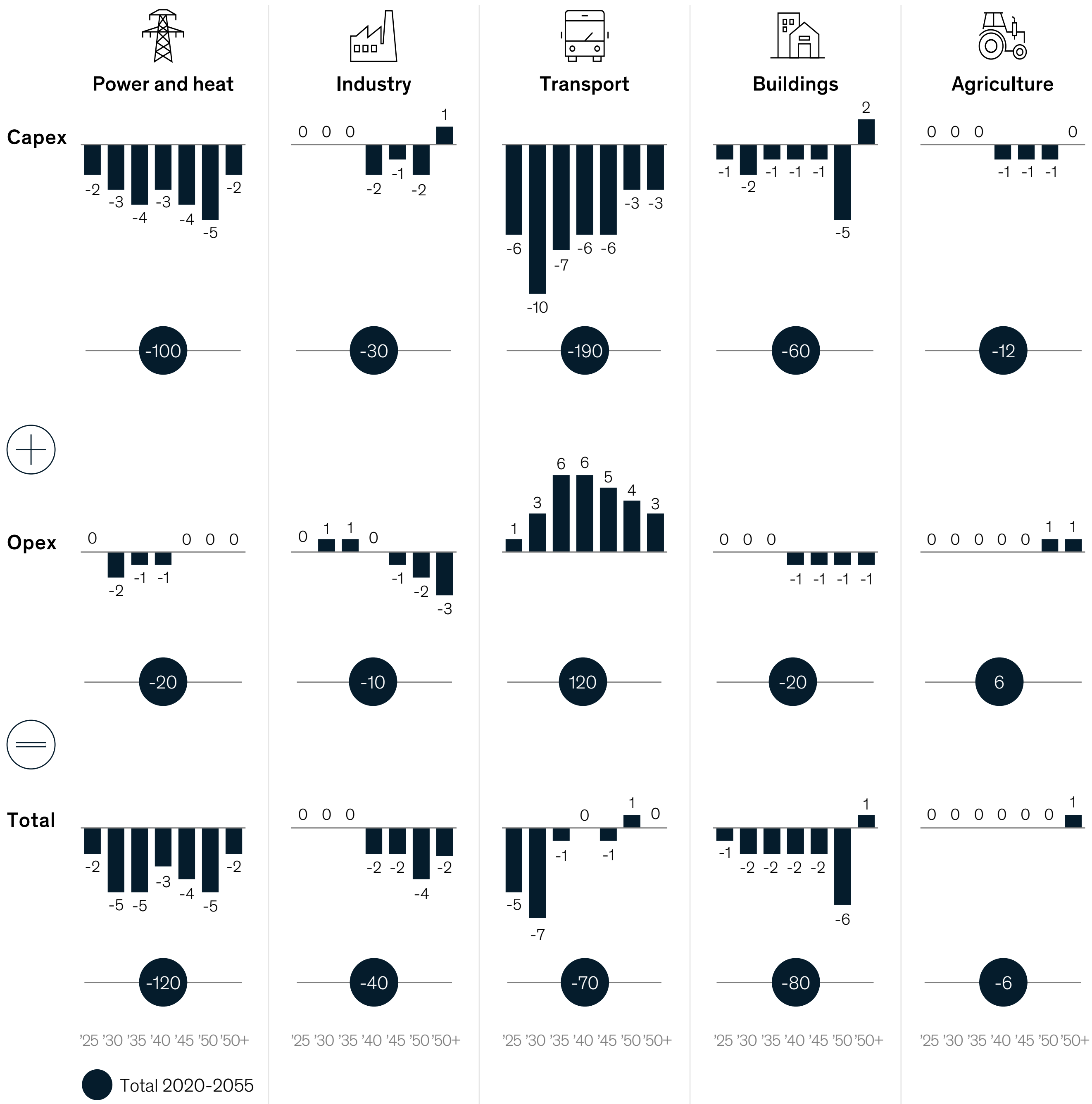
The top-line numbers for decarbonization only tell part of the story. Individual sectors exhibit different underlying financial profiles and trajectories (Exhibit 13).

Investments in decarbonization are characterized not only by their net financial impact but also by other factors, such as to whom any benefits would accrue (see sidebar "Four decarbonization lever archetypes").

Exhibit 13

Financial impact by industry for our decarbonization scenario

€ billion, 5-year averages per annum



Increasing power generation by a factor of 1.5 compared to BAU would require additional investments (capex) in power generation and will need higher opex, driven by gas generation

Cash flow in industry would be positive in next 15 years when energy efficiency measures yield returns. In 2035 to 2050 time frame, capital expenditures would increase beyond business-as-usual case; additionally, while looking beyond 2040, opex would increase to cap industrial emissions

Cash flow in transport would be net positive and would be mainly driven by substantial opex savings from lower electricity prices compared with fossil fuels

Cash flow in buildings would be net negative due to the additional capex required in insulation and heating technology. Moreover, heating technology investments typically do not result in opex savings, as current fuels have low price points

Decarbonizing agriculture would have modest financial impact. Higher capex would be mainly driven by a switch to low-carbon fuels (e.g., ammonia) in agricultural equipment

Note: Assuming a 4% WACC. For cash-flow assessment beyond 2050, 2050 run rate opex is assumed and capex is based on replacement capex as decarbonization-driven technology switches are assumed to have happened during the 2030–50 time frame.
Source: Decarbonization Pathway Optimizer McKinsey & Company

Four decarbonization lever archetypes

Each sector and decarbonization lever has different underlying dynamics. We have identified four decarbonization lever archetypes based on the return and payback profile of individual initiatives (Exhibit 14).

Decarbonization levers with stand-alone economic rationale. These levers have attractive payback periods, sufficiently high internal rates of returns (IRRs), or both. As such, they motivate profit-seeking economic agents to act.

Decarbonization levers with economic rationale but agent issues. Investments in these levers yield positive returns, but the profits accrue to different actors, thus impeding action.

Decarbonization levers with limited financial incentives. With low absolute returns and IRRs, these factors discourage agents from acting.

Decarbonization levers with no stand-alone economic rationale. These levers do not create any savings and thus give agents no economic incentive to act.

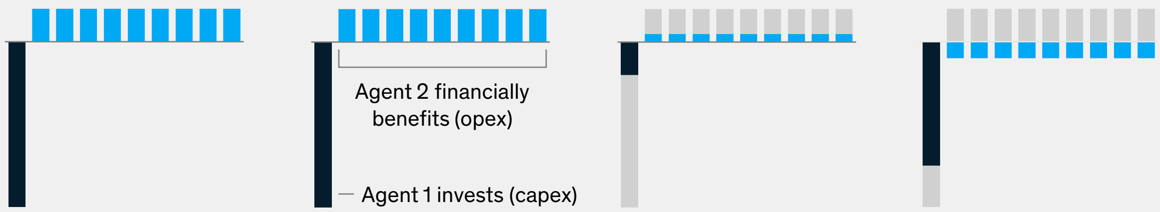
In addition to these decarbonization levers' financial characteristics, more relevant elements could make climate action complex. For instance, even with a sound economic rationale, a broad variety of barriers can limit progress, including political considerations (such as taxpayers' perspective), the regulatory landscape, infrastructure, supply chain, technology, and opposing business interests (for example, incumbents versus new industry).

Exhibit 14

Four decarbonization archetypes in our scenario

Change in capex[a] Change in opex[a]

	1 Levers with stand-alone economic rationale	2 Levers with economic rationale but agent issues	3 Levers with limited financial incentives	4 Levers with no stand-alone economic rationale
Illustrative cash flow				



	1	2	3	4
Logic of agent	Economic agent would invest in decarbonization lever because it results in opex savings with a sufficiently short payback period/high IRR	Economic agent doesn't invest in decarbonization lever because benefits are harvested by other economic agent	Economic agent would not invest in decarbonization lever because economic incentive is limited in absolute terms and/or IRR is too low	Economic agent would not invest in decarbonization as there are no savings
Climate action strategy	Promote/stimulate agents to act faster on decarbonization	Stimulate cross-agent collaboration (e.g., benefits sharing) and promote faster decarbonization	Promote/stimulate agents to act on decarbonization and seek ways to reduce efforts	Develop framework to support decarbonization for hard-to-abate/expensive activities with a level (international) playing field
Illustrative example	BEVs have higher upfront capital need but yield operational cost savings	Rental building insulation requires upfront investment by owner while tenant benefits from reduced costs	Heating technology fuel switch requires relatively limited investments with some ongoing operational costs[b]	Industrial CCUS requires both upfront investments and ongoing operational expenditures

a. Change in capex and opex vs business-as-usual technologies.
b. Electric-based heating in Poland is typically more expensive than coal- or waste-based heating.
Source: Sustainability Practice McKinsey & Company

The effects of decarbonization on trade and taxation

Decarbonization will also affect other stakeholders beyond Polish businesses and individuals. Our analysis examines changes in the trade balance, largely resulting from moving to different energy carriers and changes to taxation.

Impact on trade balance
The decarbonization transition would likely help improve Poland's trade balance by reducing reliance on fossil fuel imports. According to our analysis, Poland currently has a negative trade balance of approximately €15 billion[56] a year (Exhibit 15). In a carbon-neutral scenario, this total could be reduced to about €3 billion a year by 2050. The increased domestic spending and focus on decarbonization could positively affect employment, since the macroeconomic multiplier on virtually all other economic activities could generate more GDP and jobs domestically than fossil-fuel imports.

Impact on taxation
As decarbonization alters the way businesses operate and use products and services, it would likely affect the government's tax revenues if we assume the same system remains in place. During the long run, changes to tax policy and structures could be made, and the transport sector illustrates the potential impact.

Typically, transport infrastructure is financed by government taxes on fossil-fuel consumption (see sidebar "Taxation in transport"). Thus, the transition to zero-carbon transport would fundamentally change the infrastructure financing stream, and, if the gap is not covered, it could potentially hinder government investment including the development and maintenance of crucial infrastructure. Possible solutions for securing future financing could include a redesign of the taxation scheme across all types of fuels (including diesel, gasoline, natural gas, electric power, and hydrogen) with the right incentives for low-emissions fuels adoption or transitioning to a model based on paying for access to infrastructure.

Decarbonization could spur economic growth

In the context of the EU's decarbonization journey, Poland could further increase employment and prosperity by investing early in certain industries. To capitalize on its strengths and pursue additional economic growth, the country could develop a portfolio of decarbonization-enabling industries. A variety of factors should be considered when designing such a portfolio:

— Industry relevance in enabling a decarbonization transition

— Socioeconomic attractiveness (for example, the size of the domestic and EU markets as well as growth rate, quality, and quantity of possible job creation)

— Industry fit with Poland's characteristics—its capabilities, infrastructure, and comparative advantages compared with other countries

Growing GDP and creating jobs
Building a portfolio of decarbonization-enabling industries could structurally improve the country's GDP and help Poland create more jobs in high-growth industries.

By attracting and stimulating new economic activity in low-carbon sectors, Poland could add €10 billion to €12 billion to its GDP by 2030 (1 to 2 percent of additional GDP). This increase would mostly come from developing the offshore wind industry (€4 billion to €5 billion), with the production of industry-scale electric heat pumps and BEV components adding €2 billion to €3 billion each. Poland would further benefit as consumers from growing industries would have more to spend in the economy's other sectors.[57]

Exhibit 15

Poland's 2018 energy commodities trade balance

a. Petroleum oils and oils obtained from bituminous minerals; crude.

Source: Comtrade Database 2018

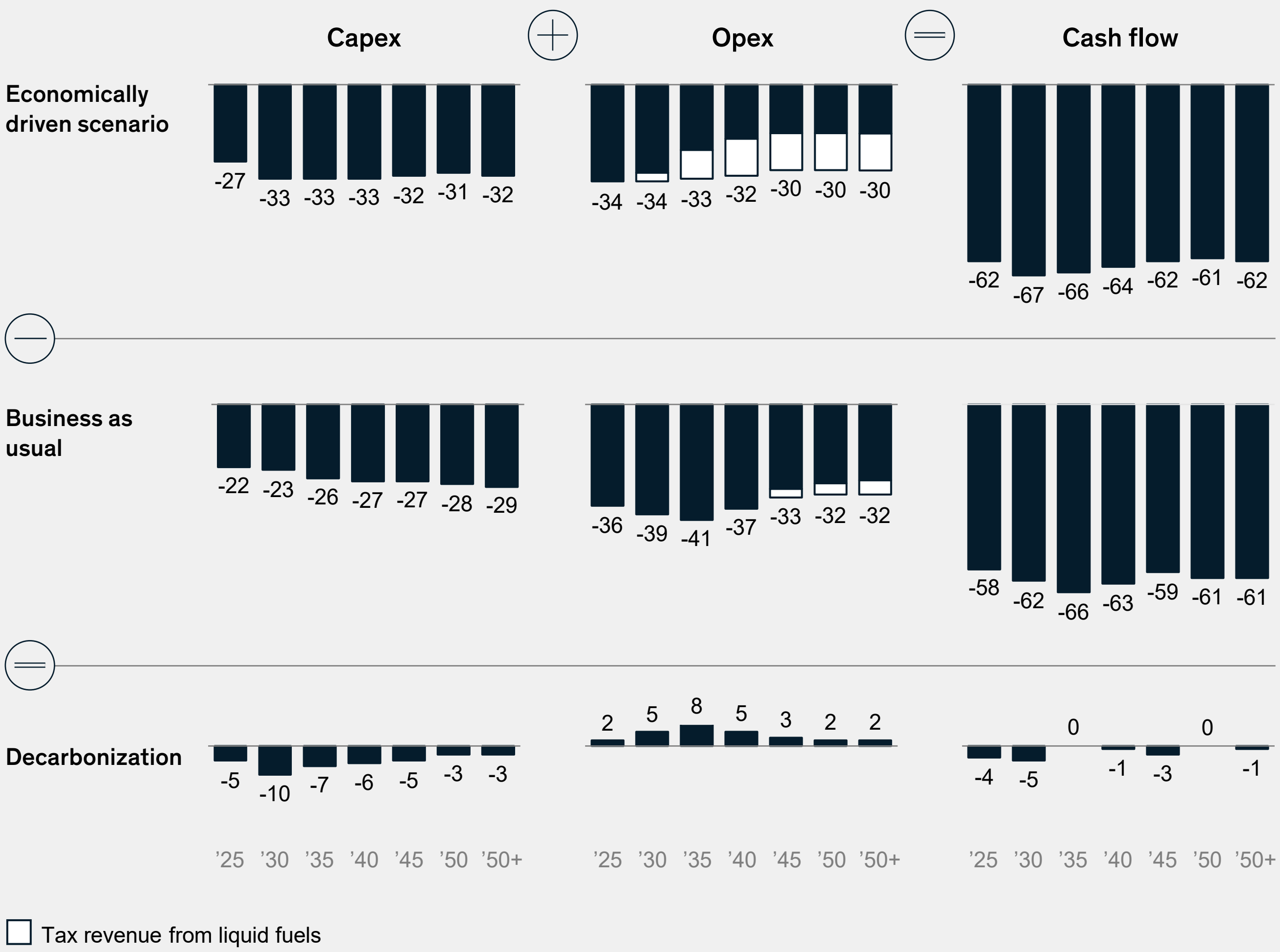
Taxation in transport

In 2018, Poland collected €16 billion from taxes on the consumption of fossil fuels in transport.[58] Electrification efforts under the economically driven decarbonization scenario would mean that annual tax revenue in 2050 would drop by €13 billion compared with base year. Under the BAU case, the erosion of tax revenue would be slower, approximately €4.5 billion by 2050 (Exhibit 16).

Theoretically, in our economically driven decarbonization scenario, the introduction of a tax on electricity would increase transport operational expenditures by 38 percent. However, when compared with the BAU case, full decarbonization scenarios still yield operational-expenditure savings. Total net cash flow including taxes would be negative until 2030 and become roughly neutral afterward.

Exhibit 16

Tax implication of decarbonization



Note: Assuming a 4% WACC. For cash-flow assessment beyond 2050, 2050 run rate opex is assumed and capex is based on replacement capex as decarbonization-driven technology switches are assumed to have happened during the 2030–50 time frame.

Source: Sustainability Practice McKinsey & Company

5

areas present promising GDP growth and job-creation opportunities

Our analysis suggests that pursuing the macroeconomic opportunities outlined below could generate more than 250,000 to 300,000 additional jobs in industries such as advanced manufacturing, research and development, and construction. At the same time, Poland's population is expected to decline, and we estimated that by 2030 the labor force will shrink by 8 percent.[59] A significant reskilling effort would be needed to help workers transition to jobs in these industries. A reskilled workforce could then be employed in less physically intensive, healthier, and higher-paying jobs that create more value.

Any stimulus created by decarbonization could be especially important to recovery from the economic slowdown caused by the COVID-19 outbreak.

Five opportunities

Five areas, from the shortest to the longest expected time to materialization, present promising opportunities.

BEV component specialist

Poland is well positioned to become Europe's major supplier of EV components for three reasons. First, the country has access to a well-educated labor force[60] with relevant skills—more than 70,000[61] students graduated with engineering degrees in 2016. Second, Poland has already established strong relationships with the German and wider European automotive industries, exporting €8.2 billion worth of auto components in 2018.[62] Third, Poland has an advantageous geographical location, with easy access and proximity to major European automotive factories.

The country's location is particularly important for battery production and assembly because of high transport costs. In fact, Poland has already attracted several Asian battery manufacturers. In 2018, LG Chem opened a 20-GWh facility—the world's second-largest battery production facility—in Poland's Lower Silesia district. It plans to expand its production capacity more than three times by 2022. In addition, at the time of publication, three other battery companies—Shenzen Capchem Technology,[63] Zhangjiagang Guotai Huarong Chemical New Material,[64] and SK Innovation[65]—have announced production plans in Poland.

In 2030, total BEV battery production in Europe is estimated to be €22 billion.[66] If Poland captures 20 percent of the market, it could attract €2.2 billion in foreign direct investments and add €2 billion to €3 billion a year to its GDP.

For Poland to be competitive in this industry, the country could facilitate carbon-free production of components. This factor is increasingly important in the supplier selection process: various automotive original-equipment manufacturers are making reducing their GHG footprint an integral part of procurement decisions.

Baltic offshore wind developer

Built-in advantages could enable Poland to become a leading offshore wind developer.[67] The Baltic Sea has good natural conditions: strong and stable winds and relatively shallow waters—about half of the Polish Exclusive Economic Zone in the Baltic Sea has an average depth of less than 50 meters.[68] This combination makes the cost of wind deployment and use competitive, with a levelized cost of energy of approximately €40 per MWh in 2035 compared with the country's weighted average cost of €44 per MWh.

Several investors have already obtained permits to build artificial islands, and two have signed agreements to connect total wind-farm generation of 2.2 GW to the power grid.[69] The expected 8 GW of offshore wind generation could contribute an additional €4 billion to €5 billion[70] in GDP a year and create 120,000 to 130,000 jobs in 2030. In addition, Poland could position itself as a leading producer and exporter of offshore wind equipment by taking advantage of its established engineering industry and existing relationships with international companies, which have production plants in Poland.

Industrial-scale electric heat pumps producer
Poland has the potential to specialize in the production of industrial-scale low- and mid-temperature electric heat pumps that could be deployed in heating networks and in industry to supply low-grade heat. Poland's domestic market for heat pumps is estimated to reach €0.5 billion by 2030.[71] Since Poland has one of the largest district heating networks in the EU, it requires more extensive modernization.

In addition, Poland could harness its existing advantages, including access to engineers and training centers and proximity to consumers. If Poland develops its industrial-scale heat pump industry before 2022, it could be a top exporter of electric heat pumps within Europe, where the market is expected to grow significantly. If the country were to supply 10 percent of European heat pumps and half of Poland's domestic heat pumps by 2030, it could generate €4 billion to €5 billion in revenue, increase GDP by €2 billion to €3 billion, and create approximately 50,000 jobs.

Electrified agriculture supplier
The development, production, and export of innovative electric or ammonia-fueled agriculture equipment offer another opportunity. Poland has an annual agricultural goods output of €24 billion[72] and uses agriculture equipment worth €34 billion.[73] Since the country's agriculture sector is fragmented and largely relies on existing carbon-heavy equipment, electric and low-carbon farm equipment could help the sector dramatically reduce emissions while increasing productivity and value creation.

In 2018, European capital spending on agricultural equipment was €49 billion, with approximately 0.4 percent spent on electric tractors and low-carbon motorvehicles.[74] Ongoing structural changes in agriculture—such as efficiency improvements that free up land to grow forests for biomass—or other sustainability policies (for example, animal welfare) will likely boost demand for new categories of equipment both domestically and within Europe. By 2030, total European expenditures in this category are expected to reach €15 billion to €20 billion.[75] If Poland could gain 10 percent of the market, it could add up to €1 billion a year to its GDP.

Bioenergy carbon capture, utilization, and storage (BECCUS) research, and development and deployment
Poland could develop CCUS technology and equipment and take a leading position in the negative emissions and bioenergy markets. Utilizing its favorable geological conditions—including the proximity of industrial sites and locations favorable for carbon storage—and sizeable natural storage, Poland is well positioned to conduct R&D and deployment for large-scale (BE)CCUS technology. Both Poland and Europe need to create substantial negative emissions to offset hard-to-abate industrial and agricultural emissions. For Poland alone, the need for negative emissions is 37 $MtCO_2e$ in 2050. In the country, CO_2 storage systems, close to industrial sources, may be developed in order to significantly reduce the costs of its transport. At the same time, thanks to the extensive geological structures in the country, capable of storing 15 Gt of CO_2, it will be possible to store CO_2 captured by CCUS systems for the next few hundred years. Poland could become a significant producer of bioenergy by using this natural advantage and investing in R&D.

Chapter 6

Charting a way forward

Decarbonizing Poland's economy within 30 years is an ambitious and highly complex endeavor. We have detailed the potential transitions that may need to occur and outlined the possible costs and benefits. While the detailed planning of the larger decarbonization transition is beyond the scope of this report, in this chapter we aim to address what a transition road map could look like.

To do so, we organize all the necessary interventions into a sample transition road map that matches our economically driven decarbonization scenario's impact and timing. We also provide a list of the decarbonization elements that would be critical for enacting this road map.

In addition, in this chapter we highlight two areas of potential focus for Poland. From the long list of interventions, we select the areas that are already economically viable—those no-regret moves that the country could look to introduce regardless of the pathway it selects in the future. We note that some technologies are not yet available for mass adoption and would likely require ten to fifteen years of R&D before they could be introduced at scale. This creates investment opportunities for Poland to consider planning for where it can benefit from a carbon-neutral future.

Creating a comprehensive transition road map

To transition the economy, a wide set of coordinated activities are recommended to be implemented. A master plan that defines sector-by-sector activities is required to facilitate the transition. The timing of individual activities would be determined by teach of their business cases. Our economically driven decarbonization scenario assumes faster adoption of the technologies with more viable business cases, followed by technologies that would require more time to reach maturity and therefore have a higher per-unit abatement cost.

Across most sectors, technology is available to launch the transition and start renewing stock in the early 2020s as well as enable full decarbonization by 2050 (Exhibit 17). The only exception is the industry sector, as the CCUS technologies required to decarbonize it are not yet available. Our scenario assumes that sustained R&D would be required to improve CCUS's affordability and availability while addressing legal and social issues related to storage.

By 2030, decarbonization efforts would need to be well under way in sectors with available cost-effective, low-carbon technologies, such as upgrading building insulation, electrifying urban transport (for example, through electric city buses), and rolling out 8 GW of offshore wind. At the same time, the country would benefit from preparing for the transition in other areas of the economy. Examples include planning an at-scale rollout of BEV passenger cars, switching fuels for agricultural vehicles, and transitioning to low-carbon district heating.

From 2030 to 2040, our road map assumes the scaling of already-launched initiatives and the adoption of additional low-carbon technologies. Examples of the latter include the introduction of negative emissions (through BECCUS) in the cement and lime industry, fuel switches in industry toward hydrogen and biogas, and the replacement of some fossil-fuel generation with nuclear power.

To close the gap to full decarbonization in 2050, action would also be needed in the hardest-to-abate economic areas. Examples include deployment of CCUS across the industry sector at scale and green district heating in Poland.

Launching a successful transition

To enable the decarbonization transition, several action areas need to be addressed. First, a comprehensive road map should be laid out to guide industries in the transition as well as to give investors confidence, thus unlocking capital for the required investments. Further, financing frameworks may need to be developed to ensure enough capital availability. Regulatory and other interventions aimed at removing transition barriers (such as ensuring a sufficiently qualified labor force and support for technology development and deployment) could be considered. These efforts would align with ensuring a supportive business environment. Last, Poland could consider strengthening, expanding, and building new infrastructure to enable certain technology switches.

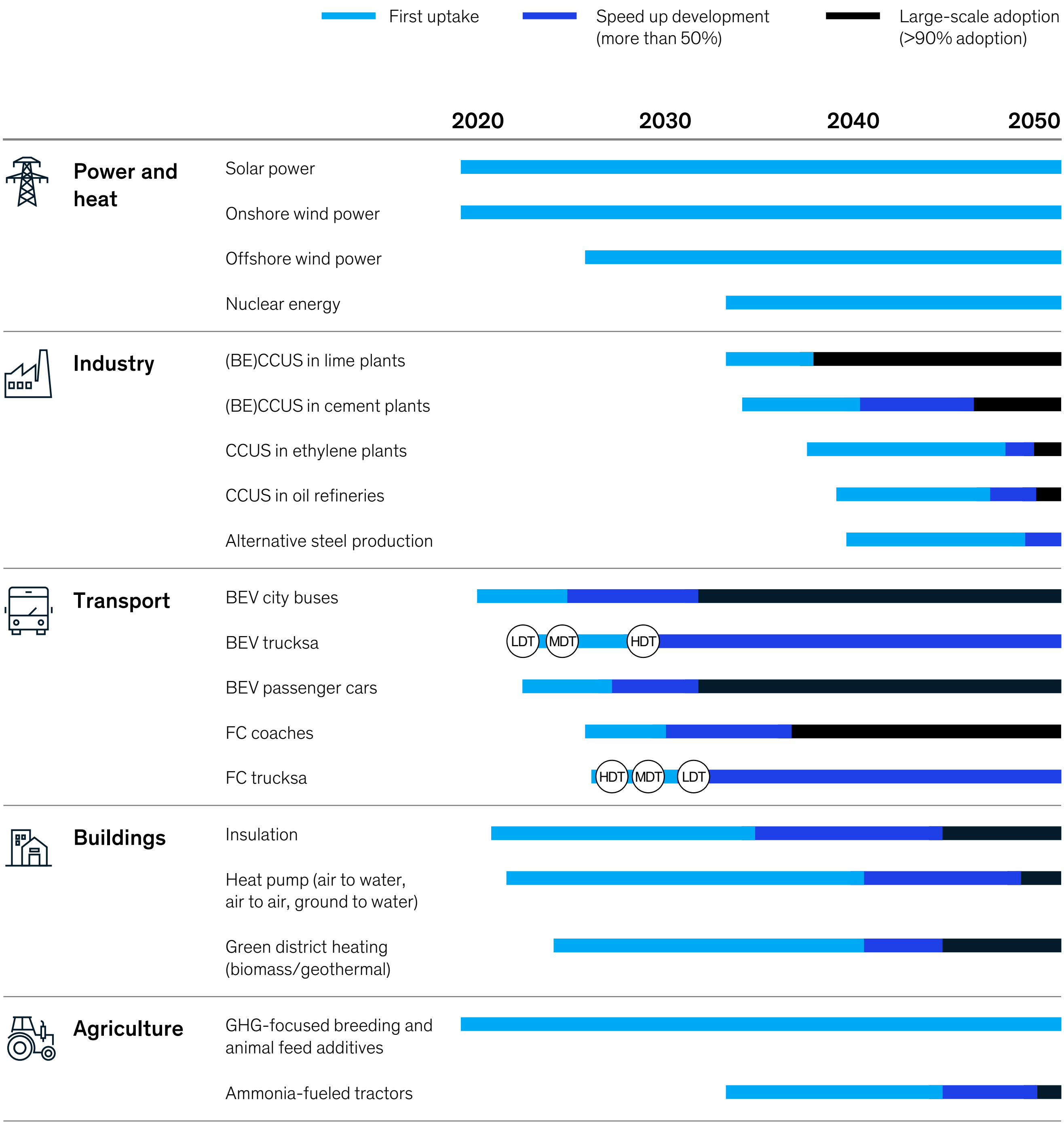
Develop smart financing frameworks
To ensure sufficient capital for low-carbon options, Poland could take two key actions.

— Make prefinancing available for private individuals. Given the high up-front costs related to decarbonization-friendly initiatives for consumers (for example, switching to BEVs and reinsulating buildings owned by private individuals) and the average Polish household's relatively low savings (18 percent of the EU average),[76] developing prefinancing solutions is crucial.

— Establish a stable regulatory environment to attract foreign direct investment. This environment could be supported, for instance, through a commitment to developing certain emerging industries by setting targets and investing in necessary infrastructure. In addition, providing a stable regulatory environment and good conditions for investments could reduce the risk and costs

Exhibit 17

A potenial decarbonization road map for Polish economy



a. LDT stands for low-duty trucks, MDT stands for medium-duty trucks, and HDT stands for heavy-duty trucks.

associated with the low-carbon economy. One example could be promoting investments in BEV through subsidies and tax relief.

Support scalable technology development and innovation
Several efforts could position Poland as a hub for innovation in low-carbon industries.

- Establish Poland as a European tech and entrepreneurial hub through the development of business incubators and R&D centers in close collaboration with universities. This effort can, for instance, be accomplished through incentives (such as R&D subsidies) to private-sector entities to devote resources and capital to innovation.
- Attract foreign innovative, high-tech businesses to establish or expand their presence in Poland and create jobs in high-growth sectors—for example, through dedicated economic zones.
- Create and support the domestic market for low-carbon, high-value-added products and services (for instance, by developing standards for maximum emissions).

Develop a qualified and sufficient labor force
A large pool of skilled talent could give Poland a competitive advantage in attracting low-carbon businesses and economic development. Potential actions to consider:

- Create incentives for universities to collaborate with the private sector and promote fields of education and research that are critical for high-growth, low-carbon industries.
- Adjust curricula to develop skill sets that suit the needs of the emerging low-carbon job market.
- Up- and reskill the labor force to ensure job mobility—for example, by providing incentives for both employers and employees to encourage continuous professional development.

Create a supportive business environment
Targeted policies can foster the development of low-carbon industries and create a critical mass for further investment. Some initiatives to consider:

- Define, clearly communicate, and deliver a long-term, stable government vision for policies and incentives that promote low-carbon activities.
- Encourage cross-industry knowledge sharing and cooperation to develop efficient and competitive supply chains and industry clusters.

Put decarbonization-critical infrastructure in place
Targeted investments in infrastructure can facilitate the construction of low-carbon assets. Potential investments could include:

To close the gap to full decarbonization in 2050, action would also be needed in the hardest-to-abate economic areas

- Expand electricity grids by reinforcing the existing network, authorizing new power lines, and investing in new interconnectors. These efforts will improve the technical resilience of electricity grids and the security of the energy supply.
- Enhance infrastructure (including road, rail, and energy networks) to facilitate connection with other European countries.
- Develop a BEV and FCEV charging infrastructure to meet anticipated consumer demand, boost the electric-vehicle market, and encourage investments in commercial electric fleets.
- Build CO_2 pipelines and reuse existing natural-gas infrastructure in strategically placed corridors to enable the deployment of CCUS technology and the utilization of CO_2 in industrial production processes.

A future-based outlook

Many activities must occur in the proper order to transition Poland's entire economy to carbon neutrality. Some activities are viable under current conditions and could be launched soon—others could materialize in 2035 to 2040 but would require R&D investments right now. These initiatives also represent opportunities to achieve technology leadership in the decarbonized world.

Consider no-regrets decarbonization actions

Adopting these actions could help reduce primary demand by switching to low-carbon products and promoting the circular economy. Intensifying asset usage through connected business models such as shared passenger cars—shared EVs emit about 40 percent less carbon per passenger-kilometer over their lifetime than unshared ICE vehicles and can save about 15 to 20 percent per kilometer in

TCO. Further, identifying and ensuring uses for end-of-life products (such as diverting organic waste streams away from landfills to anaerobic digesters for biomethane production, which could reduce emissions by a factor of five) or remanufacturing valuable products (such as machinery and consumer electronics) could recover value and cut emissions.

Add renewables to the power mix to meet electric power demand growth. By 2025, Poland's power mix could include about 30 percent renewables and 20 percent low-carbon energy carriers (such as natural gas) to reduce the reliance on high-emissions coal and lower electricity cost. Supporting RES policies and legal frameworks would enable this transition. In addition, retired capacity could be replaced with renewables at a lower levelized cost.

Provide infrastructure for transport electrification to create seamless, low-carbon, future-proof mobility. Accelerating the expansion of an EV-charging infrastructure could reduce road transport emissions by replacing about 10 percent of vehicles with BEVs by 2025.

Improve the energy efficiency of industrial processes and buildings and develop targeted business cases for technology switches. This goal could be achieved in the industry sector by introducing alternative fuels (such as hydrogen, biomass, and electricity) to replace the current reliance on coal. In the buildings sector, codes for new construction could be updated and existing poorly insulated buildings with the highest energy demand could be retrofitted to current building standards. In addition, the usage of low-quality solid fuels (such as waste) could be eliminated, and coal-based heating solutions (such as stoves) could be switched to carbon-free alternatives (for example, electric heat pumps).

Investing in the future
Longer-term investments could maintain flexibility for multiple options, including decarbonization. These outlays are typically low but could yield potentially high returns if the technology can be deployed at scale in the future.

Upgrade and extend power infrastructure to allow for zero emissions in the power and heat and transport sectors. Stakeholders could consider the future energy mix when planning investments in power transmission and distribution to facilitate higher shares of renewable electricity and enable the electrification of energy demand.

Reduce manufacturing emissions of raw materials and products. This can be achieved by offering attractive low-carbon alternatives such as carbon-free and negative-carbon cement, bio and synthetic fuels for marine and aviation, and plant-based proteins to replace meats.

Prepare to scale CCUS through R&D and deployment and piloting. Support R&D for CCUS, including developing CO_2-based products, such as synthetic fuels, in collaboration with other European countries. Moreover, CCUS pilots could be facilitated to develop CCUS technology, gain experience, and systematically reduce costs.

Nurture and expand sources of nature-based negative emissions. The hardest-to-abate segments could be offset by improving forest management practices to increase the carbon-sink potential of forests and preserve biodiversity, supporting agroforestry (particularly in areas such as reducing soil erosion and increasing soil biodiversity, where it would have broader environmental benefits), and continuing afforestation on lands with the lowest agricultural potential.

***

Decarbonizing the economy by 2050 is a significant undertaking. If Poland sets off down this road, the full engagement of the public sector, businesses and society as a whole will be required. Decarbonization would affect many areas of life – and five specific branches of the economy. But the estimates in this report show that achieving climate neutrality lies within Poland's grasp.

Our hope is that this report, by presenting the evidence in an orderly fashion, will help raise awareness about the potential for decarbonization in Poland. We have laid out the facts concerning the current situation, estimated costs, possible trade-offs and likely benefits right across the value chain. In a dynamically changing world, we believe that our analyses can help you make the right decisions – and start taking the right action.

Appendix A: Glossary of abbreviations

BAU	Business-as-usual scenario
(BE)CCUS	Bioenergy carbon capture, utilization, and storage
BEV	Battery electric vehicle
BF—BOF	Blast furnace—basic oxygen furnace
CCUS	Carbon capture , utilization, and storage
CHP plant	Combined heat and power plant (cogeneration plant)
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct air capture
DPO	Decarbonization pathway optimizer
DRI–EAF	Direct reduced iron—electric arc furnace
EEF	Enhanced-efficiency fertilizer
EU ETS	European Union Emissions Trading System (refers to price of European emissions allowances)
FC	Fuell cell
FCEV	Fuel-cell electric vehicle
GHG	Greenhouse gas
GJ	Gigajoule (1,000,000 joules)
GW	Gigawatt (1,000 MW)
GWh	Gigawatt hour (1,000 MWh)
H_2	Hydrogen
HDT	Heavy-duty truck (greater than 15 tons)
HEV	Hybrid electric vehicle
ICE vehicle	internal-combustion-engine vehicle
J	Joule
kWh	Kilowatt hour
LDT	Light-duty truck (less than 5 tons)
LNG	Liquefied natural gas
LULUCF	Land use, land-use change, and forestry
MACC	Marginal Abatement Cost Curve
MDT	Medium-duty truck (greater than 5 tons, less than 15 tons)
Mt	Megaton (1,000,000 tons)
MW	Megawatt (1,000 kW)
MWh	Megawatt hour (1,000 kWh)
N_2O	Nitrous oxide
O&M	Operations and maintenance
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule (0.278 TWh)
RES	Renewable energy sources
SMR	Steam methane reformer
SRF/CRF	Slow/controlled-release fertilizers
TCO	Total cost of ownership
t	Ton (1,000 kg)
TWh	Terawatt hour (1,000 GWh)
WACC	Weighted average cost of capital

Appendix B: Methodology

Scope of the report
In this report, we developed an economic-activity outlook based on expected and forecasted developments. Where possible, we have based this outlook on reputable, publicly available sources (for example, Statistics Poland Databases and perspectives of the government of Poland and representatives of the largest Polish companies and nongovernmental organizations related to the energy sector). We complemented these sources with proprietary perspectives, including McKinsey's Global Energy Perspective.

We neither aim to provide nor advocate a specific solution but instead examine the implications of a set of design choices regarding decarbonization. Accordingly, this report does not intend to provide a McKinsey forecast or policy recommendation.

Models used
For this analysis, we used our proprietary decarbonization modeling tool—the Decarbonization Pathway Optimizer. The DPO offers a standardized approach to industry and country decarbonization strategies and has already been deployed in a wide range of McKinsey studies.[77] The model helps answer two important questions: How can Poland decarbonize in the most cost-effective way? And what is the cost for Poland to decarbonize?

Another tool we used was our Grid Flexibility Model. The Grid Flexibility Model is a capacity-expansion model optimizing for the lowest-cost investments and operations over a defined investment period with technology and policy constraints. It can help answer important questions such as: What is the impact of the energy transition, including policies, mandates, costs, and technologies, on the evolution of the grid? And what are the roles of flexible solutions, including hydropower, battery storage, hydrogen, and power-to-gas (P2G) dispatch?

The marginal abatement cost curve (MACC)
One of the outputs of the DPO is the Marginal Abatement Cost Curve (MACC). The MACC is a standard tool used to illustrate the supply side of abatement initiatives aimed at reducing pollutant emissions, such as GHGs. Moreover, the MACC visualizes the selected abatement technologies and fuels.

Each column represents a specific technology or fuel switch that reduces emissions. The curve shows how much abatement can be realized at a given cost. The width of each column represents the realized reduction of annual CO_2 emissions associated with the measure by 2050 when compared with 2017, and the height of each column represents the average cost of abating one ton of CO_2. The columns are organized from the most economical to the most expensive measures, expressed in euros per ton of CO_2 abatement.

Appendix C: Key assumptions by industry

This appendix describes the key modeling assumptions. Most of the raw data we used came from public sources. For our analyses, we used a set of assumptions assessing how the technology mix by industry changes over time. These constraints are explained for each industry below.

Power and heat
For our analytical modeling, we used the following constraints (Exhibit 18):

— A maximum offshore wind capacity of 45 GW by 2050

— A maximum onshore wind capacity of 100 GW by 2050

— Renewable share of generation of 21 percent by 2030[78]

— CO_2 target constraints: 100 percent decarbonization by 2050; and 45 percent reduction by 2030 compared with 1990

— A minimum buildup of nuclear capacity aligned with the government target of approximately six units from 2033 to 2050

Industry
For our analysis, we used the following assumptions:

— Not all machines and processes can be decarbonized through electrification (for example, cement kilns need to heat up above 1,400°C, which is beyond electrification feasibility)

Exhibit 18

Several assumptions inform our decarbonization models

		Capex k €/MW installed			Fixed O&M cost €/MW installed/year			Fuel price €/GJ		
Energy sources	**Life** Years	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**
Solar	25	900	300	200	7,400	6,000	5,100			
Offshore wind	25	2,500	1,600	1.400	73,000	55,000	50,000			
Onshore wind	25	1,200	1,000	900	25,000	21,000	20,000			
Nuclear	50	6,000	5,700	5,100	38,000	38,000	38,000	0.5	0.5	0.5
Biomass	20	2,400	2,000	1,800	83,000	71,000	65,000	15	15	15
CCGT (combined cycle gas turbine)	25	900	900	900	18,000	18,000	18,000	7	7	5
Lignite	35	1,600	1,600	1,600	30,000	30,000	30,000	2	2	1
Coal	35	1,400	1,400	1,400	31,000	31,000	31,000	3	3	2

- Electricity prices are expected to be in the range of €30 to €50 per MWh from 2030 to 2050
- The amount of CO_2 from ammonia production used for urea will remain at 2019 levels
- Externally purchased clean hydrogen is limited to 5 percent of total production needs
- Naphtha will remain the main feedstock in ethylene, as a switch to ethane will reduce the production of other high-value chemicals
- Direct separation technology in cement is not considered (this means that CCUS must cover energy and process emissions together)

Transport
For our analysis, we used the following assumptions:

- Each passenger car will need its battery replaced once in its lifetime
- Import of secondhand cars will stay at the 2019 level (with a gradual shift to BEVs)
- Average age of imported BEVs will be about seven to eight years, just before expected battery replacement
- Imported BEVs will receive a battery replacement in Poland
- At least 5 percent of internal-combustion-engine trucks will still be on the road in 2050

Exhibit 19

Detailed assumptions for the transport sector

Lifetime of each vehicle type, in years

Type of vehicle		Lifetime Years
Passenger cars		14
Low-duty trucks	Long haul	7
	Regional	9
	Urban	11
Medium-duty trucks	Urban	11
	Regional	9
	Long haul	7
Heavy-duty trucks	Urban	8
	Regional	7
	Long haul	6

Exhibit 20

Detailed assumptions for the transport sector

Example: Passenger cars, gasoline, BEV, and FC

	Capex k € /vehicle			Opex € /km		
Type of fuel	**2020**	**2035**	**2050**	**2020**	**2035**	**2050**
Gasoline A/B	13.4	13.5	13.5	0.1	0.1	0.1
Gasoline C/D	22.1	23.8	23.8	0.1	0.1	0.1
Gasoline E/F	55.7	59.4	59.4	0.1	0.1	0.1
Gasoline J	31.0	33.3	33.3	0.2	0.2	0.1
BEV A/B	16.4	13.4	13.4	0.0	0.0	0.0
BEV C/D	29.2	23.8	23.8	0.0	0.0	0.0
BEV E/F	68.8	62.5	62.5	0.0	0.0	0.0
BEV J	46.6	37.5	37.5	0.0	0.0	0.0
FC A/B	33.4	26.6	26.6	0.3	0.1	0.1
FC C/D	54.5	43.4	43.4	0.3	0.1	0.1
FC E/F	134.3	107.1	107.1	0.4	0.2	0.2
FC J	59.7	47.5	47.5	0.4	0.2	0.2
Diesel A/B	14.3	15.8	15.8	0.1	0.1	0.1
Diesel C/D	24.7	27.1	27.1	0.1	0.1	0.1
Diesel E/F	59.3	64.4	64.4	0.1	0.1	0.1
Diesel J	34.1	37.3	37.3	0.1	0.1	0.1

Buildings

For our analytical modeling, we used the following assumptions:

— Biomass can replace up to 66 percent of CHP plant capacity

— Light insulation costs €3,600 for apartments and €7,200 for houses, with 25 percent heat demand reduction that can be applied to a maximum of 40 percent of buildings

— Deep insulation costs €9,000 for apartments and €18,000 for houses, with 50 percent heat demand reduction that can be applied to a maximum of 40 percent of buildings

— A maximum of 20 percent of apartments are suitable for an air-to-air heat pump switch

Agriculture

For our analysis, we used the following assumptions:

— A maximum of 54 percent of farmers can adopt all enteric fermentation decarbonization technologies

— For agricultural equipment, maximum of ammonia blend is 60 percent in 2050

— Electric agricultural equipment has a higher TCO than equipment that runs on an ammonia blend

— Low-tillage methods offer a 43 percent emissions reduction compared with conventional tillage

— Optimized fertilization offers a 33 percent emission reduction compared with conventional fertilization practices

— There is no established technology to eliminate direct emissions

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