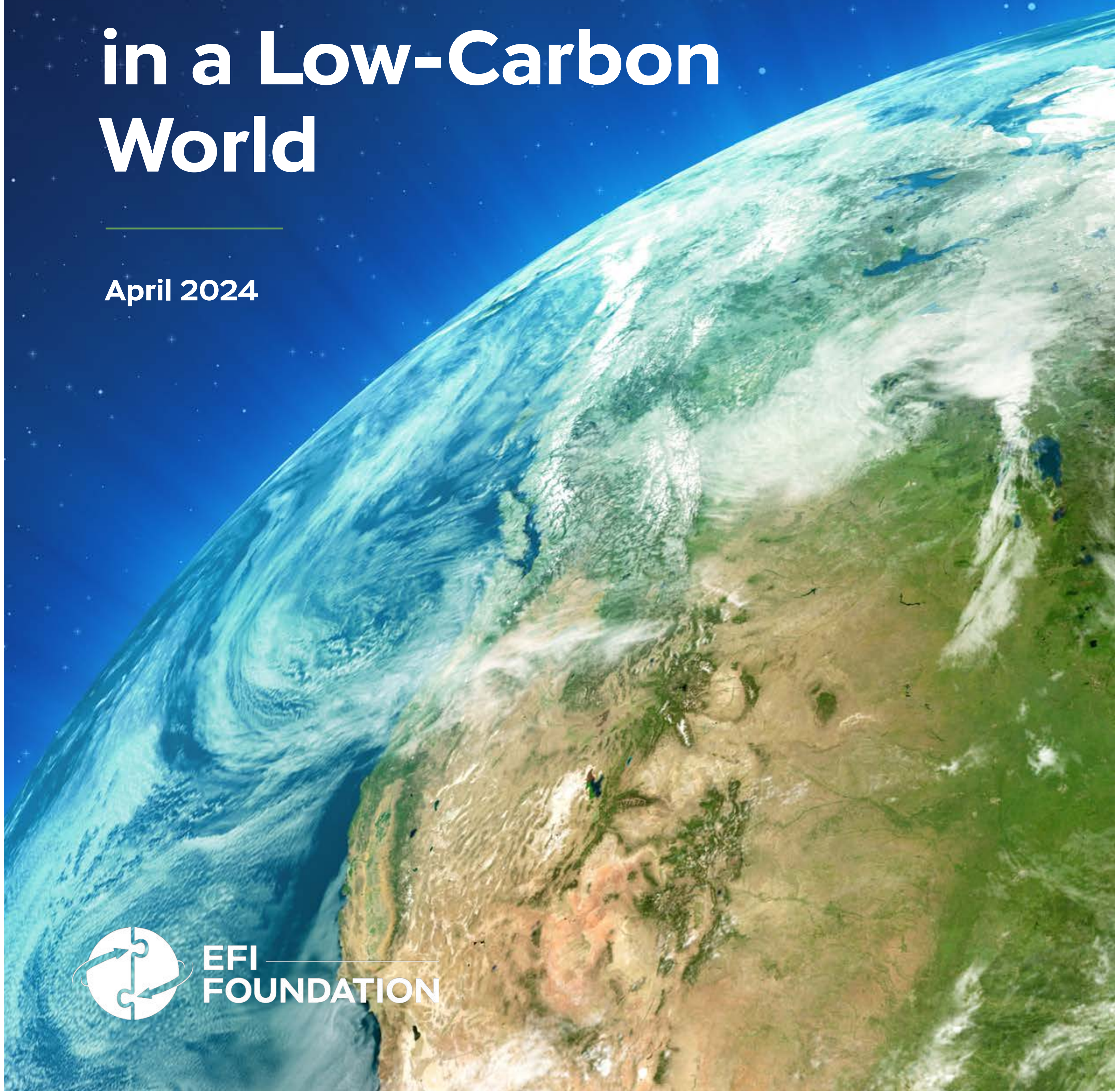
The Future of Natural Gas in a Low-Carbon World

April 2024



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Acknowledgments

The EFI Foundation would like to thank the following organizations for co-hosting the regional roundtables in Europe and Asia:

Center for the Study of Democracy (CSD)

German Marshall Fund (GMF)

Partnership to Address Global Emissions (PAGE)

The Institute of Energy Economics, Japan (IEEJ)

Economic Research Institute for ASEAN and East Asia (ERIA)

The EFI Foundation would also like to thank the following authors of "Industrial Decarbonization and the Role of Natural Gas," a white paper used as part of this study:

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The EFI Foundation acknowledges that Wood Mackenzie report data was utilized in this report.

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The EFI Foundation advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, the EFI Foundation conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI Foundation maintains editorial independence from its public and private sponsors.

About This Report

In 2021, the EFI Foundation (EFIF) conducted a study titled "The Global Future of Natural Gas in a Low-Carbon World," the first of a two-phase study. EFIF published the Phase I results in June 2021 in *The Future of Natural Gas in a Deeply Decarbonized World,* a report summarizing key findings from eight regional workshops with local experts and stakeholders around the world. EFIF then held a workshop in February 2022 and issued a summary report titled *Energy Security and Economic Interdependence in the U.S.-Asia Relationship* to better understand the role of natural gas in energy security, the economy, and decarbonization goals between the United States and Asia.

The February workshop kicked off EFIF's Phase II study to analyze and inform policies and promote technologies and pathways concerning the role of natural gas in a decarbonizing world, including how natural gas can help advance the low-carbon energy transition. However, the launch of the Phase II study was within days of Russia's invasion of Ukraine. After recalibrating areas of focus in response to Russia's weaponization of its energy supplies, EFIF relaunched Phase II in December 2022 to reflect new energy realities and energy security concerns within the original context of the study.

EFIF conducted a workshop (United States) and three roundtables (Europe and Asia) to gather broad-based information from experts globally to frame the research and analysis. The January 2023 inaugural workshop was attended by policymakers and industry and nongovernmental organization (NGO) representatives to discuss the role of U.S. natural gas in global energy security and decarbonization. The White House sent a high-level official to address participants.

After Russia's invasion and the subsequent sanctions, it was evident that Eastern and Western Europe had different energy needs and security concerns. Accordingly, EFIF held roundtables in both regions of the continent. The first was in June in Sofia, Bulgaria, the second was in Brussels, Belgium. These roundtables focused on Europe's energy security crisis following the invasion. As anticipated, participants expressed different views on the role of natural gas among European stakeholders. The final roundtable was held in Singapore on the margins of the Gastech 2023 conference and focused on the various views on natural gas's role in Northeast, Southeast, and South Asia.

EFIF has published three summary reports on the workshop and roundtables for Phase II: *Asia Roundtable Summary*, *Europe Roundtable Summaries*, *and* *U.S. Workshop Report*. Also, together with this report is an appendix that was an initial assessment of natural gas and industrial decarbonization.

Acronyms and Abbreviations

Acronym	Definition
45Q	Section 45Q, carbon oxide sequestration tax credit (U.S.)
ADB	Asian Development Bank
ADNOC	Abu Dhabi National Oil Company
AEO	Annual Energy Outlook
AGI	acid gas injection
APS	Announced Pledges Scenario
Bcm	billion cubic meters
Bcme	billion cubic meters equivalent
BECCS	bioenergy with carbon capture and storage
BF	blast furnace
BIL	Bipartisan Infrastructure Law (U.S.)
BOF	basic oxygen furnace
Btu	British thermal units
CaO	calcium oxide
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CBAM	Carbon Border Adjustment Mechanism (EU)
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CCU	carbon capture and utilization
CCUS	carbon capture, utilization, and storage
CDR	carbon dioxide removal
CEQ	Council on Environmental Quality
CH_4	methane
CHP	combined heat and power
CNG	compressed natural gas

CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	United Nations Climate Change Conference of the Parties
CPCN	certificate of public convenience and necessity (U.S.)
CSLF	Carbon Sequestration Leadership Forum
DAC	direct air capture
DNG	differentiated natural gas
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior - BLM: Bureau of Land Management - USFS: U.S. Forest Services - NPS: U.S. National Park Services
DR	direct reduction
DRI	direct reduced iron
EAF	electric arc furnace
EBRD	European Bank for Reconstruction and Development
EFIF	EFI Foundation
EIA	U.S. Energy Information Administration
EIB	European Investment Bank
EMDE	emerging markets and developing economies
EPA	U.S. Environmental Protection Agency
ESD	energy security determination (U.S.)
ESG	environmental, social, and governance
ETS	emission trading system
EU	European Union
EV	electric vehicles
FCCU	fluidized catalytic cracking units
FERC	U.S. Federal Energy Regulatory Commission

FOAK	first-of-a-kind
FTA	free trade agreement (U.S.)
GDP	gross domestic product
GEM	Global Energy Monitor
GHG	greenhouse gas
GIIGNL	International Group of Liquefied Natural Gas Importers
Gt	gigaton
H_2	hydrogen gas
H_2S	hydrogen sulfide
HBI	hot briquetted iron
Hg	mercury
IEA	International Energy Agency
IEEJ	Institute of Energy Economics, Japan
IEO	International Energy Outlook
IIJA	Infrastructure Investment and Jobs Act (U.S.)
IMEO	International Methane Emissions Observatory
IRA	Inflation Reduction Act of 2022
IRENA	International Renewable Energy Agency
Kt	kiloton
LCA	life cycle assessment
LCFFES	low-carbon fuels, feedstocks, and energy sources
LCFS	Low Carbon Fuel Standard (California)
LCOA	levelized cost of ammonia
LCOE	levelized cost of electricity
LCOS	levelized cost of storage
LDAR	leak detection and repair
LNG	liquefied natural gas
MARS	Methane Alert and Response System

MDB	multilateral development bank
MENA	Middle East and North Africa
MJ	megajoule
MMBtu	million British thermal units
MMcf	million cubic feet
MMmt	million metric tons +e: equivalent
MMtpa	million metric tons per annum
MRV	monitoring, reporting, and verification
Mt	million tons, or megatons
Mtoe	million metric tons of oil equivalent
MW	megawatt
MWh	megawatt-hour
NASEM:	National Academies of Sciences, Engineering, and Medicine (U.S.)
NATO	North Atlantic Treaty Organization
NDC	nationally determined contribution
NEPA	National Environmental Policy Act (U.S.)
NETL	National Energy Technology Laboratory (U.S.)
NG	natural gas
NGA	Natural Gas Act of 1938 (U.S.)
NGCC	natural gas combined cycle
NOAK	nth-of-a-kind
NOx	nitrogen oxides
NZE	Net-Zero
NZIA	Net-Zero Industry Act (EU)
OECD	Organization for Economic Co-operation and Development
OGDC	Oil and Gas Decarbonization Charter
OGMP 2.0	Oil & Gas Methane Partnership 2.0
OPEC	Organization of the Petroleum Exporting Countries

Oxy	Occidental Petroleum Corp.
Oz	ounce
PHMSA	Pipeline and Hazardous Materials Safety Administration (U.S.)
P.M. 2.5	fine particulate matter of 2.5 microns or less in diameter
PPM	parts per million
R&D	research and development
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
RNG	renewable natural gas
ROW	rights-of-way
SEM	strategic energy management
SMR	steam methane reforming
SNG	synthetic natural gas
SO_2	Sulfur dioxide
STEPS	Stated Policies Scenario
TBtu	trillion British thermal units
Tcf	trillion cubic feet
TTpa	thousand metric tons per annum
TWh	terawatt-hour
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
WEC	World Energy Council
WEO	World Energy Outlook
WHO	World Health Organization

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Executive Summary, Key Findings, and Recommendations

At the 28th United Nations Climate Change Conference of the Parties (COP28), countries agreed that “transitional fuels can play a role in facilitating the energy transition while ensuring energy security,” even as they are “transitioning away from fossil fuels in energy systems in a just, orderly, and equitable manner.”[1] The recent global energy crisis—partly the result of Russia’s war on Ukraine and its ripple effects—has placed energy security at the center of global energy concerns and debates.

This crisis and the heightened focus on energy security have not diminished the need for deep decarbonization and the clean energy transition. It has, however, added the need for energy solutions that address both energy security and decarbonization goals. There is ample evidence that energy availability and affordability are crucial for building and sustaining public support for decarbonization. In this context, natural gas is playing an essential role. The flexible and available natural gas supply from the United States and the lack of destination clauses in licenses for U.S.-produced liquefied natural gas (LNG) exports made a significant contribution to the energy security of our European allies by largely filling the supply gap after Russia’s invasion of Ukraine.

Another reality, although seldom acknowledged in discussions of global decarbonization, is that the pace will vary in countries at different levels of economic development. In this sense, the future of global natural gas supply and consumption factors directly into social equity considerations.

The most serious challenge facing natural gas suppliers and consumers, however, is mitigating greenhouse gas (GHG) emissions from the natural gas supply chain, including from its uses as a fuel and as a feedstock for key industrial processes. Globally, since 2015, carbon dioxide (CO_2) and methane (CH_4) emissions from gas systems have increased along with gas consumption. For natural gas to be aligned with net-zero commitments, CH_4 and CO_2 emissions across the supply chain must be dramatically reduced.

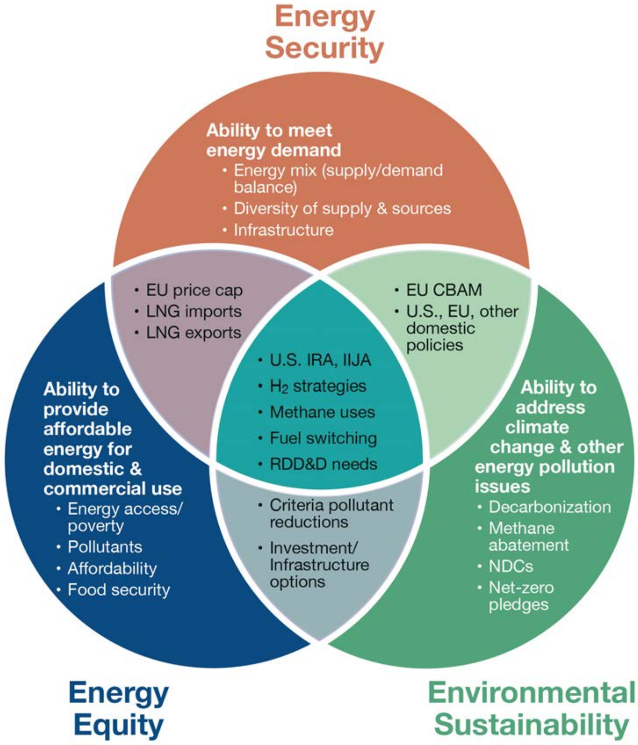
Clearly, the debates around natural gas use are often contentious in the United States and elsewhere, as the imperatives of mitigating climate change, enhancing energy security, and addressing social equity concerns are cast as in deep conflict. This analysis rejects that view. These three elements of the “energy trilemma” must be part of one conversation, as failure in any of these dimensions produces significant headwinds for the other two.

Indeed, the parameters of the debate are very different in countries with different conditions (producer/consumer, industrialized/developing, etc.). It must be recognized that long-term, accelerated progress in all three goes hand in hand and natural gas is at the heart of the optimization challenge. The industrialized and developing economies naturally weight these factors differently, but everyone has a direct interest in all three as they affect the transition from today's carbon-intensive economy to a low-carbon end state. It is the hard work of managing the transition that needs everyone's attention and constructive contribution. This analysis has been conducted and guided by these realities and how the role of natural gas is addressed in the multidecadal low-carbon transition.

This analysis is focused on the role of natural gas in a deeply decarbonized world and is the second of a two-phase study. Global Gas Phase I analyzed eight global regions from the perspective of regional experts and identified shared and divergent views on the continued role of natural gas in a decarbonizing global economy.

Phase II examines the role of natural gas in a low-carbon world from both a global perspective and the perspectives of key regions/countries: Asia (Northeast and Southeast Asia, South Asia, and China); Europe (Eastern and Western Europe); and the United States. The analysis of natural gas consumption and supply in these regions is structured around its role in addressing the three dimensions of the "energy trilemma": energy security, energy equity, and environmental sustainability (Figure ES-1). As seen in the figure, these dimensions are both discrete and overlapping; they are analyzed in detail in Chapters 1-4. Chapter 5 analyzes the role of natural gas in the industrial sector. This "deep dive" was viewed as important as the sector supports very significant economic activity and jobs, even as natural gas's GHG emissions in the sector are considered by many to be challenging to abate. Chapter 6 includes a detailed set of recommendations.

Figure ES-1. The energy "trilemma" and the role of natural gas



Source: EFI Foundation

Framing and Baseline Trends

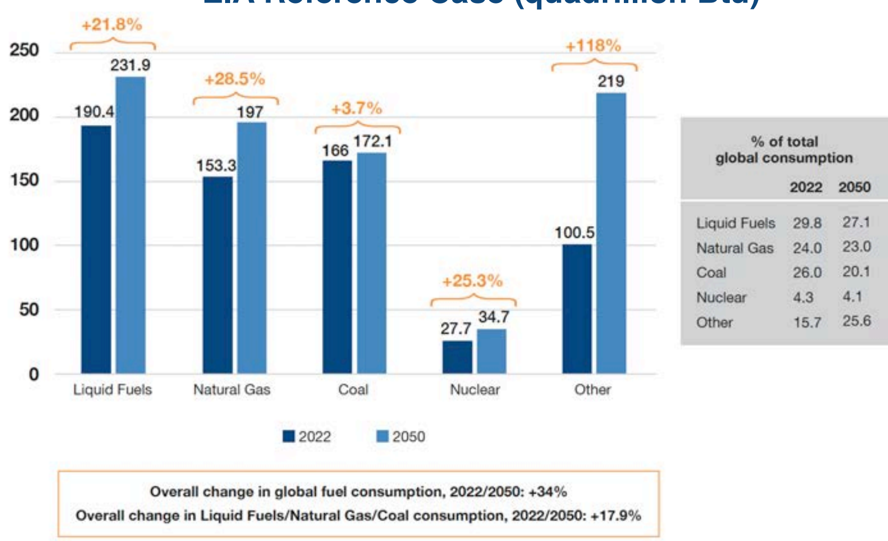
Natural gas has a critical role in balancing the energy trilemma. The overarching challenge that this report addresses is identifying policies, programs, and options for developing pragmatic, sequenced, and regionalized approaches to the role of natural gas in a deeply decarbonized world.

Energy security is measured by the ability of a country or region to reliably meet current and future energy demand. Energy equity is measured by the degree to which a country or region provides access to reliable, affordable, clean, and abundant energy for domestic and commercial use to all its citizens. Environmental sustainability is measured by how much a country or region transitions its energy systems to help mitigate environmental harm and climate change impacts. These three critical needs overlap—and at times compete—and they are managed differently around the world. Global Gas Phase II analyzes these needs, with a focus on the United States, Europe, and Asia. The challenges clearly exist in other parts of the world as well, but this study focuses on the largest supply/demand hubs for LNG. Challenges exist in other parts of the world as well, but this study focuses on the current largest supply and demand hubs for natural gas and LNG.

In this context, it is important to understand current and forecast world primary energy consumption (Figure ES-2).[2] These data are from the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2023 Reference Case described in detail in Box 1, Chapter 1.

In the Reference Case, overall global primary energy consumption increases by 34% between 2022 and 2050, with the largest absolute and percentage increases coming in “other” fuels. Natural gas is second in both absolute and percentage increases, with a 28.5% increase in that period. Chapter 1 examines this and other forecasts in detail to understand the impacts of a range of policies and scenarios on overall gas supply, consumption, and emissions by midcentury.

Figure ES-2. World primary energy consumption by fuel, 2022/2050, EIA Reference Case (quadrillion Btu)



“Other” includes wind, solar, and other renewables. Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

Key Findings

Natural gas can, depending on the specific country or region covered in this analysis, play a critical role in balancing the energy trilemma. It is abundant and versatile, is sold at a relatively low cost, can help manage the intermittency of wind and solar power generation, and is playing an essential role in meeting growing energy demands.

Natural gas utilization varies widely in the range of forecasts, and its future in a low-carbon world remains unclear. As seen in Figure ES-2, the EIA's Reference Case forecasts an overall increase in global natural gas demand of almost 44 trillion cubic feet (Tcf). The largest absolute increases are forecast in the Asia-Pacific region, where demand grows by about 19 Tcf, or around a 54.7% of the total increase in gas consumption for the region. Natural gas demand in India shows the highest percentage growth, at 233%, although absolute consumption increases by only 5.8 Tcf. China represents the highest growth in absolute demand in the region, at about 10 Tcf. As discussed further in Chapter 1, a range of scenarios from the EIA and the International Energy Agency (IEA) still show significant global natural gas consumption by 2030.

At the same time, around three-quarters of the world's countries and almost 1,000 global companies have net-zero targets, which will affect future investments in energy systems including natural gas systems. In the mid- to long term, the most serious challenge for natural gas's continued use is that it is a GHG-emitting fossil fuel (CO_2 and CH4). While CO_2 emissions from natural gas combustion are substantially lower than those from coal or oil, the challenges associated with these GHG emissions will ultimately determine the role of natural gas in the energy transition between now and midcentury.

From the environmental dimension of the energy trilemma, it should be noted that coal-to-gas fuel switching for power generation has resulted in lower emissions in many regions of the world. While such emissions reduction from fuel switching could provide reduction pathways in many countries in Asia, reducing overall CO_2 emissions from natural gas use is still a critical need.

Methane abatement also remains a critical issue. Capturing methane emissions from natural gas systems, essential for meeting net-zero targets, could reduce total global methane emissions by 10% and—because methane's residence in the atmosphere is from 10 to 12 years compared to 1,000-plus years for CO_2—could help achieve early and substantial gains in mitigating climate change. Also, the carbon footprint of natural gas, while lower than some alternatives, must be dramatically reduced further, through means such as efficiency; carbon capture, utilization, and storage (CCUS); and switching to clean alternatives. Overcoming these challenges will ultimately determine whether natural gas is indeed a transitional fuel or an integral part of the long-term global energy mix.

Energy Security

As seen in Figure ES-1, energy security must be considered in the context of energy equity and environmental sustainability where there are overlapping issues such as deep decarbonization, infrastructure needs, and affordability.

From an energy security perspective, without U.S. LNG exports and flexible U.S. contracts, Europeans would not have had sufficient fuel to heat their homes and generate electricity in the winter of 2022-23 after the Russian invasion of Ukraine. Europe lost 22 billion cubic meters (Bcm) of natural gas that winter, and the United States was able to make up for 19 Bcm of the loss. While high-income LNG-importing countries in Europe and Asia were able to absorb the shock of high energy prices after Russia's invasion of Ukraine, high prices were a problem in many countries, especially developing nations where energy prices and affordability are important for economic stability and growth. Unfortunately, high prices led to increased coal use in some countries.

In addition, following Russia's invasion, the 2022 energy crisis in Europe motivated investors to support the construction of regasification infrastructure for non-Russian LNG supply. Europe's and Asia's LNG regasification capacity (reflecting the capability to accept LNG imports) is expected to increase dramatically by 2025. Compared to the previous 10 years, the rate of new approvals for liquefaction capacity have doubled since the invasion.

Europe and Asia still face substantial challenges to their long-term energy pathways. In these regions, domestic energy resources are limited, so imports of energy sources for domestic consumption are crucial for economic stability and growth. These supply limitations and growing energy demand have made Europe and Asia the world's largest regional importers of LNG, accounting for more than 90% of the world's total LNG import volumes. This reliance on imports has motivated these regions to expedite domestic renewable energy resources and clean energy production support to address both energy security and climate goals.

It is difficult, however, to develop and deploy affordable and adequate supplies of renewable and other net-zero energy options (e.g., green hydrogen) fast enough to meet the energy demands of these regions in the near and, most likely, midterm. Moreover, developing countries in these regions are sensitive to the challenges of affordability in meeting growing energy demands that support economic growth.

As noted, at COP28, nations agreed on the role of "transitional fuels" in facilitating the energy transition while ensuring energy security. Also recognized was that time frames for peaking GHG emissions may be shaped by each country's "sustainable development, poverty eradication needs, and equity and be in line with different national circumstances."[3] These results of COP28 provide some signals for the direction of the global energy transition but do not answer questions on how significant of a role natural gas could play. Countries still face challenges in developing pathways for the energy transition and the use of energy sources, including natural gas, as conflicting factors such as moving away from fossil fuels, use of transitional fuels, sustainable development, and other national-level concerns merit consideration.

The United States can play a leading role in the strategic use of natural gas during the transition not only by providing stable supplies to its allies and trading partners but also by leading efforts to green the supply chain. U.S. LNG has supported energy security, energy transition, and economic development worldwide, and many regions expect the United States to continue to serve in this role. The United States is already the leading exporter of LNG, and the EIA expects the United States and the Middle East to be the world's primary natural gas exporters in 2050. Considering future LNG demand, Table ES-1 below notes the LNG import infrastructure and expected demand in million metric tons per annum (MMtpa) by 2050 in Europe and Asia.

Table ES-1. LNG import infrastructure capacity in development and LNG demand in 2050, Asia and Europe

Region	LNG import infrastructure capacity (in operational and under construction)	LNG Demand in 2050	Gap in 2050 without additonal capacity
South Asia	98.2	187.7	-89.5
Southeast Asia	66.8	143.2	-76.4
China and Northeast Asia	534.2	187.7	+346.6
Europe	206.2	77.7	+128.5
Total (Europe and Asia)	905.4	596.3	309.2
Note: Data from Global Energy Monitor, World Energy Review 2023, and Wood Mackenzie			

Source: EFI Foundation with data from data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023)

Asia includes countries that are, to some degree, more focused on energy affordability and equity than deep decarbonization. As climate change is a global issue, it is in the interest of the developed world to help ensure that these Asian countries can accomplish both.

As a country, in 2021, China was the second-largest importer of U.S. LNG at 453,304 million cubic feet (MMcf), right behind the largest importer that year, South Korea at 453,483 MMcf.[4] This shifted dramatically after the Russian invasion of Ukraine: China and South Korea fell to 173,247 and 275,779 MMcf, respectively; the Netherlands, France, and the U.K. increased to 588,557, 492,696, and 450,694 MMcf in 2023 from 174,339, 170,780, and 195,046 MMcf, respectively, in 2021.[5]

That shift underscores the ongoing demand for U.S. LNG and the significant impacts of the invasion on LNG trade routes. This, along with China offering incentives for coal-to-gas fuel switching, highlights a key point of shared interest and need, providing a basis for strategic discussions between the U.S. and China.

As a region, Europe remains the largest importer of U.S. LNG. Even with this demand, U.S. LNG suppliers have faced, and will continue to face, numerous challenges to building LNG export infrastructure. These include uncertain projections of global LNG supplies, as well as permitting and regulatory challenges. The recent announcement on January 26, 2024, by the Biden administration of a “pause” on LNG export permits, pending environmental/climate, economic, and security assessments and reviews, is another uncertainty that will impact LNG supply and demand.

Key Findings

Following European sanctions after Russia’s invasion of Ukraine, Russia has been searching for new markets for its natural gas. The country’s efforts to find customers may run counter to longer-term global security, if a new set of nations becomes reliant on Russian resources. It is not in the geostrategic interest of the United States, Europe, or Asian allies and trading partners to rely on a single source of supply, as better diversity can satisfy many energy security and environmental concerns.

The critical energy security role of U.S. LNG was demonstrated after the Russian invasion of Ukraine. U.S. supplies of LNG to Europe after the 2022 invasion were instrumental in ensuring Europeans had adequate energy to get through that winter. This, however, raised availability and price concerns for Asian customers, underscoring the need for additional LNG supplies in the near to midterm.

In Europe, however, near-term demand for natural gas (via LNG) continues, although the long-term demand is likely to decline, driven by accelerated decarbonization efforts and energy security concerns. Many Western European countries saw the recent energy crisis as an opportunity to accelerate the energy transition by pursuing electrification and increasing domestic energy production. Eastern European countries regard natural gas as a critical fuel source for the energy transition, especially in the industrial sector, but they view LNG as expensive and difficult to source in a tight global market.

In Asia, mid- to long-term demand for natural gas is expected to increase, driven by China in the next decade and Southeast Asia and South Asia in the longer term. The long-term demand forecasts for natural gas in China are, however, challenging due to complex factors affecting supply and demand, including continued investments in renewables, the government’s pursuit of coal for energy security, growing domestic natural gas production, and imports from Russia via pipelines. Thus, China is expected to be opportunistic in its use of LNG and natural gas.

The growing energy demand, driven by economic and population growth, will increase Southeast Asia's long-term demand for natural gas, while in South Asia, declining domestic production and rising demand for natural gas will boost the nation’s reliance on imported LNG.

Globally, the conflict between the need to increase LNG imports to meet short- and midterm demand and policies and some forecasts of dramatically reduced natural gas consumption raises reasonable concerns about the merits of investing in natural gas infrastructure and the potential for stranded assets. Also, differing forecasts of global long-term demand for natural gas discourage investment in LNG supply infrastructure. The decreasing scale of investment in infrastructure has already led to concerns about a potential supply shortage starting around 2030. Europe, China, and Northeast Asia could have a substantial amount of underutilized assets since the capacity of their LNG import infrastructure far exceeds the projected LNG demand through 2050.

The United States will continue to be the world's top exporter of LNG through 2050. The country has an opportunity to embrace a global leadership role as an energy supplier and ensure global energy security as a reliable trading partner, unless it concedes this role to alternative suppliers such as Russia. To meet growing international demand, the United States needs additional LNG export terminal capacity in the near and midterm, especially as Europe continues to move away from importing Russian natural gas. In addition to uncertain demand forecasts, U.S. LNG suppliers will continue to face numerous hurdles in building LNG export infrastructure, including legal and regulatory challenges and those related to reducing GHG and environmental impacts of new infrastructure.

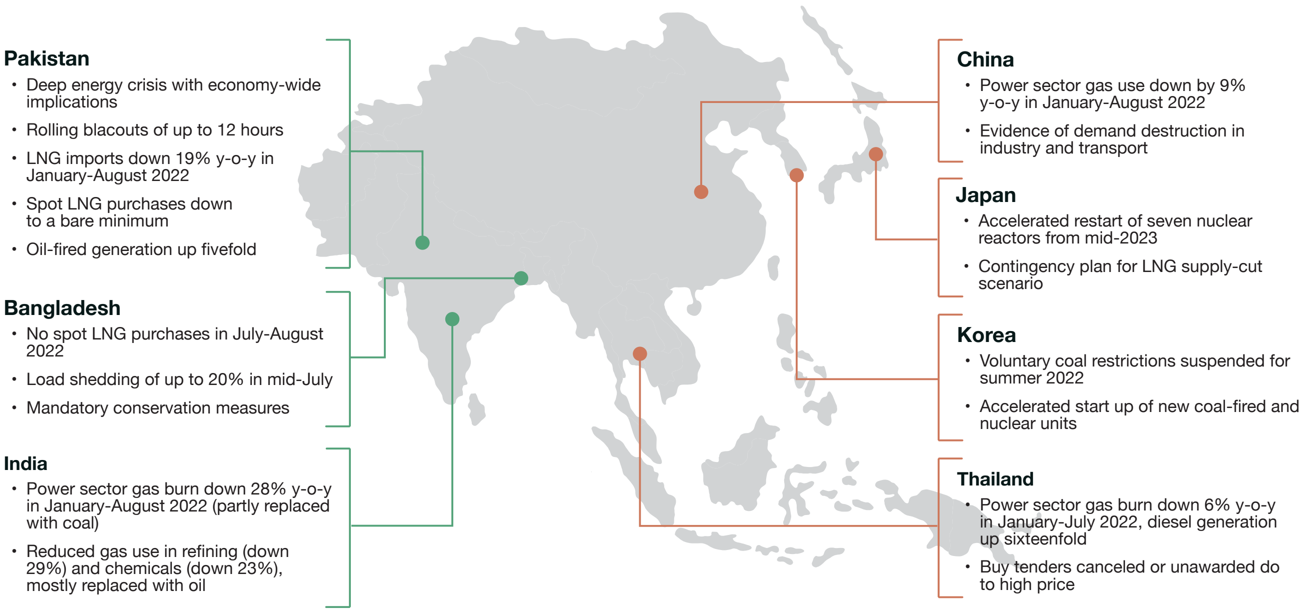
Energy Equity

In this analysis, energy equity covers access to energy, energy affordability, and access to clean energy. Progress had been made on energy poverty, but the COVID-19 pandemic and related economic slowdown stifled this headway. With higher energy prices associated with the post-COVID recovery, energy-importing nations, especially those in the developing world, are struggling with issues of energy affordability including for natural gas. Affordability is, as noted, critical for economic growth. This could have another negative impact: Nations that lack the infrastructure to take advantage of new natural gas flows are likely to utilize coal. This could result in higher emissions over the long life spans of new coal plants and infrastructure, with a corresponding impact on decarbonization goals.

Russia's invasion of Ukraine raised energy equity issues. The invasion created a fundamental shift in the natural gas markets, both in terms of trade flows and price increases. As noted, Europe is in the process of eliminating Russian natural gas imports, a staple of European gas markets for decades. This has, however, resulted in price shocks for European consumers. The EU and governments in Europe have taken various actions, ranging from tax relief and subsidies to efforts to reform energy infrastructure—all of which have brought consumers minimal relief.[6]

Asian markets, while slightly more insulated from similar price shocks by greater reliance on long-term contracts, are at an inflection point as most of their long-term contracts will expire by 2030. The spot market, however, does have significant impacts in Asia that vary by country, as seen in Figure ES-3.[7] How Asia responds will have significant cost and security implications. China and India have increased their consumption of Russian gas, a shift in trade flows that may become a long-term reality, with a range of implications for costs, U.S. supply, and geopolitics. While the United States can help fill part of the gap for Europe, developing countries in Europe and Asia may suffer the most from high prices.

Figure ES-3. Impacts of high spot LNG prices across Asia



Source: IEA, Gas Market Report, Q4-2022 including Global Gas Security Review 2022, https://www.iea.org/reports/gas-market-report-q4-2022.

Key Findings

Natural gas has numerous attributes that could help improve energy equity. These include providing reliable power generation and backup generation for intermittent renewables; supporting cleaner air relative to coal; lower CO_2 emissions than other fossil fuels, important for power generation, heat, and industry; and the potential for access to global markets and the associated economic benefits.

Rising global energy demand, driven by population growth and economic development, highlights the importance of abundant, affordable, and clean energy sources that are available for all nations, including developing countries. A continuous growth of global primary energy consumption is expected for the long term, especially in emerging markets and developing countries. Emerging markets and developing economies account for over two-thirds of global growth in electricity demand in the IEA's scenarios.

The population in the Asia-Pacific region is projected to increase by almost half a billion people in the next 26 years and account for 25% of the total increase in global population. Population increases in developing parts of Asia will require significant amounts of energy and electricity to support economic and social development. In addition to meeting rising energy demands, developing countries face other energy-related development challenges, such as providing universal electricity and energy access, reducing air pollution, and establishing infrastructure in urban areas. In 2022, the number of people without access to electricity reached 775 million worldwide, the first increase in decades.

Also, while climate change raises existential concerns, air pollution and air quality are also significant issues, affecting health and quality of life, especially in regions and countries that lack air quality standards. It is estimated that in 2019, long-term exposure to particulate matter (P.M. 2.5) was responsible for 4.1 million deaths worldwide.

The recent energy crisis has posed challenges to energy equity worldwide as it increased natural gas prices and brought significant market volatility. Europe's reductions of Russian natural gas negatively impacted European consumers. Europe spent 400 billion euros more on natural gas imports in 2022 than in 2021, a 300% increase in a year. Developing countries are impacted more severely by changes in international energy trade flows and price fluctuations as many are more reliant on energy imports.

LNG volumes not under long-term contracts are more often tied to spot market prices, exposing consumers and importers in these countries to price and market fluctuations. High LNG prices in Asian spot markets negatively affected demand in price-sensitive parts of Asia in 2022. Asian LNG demand decreased to 250 million tons in 2022 from 270 million tons in 2021. India and other developing Asian countries are likely to use more coal to meet their rapidly growing energy demand because of its affordability and availability.

Environmental Sustainability

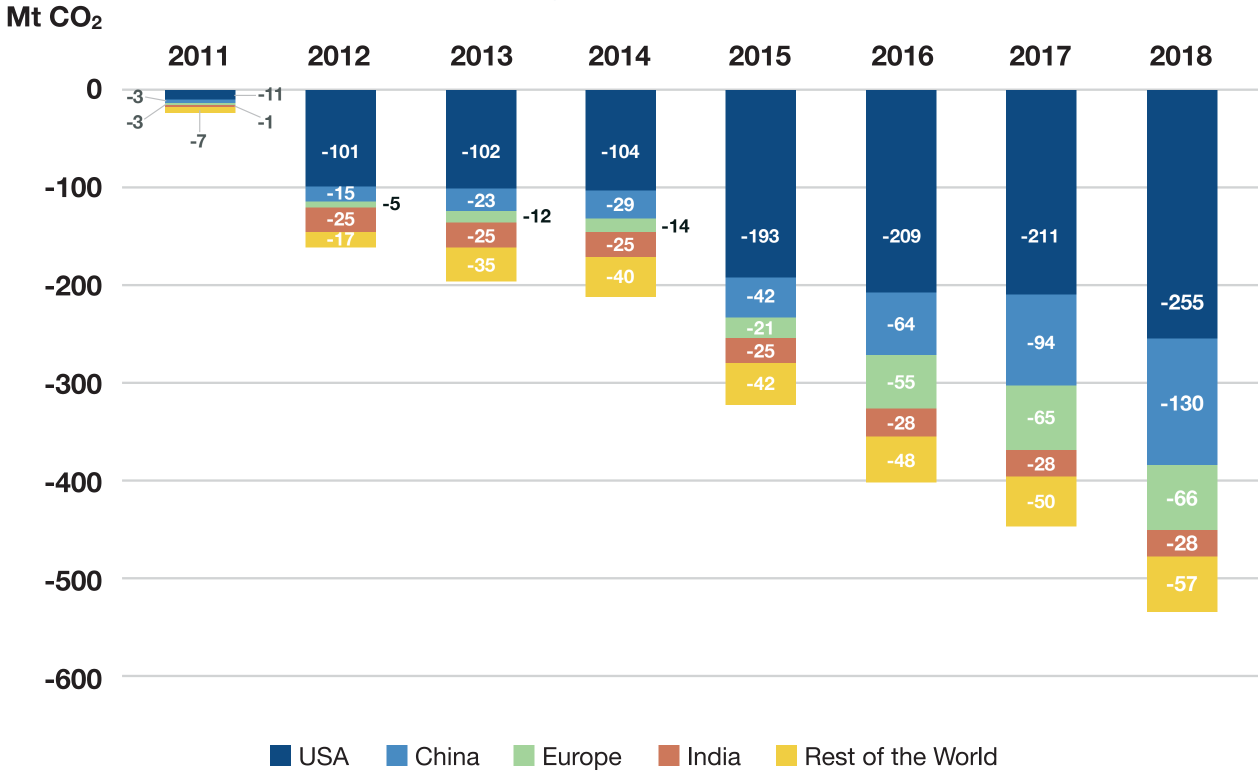
For natural gas to be aligned with net-zero commitments, methane and CO_2 emissions across the supply chain must be dramatically reduced. According to the IEA, despite the proliferation of initiatives to reduce GHG emissions, these initiatives have had extremely limited success. Globally, since 2015, emissions from gas systems have increased along with an increase in natural gas consumption, and global methane emissions from natural gas systems have not significantly declined since 2019, a record-high year for global methane emissions.

The increase of U.S. LNG exports to Europe after the Russian invasion of Ukraine in 2022 had other impacts on Asia. Less gas availability to Asian countries meant increased emissions from coal, higher prices for industrial uses of natural gas, and increased energy security concerns for energy import-dependent nations in Asia.

It should be noted that coal-to-gas fuel switching for power generation has resulted in lower emissions in many regions of the world. Analysis by the IEA shows that between 2001 and 2018, coal-to-gas fuel switching reduced power sector CO_2 emissions by roughly 4% globally, approximately 8% in China's power sector, and roughly 14% in the U.S. power sector[8] (Figure ES-4) [9]

Between 2005 and 2020, the U.S. was the No. 1 country in the world in CO_2 emissions reductions.[10] This was due in part to coal-to-gas fuel switching in the power sector. According to the EIA, between 2006 and 2021, natural gas and non-carbon power generation were responsible for reducing CO_2 emissions from the U.S. power sector by 7,202 MMmt, with 61% of these reductions attributed to coal-to-gas fuel switching. This data underscores the value of natural gas to climate change mitigation relative to coal use.

Figure ES-4. CO_2 savings from coal-to-gas switching in selected regions compared to 2010



Source: International Energy Agency (IEA), The Role of Gas in Today's Energy Transitions, July 2019, https://iea.blob.core.windows.net/assets/cc35f20f-7a94-44dc-a750-41c117517e93/TheRoleofGas.pdf.

Also, at COP28, in addition to the communique's focus on the transition away from fossil fuels, 50 oil and gas companies announced they would reduce methane leaks from their systems to "near zero" by 2030. This follows the Global Methane Pledge launched at COP26 in 2021, in which 150 countries committed to reducing methane emissions from all sectors by at least 30% by 2030. The pledge has led to diverse international, national, and industry efforts in methane reductions. Following the Global Methane Pledge, other GHG reduction initiatives have been formulated, such as the creation of an international market for fossil fuel emissions abatement. Technologies such as carbon capture, utilization, and storage (CCUS) are regarded as the options with the most significant potential to reduce CO_2 emissions across the natural gas supply chain and for industrial processes that use natural gas and coal. One of the most significant uses of CCUS technologies to date is for upstream gas processing.

Despite the proliferation of initiatives and commitments, global methane and CO_2 emissions from natural gas systems have not decreased significantly. The IEA's Global Methane Tracker 2023 found that the global energy industry emitted 135 Mt of methane in 2022, only slightly below the record-high emissions in 2019. The CO_2 emissions from natural gas have increased, although there was a slight decrease during the COVID-19 shutdowns and the supply chain disruptions that resulted from Russia's invasion of Ukraine.

Given the urgency of GHG emissions reductions from the natural gas supply chain, the commitments and action plans for methane abatement should be turned into detailed policies and regulations with clear signals for industry. In addition, policies promoting CCUS deployment and removal of barriers to deployment are needed. In this regard, legislation such as the U.S. Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act of 2022 (IRA) provide industry incentives to deploy technologies to further reduce emissions.

Key Findings

Growing international, national, and industry efforts to cut CO_2 emissions from natural gas systems have not yet led to large-scale reductions. Those emissions have continuously increased in the last decade, except for a slight decrease in 2020 and 2022 due to the COVID-19 shutdowns and the supply disruptions resulting from Russia's invasion of Ukraine. Expected growth in CO_2 emissions underscores the critical need to accelerate the development and deployment of net-zero emissions technologies, and for support from the developed world for decarbonization efforts in the developing world.

It also shows an ongoing need to invest in clean energy technologies. The EIA's Low Zero-Carbon Technology Cost scenario shows overall emissions reductions between 2022 and 2050 of around 7% globally. U.S. emissions show the largest decline, Western Europe sees a modest decline, and Eastern Europe/Eurasia shows a significant increase, more than offsetting any gains from Western Europe. While China shows a 17.8% decline in emissions, even in a low technology cost scenario, India's emissions almost double and emissions from "other Asia-Pacific" nations increase by 62%. These emissions underscore the critical need to accelerate the development and deployment of zero-emissions technologies and for support needed from the developed world for decarbonization efforts in the developing world.

Methane emissions reductions are also critical, especially for near-term gains in GHG emissions reductions. At COP28, the Oil and Gas Decarbonization Charter (OGDC), a voluntary commitment to accelerate climate action in the sector, was signed by 50 leading oil and gas companies, pledging to eliminate routine flaring and reach near-zero methane emissions by the end of the decade. The signatories include several international companies, including ExxonMobil, BP, and Shell, and several national oil companies, such as Saudi Aramco, ADNOC, Petrobras, and Petronas. In total, these companies represent about 40% of global oil and gas production. As noted, the Global Methane Pledge Energy Pathway was launched in 2022 by the United States, the EU, and 11 other countries to catalyze methane emissions reductions from the oil and gas sector. That same year, the United States, the EU, and five other countries committed to creating an international market for fossil energy "that minimizes flaring, methane, and CO_2 emissions across the value chain to the fullest extent practical." The United States also introduced several policies in 2022, including the Methane Emissions Reduction Action Plan—the U.S. Environmental Protection Agency's (EPA) proposal to reduce methane in oil and gas operations—as well as funding for methane abatement.

The fugitive methane emissions from upstream and midstream natural gas supply chains are highly variable and tend to be poorly measured. The methane leakage from each component of the natural gas supply chain, including producing wells, processing facilities, and transmission and distribution facilities, could substantially undercut the emissions reduction benefits from the lower carbon intensity of natural gas compared to coal. The CO_2 emissions from downstream combustion are well understood and measured compared to upstream methane emissions, but the emissions vary among facilities depending on energy efficiency and the type of plant.

Finally, CCUS is an effective option for reducing CO_2 emissions across the natural gas supply chain and has already been used in upstream processing. However, there is no natural gas-fired power plant with CCUS in operation worldwide as of July 2023. As noted, coal-to-gas switching has reduced significant CO_2 emissions and has great potential to contribute to global GHG emissions reduction, but high cost could be a barrier to coal-to-gas switching in many countries.

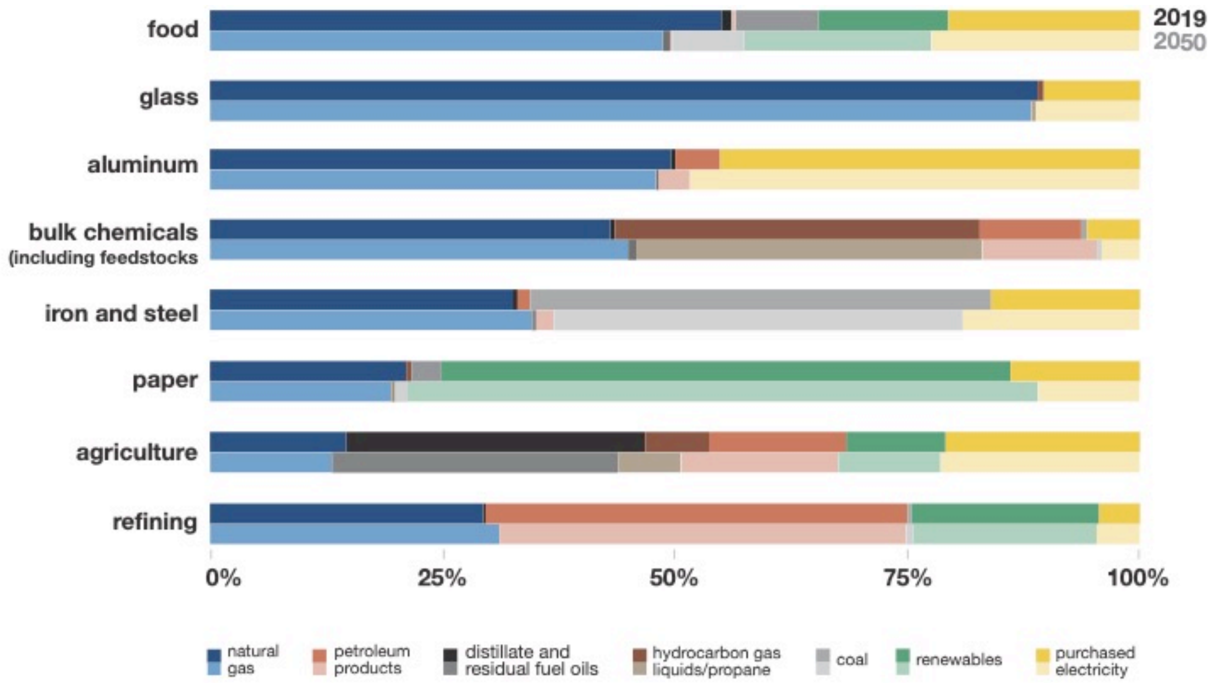
Industrial Decarbonization

The industrial sector is critical to national and regional economies and economic development in the least developed countries. At the same time, it is a major emitter of greenhouse gases, responsible for around a quarter of all global emissions. These issues were key drivers of this analysis's focus on industrial decarbonization.

According to the EIA, "The industrial sector consists of all facilities and equipment used for producing, processing, or assembling goods." The sector includes manufacturing, agriculture, construction, fishing, forestry, and mining (which includes oil and natural gas extraction). Industry uses fossil fuels and renewable energy sources for heat in industrial processes and space heating in buildings; boiler fuel to generate steam or hot water for process heating and generating electricity; and as feedstock for the manufacture of products such as plastics and chemicals."[11]

The United States offers an example of the role natural gas can and does play in the industrial sector (Figure ES-5).[12] As seen in the figure, natural gas is a key energy source for a range of industrial processes. In the near term, it provides an option for lowering industrial sector GHG emissions in many parts of the world since decarbonization options—including electrifying key industrial processes, hydrogen options for providing high-temperature heat, and CCUS—are either at the early phases of commercialization, not produced in sufficient quantities to meet industrial needs, or expensive.

Figure ES-5. U.S. energy consumption by fuel in industry subsectors, 2019/2050, AEO2020 Reference Case



Source: U.S. Energy Information Administration, Annual Energy Outlook 2020 with Projections to 2050, January 29, 2020. https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf.

Given the complex value chain of critical industrial manufacturing sectors, the value to national economies and jobs, and the lack of current commercialized, deployed, and affordable technologies for high-heat electrification of a significant percentage of industrial processes, it is likely that natural gas will continue to play a major role in the U.S. industrial sector. The industrial decarbonization road map from the U.S. Department of Energy (DOE), for example, shows that even in 2050, natural gas will continue to account for a large share of the energy consumption of key, albeit carbon-intensive, industrial subsectors.

Key Findings

The industrial sector is a major contributor to the global gross domestic product. In 2022, the steel, aluminum, pulp, and paper markets had a combined value of more than $2.2 trillion. The chemical industry's contribution to global gross domestic product alone was almost $6 trillion, the equivalent of 7% of global GDP. Concrete, steel, aluminum, glass, and iron are essential materials for construction and building renewable generation technologies, e.g., wind turbines. Ammonia, as a key component of fertilizer, is essential for food security.

The industrial sector is also a major energy consumer and accounts for nearly one-quarter of global carbon emissions. More than 30% of industrial processes require high-temperature process heat, which in turn requires a fuel for economic operation. Absent enhanced policies, actions, and affordable technologies, the industrial sector will remain one of the leading sources of increases in CO_2 emissions.

No single option enables deep decarbonization of the industrial sector. DOE's *Industrial Decarbonization Roadmap*, the path to net-zero industrial emissions for five U.S. carbon-intensive subsectors, identified that CCUS, industrial electrification, low-carbon fuels/feedstocks/energy sources (including hydrogen), and enhancing energy efficiency should be adopted to decarbonize the U.S. industrial sector.

Enhanced electrification of certain high-heat manufacturing processes and green hydrogen could replace other fuel sources. However, production and industrial technologies are expensive and in the early stages of demonstration, deployment, and commercialization. Technology development timelines vary but generally have decades-long spans. Acceleration of these timelines for several industrial decarbonization options is important for meeting midcentury net-zero targets. Green steel projects could have a higher impact on emissions if China and India, where the majority of global steel products are produced, make greater inroads in reducing emissions from steel manufacturing. The steel business case study highlights that cost will be a major issue in implementing a change to green steel in the near term.

Recommendations in Brief

Based on the findings from analysis, this report provides recommendations for decision-makers to clarify the role of natural gas in the global energy mix while balancing the competing priorities of the energy trilemma (energy security, energy equity, and environmental sustainability). The recommendations are organized around the dimensions of the energy trilemma, with key crossover issues highlighted in each section.

Energy Security

- Establish a collective action mechanism to develop energy security strategies for nations that produce and consume natural gas.
- Include an "Energy Security Determination" as a key component of the public interest determination for approving U.S. LNG export permits to non-free trade agreement (FTA) countries, with a focus on the impacts on U.S. allies and trading partners. This builds on the G7/EU 2014 commitment to energy security as a collective responsibility among allies and friends.
- The United States should commit to an ongoing global leadership role in meeting global energy security objectives, focused on those associated with U.S. natural gas exports.
- U.S. exporters of LNG should maintain destination flexibility by continuing to not require destination clauses in the consideration of LNG export licenses to non-FTA countries.
- Establish information-sharing requirements in the United States and a convening authority to harmonize federal, state, local, and tribal permitting requirements.
- Further analyze supply needs and operational implications of announced and under-construction natural gas-fired power plants and associated infrastructure in Europe and Asia.

Energy Equity

- Enhance international support for the clean energy transition in developing countries, including support for securing reliable and affordable natural gas supplies, mitigation technologies, and infrastructure. This serves all three dimensions of the energy trilemma.
- Support additional public and private sector funding for the implementation of the ALTÉRRA fund or similar private funds.[a]
- Reestablish an MDB CCUS trust fund for developing countries with broader support from more donors.
- Analyze and develop a comprehensive energy security road map through 2050 for the Asia-Pacific region.

Environmental Sustainability

- Build international consensus on GHG disclosure requirements for LNG.
- Assess the potential for additional natural gas and biogas supplies associated with methane emissions and provide support for innovation in difficult-to-abate sectors, e.g., agriculture.
- To meet both critical climate change and energy security imperatives in a timely way, the U.S. Council on Environmental Quality (CEQ) should be tasked with clarifying and routinizing the assessment criteria and guidance for emissions from U.S. LNG projects.
- Accelerate the implementation of the Global Methane Pledge through biannual convenings of participating regions/nations.
- Assess and quantify methane emissions from shipping LNG.
- Enhance cooperation among allies and trading partners on developing national and regional industrial decarbonization pathways for natural gas systems and supply chains.
- Incentivize and accelerate research and development in new technologies and policies to reduce the cost of electrifying industrial heat.
- Accelerate international collaboration on deployment of CCUS technologies.
- Incentivize industry to switch to low-carbon hydrogen to meet existing demand for industrial feedstocks.

[a] ALTÉRRA is a $30B investment fund designed to mobilize investment for a new climate economy https://www.alterra.ae/.

Crosscutting Needs: Cooperation in the Development and Implementation of Energy Transition Pathways

- Identify the appropriate international entity to develop consistent, transparent, and accurate methodologies for calculating Scope 1, 2 and 3 emissions.[b]
- Through an organization similar to the International Organization for Standardization, establish and maintain accurate and comprehensive methodologies for GHG accounting across energy systems and supply chains, including those for natural gas.
- The IEA should add to its decarbonization modeling portfolio a scenario in which carbon emissions targets accommodate economic development metrics, e.g., different decarbonization target dates for industrialized, emerging, and developing economies.
- Under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), complete a price-based climate policy economic analysis.

[b] The UNFCCC defines Scope 1-3 Emissions as: Scope 1 – All direct emissions; Scope 2 – Indirect emissions; and Scope 3 – All other indirect emissions. For a more detailed explanation please see: https://unfccc.int/sites/default/files/resource/ThePathtoClimateNeutrality-Measure-TheBasics_May26.pdf.

1. The Role of Natural of Natural Gas in Addressing the Challenges of the Energy Trilemma: Framing Policy Options and Pathways

Findings in Brief

- Natural gas could play a significant role in managing the "energy trilemma," which includes three difficult but critical objectives that must be addressed simultaneously: energy security, energy equity, and environmental sustainability.
- As of June 2023, around three-quarters of the world's countries and almost 1,000 global companies had net-zero targets; this will affect future investments in energy systems including natural gas systems.
- The climate change impacts of natural gas represent the most serious challenge for its continued use. While CO_2 emissions from natural gas combustion are substantially lower than those from coal or oil, the challenges associated with these GHG emissions will ultimately determine whether natural gas is merely a transitional fuel or an integral part of the longer-term global energy mix.
- Forecasts for natural gas consumption underscore the ongoing need for policy support, emissions reduction technologies such as CCUS, and investments that support the substantial demand for natural gas through 2050, while also decarbonizing its uses and supply chains.
- EIA's Reference Case shows an overall increase in global natural gas of almost 44 Tcf or a 29% overall increase by 2050. The largest absolute increases are in the Asia-Pacific region, where demand grows by about 19 Tcf, or around a 54.7% of the total increase in gas consumption in the region. Consumption in India shows the highest percentage growth, at 233%, although absolute consumption increases by only 5.8 Tcf. China represents the highest growth in absolute demand in the region, at about 10 Tcf.
- Without U.S. LNG exports and flexible U.S. contracts that lack destination clauses, Europeans would have had insufficient fuel to heat their homes and generate electricity the winter after the Russian invasion of Ukraine. Europe lost 22 Bcm of natural gas that winter; the United States provided Europe 19 Bcm.
- Europe's and Asia's LNG regasification capacity is expected to increase dramatically by 2025. Following Russia's invasion of Ukraine, the 2022 energy crisis in Europe motivated investors to support the construction of regasification infrastructure for non-Russian gas supply. Compared to the previous 10 years, the rate of new approvals for liquefaction capacity have doubled since the Russian invasion.

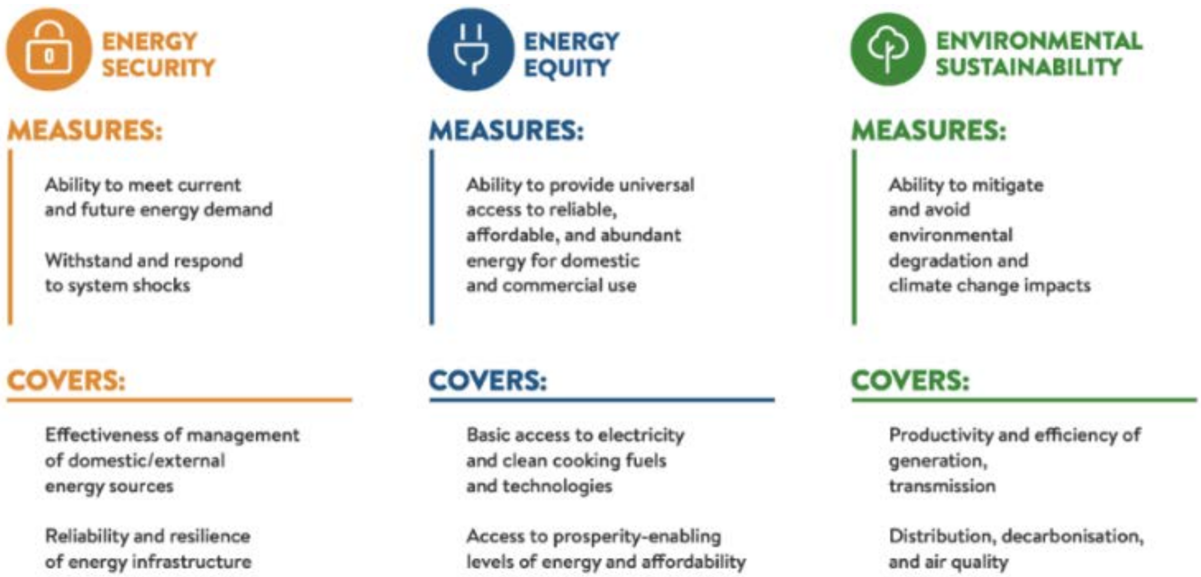
- While high-income LNG-importing countries in Europe and Asia were able to absorb the shock of high energy prices after Russia's invasion of Ukraine, high prices were a problem in many countries, especially developing countries where energy prices and affordability are important for economic stability and growth. This has led to increased coal use.
- Underinvestment in natural gas infrastructure could inhibit a stable long-term supply of natural gas, raise energy security and affordability concerns in many countries, and potentially resulting in more coal consumption and the associated higher CO_2 emissions.
- Capturing methane emissions from natural gas systems, essential for meeting net-zero targets, could reduce total global methane emissions by 10% and—because methane's residence in the atmosphere is 10 to 12 years compared with 1,000-plus years for CO_2—could help achieve early and substantial gains in mitigating climate change.

At the 28th United Nations Climate Change Conference of the Parties (COP28), countries agreed that "transitional fuels can play a role in facilitating the energy transition while ensuring energy security," even as they are "transitioning away from fossil fuels in energy systems in a just, orderly, and equitable manner."[13] At the same time, the recent global energy crisis—the result of Russia's war on Ukraine and its ripple effects—has placed energy security at the center of global energy concerns and debates. This has not diminished the need for deep decarbonization and the clean energy transition. It has, however, added to the need for solutions that address both energy security and decarbonization goals. It also underscores the potentially significant role of natural gas in the transition to the low-carbon economy and further complicates technology, policy, and investment needs and options.

The Energy Trilemma

This study analyzes the role of natural gas through the lens of the "energy trilemma": energy security, energy equity, and environmental sustainability. This construct is used by the World Energy Council (WEC) for its World Energy Trilemma Index, described by the WEC as "an energy policy pathfinding tool" (Figure 1).[14] The WEC's highly insightful construct and ordering are used in this study to organize its analysis of the role of natural gas in a low-carbon world and to make recommendations to inform policymakers and investors worldwide regarding the role of natural gas in energy security, equity, and environmental sustainability goals.

Figure 1. Energy trilemma dimensions



Source: Philip Lowe et al., "World Energy Trilemma Index 2020. Report + Summary," 2020, https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2020

For the purposes of this EFI Foundation analysis, energy security is measured by the ability of a country or region to reliably meet current and future energy demand. Energy equity is measured by the degree to which a country or region provides access to reliable, affordable, clean, and abundant energy for domestic and commercial use. Environmental sustainability is measured by the degree to which a country or region transitions its energy systems to help mitigate environmental harm and climate change impacts.

This analysis focuses on the role of natural gas in addressing this energy trilemma. Using this framework, it analyzes natural gas both globally and with a specific focus on Europe, Asia, and the United States.

Energy Security

The recent global energy crisis has placed energy security at the center of global energy discussions and debates. At COP28, countries agreed that "transitional fuels can play a role in facilitating the energy transition while ensuring energy security."[15]

Energy security was also a concern after Russia's invasion of Crimea in 2014, after which the G7 countries and European Commission issued a set of "modernized" energy security principles. The 2014 communique from the leaders noted, "The crisis in Ukraine makes plain that energy security must be at the center of our collective agenda," and the principles endorsed by the leaders included a significant focus on natural gas, calling for:

- Development of flexible, transparent, and competitive energy markets, including gas markets. Diversification of energy fuels, sources and routes, and encouragement of indigenous sources of energy supply
- A reduction in GHG emissions and an acceleration of the transition to a low-carbon economy as a key contribution to sustainable energy security

Eight years after its invasion of Crimea, the 2022 Russian invasion of Ukraine once again brought natural gas to the forefront of Europe's energy security needs and concerns. A major difference between Russia's Ukraine invasions between 2014 and 2022, however, was that over that period, the United States became the largest gas producer and LNG exporter in the world. The importance of this prominence was evident in the winter of 2022-2023, when U.S. LNG was able to replace 19 billion cubic meters (Bcm) of the 22 Bcm that Europe lost because of the Russian invasion and subsequent sanctions.[c]

Without this critical supply, Europeans would have had insufficient fuel to heat their homes and generate electricity. The lack of destination clauses in U.S. LNG contracts was critical for helping to fill this supply gap. Natural gas will continue to bolster energy security, which has become one of the top national priorities in many countries.

While high-income LNG-importing countries in Europe and Asia were able to absorb the shock of high energy prices after Russia's invasion of Ukraine, high prices were a problem in many countries, especially developing nations where energy prices and affordability are important for economic stability and growth. This led to increased coal use, along with the associated increases in emissions.

A major difference between Russia's Ukraine invasions in 2014 and 2022 was that over that period, the United States became the largest gas producer and LNG exporter in the world. The importance of this prominence was evident in the winter of 2022-2023, when U.S. LNG was able to replace 19 Bcm of the 22 Bcm Europe lost because of the Russian invasion and subsequent sanctions. Without this critical supply, Europeans would have had insufficient fuel to heat their homes and generate electricity.

The recent energy crisis in Europe motivated investors to support the construction of regasification infrastructure for non-Russian gas supply. Compared to the previous 10 years, the rate of new approvals for regasification capacity has doubled since the Russian invasion. Going forward, Europe and Asia are facing substantial challenges to their long-term energy pathways. In these regions, domestic energy resources are limited and imports of energy sources for domestic consumption are crucial for energy security, economic stability, equity, and growth. These supply limitations and growing energy demand have made Europe and Asia the world's largest regional

[c] See Appendix for details for units and conversion factors.

importers of LNG, accounting for more than 90% of the world's total LNG import volumes. As a region, Europe is the largest importer of U.S. LNG. China is currently the largest importing country of U.S. LNG, replacing South Korea, which was the largest importer of U.S. LNG from 2019 to 2022. This shared interest and trading relationship between the United States and China should be acknowledged and managed. Regasification capacity is expected to dramatically increase by 2025.

Even with this demand, U.S. LNG suppliers have faced, and will continue to face, numerous challenges to building LNG export infrastructure. These include uncertain and divergent forecasts of longer-term natural gas demand, the availability of global LNG supplies and the associated permitting, and regulatory challenges. At the same time, this reliance on imports has motivated these countries and regions to expedite the development of both conventional and renewable energy resources to address their energy security and climate goals, introducing additional issues of uncertainty into longer-term demand for U.S. LNG.

It is difficult, however, to develop and deploy affordable and adequate supplies of renewable and other net-zero energy options, e.g., green hydrogen, fast enough to meet the energy/fuel demands of these regions in the near and midterm while simultaneously addressing energy security needs. Moreover, developing countries in these regions are sensitive to the challenges of affordability in meeting growing energy demands that support economic growth. Informed and sequenced policies will be needed to meet net-zero targets by midcentury while ensuring the energy security of the countries and regions focused on in this analysis and addressing energy equity, affordability, and climate change mitigation issues.

Energy Equity

For this analysis, energy equity includes access to energy, energy affordability, access to clean energy, and food security. Most recently, energy equity issues were raised by Russia's invasion of Ukraine. The invasion created a fundamental shift in the natural gas markets and the associated trade flows. Europe is in the process of eliminating Russian natural gas imports, a staple of European gas markets for decades. This has resulted in price shocks for European gas consumers. In response, the EU and governments in Europe took a variety of actions, ranging from tax relief and subsidies to efforts to reform energy infrastructure—all of which have brought consumers minimal relief.[16]

Asian markets, while slightly more insulated from price shocks because of their greater reliance on long-term contracts, are at an inflection point as most of their long-term contracts will expire by 2030. How Asian countries and regions respond will have significant cost and security implications. Importantly, China and India have increased their consumption of Russian gas, a shift in trade flows that may become a long-term reality, with a range of implications for costs, U.S. supply, and geopolitics. While the United States can help fill part of the gap for Europe, developing countries in Asia may suffer the most from high prices.

Progress had been made on energy poverty, but the COVID-19 pandemic and the related economic slowdown have diminished this headway. With higher energy prices associated with the post-COVID recovery, energy-importing nations, especially those in the developing world, are struggling with issues of energy affordability, including natural gas (although recent price declines have been substantial). Affordability is, as noted, critical for economic growth. This could also have another negative impact: Nations that lack the infrastructure to take advantage of new natural gas flows are likely to utilize coal. This could result in higher emissions over the long life spans of new coal plants and infrastructure, with a corresponding impact on decarbonization goals.

Environmental Sustainability

At COP28, in addition to the communique's focus on the transition away from fossil fuels, 50 oil and gas companies announced they would reduce methane leaks from their systems to "near zero" by 2030. This follows the Global Methane Pledge launched at COP26 in 2021, at which 150 countries committed to reducing methane emissions from all sectors by at least 30% by 2030. The pledge has led to diverse international, national, and industry efforts in methane reductions. Following the Global Methane Pledge, other GHG reduction initiatives have been formulated, such as the creation of an international market for fossil fuel emission abatement.

Technologies such as CCUS are regarded as the option with the most significant potential to reduce CO_2 emissions across the natural gas supply chain and for industrial processes that use natural gas and coal. One of the most significant uses of CCUS technologies to date is for upstream gas processing.

Despite the proliferation of initiatives and commitments, global methane and CO_2 emissions from natural gas systems have not significantly decreased. The Global Methane Tracker 2023 from the International Energy Agency (IEA) found that the global energy industry emitted 135 million tons (Mt) of methane in 2022, only slightly below record.[17] The CO_2 emissions from natural gas have increased, although there was a slight decrease during the COVID-19 shutdowns and the supply chain disruptions that resulted from Russia's invasion of Ukraine. Given the urgency of GHG emissions reductions from the natural gas supply chain, the commitments and action plans for methane abatement should be turned into detailed policies and regulations with clear signals for industry. In addition, policies promoting CCUS deployment and removal of barriers to its deployment are needed. In this regard, legislation such as the U.S. Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act of 2022 (IRA) provides incentives to industry to deploy technologies to further reduce emissions.

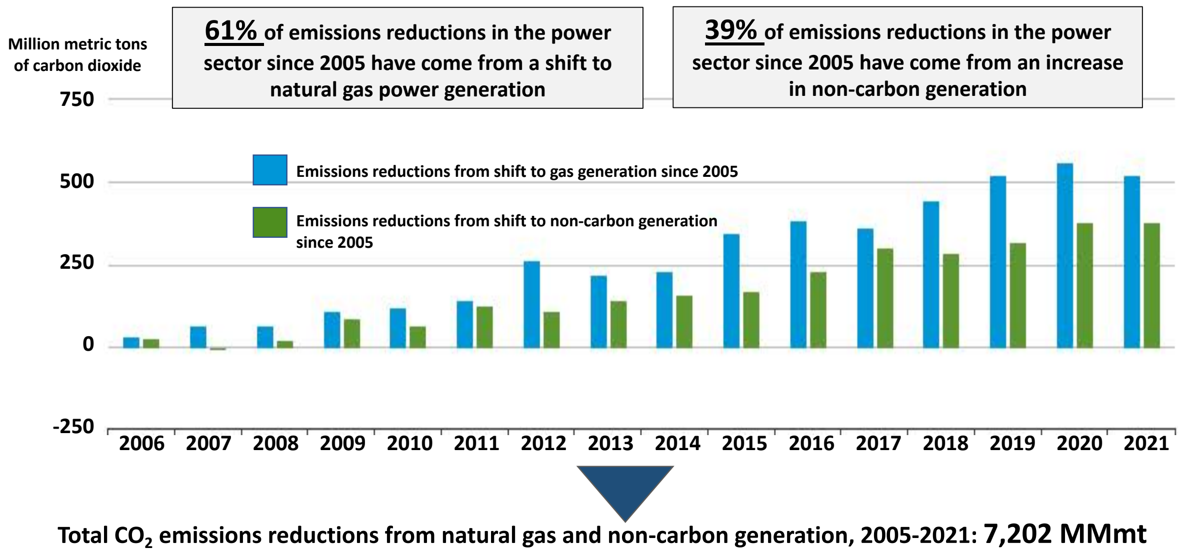
Natural gas can also address energy equity and affordability issues. Natural gas has been an essential component of lowering the cost of decarbonization by complementing intermittent[d] renewable energy generation from wind and solar. Natural gas can be used in key industrial processes, ensuring the affordability and competitiveness of a country's industrial sector, while lowering emissions of CO_2 and other pollutants. These roles of natural gas, while country-specific, have made it a key enabler of global and regional energy security and economic growth, while offering reliable and generally affordable energy.[18,19,20]

From the environmental dimension of the energy trilemma, it should be noted that coal-to-gas fuel switching for power generation has resulted in lower emissions in many regions of the world.[21] Analysis by the IEA shows that between 2001 and 2018, coal-to-gas fuel switching reduced power sector CO_2 emissions by roughly 4% globally, by approximately 8% in China's power sector, and by roughly 14% in the U.S. power sector.[22]

[d] "Intermittency" refers to the challenge that renewable (wind and solar) energy cannot always consistently produce electricity.

Between 2005 and 2020, the U.S. was the No. 1 country in the world in CO_2 emissions reductions.[23] This was due in part to coal-to-gas fuel switching in the power sector. According to the U.S. Energy Information Administration (EIA), between 2006 and 2021, natural gas and non-carbon power generation were responsible for reducing CO_2 emissions from the U.S. power sector by 7,202 MMmt, with 61% of those reductions attributed to coal-to-gas fuel switching (Figure 2).[24] This data underscores the value of natural gas to climate change mitigation relative to coal use.

Figure 2. U.S. CO_2 emissions reductions from coal-to-gas fuel switching, 2006 to 2021



Source: EFI Foundation with data from EIA, U.S. Energy-Related Carbon Dioxide Emissions, 2022, https://www.eia.gov/environment/emissions/carbon/index.php/pd/pdf/2019_co2analysis.pdf.

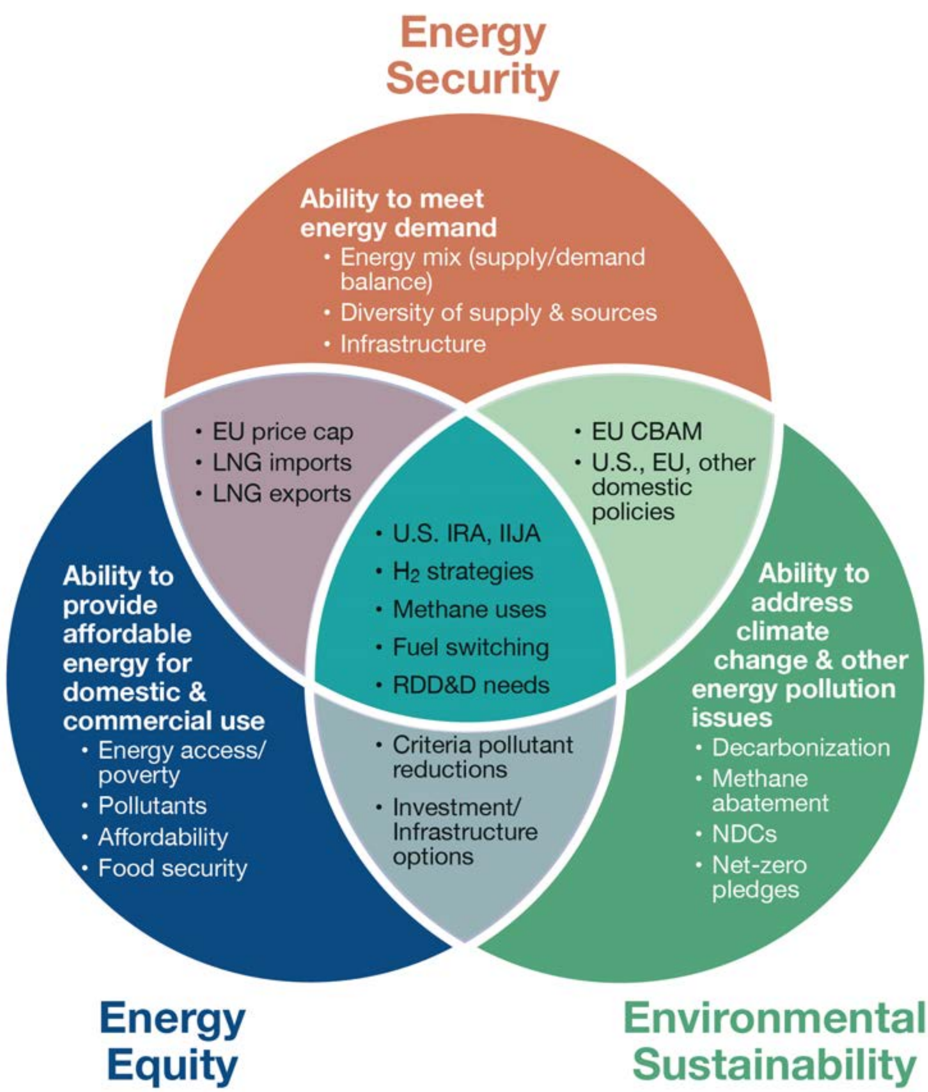
Nevertheless, the most serious challenge facing natural gas suppliers and consumers is mitigating GHG emissions from the natural gas supply chain, including from its uses as a fuel and a feedstock for key industrial processes. For natural gas to be aligned with net-zero commitments, methane and CO_2 emissions across the supply chain must be dramatically reduced. According to the IEA, despite the proliferation of initiatives to reduce GHG emissions, these initiatives have had extremely limited success. Globally, since 2015, emissions from gas systems have increased along with gas consumption[25] and global methane emissions from natural gas systems have not significantly declined since 2019, a record-high year.[26]

The most serious challenge facing natural gas suppliers and consumers is mitigating GHG emissions from the natural gas supply chain, including its uses as a fuel and a feedstock. For natural gas to be aligned with net-zero commitments, methane and CO_2 emissions across the supply chain must be dramatically reduced.

The Energy Trilemma and Natural Gas: Opportunities and Challenges

There are significant opportunities and an essential role for natural gas in addressing the dimensions of the trilemma. There is also substantial crossover between the elements of the energy trilemma as seen in Figure 3. For example, U.S. LNG exports are closely related to energy security and energy equity in major importing countries in Europe and Asia as the volume of supply and prices directly influence their national economies and the reliability of energy systems. Environmental and climate policies are commonly related to energy security and energy equity as they affect the supply and affordability of energy sources, including natural gas.

Figure 3. The energy trilemma and natural gas



Source: EFI Foundation

While there are opportunities for natural gas to address the three dimensions of the energy trilemma, there are also limitations. These include various regional and national factors such as a country's energy mix, natural gas and coal reserves, the maturity of decarbonization technologies, and relevant policies and regulations.

For example, although Europe considers U.S. LNG a near- and midterm solution for meeting its energy security needs while reducing its imports of natural gas from Russia, countries in the region are concerned that a substantial share of natural gas will still come from outside Europe. Natural gas consumption, even in the near to midterm, is also viewed by many, particularly in Western Europe, as being inconsistent with the region's climate goals. Developing Asian nations, on the other hand, have expressed concerns that prices of imported LNG are too expensive for their consumers.

As noted, this analysis will focus on the three challenges of the trilemma as well as the crosscuts where policies and investments might simultaneously address more than one element of the trilemma. In addition to the construct of the energy trilemma, the data and analysis in Chapter 1 use cases and scenarios to identify and inform issues and potential policy, regional, technology, geopolitical, and investment pathways for the role of natural gas in a low-carbon world. Box 1 describes the cases and scenarios referenced in this chapter.

Baseline Data and Forecasts: Informing the Role of Natural Gas in a Low-Carbon World

To understand the role—and future—of natural gas in a deeply decarbonized world, albeit one that currently relies on natural gas for energy security, cleaner air, competitiveness, and affordability, it is critical that natural gas be understood and analyzed in the context of supply and demand, relative to other fuels. Data in this and other chapters is informed, in part, by the scenarios and cases described in Box 1.

Box 1

Cases/Scenarios Used for Analysis in Chapter 1 of *The Future of Natural Gas in a Low-Carbon World*

The EIA Reference Case. The EIA Reference Case models projections under assumptions that reflect current energy trends and relationships, existing laws and regulations, and select economic and technological changes. The Reference Case includes existing non-U.S. laws and regulations as of spring 2023 and reflects legislated energy sector policies that can be reasonably quantified in the World Energy Projection System (WEPS).

The IEA Stated Policies Scenario (STEPS). STEPS is "designed to provide a sense of the prevailing direction of energy system progression, based on a detailed review of the current policy landscape. … The policies assessed in the STEPS cover a broad spectrum, including Nationally Determined Contributions under the Paris Agreement and much more. The bottom-up modelling for this scenario requires extensive detail at the sectoral level, including pricing policies, efficiency standards and schemes, electrification programs, and specific infrastructure projects. The scenario considers relevant policies and implementation measures adopted as of the end of August 2023, together with relevant policy proposals, even if the specific measures needed to put these proposals into effect have yet to be fully developed."

The IEA Announced Pledges Scenario (APS). The APS is designed to illustrate "the extent to which announced ambitions and targets can deliver the emissions reductions needed to achieve net-zero emissions by 2050. It includes all recent major national announcements as of the end of August 2023, both 2030 targets and longer-term net-zero or carbon neutrality pledges, regardless of whether these announcements have been anchored in legislation or in updated Nationally Determined Contributions. In the APS, countries implement their national targets in full and on time."

The IEA Net Zero Scenario (NZS). The NZS is based on the following principles: "1) the uptake of all the available technologies and emissions reduction options is dictated by costs, technology maturity, policy preferences, and market and country conditions; 2) all countries co-operate towards achieving net-zero emissions worldwide. This involves all countries participating in efforts to meet the net-zero goal, working together in an effective and mutually beneficial way, and recognizing the different stages of economic development of countries and regions, and the importance of ensuring a just transition; and 3) an orderly transition across the energy sector. This includes always ensuring the security of fuel and electricity supplies, minimizing stranded assets where possible and aiming to avoid volatility in energy markets."

The EIA High Zero-Carbon Technology Cost Case (High-cost). The High-cost case examines the sensitivities around capital costs for electricity-generating technologies that produce zero emissions, which include renewables, nuclear (a zero-carbon technology included in these cases for the first time in this AEO), and diurnal storage technologies. It assumes no capital cost reductions from learning by doing: The overnight capital cost is held constant at the 2022 level throughout the projection period for all covered technologies.

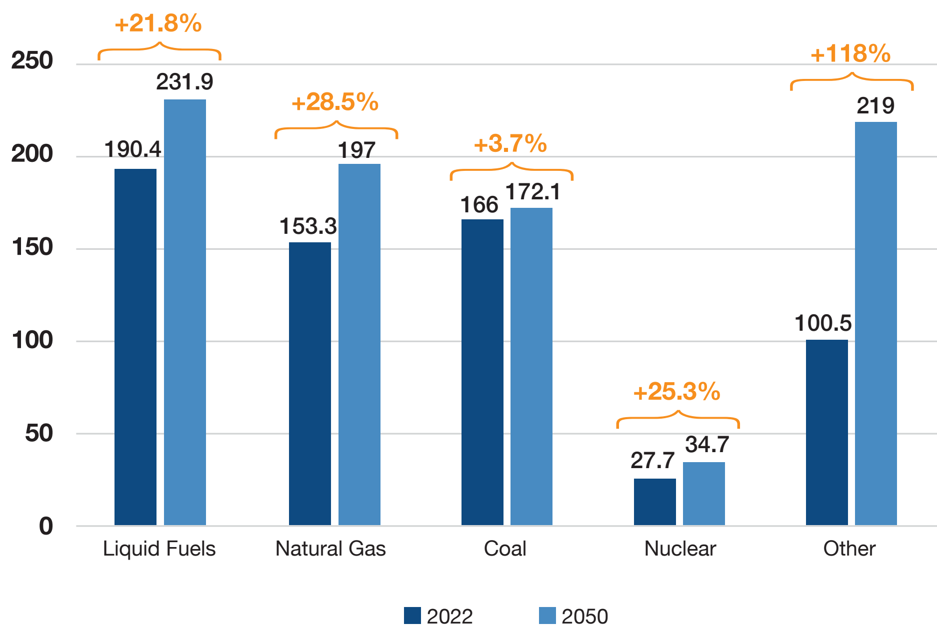
The EIA Low Zero-Carbon Technology Cost Case (Low-cost). The Low-cost case examines the sensitivities around capital costs for electricity-generating technologies that produce zero emissions, which include renewables, nuclear (a zero-carbon technology included in these cases for the first time in this AEO), and diurnal storage technologies. It assumes faster, exogenously determined technology cost declines through 2050, resulting in about a 40% cost reduction by 2050 compared with the Reference Case for each zero-carbon technology.

It should be noted that, because of how EIA and IEA—the world's foremost energy data-gathering entities—collect information, data in the following sections do not precisely reflect the specific regions, subregions, and countries on which this analysis focuses in subsequent chapters; these data and groupings reflect major categorizations and groupings by the EIA and the IEA. Their data, however, are sufficiently detailed and generally focused on the areas of inquiry sufficient to provide critical baseline and directional data to inform this analysis.

Primary Energy Consumption

It is important to understand the role of natural gas in energy security, equity, and sustainability in the context of primary energy consumption by fuel shown in Figure 4.[27] In addition to an overall increase in primary energy consumption of 34% between 2022 and 2050, of note for this study is a significant increase in absolute natural gas consumption over that time period, from 153.3 quadrillion Btu (quads) to 197 quads in EIA's International Energy Outlook 2023 Reference Case, a 28.5% increase. Also of note: a more modest increase in liquid fuels[e]; a very small increase in coal consumption, from 166 quads to 172 quads; and a large absolute increase in "other" fuel consumption (defined by the EIA as renewables including wind, solar and hydro), from 100.5 quads to 219 quads,[f] making this category the largest volume of energy consumed by 2050. Different forecasts that assume a range of climate policies are discussed in the next section of this chapter and in greater detail in Chapter 4.

Figure 4. World primary energy consumption by fuel, 2022/2050, EIA Reference Case (quadrillion Btu)



% of total global consumption	2022	2050
Liquid Fuels	29.8	27.1
Natural Gas	24.0	23.0
Coal	26.0	20.1
Nuclear	4.3	4.1
Other	15.7	25.6

Overall change in global fuel consumption, 2022/2050: +34%
Overall change in Liquid Fuels/Natural Gas/Coal consumption, 2022/2050: +17.9%

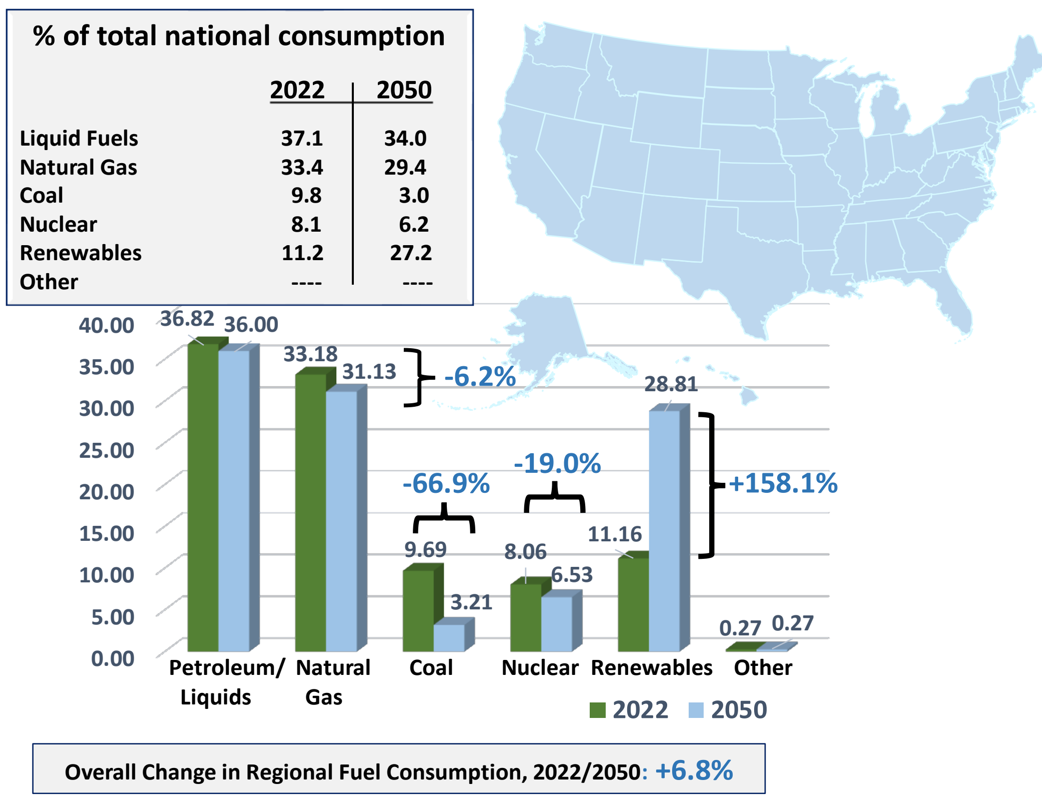
"Other" includes wind, solar and other renewables. Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

[e] EIA's definition of liquid fuels includes "all petroleum including crude oil and products of petroleum refining, natural gas liquids, biofuels, and liquids derived from other hydrocarbon sources (including coal to liquids and gas to liquids)."
[f] "Other" is renewable energy including wind, solar and hydro.

In the EIA Reference Case, natural gas and renewables combined represent 60% of the total increase in global fuel consumption between 2022 and 2050. This and the remaining 40%—liquid fuels and coal—underscore the ongoing need for managing emissions from these fuels using technologies such as carbon capture and storage (CCS), discussed in greater detail in Chapters 4 and 5. Large increases in energy consumption in key regions of the world also suggest growing competition for energy supplies, with a range of associated geopolitical, supply chain, and competitiveness issues.

Primary energy consumption by fuel in the United States in the EIA Reference Case is shown in Figure 5.[28] Several issues raised by these data are important for this analysis. In 2050, natural gas is still 29.4% of total primary energy consumption in the United States, second only to liquid fuels. Coal shows a very steep decline and will be only 3% of primary consumption in 2050. Renewable energy increases by the highest percentage of any of the fuels by far, growing by over 158% by midcentury, making renewables over 27% of primary energy consumption, just slightly lower than absolute amounts of natural gas and the third-largest source of energy consumption in the United States in 2050.

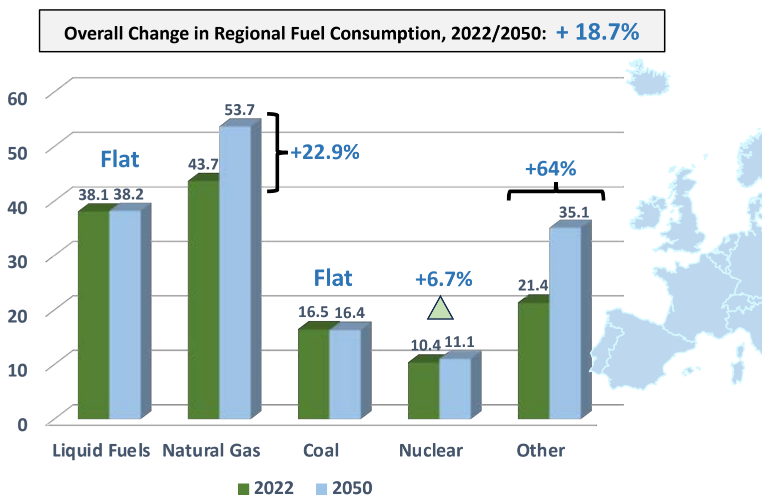
Figure 5. U.S. primary energy consumption by fuel, 2022/2050, EIA Reference Case (quadrillion Btu)



Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

Figure 6 shows data on primary energy consumption by fuel for Europe and Eurasia (including Russia) over the same period in the EIA Reference Case.[29] Trends in this region—significant increases in natural gas and renewable energy consumption—are similar to larger global trends. In the Europe/Eurasia region, 97% of total fuel consumption increases are in natural gas and renewables, compared with 60% in the world overall. Consumption of liquid fuels and coal in Europe and Eurasia between 2022 and 2050 is flat.

Figure 6. U.S. Europe/Eurasia primary energy consumption by fuel, 2022/2050, EIA Reference Case (quadrillion Btu)



% of total regional consumption

	2022	2050
Liquid Fuels	29.3	24.7
Natural Gas	33.6	34.9
Coal	12.7	10.6
Nuclear	8.0	7.2
Other	16.4	22.7

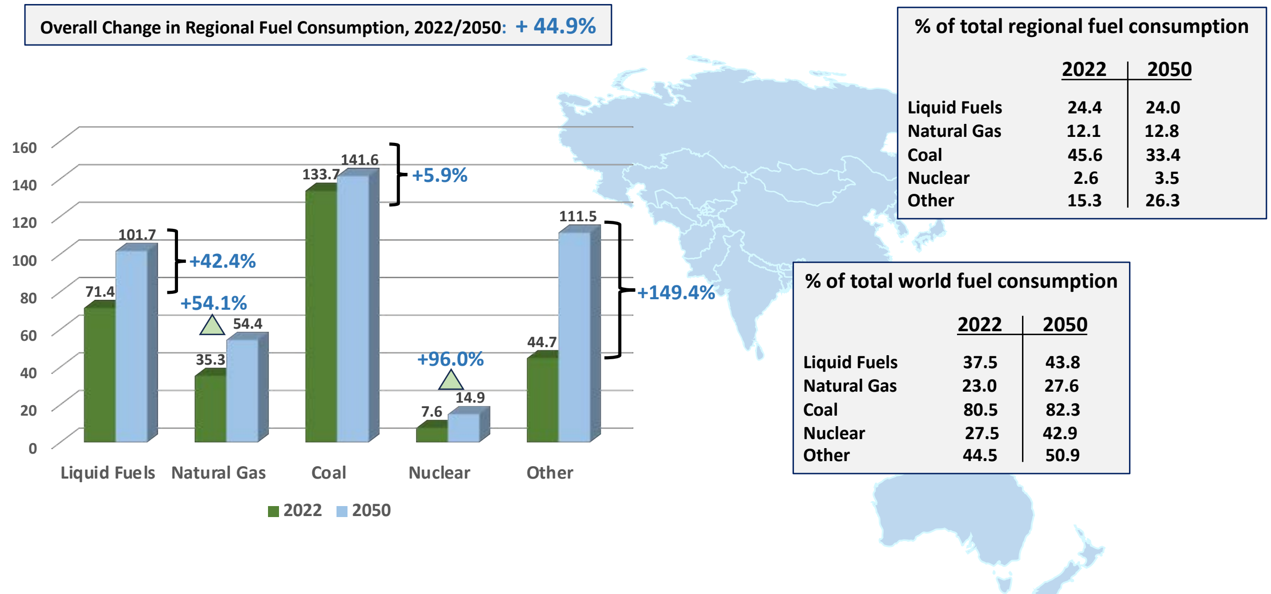
% of total world fuel consumption

	2022	2050
Liquid Fuels	22.9	23.1
Natural Gas	28.5	27.2
Coal	9.9	9.5
Nuclear	37.5	31.7
Other	21.3	16.0

Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, [https://www.eia.gov/outlooks/ieo/.](https://www.eia.gov/outlooks/ieo/)

Figure 7 shows primary energy consumption by fuel for the Asia-Pacific region in 2022 and EIA's Reference Case forecasts for 2050.[30] The overall change in absolute energy consumption is almost a 45% increase. Of note, in 2022, this region represented 80.5% of the world's coal consumption. By 2050, coal consumption in the region increases, representing 82.3% of the world's total.

Figure 7. Asia-Pacific primary energy consumption by fuel, 2022/2050, EIA Reference Case (quadrillion Btu)



% of total regional fuel consumption	2022	2050
Liquid Fuels	24.4	24.0
Natural Gas	12.1	12.8
Coal	45.6	33.4
Nuclear	2.6	3.5
Other	15.3	26.3

% of total world fuel consumption	2022	2050
Liquid Fuels	37.5	43.8
Natural Gas	23.0	27.6
Coal	80.5	82.3
Nuclear	27.5	42.9
Other	44.5	50.9

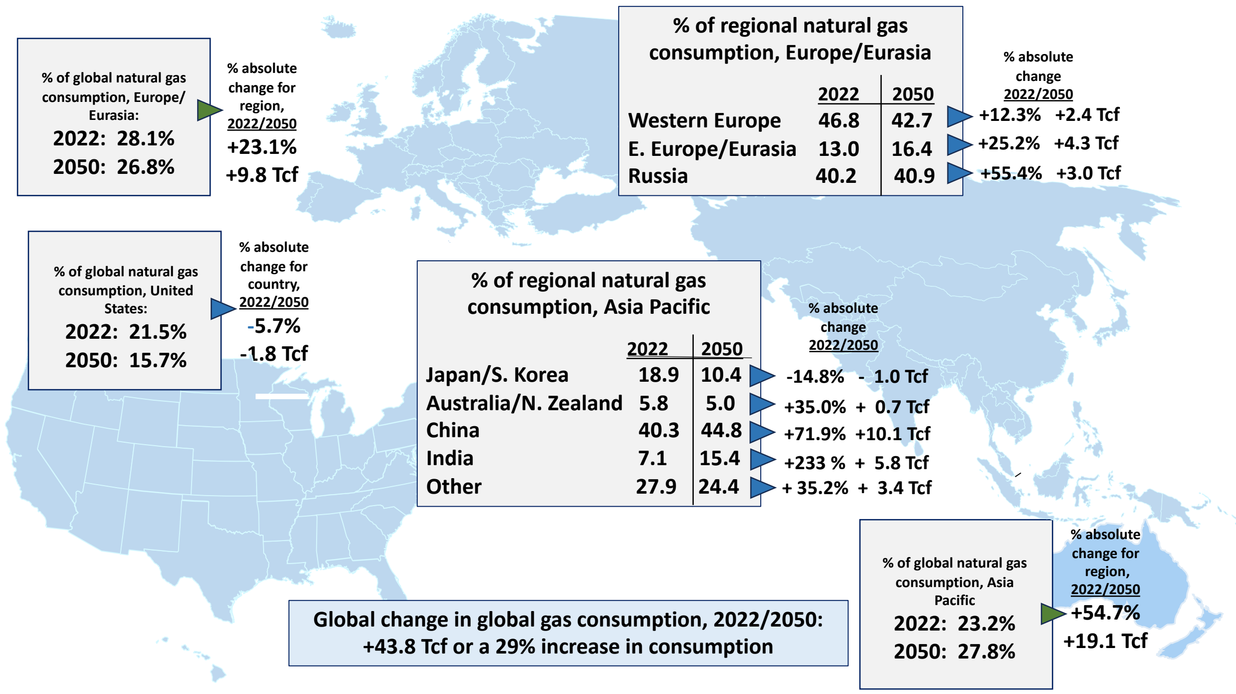
Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, *https://www.eia.gov/outlooks/ieo/.*

High levels of coal consumption have significant implications for CO_2 emissions in the Asia-Pacific region. Eighteen countries in the region have net-zero commitments, which could impact demand for natural gas, as it could help lower emissions. As seen in Figure 7, the largest increases in both percentage and absolute amounts are, like those globally, in renewables and natural gas. Natural gas, however, is still a relatively small percentage of overall primary energy consumption in the region, which, as seen in the figure, could have significant emissions implications for the region and options for their mitigation, e.g., fuel switching.

Scenarios for Natural Gas, Coal, and Renewables Consumption

To further analyze the emissions implications of regional and national primary energy consumption, it is important to understand more details about the primary fuels being consumed by the regions analyzed in this study. Figure 8 shows additional details on natural gas consumption in the United States, Europe/Eurasia (including countries and subregions), and the Asia-Pacific region (including countries and subregions) in 2022 and 2050, based on forecasts in the EIA Reference Case.[31] Detailed information shows both absolute and percentage changes in these countries/regions as well as percentages of world total natural gas consumption in 2022 and 2050; these details are also shown below for coal and renewables.

Figure 8. Regional/national natural gas consumption, 2022/2050, EIA Reference Case



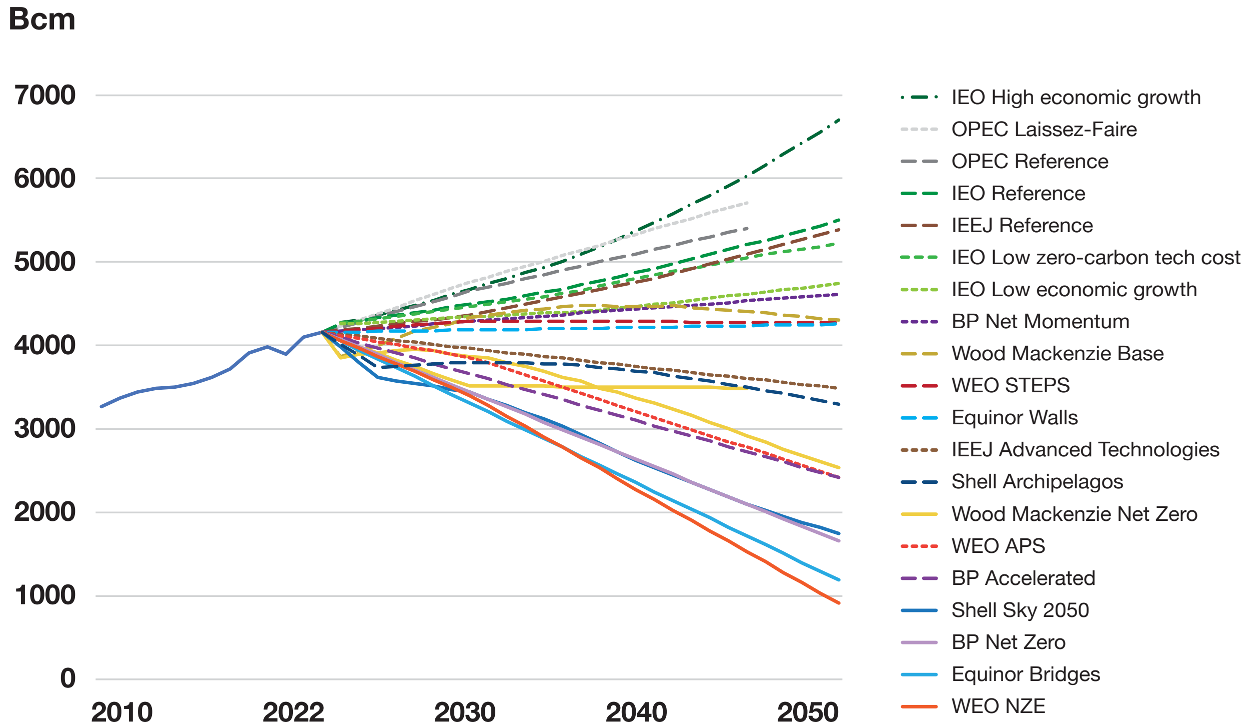
Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

The data show an overall increase in global natural gas consumption over the period of almost 44 Tcf, or a 29% overall increaseThe largest absolute increases are in the Asia Pacific region where demand grows by about 19 Tcf or a 54.7% of the total increase in gas consumption in the region. Consumption in India shows the highest percentage growth, at 233%, although absolute consumption increases by only 5.8 Tcf. China represents the highest growth in absolute demand in the region, at about 10 Tcf.

Eastern Europe also sees a large increase in percentage of demand growth; absolute demand growth in the region is less than that in Russia but higher than Western Europe's. At the same time, absolute consumption in Europe/Eurasia increases by 54.5%, substantially higher than the percentage increase in the Asia-Pacific region, although at a substantially lower absolute volume. In this scenario, the United States, while currently the world's largest producer and exporter of natural gas, declines slightly in consumption on both a percentage and volume basis by 2050.

Other energy scenarios and experts also conclude that natural gas will have an ongoing role in the energy transition, at least in the near to midterm (Figure 9).[32,33,34,35,36,37,38,39] Global energy scenarios show substantial demand for natural gas in the short term—although they show a wide divergence in the midterm—but net-zero scenarios show a wide divergence in 2050 projections. As shown in Figure 9, the IEA's Net-Zero Emissions by 2050 (NZE) scenario forecasts 919 Bcm of natural gas demand in 2050, while Wood Mackenzie's net-zero scenario forecasts 2,536 Bcm.

Figure 9. Natural gas demand in global energy scenarios

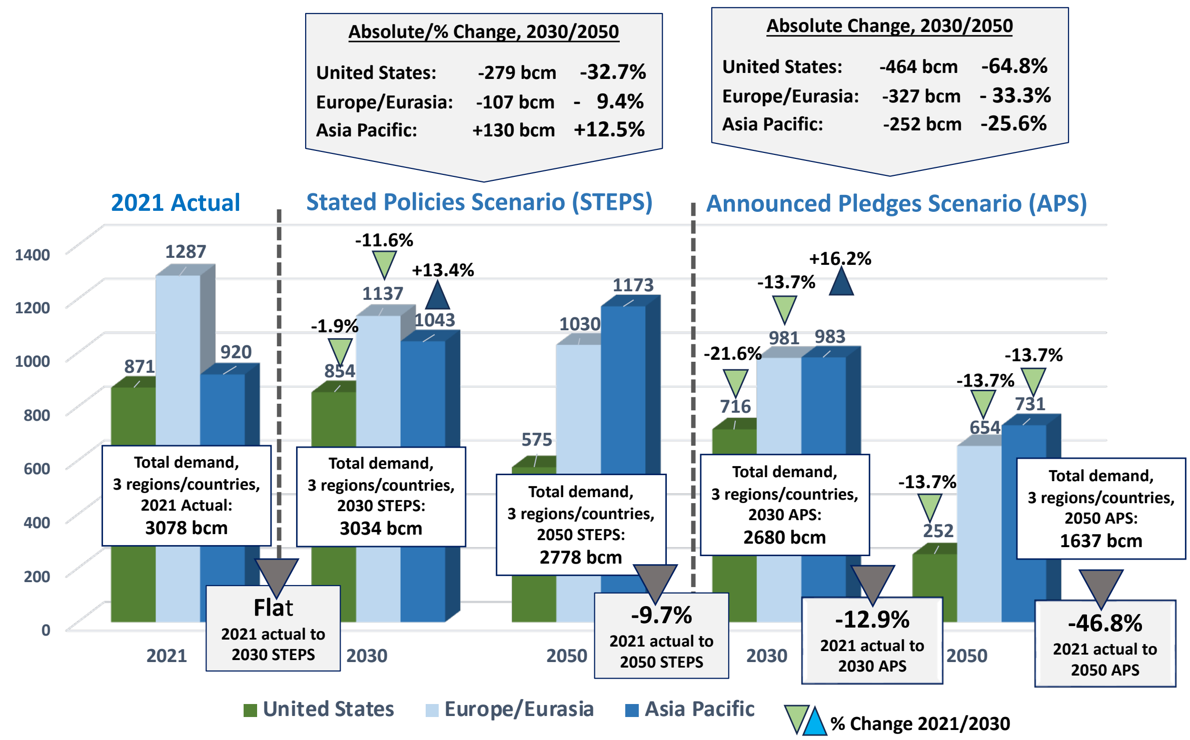


In the scenarios, many data points between 2022 and 2050 were extrapolated linearly to fill data gaps. Data from: See first figure mention in text for sources.

IEA's Stated Policies Scenario (STEPS), compared to its Announced Pledges Scenario (APS) and 2022 actual natural gas demand, underscores some of the challenges facing natural gas systems and investments over the next 25 years.

As seen in Figure 10, regardless of the IEA scenario, there is still substantial natural gas consumption in 2050.[40] In STEPS, natural gas consumption in 2050 in the United States, Europe/Eurasia, and Asia-Pacific is 2,613 Bcm in total, down by 13% compared to 2022. In the APS, the natural gas consumption in these regions is 1,375 Bcm in 2050, showing a 54% reduction compared to 2022. This data underscores some of the ongoing needs for policy support, technologies such as CCUS, infrastructure, production technologies, and investments that support the high-level indicators and forecasts of ongoing and substantial demand for natural gas through midcentury. These needs, however, will likely be considered by many countries to be in conflict with their net-zero policies and targets.

Figure 10. Global natural gas consumption, 2021 actual, STEPS, APS scenarios 2030/2050



Source: EFI Foundation with data from IEA, World Energy Outlook 2023, October 2023, *https://www.iea.org/reports/world-energy-outlook-2023*.

These issues are underscored in two of EIA's scenarios, the Low Zero-Carbon Technology Cost (Low-cost) and High Zero-Carbon Technology Cost scenarios (High-cost).[g] In the High-cost scenario, natural gas consumption increases by 32% and increases in all regions of the world in 2050 relative to the 2022 baseline. Asia has both the highest absolute and percentage (52.7%) increases in the High-cost scenario (Figure 11).[41]

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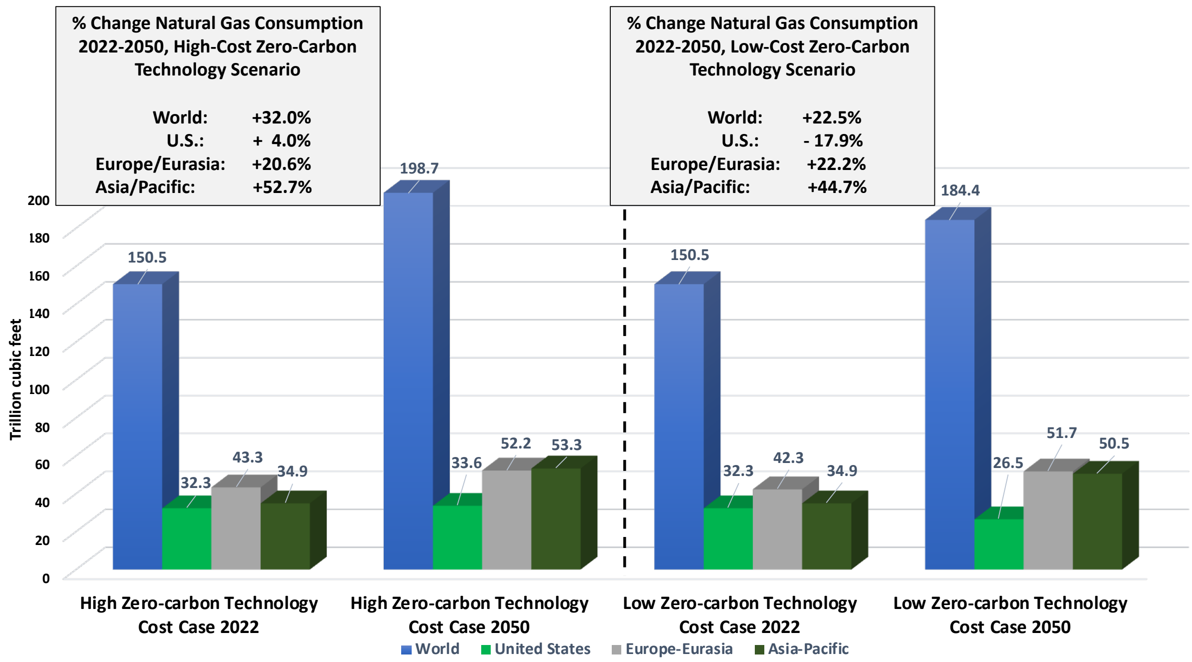
[g] The EIA defines the Zero-Carbon Technology Cost Cases in the Annual Energy Outlook 2023: Case Descriptions (https://www.eia.gov/outlooks/aeo/assumptions/pdf/case_descriptions.pdf, page 8)
In the "High Zero-Carbon Technology Cost" case, the overnight capital cost is held constant at the 2022 level throughout the projection period for all of the technologies listed.
In the "Low Zero-Carbon Technology Cost" case, overnight capital costs and fixed operating and maintenance costs decline more rapidly than in the Reference Case, falling 40% below their Reference Case equivalents by 2050 for all of these technologies.

Figure 11. Regional/national natural gas consumption, EIA High- and Low-Cost Zero Carbon Technology, 2022/2050 (Tcf)

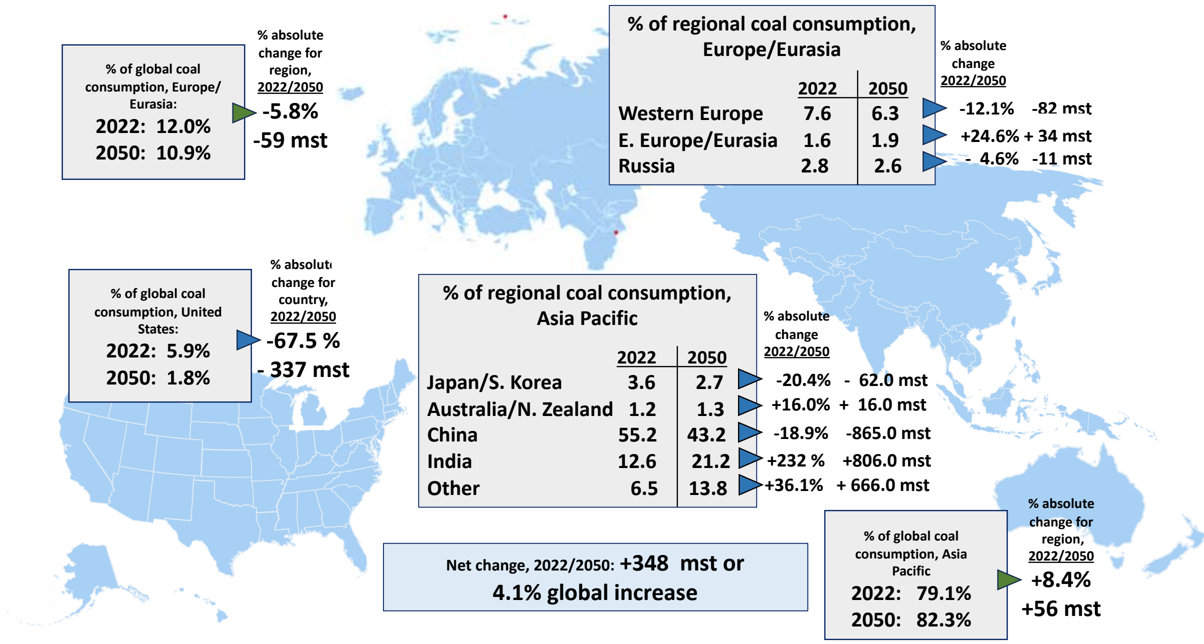


Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

In the Low-cost scenario, global gas consumption increases by 22.5% by 2050 relative to the 2022 baseline. The United States shows a substantial decrease in consumption, while Europe/Eurasia's consumption in the Low-cost scenario increases by a higher percentage than in the High-cost scenario. As in the High-cost scenario, Asia leads in largest percentage and absolute increases.

Consumption trends for coal and renewables are also important for understanding the future of natural gas, both globally and in the regions that were analyzed. Figure 12 shows data from EIA's 2023 Reference Case on global/national and regional coal consumption in 2022, with forecasts to 2050.

Figure 12. Regional/national coal consumption, 2022/2050, EIA Reference Case (million short tons)[42]



Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

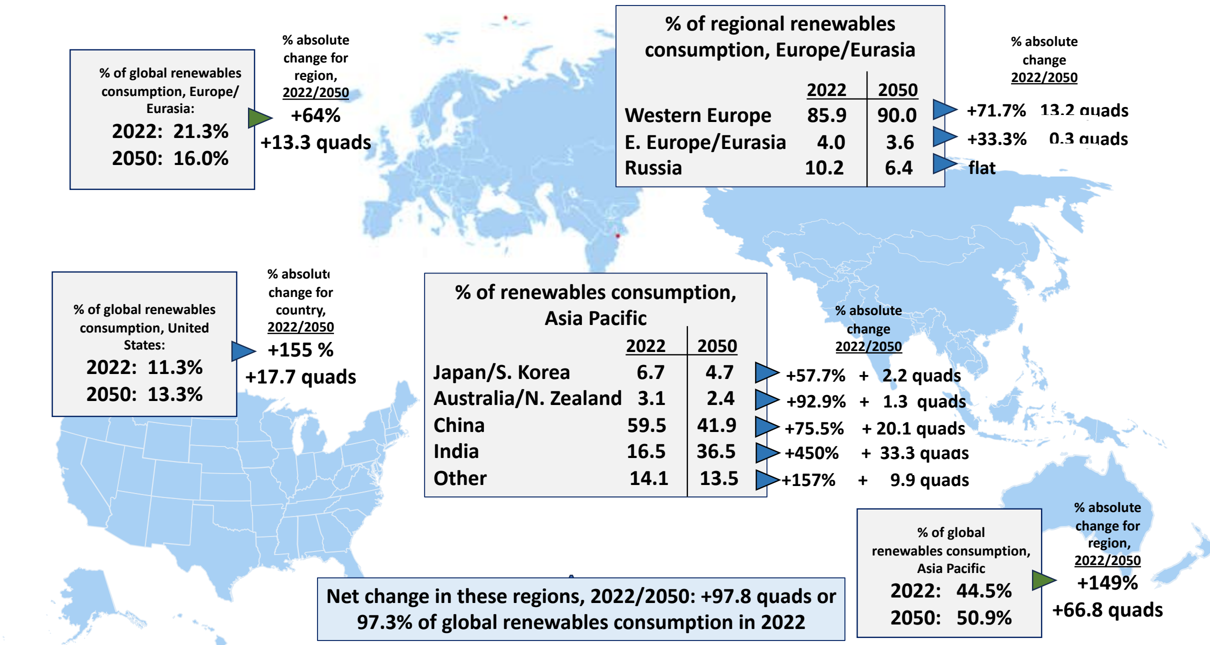
While growth in global coal consumption is only just over 4% between 2022 and 2050, consumption in India rises by 76%, in Eastern Europe/Eurasia by almost 25%, and in the Asia-Pacific region by 8.4%. These increases are largely offset by declines in Western Europe and the United States, which see coal consumption drop by 5.8% and 67.5%, respectively. Coal-to-gas[h] fuel switching in manufacturing and power generation could help countries in Asia meet their climate targets in particular where large increases in coal demand are forecast and where countries have net-zero targets, such as India, Vietnam, and Thailand.

Also important in the context of natural gas demand and uses is the deployment of renewables, which are, as noted, categorized as "other" in EIA's 2023 International Outlook. Figure 13 shows deployment of "other" generation in the regions/countries that are the focus of this analysis and provides a potential road map for regions where renewables and natural gas may work together.

As seen in Figure 13, the Asia-Pacific region is the leader in renewables consumption, adding 66.9 quads between 2022 and 2050, and half of that consumption is in India alone.[43] The United States will add 17.7 quads, and although smaller than Asia, this represents a 155% increase over 2022 consumption. Western Europe increases its renewables consumption by almost 72% over that period. It should also be noted that renewables consumption in 2050 will be almost double that of 2022 levels.

[h] "Coal-to-gas switching" is defined as a transfer from coal generation use at existing power plants to utilizing natural gas for power generation.

Figure 13. Regional/national renewables consumption, 2022/2050, EIA Reference Case (quadrillion Btu)



Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

It is important to understand the potential impacts of the cost of zero-emissions technologies on renewable energy consumption at midcentury. Not surprisingly, in the Low-cost scenario, global renewable consumption increases by almost 150% by 2050, U.S. consumption by 220% and the Asia-Pacific region by 188%. What is surprising is that even in the high technology cost scenario, global renewable energy consumption doubles, consumption in the Asia-Pacific region grows by over 137%, and U.S. consumption grows by almost 94%.

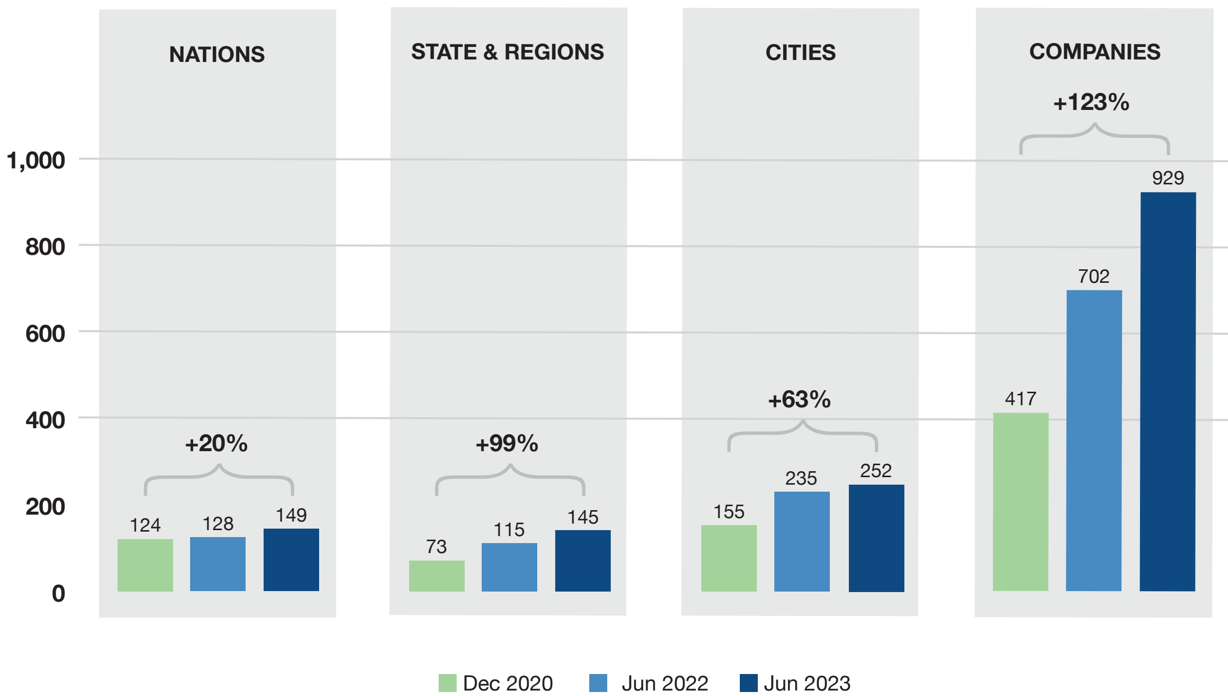
Net-Zero Emissions: Commitments, Emissions, Forecasts

The future of natural gas and its role in deep decarbonization must be understood in the context of national, regional, and company commitments to deep decarbonization. The drivers of decarbonizing the natural gas supply chain are growing commitments to net-zero targets across the globe.

While climate change is a global crisis, individual governments must define both the specific long-term and interim targets for meeting the Paris Agreement's 1.5 degrees Celsius target and the corresponding national strategies. Within the framework of the agreement, 191 countries, representing over 90% of global CO_2 emissions from energy and industrial processes, have submitted their nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC). These NDCs vary in terms of targets and the level of ambition, reflecting the diverse approaches taken by different nations.[44]

The role of natural gas in the specific subregions that are being analyzed in this study must be viewed in the context of the number of countries, states and regions, cities, and companies that have made pledges to reduce GHG emissions to net zero, which are rising (Figure 14).[45] As of June 2023, 149 countries, 252 cities, and—very important for future investments in energy supply and infrastructure including natural gas—929 companies (a 123% increase in a little over two years) have net-zero targets. Companies that have established net-zero targets may alter investments in energy systems including natural gas systems.[46] These commitments represent 88% of global emissions, 92% of global GDP, and 89% of global population.[47] At the same time, however, global CO_2 emissions continue to rise, highlighting the need for more policy mechanisms and technologies to reduce emissions.

Figure 14. Net-zero commitments/pledges, 2020-2023



Source: Net Zero Tracker, "Net Zero Stocktake 2023," June 11, 2023, https://zerotracker.net/analysis/net-zero-stocktake-2023.

Important for this analysis, the United States and 30 countries in Europe, including Russia and Turkey, have net-zero targets, although dates for meeting those targets vary. Some targets are in law, and some are in policy documents; two countries have net-zero targets under discussion. At the same time, 12 countries in Europe—many of them in Central and Eastern Europe—do not have net-zero targets (Figure 15).[48]

Figure 15. Status of net-zero targets in Europe, 2023

Source: EFI Foundation with data from Net Zero Tracker, https://zerotracker.net.

Sixteen countries in the Asia-Pacific region also have net-zero targets, and one country, Bhutan, has indicated that it has met net-zero targets. Five countries in the region do not have net-zero targets, and four countries in Asia are discussing them (Figure 16).[49]

Figure 16. Status of net-zero targets in Asia, Australia, New Zealand, 2023

Source: EFI Foundation with data from Net Zero Tracker, https://zerotracker.net.

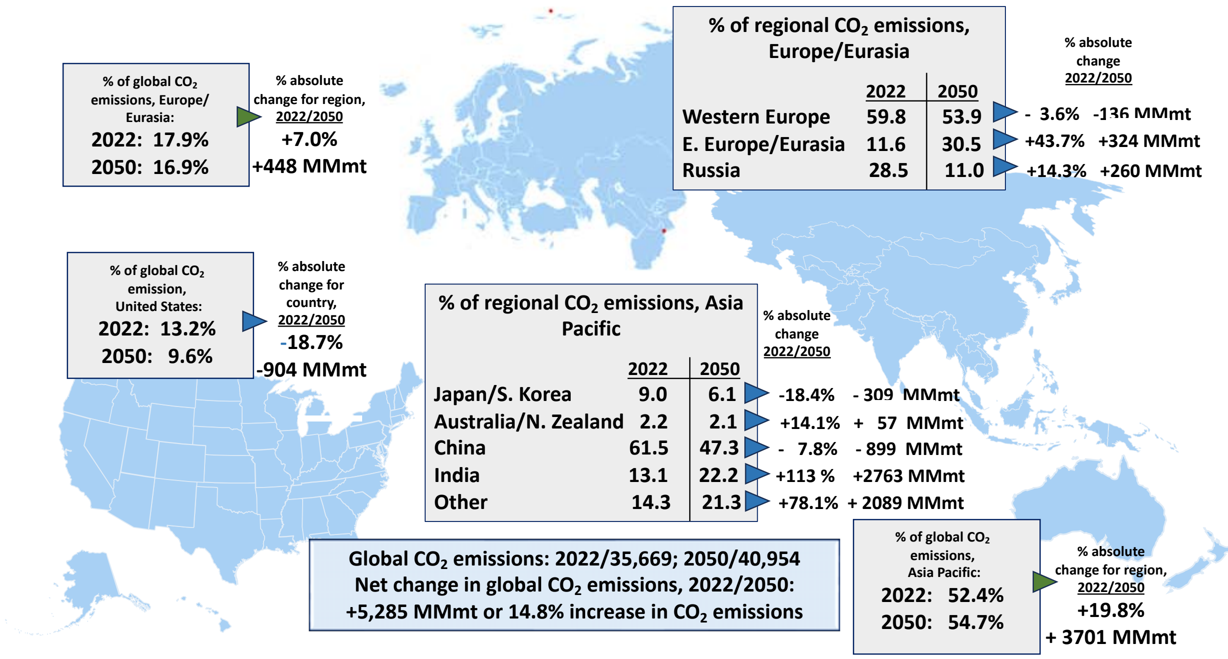
Greenhouse Gas Emissions

National climate change commitments must be considered in the context of actual and forecast CO_2 emissions to start framing the options for the deep decarbonization of energy systems needed to meet these targets, including the deep decarbonization or replacement of natural gas systems and natural gas's use as a feedstock or a fuel. Chapter 4 includes more specific global, regional, and national data based on the EIA's two High- and Low-cost zero-carbon technologies and IEA's STEPS and APS forecasts.

Global CO_2 emissions from fossil fuels break down as follows: coal, 15,804 MMmt (44.3%); oil, 11,778 MMmt (33%); and natural gas, 8,087 MMmt (2.7%). According to the IEA, overall CO_2 emissions rose by almost 1% between 2022 and 2023. Emissions from natural gas, however, fell by 1.6% over that period, but those from coal increased by 1.6%. The IEA attributes both changes to the loss of Russian gas post-Ukraine invasion. Emissions from oil also increased by 2.5%, attributed in part to post-COVID increases in air travel.[50]

From a regional perspective, Figure 17 shows CO_2 emissions for the United States, Europe/Eurasia, and the Asia-Pacific region in the EIA's Reference Case.[51]

Figure 17. Regional/national CO_2 emissions 2022/2050, EIA Reference Case

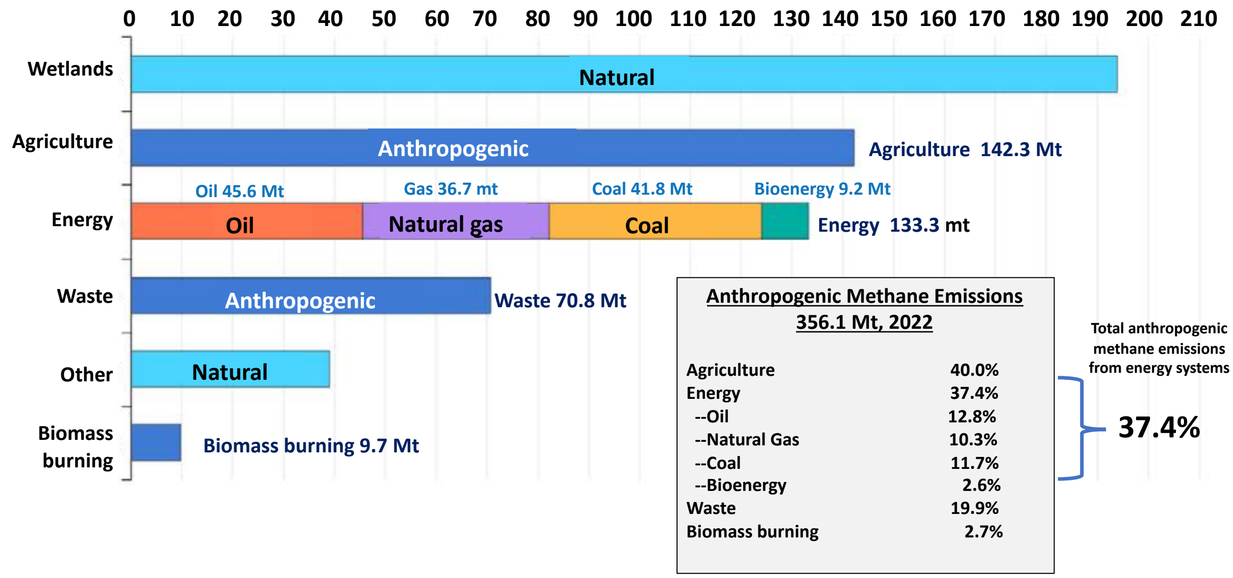


Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/.

In the EIA Reference Case, between 2022 and 2050, CO_2 emissions in the United States decline by close to 20%, while Europe/Eurasia emissions increase by 7%, with the largest percentage and absolute increases in the region occurring in Eastern Europe/Eurasia (43.7%). The most significant increases, however, are seen in the Asia-Pacific region, where absolute emissions increase by 3,701 MMmt. India's CO_2 emissions increase by 113%, and "other" Asia-Pacific countries' emissions increase by 78%.

In addition to CO_2 emissions, methane emissions reductions are also important for meeting net-zero targets, especially in the near term. According to the IEA, methane emissions are responsible for about 30% of the rise in global temperature since the Industrial Revolution. The energy sector accounts for almost 40% of anthropogenic methane emissions. Natural gas accounted for about 10% of total global anthropogenic methane emissions in 2020 (Figure 18).[52]

Figure 18. Global methane emissions by source, 2022



Source: IEA, Global Methane Tracker 2023, 2023, https://www.iea.org/reports/global-methane-tracker-2023.

Due to its structure, methane traps more heat in the atmosphere per molecule than CO_2, making it 80 times more harmful than CO_2 in the near term. The residence of methane in the atmosphere, however, is from 10 to 12 years compared to over 1,000 years for CO_2. This makes methane emissions reductions critical for near-term efforts to mitigate climate change, especially as many of the technologies for deep decarbonization are in the early stages of development and deployment.

According to DOE, "methane has a short atmospheric life—therefore, the immediate reduction of methane emissions is a key opportunity to slow the rapid rate of global warming."[53] Also, technologies already exist for capturing or eliminating most of the methane emissions from oil and gas systems.

For the areas where additional and affordable technologies are needed, the DOE Methane Mitigation Technologies Program focuses on "advanced materials of pipeline construction, monitoring sensors, data management systems, and more efficient and flexible compressor stations. Research efforts for methane emissions quantification will focus on developing technologies to detect, locate, and measure emissions. This includes the development and validation of measurement sensor technologies for the collection, dissemination, and analysis of emissions data, which will inform efforts such as the Greenhouse Gas Inventory and orphan well remediation programs of the U.S. Environmental Protection Agency (EPA) and U.S. Department of the Interior (DOI), respectively."[54] As seen in Figure 18, methane emissions from natural gas use are 10.3% of global methane (CH_4) emissions and from coal is 11.7%. This suggests that coal-to-gas fuel switching could reduce both CH4 and CO_2 emissions.

Methane leakage rates show a wide divergence among natural gas facilities. A survey of studies on methane leakage rates revealed that the rates range from 0.65% to 66% from U.S. gas systems[55] and that sufficiently high leakage rates could negate the emissions reduction value of coal-to-gas fuel switching. High methane leakage rates have been a concern of many stakeholders, leading to concerted efforts to cut the leaks throughout the natural gas supply chain. This is discussed in greater detail in Chapter 4.

Baseline Data Summary

This study is a comprehensive examination of the critical factors affecting the role of natural gas in the transition to deeply decarbonized energy systems that influence the need for universal access to energy, economic development, equity issues, and the ongoing need for energy security. This baseline informs the region- and country-specific analyses in the remaining chapters, providing both a framing and context for the subsequent areas of focus.

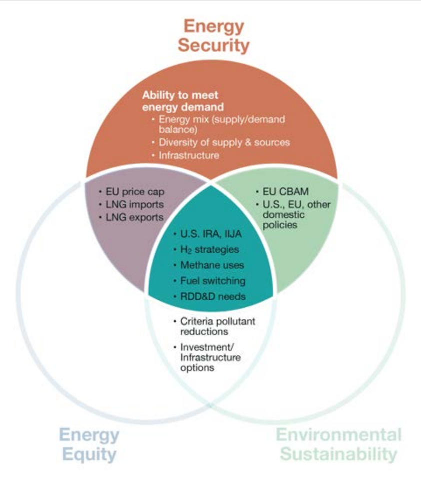
The recent global energy crisis has placed energy security at the center of global energy discussions. These debates include a focus on the ongoing role of natural gas in ensuring energy security in the near to midterm. The range of scenarios highlighted in this chapter show ongoing demand for natural gas, with significant demand growth in Asia. Total demand for gas varies greatly, however, introducing levels of uncertainty into investments in infrastructure, policies, and technologies that support the need for dramatic emissions reductions from natural gas systems, while also supporting the demand for gas.

The scope of this study is global, with deeper analysis of the United States, Europe, and Asia, regions that are critical to understanding the challenges and opportunities for the utilization of natural gas in a deeply decarbonizing world.

The remainder of this report is divided into five chapters. Chapter 2 analyzes how natural gas has been and can be used to enhance global, regional, and national energy security, with a more detailed and focused analysis of Europe and subregions in Asia. Chapter 3 examines the opportunities and challenges of natural gas as an affordable global energy source. Chapter 4 is an analysis of the status of efforts in reducing GHG emissions across the natural gas value chain. Chapter 5 analyzes the role of natural gas in industrial decarbonization and includes case studies of the glass, cement, steel, and ammonia subsectors. Chapter 6 includes recommendations based on the analyses in previous chapters.

2. Energy Security

Findings in Brief



- Russia's 2022 invasion of Ukraine and the ongoing conflict have altered energy markets globally. Changes range from shorter-term energy market disruptions to longer-term energy and climate policy revisions.
- The critical energy security role of U.S. liquefied natural gas (LNG) was demonstrated after the invasion. U.S. supplies of LNG to Europe were instrumental to ensuring that Europeans had adequate energy supplies to get through that winter. This, however, raised availability and price concerns with Asian customers, underscoring the need for additional LNG supplies in the near to midterm.
- In response to European sanctions after the invasion, Russia has been searching for new markets for its natural gas. Russian efforts to find customers may run counter to longer-term global security, if a new set of nations becomes reliant on Russian resources. It is not in the geostrategic interest of the United States, Europe, or Asian allies and trading partners to let Russia fill the supply gap.
- In Europe, near-term demand for natural gas (via LNG) continues. Long-term demand for natural gas is likely to decline, driven by accelerated decarbonization efforts and energy security concerns.
    - Western European countries saw the recent energy crisis as an opportunity to accelerate the energy transition by pursuing electrification and increasing domestic energy production.
    - Eastern European countries regard natural gas as a critical fuel source for the energy transition, especially in the industrial sector, but they view LNG as expensive and difficult to source in a tight global market.
    - The conflict between the need to increase LNG imports to meet short- and midterm demand and policies and forecasts that dramatically reduce natural gas consumption raises reasonable concerns about the potential for stranded assets.
- In Asia, mid- to long-term demand for natural gas is expected to increase, driven by China in the next decade and Southeast Asia and South Asia in the longer term.
    - Long-term demand forecasts for natural gas in China are challenging due to complex factors affecting supply and demand, including continued investments in

    - renewables, the government's pursuit of coal for energy security, growing domestic natural gas production, and imports from Russia via pipelines. Thus, China is expected to be opportunistic in its use of LNG and natural gas.
    - Growing energy demand, driven by economic and population growth, will increase Southeast Asia's long-term demand for natural gas.
    - Declining domestic production and rising demand for natural gas will boost South Asia's reliance on imported LNG.
- Europe, China, and Northeast Asia could have a substantial amount of underused assets since the capacity of LNG import infrastructure far exceeds the projected LNG demand through 2050.
- Differing forecasts of global long-term demand for natural gas discourage investment in LNG supply infrastructure. The decreasing scale of investment in LNG supply infrastructure has already led to concerns about a potential supply shortage starting around 2030.
- The United States will continue to be the world's top exporter of LNG through 2050.
    - The United States has an opportunity to embrace a global leadership role and ensure global energy security as a reliable trading partner or concede this role to alternative suppliers, such as Russia.
    - The United States needs additional LNG export terminal capacity to meet growing international demand in the near and midterm, especially as Europe continues to move away from importing Russian natural gas.
- In addition to uncertain demand forecasts, U.S. LNG suppliers have faced and will continue to face numerous challenges in building LNG export infrastructure, including legal and regulatory challenges and reducing GHG and environmental impacts of new infrastructure.
- Energy security must be considered in the context of energy equity and environmental sustainability where overlapping issues (e.g., net-zero policies, deep decarbonization, infrastructure needs, and affordability) must be considered in the larger energy security context.

Energy security is measured by the ability of a country or region to reliably meet current and future energy demand. Chapter 1 provided high-level framing data for the United States, Europe, and Asia, including data for a range of scenarios. This chapter analyzes risks and uncertainties in the global demand for natural gas, focusing on energy security issues in Europe and Asia, with data and forecasts on subregions in Asia.

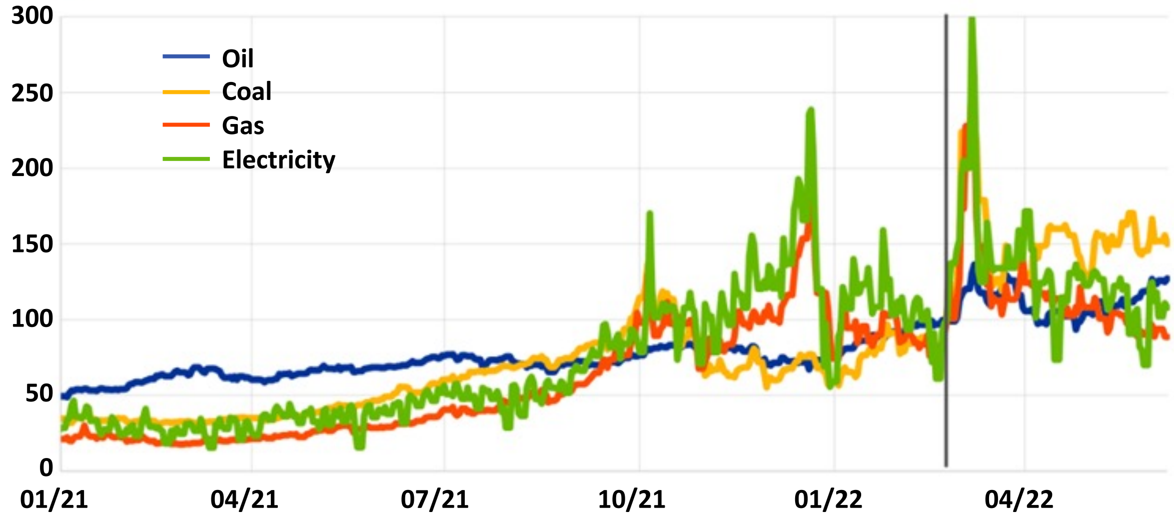
Given the disparity between developing and developed countries within the regions, how these two natural-gas-consuming regions develop and decarbonize creates uncertainties in the trajectory of global natural gas markets, with associated energy security concerns. Analysis of the complicated geopolitical, socioeconomic, and environmental issues in these regions will provide a better understanding of the role of natural gas in providing energy security while countries seek to decarbonize energy systems. For the purpose of analyzing energy security issues for the regions and subregions in this chapter, natural gas and LNG data from Wood Mackenzie is used.

Global demand for natural gas is expected to remain high in the near term. All major energy scenarios agree on solid demand for natural gas through 2030. After 2030, however, the demand

projections diverge because of a mix of energy, economic, and climate policies across regions worldwide. The uncertainty implied in this divergence is further amplified by the commitment to transition away from fossil fuels during COP28.

Russia's invasion of Ukraine and the ongoing conflict there sent shock waves through the energy world, with significant impacts on natural gas and oil markets. Although they have recently declined, the prices of energy commodities, including natural gas, rose rapidly after the invasion, as shown in Figure 19.[56] The sanctions and high prices forced countries to find natural gas from new suppliers, and high prices and competition for LNG supplies forced some countries (e.g., China, India, and Germany) to increase their coal use.

Figure 19. Energy prices before and after the invasion of Ukraine (index: 02/23/22 = 100)



Oil prices are Brent crude oil prices; gas prices are the Dutch Title Transfer Facility Day-Ahead prices; and coal prices are the nearby Rotterdam Coal Futures prices. Wholesale electricity prices for the euro area were calculated as a weighted average (applying net electricity generation as weights) of prices observed in the five biggest markets. The vertical line marks the start of the Russian invasion of Ukraine. Source: Jakob Feveile Adolfsen et al., "The Impact of the War in Ukraine on Euro Area Energy Markets," 2022, https://www.ecb.europa.eu/press/economic-bulletin/focus/2022/html/ecb.ebbox202204_01~68ef3c3dc6.en.html.

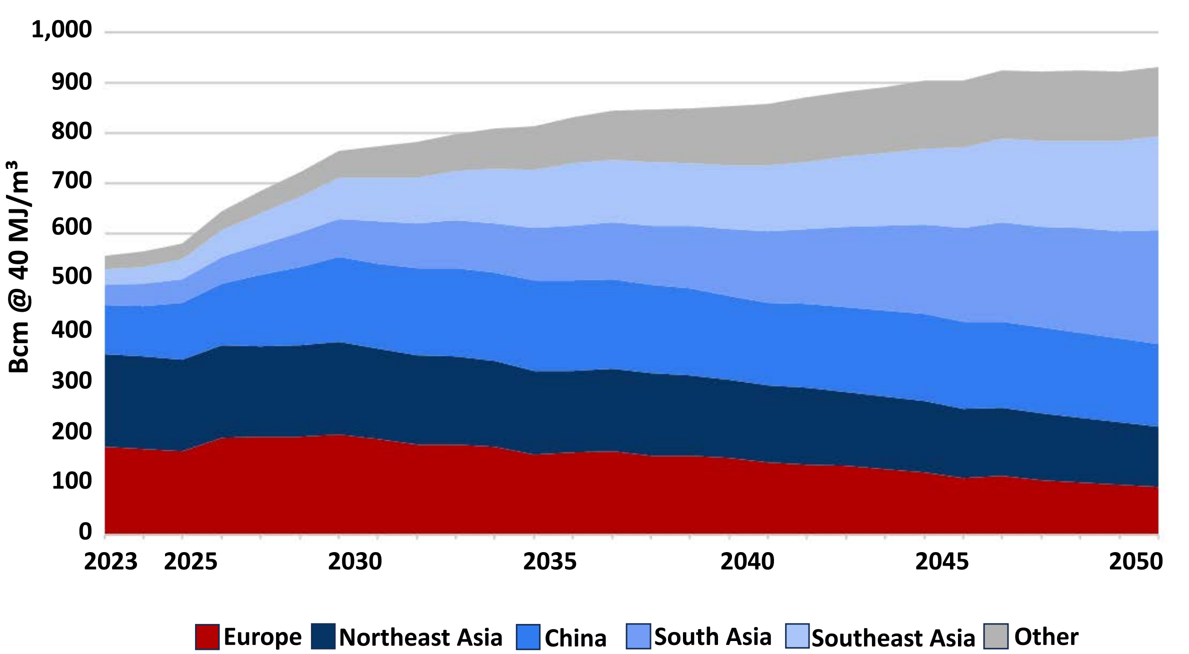
According to the World Economic Forum, "The world's energy problems did not start with Russia's invasion of Ukraine, but the subsequent energy crisis has created a significant number of seismic changes to the energy sector. Some changes will be temporary, some will be permanent, but the decisions being made today are reshaping the energy sector forever."[57]

Importantly, the invasion altered traditional trade routes. Affected countries quickly established new trade routes and energy policies that were designed not only to prioritize long-term energy security but also to meet short-term[i] demand.[58] European countries lacked sufficient port infrastructure for significant increases in the volumes of LNG imports and had to purchase LNG largely on the spot market at high prices. The lack of destination clauses in U.S. LNG exports made diversion of LNG cargoes to Europe possible, although this tended to come at the expense of Asian buyers. This increase in demand also caused prices to increase to nearly 10 times the average.[59]

Europe and Asia are also facing substantial challenges to secure energy supply for the long term. As domestic conventional energy production is limited, these regions are dependent on imports. Europe and Asia import more than 90% of total LNG volumes in the global market (Figure 20).[60] This has motivated these regions to increase domestically produced energy sources, such as renewable energy or green hydrogen in developed economies in Western Europe and Northeast Asia, and coal in developing economies in Eastern Europe, Southeast and South Asia.

However, it is difficult to develop and deploy sufficient volumes of renewable energy or green hydrogen to meet the energy demand in these regions in the near term, and using coal poses challenges to decarbonization goals. Moreover, developing countries in these regions are sensitive to the challenge of affordability in meeting the energy demands associated with economic development and growth.

Figure 20. Global LNG demand by region



Europe: Entire continent, EU and non-EU; Northeast Asia: Japan, South Korea, and Taiwan; South Asia: India, Bangladesh, Afghanistan, Bhutan, Maldives, Nepal, Pakistan, and Sri Lanka; Southeast Asia: Indonesia, Thailand, Singapore, Malaysia, Myanmar, Vietnam, Laos, East Timor, Philippines, Brunei, and Cambodia; Other: North, Central, and South America, Africa, Australia/Oceania. Source: Massimo Di Odoardo et al., "Global Gas Strategic Planning Outlook," Wood Mackenzie, March 2023.

[i] The short-term is generally considered to be less than five years.

Even with the spot price of LNG in Asia coming down from its peak, there has been a reduced appetite for LNG in many Asian countries as LNG in developing markets is seen as an "unreliable fuel."[61] At the same time, in August 2023, global oil demand surged to a record high due in large part to robust consumption in China,[62] underscoring the fact that fossil fuels are still essential to the economic growth plans of Asian nations. However, the resumption of Asian natural gas and LNG demand to pre-pandemic levels remains uncertain.

Much of Asia's natural gas supply is imported LNG, tying it to global/regional markets and perturbations associated with the energy trilemma. The larger region can be divided into subregions that further vary based on the importance of security of supply as well as reliability. Northeast Asia's natural gas utilization is driven by energy security, which is achieved through a diversity of sources and long-term contracts. Affordability is a more significant driver for Southeast Asia. Finally, both India and China are opportunistic in their use of natural gas and adapt based on market conditions. India only recently allowed the use of LNG imports for sectors other than industry as it was considered the highest-value use of natural gas.

The IEA has summarized the importance of LNG in energy security and the range of uncertainties it presents:

> *Starting in 2025, an unprecedented surge in new LNG projects is set to tip the balance of markets and concerns about natural gas supply. In recent years, gas markets have been dominated by fears about security and price spikes after Russia cut supplies to Europe. ... Projects that have started construction or taken final investment decision are set to add 250 billion cubic meters per year of liquefaction capacity by 2030, equal to almost half of today's global LNG supply. Announced timelines suggest a particularly large increase between 2025 and 2027. More than half of the new projects are in the United States and Qatar.*
>
> *This additional LNG arrives at an uncertain moment for natural gas demand and creates major difficulties for Russia's diversification strategy towards Asia. The strong increase in LNG production capacity eases prices and gas supply concerns but comes to market at a time when global gas demand growth has slowed considerably since its "golden age" of the 2010s. Alongside gas contracted on a longer-term basis to end-users, we estimate that more than one-third of the new gas will be looking to find buyers on the short-term market. However, mature markets—notably in Europe—are moving into stronger structural decline and emerging markets may lack the infrastructure to absorb much larger volumes if gas demand in China slows. The glut of LNG means there are very limited opportunities for Russia to secure additional markets. Russia's share of internationally traded gas, which stood at 30% in 2021, is halved by 2030 in the STEPS.*

Corresponding information on key issues is critical for understanding LNG demand and natural gas demand in general. In the scenario, global gas plants under construction worldwide, as of February 2024, produce 198,818 megawatts (MW), with an additional 255,741 MW in the preconstruction phase, for a total of 454,559 MW.[63]

Of this total, 44,438 MW is in Southeast Asia (10% of total), 144,974 MW in East Asia (32%), and 31,170 MW (7%) in the rest of Asia; 49% of natural gas power generation capacity in the construction or preconstruction phase in the world is in Asia.

In Europe, there were 49,599 MW in this phase, and in North America, 27,479 MW were under construction or in the preconstruction phase. Total natural gas generation in the construction or preconstruction phases in these three regions represented 297,662 MW or 65% of the world total.

As of January 2024, 485,329 MW of coal generation was under construction or in the preconstruction phase. A staggering 95.8% of this volume was in Asia.[64] This shows the need for additional power generation in the region. It highlights an opportunity for reducing regional emissions with natural gas generation.

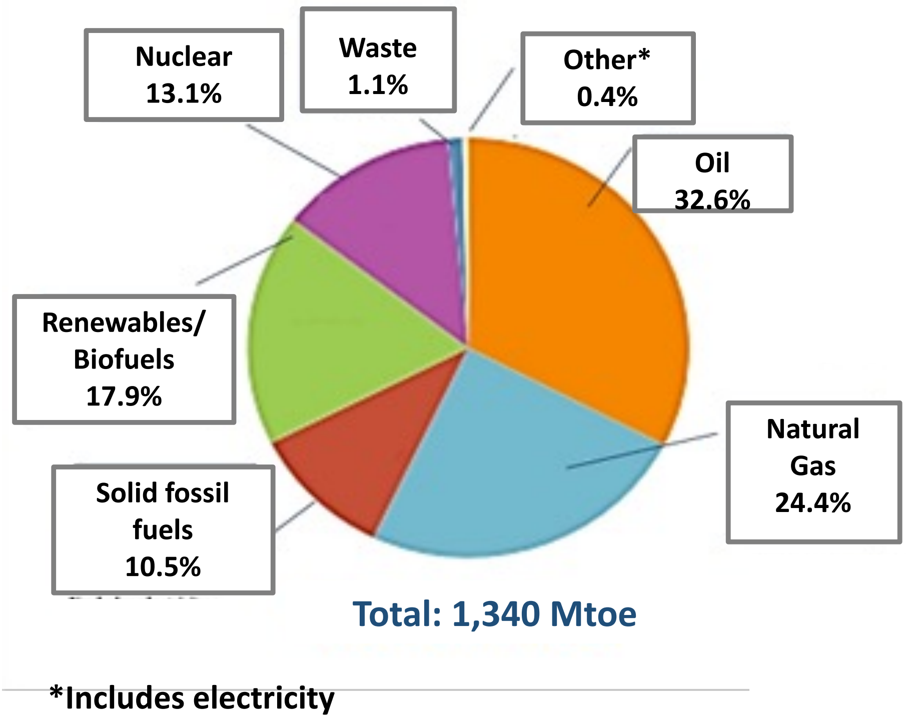
It is also important to note that, according to the Global Energy Monitor, as of December 2023, "approximately 69,700 kilometers (km) of gas transmission pipelines are under construction globally, an 18% increase over the previous year, at a cost of $193.9 billion." It notes that "Asia leads the world in [natural gas] pipeline construction, accounting for 82% at an estimated cost of $117.2 billion, with China and India responsible for 65% of global construction." It also reports that "globally 228,700 km of gas transmission pipelines are in development—counting projects that are in construction or have been proposed—at a total price tag of $723 billion."65 The potential stranding of these assets as a result of net-zero or other policies would have significant energy security and cost implications.

Europe: Declining Demand Driven by Decarbonization and Energy Security Concerns

Natural gas plays a key role in European energy systems and as demonstrated after the Russian invasion of Ukraine, in its energy security, at least for the near and midterm. In 2020, natural gas accounted for approximately 25% of energy consumption in the EU (Figure 21),[66] was the second-largest energy source in the EU, and was used in multiple sectors for power generation, home heating, and industrial processes.

More than 80% of Europe's natural gas volumes in 2020 were imported, with Russia supplying 43% of natural gas imports. Since the war in Ukraine began, imports via pipeline from Russia have been replaced with LNG imports, largely from the United States. Europe's LNG imports rose by 70% in 2022 compared with 2021.

Figure 21. EU energy consumption by source, 2020



Mtoe = million tons of oil equivalent. Source: European Union, EU Energy in Figures: Statistical Pocketbook 2022, 2022, https://op.europa.eu/en/publication-detail/-/publication/7d9ae428-3ae8-11ed-9c68-01aa75ed71a1/language-en.

As noted, energy security in Europe was put at risk after Russia invaded Ukraine, but even before then, European countries were concerned about tight supplies of natural gas after the post-COVID-19 pandemic surge.[67] After the invasion, EU countries cut gas supplies from Russia significantly. Russia's share of total EU natural gas imports fell from 40% in 2021 to below 10% by the end of 2022. However, as noted by experts in the workshops held to inform this analysis in Sofia, Bulgaria, and Brussels, EU sanctions in 2022 were believed to be largely ineffective and negatively impacted European consumers. In 2022, Europe ended up spending 400 billion euros more on natural gas imports than in 2021, a 300% increase in a year.

Energy scenarios and studies generally agree on declining natural gas demand after 2030 in Europe, driven by ambitious clean energy policy initiatives.[68,69,70] The EU is strongly committed to the clean energy transition and has made policy-driven progress. Energy security concerns have motivated some European countries to adopt policies to accelerate the clean energy transition even as some countries reverted to using coal in lieu of natural gas post-invasion.

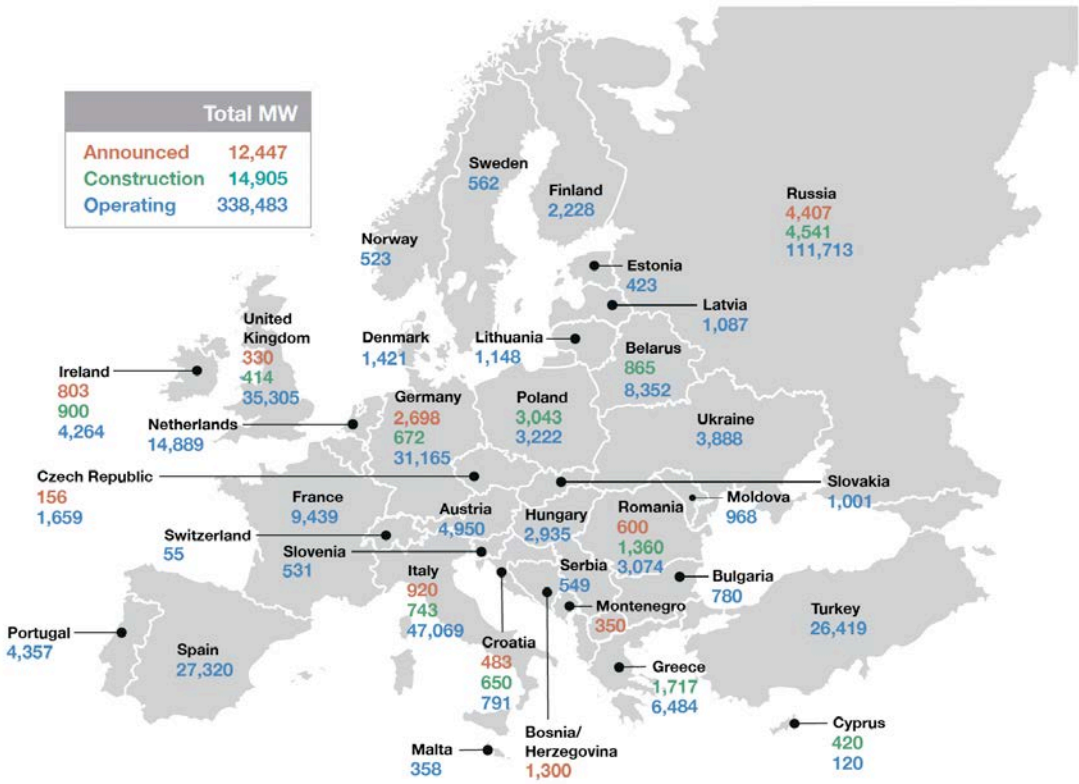
The EU has a goal of carbon neutrality by 2050, and in 2020 established the European Green Deal as a strategy for achieving this goal. In April 2023, the European Parliament approved Fit for 55, a set of proposals that revised EU legislation to ensure policy alignment with the target of reducing GHG emissions by at least 55% by 2030. REPowerEU has emerged in response to the disruption of the global energy market; it is designed to support the energy transition and limit the EU's dependence on Russian fossil fuels. It focuses on action plans that will affect the natural gas market, including:

- Establishing agreements with other third countries for pipeline imports
- Investing in common purchase of LNG
- Signing agreements with Egypt and Israel for the export of natural gas to Europe
- Putting a limit on gas prices until February 2024,[j] extended to January 2025

In the context of the REPowerEU initiative, and important for both Western and Eastern Europe, is the ongoing investment in natural gas power generation. Adding to the data discussed above, Figure 22 shows volumes of gas power generation (MW) by European country for announced projects and projects under construction, as well as total MW of operating plants in Europe projects.[71]

It should be noted that as of February 2024, Europe had 12,447 MW of announced natural gas generation plants, 14,905 MW of natural gas power generation under construction, and 338,483 MW of operating natural gas generation plants. This represents 5.1%, 6.2%, and 18.7% of global totals, respectively.

Figure 22. EU energy consumption by source, 2020



The plants in "construction" are the projects for which equipment installation has begun. The plants in "announced" are the projects that have been publicly reported but have not yet moved forward by applying for permits or seeking land, material, or financing. Source: Global Energy Monitor, Global Gas Infrastructure Tracker, February 2024, https://globalenergymonitor.org/projects/global-oil-gas-plant-tracker/.

[j] In December 2023, the EU extended the price cap until the end of January 2025.

These facilities will need infrastructure support, including natural gas transmission pipelines. As of the end of 2023, Europe had 5,569 kilometers of natural gas pipelines under construction and 37,220 kilometers in the proposed/construction phase. Importantly, 28,964 total kilometers (77.8%) in the proposed/construction phase are in Eastern Europe. This points to the need for additional planning, capital, and policies to support this buildout, especially because in the EIA Reference Case highlighted in Chapter 1, coal generation in Eastern Europe is forecast to increase by 24.6%. Policies to enable the buildout of both gas generation and the associated infrastructure could help reduce CO_2 emissions in the region and subregion.

Eastern Europe[k]

Eastern Europe faces considerable challenges to its energy security and in the energy transition because of its high dependence on Russian gas.[72] In 2021, Russian gas accounted for almost half of the gas supply in Central and Eastern Europe, compared with about 20% in the rest of Europe.[73] A phaseout of Russian gas would require a rapid scale-up of energy infrastructure and alternative energy supply, renewable energy generation, LNG import terminals, and pipelines depending on each country's energy pathway.

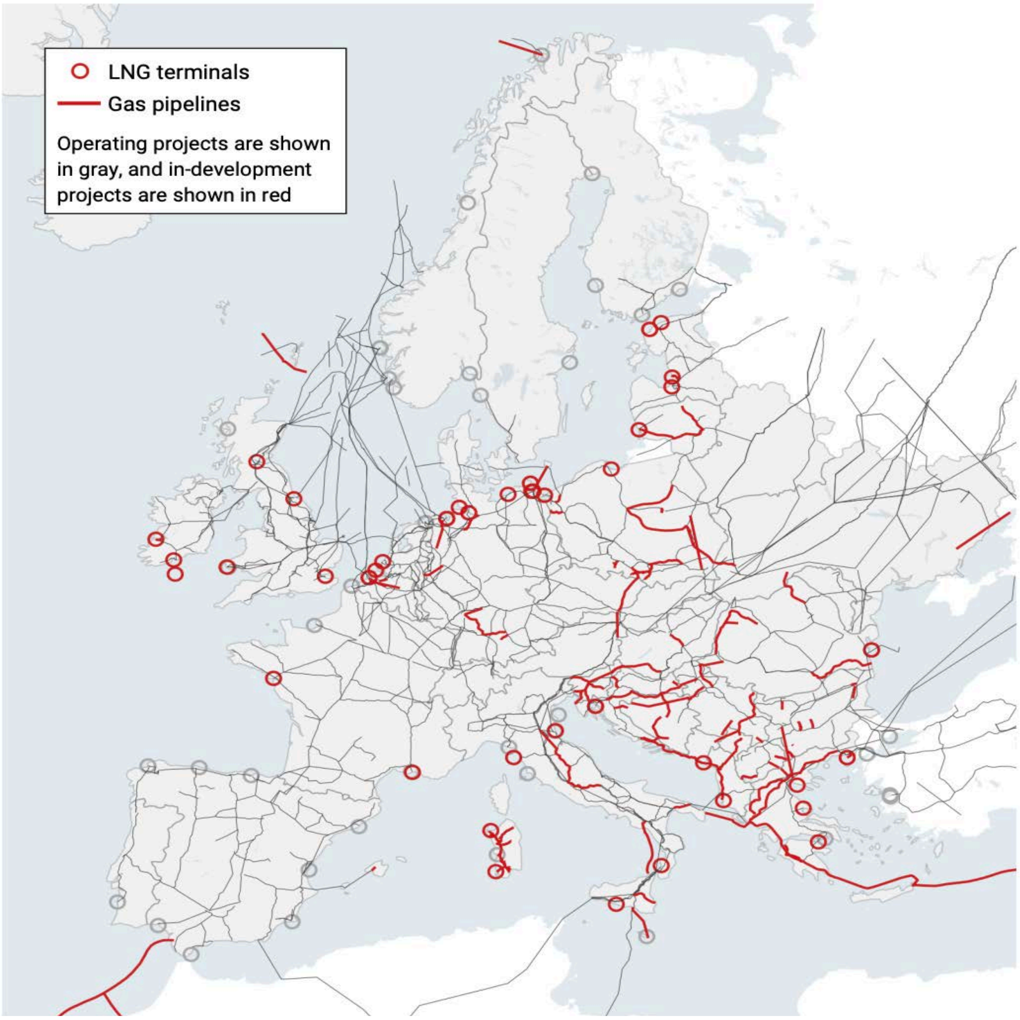
In the EFIF workshop in Sofia, experts from Eastern European countries regarded natural gas as a critical fuel for the energy transition. Workshop participants recognized the importance of natural gas to Bulgaria's economy, especially for its chemical, glass, and porcelain industries. These subsectors are difficult to decarbonize as these industrial processes require high-temperature process heat, and the only affordable options are natural gas and coal. The participants from Eastern Europe and Bulgaria saw the need to decouple natural gas from other fossil fuels to use natural gas in the energy transition until other low-carbon energy and technology alternatives become available and competitive.

Despite the importance of natural gas, representatives of the countries and industries in the region were concerned about using LNG. They viewed LNG imports as expensive and not able to respond quickly to changing market conditions because LNG purchased on the spot market requires several months for delivery and many countries lack sufficient natural gas storage capacity. The participants in Bulgaria noted that switching from coal to natural gas could reduce GHG emissions to meet the country's climate ambitions, but that this would require affordable and reliable natural gas supplies, which are currently unavailable.

It should be noted that in Figure 22 showing natural gas power generation plants under construction, 66% were in Eastern Europe, where 13,316 MW of natural gas power plants (38% of the European total) were in the construction phase. Italy and Poland are in the top 15 countries in the world ranked by gas pipelines either proposed or under construction (see Figure 23 for additional information).[74]

[k] Eastern Europe in this analysis covers: Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Hungary, Kosovo, Moldova, Montenegro, North Macedonia, Poland, Romania, Serbia, Turkey, and Ukraine.

Figure 23. European natural gas pipeline and LNG terminal networks



Operating and in-development LNG terminals and gas pipelines as of January 2024. Source: Global Energy Monitor, Europe Gas Tracker Report 2024, March 2024, https://globalenergymonitor.org/report/europe-gas-tracker-2024/.

Many Eastern European countries, especially those that more recently joined the EU, have difficulty building renewable energy infrastructure because their capital markets are less developed than those in Western European countries.[75] In Eastern Europe, for example, only Poland was among the top 40 most attractive markets for renewable energy investment and deployment opportunities in 2023, compared with 17 nations from Western Europe.[76]

Western Europe[l]

Although countries in Western Europe have used LNG imports to address the energy security crisis that followed Russia's invasion of Ukraine, policymakers in the region have raised concerns about LNG and natural gas in general as a longer-term solution, because of the associated climate impacts. At the Brussels workshop, participants raised climate concerns and issues of affordability when discussing LNG imports, noting that they were expensive and too emissions-intensive to be part of longer-term decarbonization strategies. Most Western European countries continue to pursue decarbonization strategies that phase out natural gas in favor of renewables and green hydrogen.

At the Brussels workshop, many experts strongly supported eliminating fossil fuels from Europe's energy systems. The energy crisis was seen as an opportunity to accelerate the energy transition by pursuing electrification and domestic energy production. Although coal-to-gas switching was an effective decarbonization measure in the United States, the experts from Western European countries did not expect it to have the same impacts in Europe because of relatively low levels of coal generation, particularly in Western Europe, as well as a lack of domestic and regional natural gas supplies and reserves.

Experts at the workshop reported that Western European countries are advancing energy efficiency and renewable energy development rather than signing long-term natural gas contracts with the United States.[77] Some pointed out that reliance on the United States as a significant natural gas supplier raises energy security concerns about reliance on a single foreign supplier. Further, the United States was not perceived as a reliable supplier given the uncertainty of U.S. domestic policy concerning LNG exports, a concern underscored by the recent pause on LNG export permits.

Electrification and domestic renewable energy production were viewed as key enablers of Europe's energy transition, but it was acknowledged that substantial challenges exist, the most notable of which is decarbonizing the industrial sector. Since technologies for the electrification of many industrial processes that require heat higher than 1,000 degrees Celsius are not available, are in early phases of development, or are very expensive, fuels will be needed for the foreseeable future. It should be noted that hydrogen produced by renewable electricity has potential as an alternative to natural gas as fuel for producing the high levels of heat needed for processes in many industrial subsectors. However, hydrogen accounts for less than 2% of energy consumption in Europe, and 96% of this hydrogen is produced with natural gas. It will be challenging to scale up hydrogen production quickly because of the need for substantial renewable capacity to produce green hydrogen, challenges with storage, high costs, and the lower energy density of hydrogen compared with natural gas.

In the near term, demand for LNG imports in Western Europe is likely to remain high to compensate for the loss of Russian pipeline gas and declining natural gas production in the region. A recent analysis by Wood Mackenzie concluded that LNG would continue to increase its share of the European energy mix as gas from Norway and other piped gas imports continue to decline.[78]

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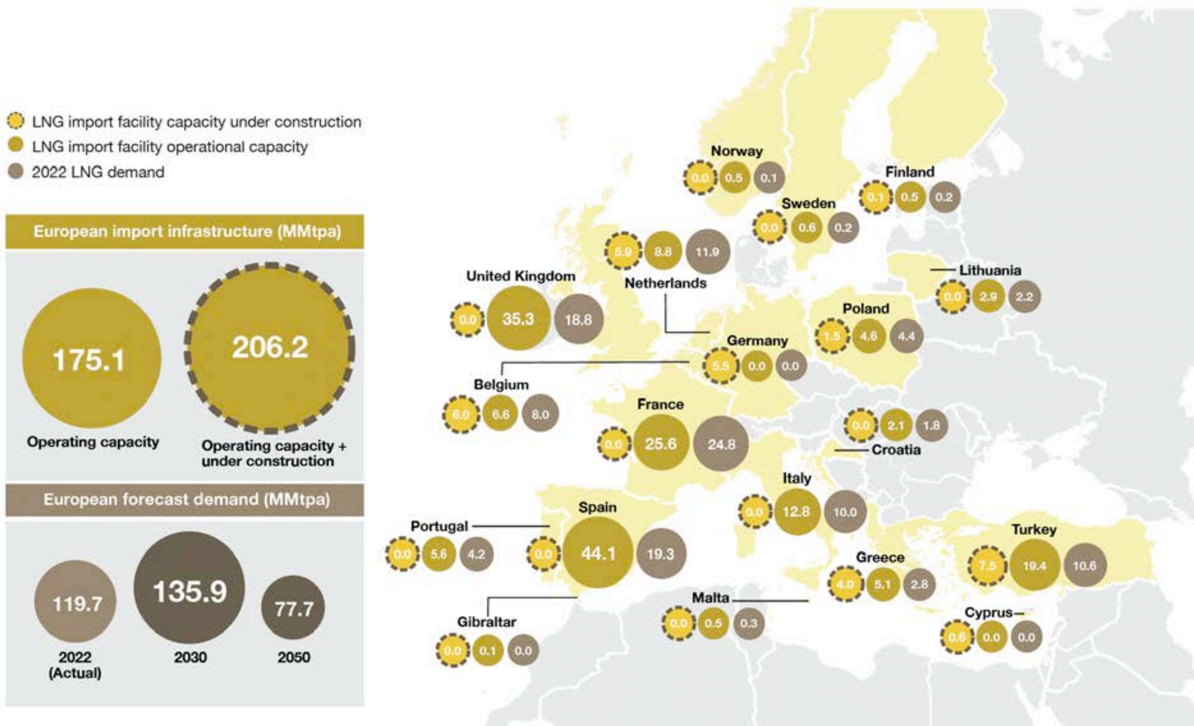
[l] Western Europe in this analysis covers: Austria, Belgium, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovak Republic, Slovenia, Spain, and Sweden.

However, LNG imports in Northwest Europe are expected to peak around 2028 to 2030 and start declining as accelerated decarbonization efforts result in significant declines in natural gas demand.[79]

The conflict between Increasing short- and midterm demand and declining long-term demand for LNG raises reasonable concerns about the potential for stranded assets. As of 2022, Europe's LNG import infrastructure capacity in operation is 175 MMtpa, which is expected to increase to 206 MMtpa, assuming completion of capacity under construction (Figure 24).[80,81,82] Since total capacity far exceeds the forecast LNG demand in 2030 and 2050, there could be a substantial number of stranded assets in Europe.

Figure 24. LNG import infrastructure in operation and under construction, Europe, 2022



Source: EFI Foundation with data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023).

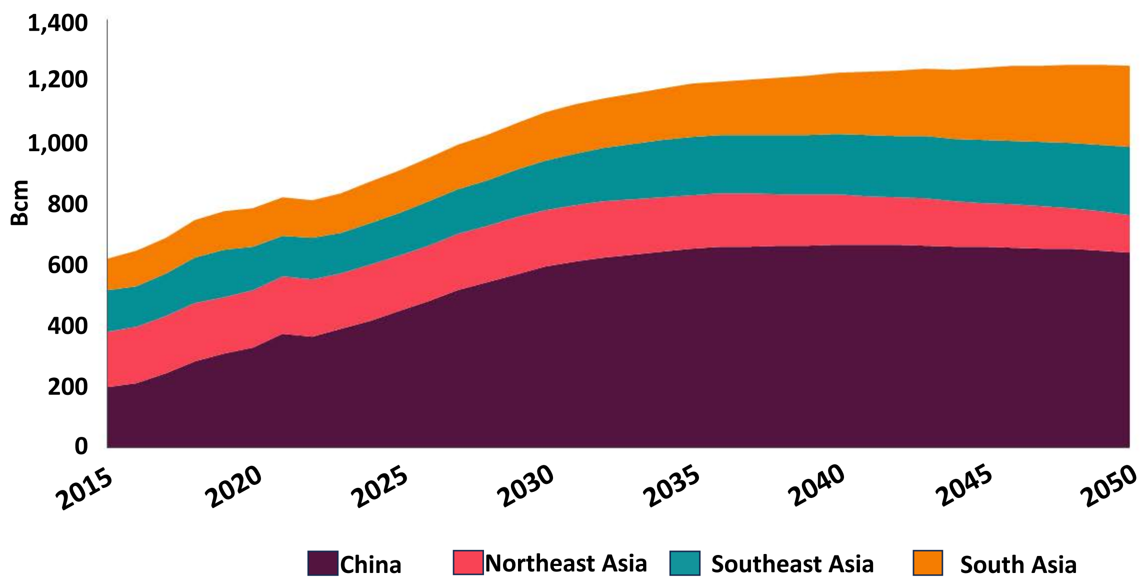
Assuming significant LNG import capacity in the region declines over time, repurposing the import infrastructure could be an option. LNG terminals could be converted to import hydrogen, but significant challenges are associated with this option, including the replacement or significant modification of the equipment at the import facility. The relatively low energy density of liquefied hydrogen compared with LNG translates into a need for additional tankers.

Repurposing an LNG import terminal for ammonia imports is less challenging than for liquefied hydrogen but still presents technical and economic difficulties. Since repurposing terminals is costly, a more economically viable option is for a new LNG terminal to be designed from the start with the ability to be converted to receive liquefied hydrogen or ammonia.[83]

Asia: Growing Demand and Energy Affordability

The absolute demand for natural gas is expected to increase in different regions of Asia through 2050. Figure 25 shows China as the major driver of demand growth through 2035, with Southeast Asia and South Asia driving growth in the long term. 84 Demand in Northeast Asia shows a slight decline starting around 2035.

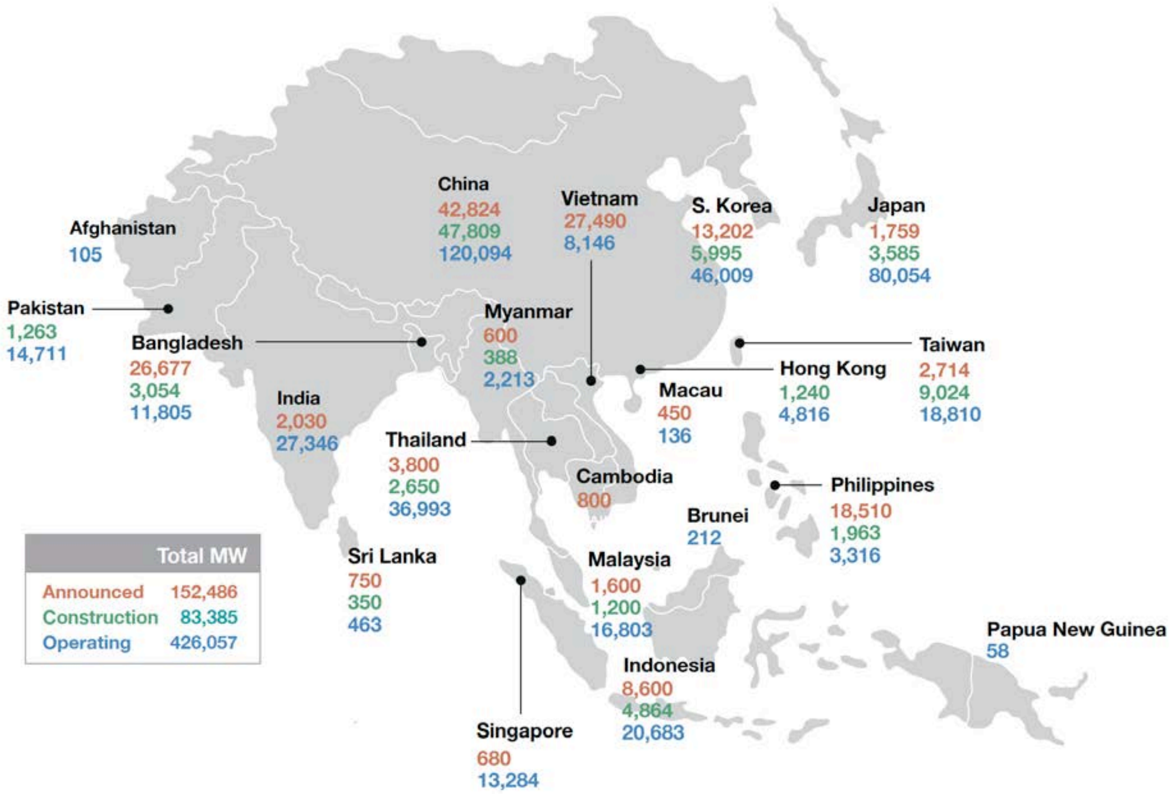
Figure 25. Natural gas demand by in Asia by region, 2015 to 2050



Source: Wood Mackenzie, Global Gas Asia Regional Market Report, November 2023.

To place this demand in perspective, Figure 26 shows the natural gas power plants in Asia by country, including announced generation volumes, volumes under construction, and operating volumes as of February 2024.[85]

Figure 26. Gas plants announced, under construction, and operating, Asia, as of February 2024



Source: EFI Foundation with data from Global Energy Monitor, Global Oil and Gas Plant Tracker, https://globalenergymonitor.org/projects/global-oil-gas-plant-tracker/.

Announced gas generation projects in Asia as seen in Figure 26 represent 59.5% of the global total as of February 2024. Gas generation projects under construction in the region represent about 42% of the global total, and existing gas generation is 22% of the global total. These data underscore the degree to which Asian countries are investing in a gas generation future. Policymakers and investors should take note that both announced and plants under construction have significant implications for both security of supply and the infrastructure needed for ongoing operations. This information (Figure 26) does not indicate whether the plants are natural gas "peaker" plants, i.e., plants for use during times of peak electricity demand, or natural gas combined cycle plants (NGCC). Additional information would be helpful for understanding the intended uses and system value of these plants.

Regardless, the total generation capacity of the announced plants and plants under construction represents long-term investments based on the life spans of these plants. Policymakers must accommodate these investments as they consider the security, technology, and decarbonization needs and policies going forward.

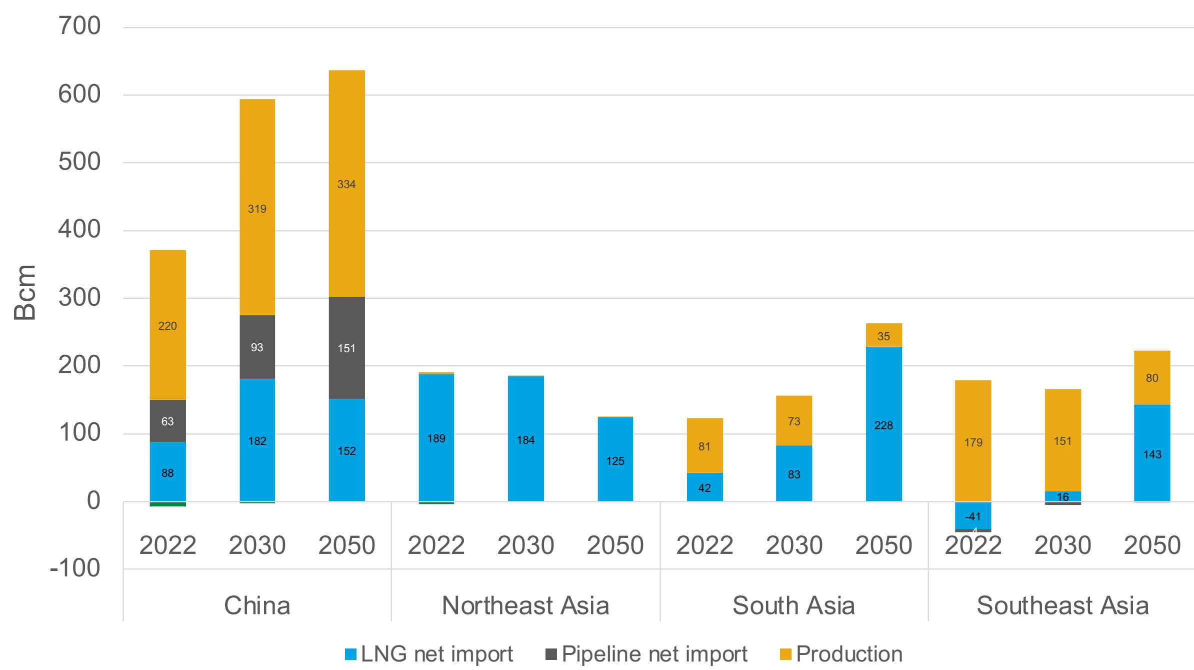
China

Long-term demand for natural gas in China is difficult to forecast because of the complexity of the factors affecting supply and demand. The reference scenarios of IEA and Wood Mackenzie expect demand to rise through the 2030s, with a sustained plateau from then to 2050.[86,87] EIA's reference scenario forecasts a continued increase in natural gas demand through 2050.[88]

Natural gas is less than 10% of China's energy mix.[89] In the Asia workshop, many experts indicated that China's natural gas demand would not rapidly increase as China regards coal as a central pillar of its energy security even as it makes considerable investments in solar and wind energy. One expert even expected possible declines in LNG demand in China as it diversifies its energy supplies and uses.

Natural gas is a viable alternative for China to reduce its CO_2 emissions by replacing coal-fired power generation and coal use in its industrial sector. Given the centralized structure of China's government, it could be easier, relative to Western democracies, to quickly switch energy sources and the associated infrastructure and remain opportunistic in the use of natural gas; it would, however, likely be more expensive. China is also better positioned to secure natural gas supply than other regions in Asia. Its growing domestic natural gas production will help meet the need for natural gas infrastructure, and it has an established import regime via imports from Russia and Central Asian nations via pipelines (Figure 27).[90] The figure suggests that China's domestic production will continue to increase through 2050.

Figure 27. Natural gas supplies by production and delivery type, Asia, 2022, 2030, 2050

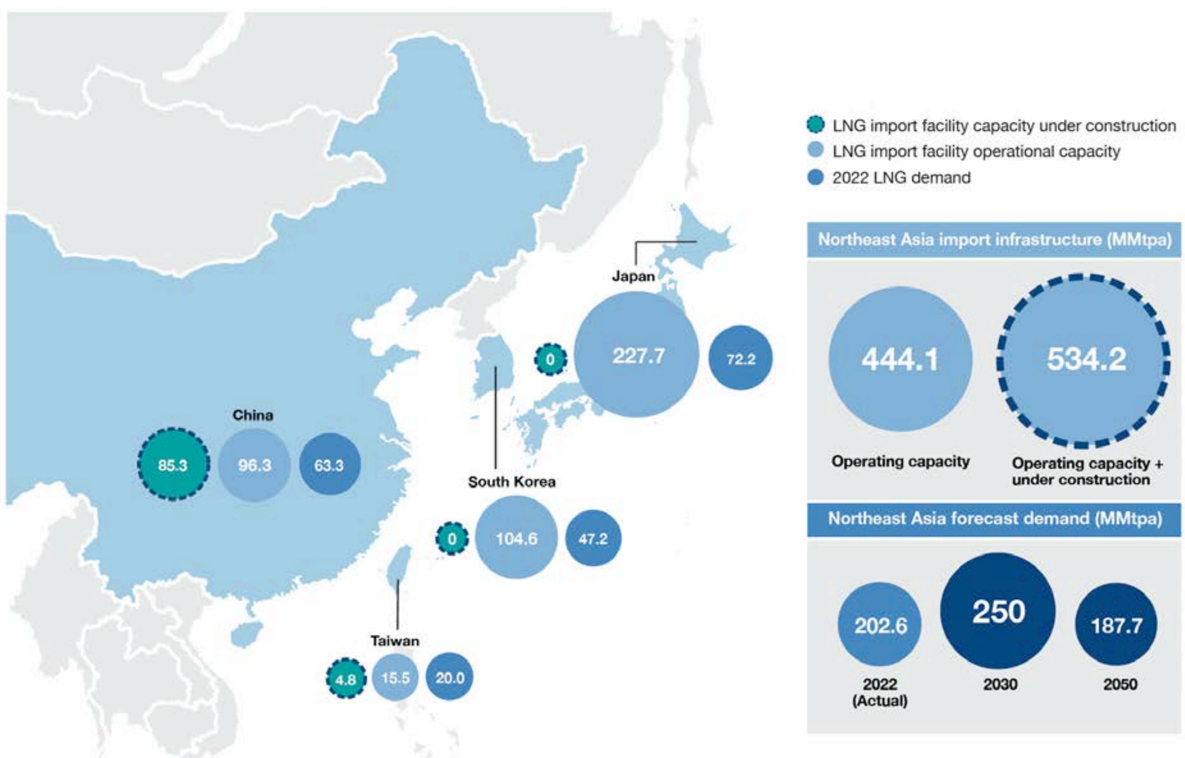


Source: EFI Foundation with data from Wood Mackenzie, Global Gas Asia Regional Market Report, November 2023.

Following European sanctions after its invasion of Ukraine, Russia has been searching for new markets for its natural gas. It is not in the geostrategic interest of the United States, Europe, or Asian allies and trading partners to let Russia fill the supply gap by which a new set of nations becomes reliant on Russian resources.

Despite increasing domestic production and pipeline imports, LNG imports are also expected to grow to meet China's rising demand in the midterm.91 The sizable LNG import infrastructure under construction suggests that China will likely expand its LNG imports (Figure 28).[92,93,94] Also, in 2022, China's natural gas imports from Russia via pipeline increased by 93%, from 7.6 Bcm in 2021 to 14.7 Bcm.[95] In February 2022, China agreed to import natural gas from Russia's Far East Island of Sakhalin via a new pipeline. China and Russia have also been in talks about building new natural gas pipelines from Western Siberia and Altai region (Russia and Kazakhstan) to northwestern China.[96]

Figure 28. LNG import infrastructure in operation and under construction, China and Northeast Asia 2022 (MMtpa)



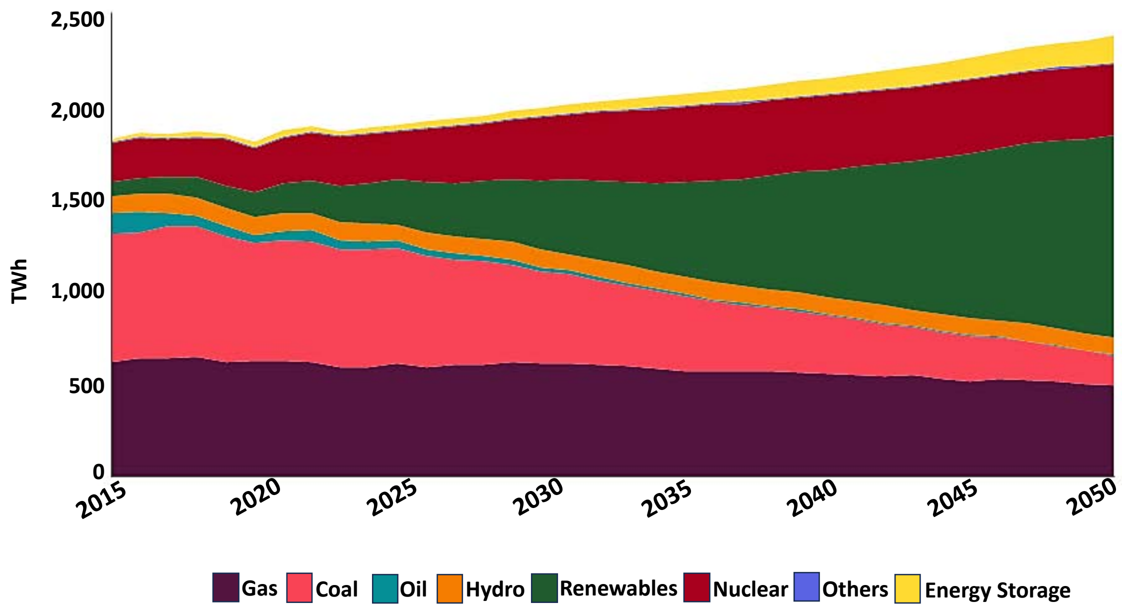
Source: EFI Foundation with data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023).

As Figure 28 shows, China has been investing in LNG regasification capacity. If all projects under construction are completed, China's LNG regasification capacity would double, far exceeding current LNG demand in China. This positions China for arbitrage. As seen during the recent energy crisis, when China had a surplus of natural gas due to COVID-19, it was able to redirect LNG contracted for domestic use to the European market. Given China's authoritarian government, it could be easier for the country to quickly switch energy sources and remain opportunistic in the use of natural gas.

Northeast Asia[m]

Forecasts show that demand for natural gas in Northeast Asia is expected to be strong until the early 2030s. However, demand may decline in the longer term because of slow GDP growth, rapidly aging populations, and accelerated efforts to meet net-zero emissions goals. The most significant part of the demand decline would likely come from the power sector as renewables, energy storage, and nuclear energy scale up. In the baseline scenario of Wood Mackenzie, the share of natural gas in electricity generation is expected to decrease to 21% by 2050 from 33% in 2022 (Figure 29).[97]

Figure 29. Generation mix by fuel, Northeast Asia



Source: Wood Mackenzie, Global Gas Asia Regional Market Report, November 2023.

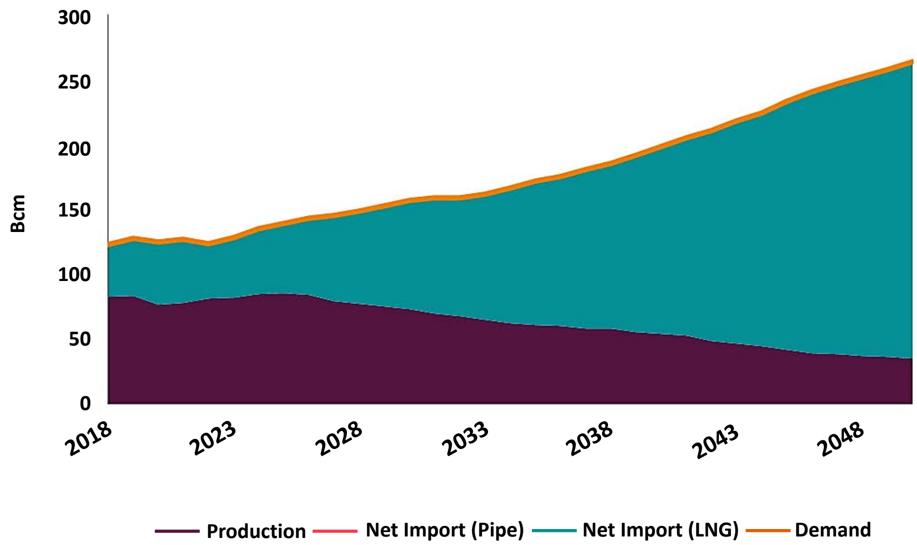
[m] In this analysis Northeast Asia is Japan, South Korea, and Taiwan.

South Asia[n]

Demand for natural gas will rapidly increase in all sectors in South Asia by 2050. Coal and renewables will be significant power generation sources, but natural gas will play a role in providing backup generation for renewables and managing peak load demand. The share of natural gas in the generation mix is expected to be flat, but rising electricity demand could change this trajectory, assuming adequate and affordable supplies and the associated infrastructure. The use of natural gas in the industrial sector is expected to continue to increase in the long term, driven by the refinery and fertilizer industries in India and the textile industry in Pakistan and Bangladesh.

The demand for natural gas will rapidly increase in all sectors in South Asia by 2050. Coal and renewables will be significant power generation sources, but natural gas will play a role in providing backup generation for renewables and managing peak load demand. The use in the industrial sector is expected to continue to increase in the long term, driven by the need for the refinery and fertilizer industry in India and the textile industry in Pakistan and Bangladesh.

Figure 30. Natural gas balance, South Asia



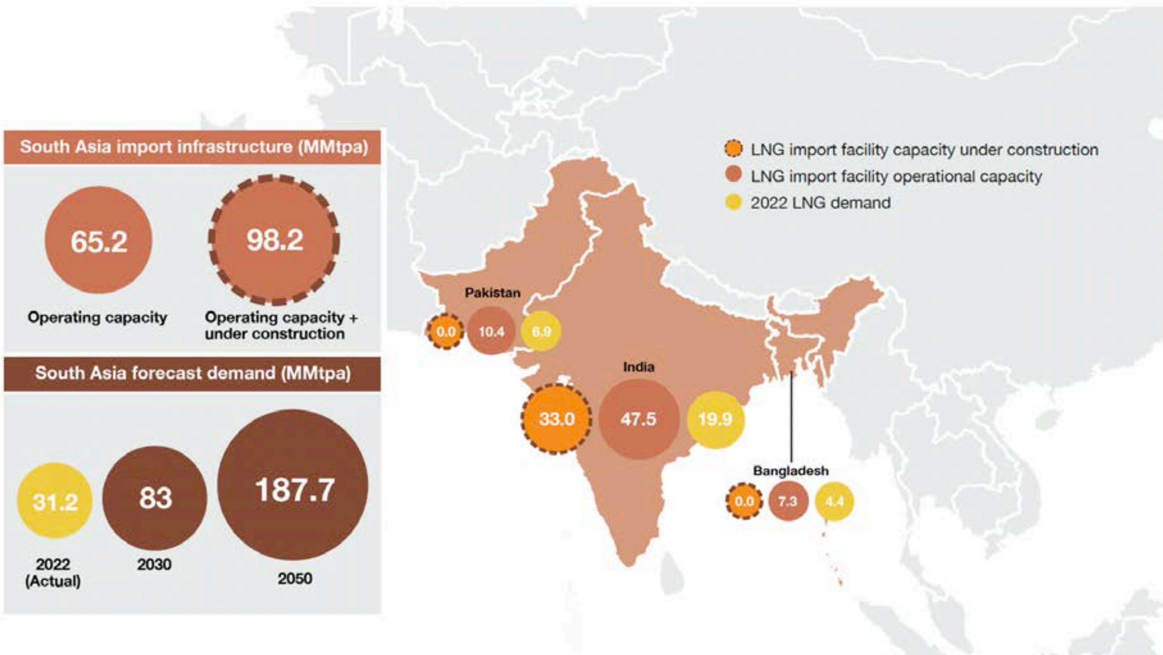
Source: Wood Mackenzie, Global Gas Asia Regional Market Report, November 2023.

The region will increasingly rely on LNG imports as its natural gas production is expected to decline (Figure 30).[98] Despite India's near-term growth in gas production, declining domestic production in Pakistan and Bangladesh would lead to the region's rapid decline in gas production. Declining domestic production and rising demand for natural gas would boost the region's reliance on imported LNG.

[n] In this analysis South Asia is India, Pakistan, and Bangladesh.

Increases in LNG imports will require significant regional investment in infrastructure. The LNG import infrastructure in operation and under construction will be able to meet rising LNG import demand through 2030, but the continued increase of LNG demand would require additional LNG import infrastructure capacity after 2030. The region's demand is forecast to reach 188 MMtpa by 2050, but the total LNG import capacity would reach 98 MMtpa even after the facilities under construction are operational (Figure 31).[99,100,101] To meet the long-term demand forecast, LNG import and takeaway capacity will need to increase substantially by 2050.

Figure 31. LNG import infrastructure in operation and under construction, South Asia, 2022



Source: EFI Foundation with data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023).

Southeast Asia[o]

Growing energy demand, driven by economic and population growth, will increase the long-term demand for natural gas in Southeast Asia. With high levels of energy poverty in the region, affordable energy solutions are essential. This suggests that high-priced low-carbon fuels, such as hydrogen, ammonia, or renewables with storage, could be problematic for the economic development goals of countries in the region. The growth of natural gas consumption in the power

[o] In this analysis Southeast Asia is Brunei, Indonesia, Malaysia, Philippines, Singapore, Thailand, Timor-Leste, Vietnam, and Myanmar.

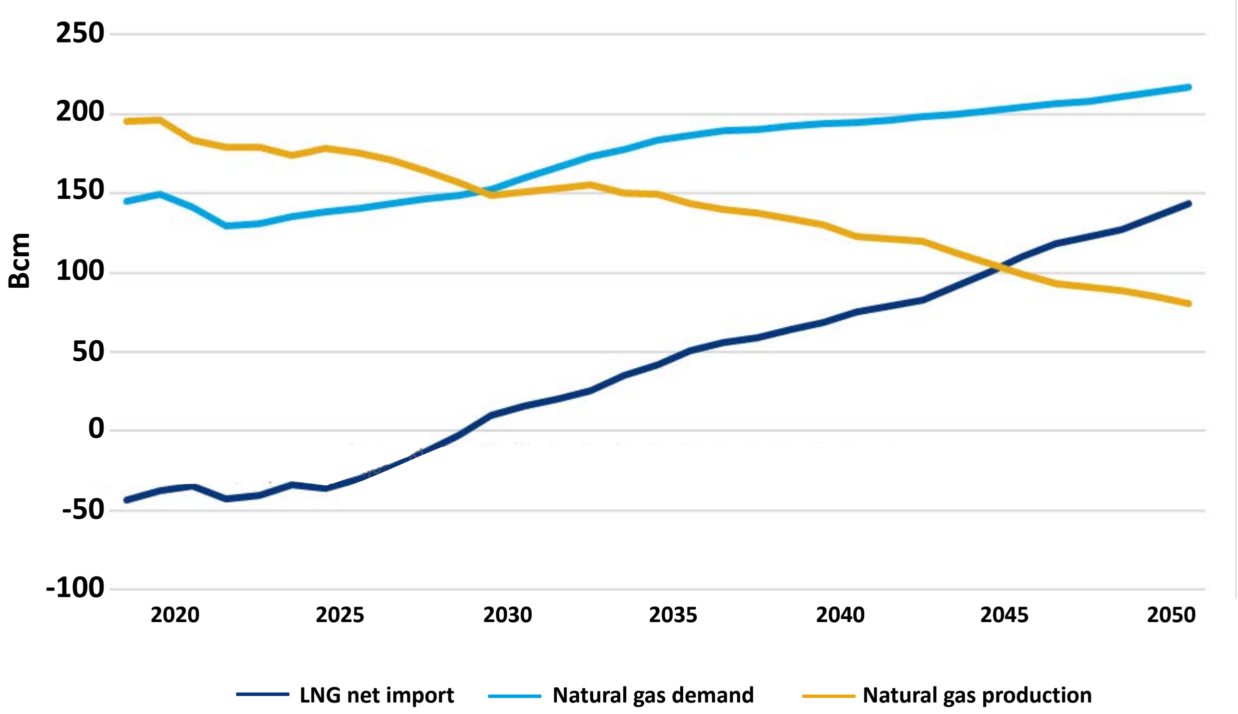
sector, however, will be constrained in the midterm because of high and volatile prices of LNG, slow infrastructure development, and lower-cost coal.

In the longer term, demand for natural gas could surge as the demand for electricity rises and the region's industrial sector develops. Coal-to-gas fuel switching in the region's existing industrial sector could also drive natural gas demand in the region. This is especially important in view of the commitments of most countries in the region to 2050 climate mitigation goals.

The region has been a net exporter of natural gas based on ample gas resources and low demand. However, starting in the late 2020s, the region's LNG imports will likely increase because of declining domestic production, primarily from Indonesia, and rising demand (Figure 32).[102] Production in the region is expected to continue declining as mature fields are depleted and new fields face commercialization challenges due to high break-even costs. Current production would decrease by over half in the next decade, and the technical reserves would not be sufficient to replace declining production in legacy fields.

Surging demand and declining production will likely make Southeast Asia a net natural gas importer before 2030. Indonesia and Malaysia, the region's largest producers of natural gas, will shift from net exporters to net importers in the long term.

Figure 32. Natural gas demand, production, and LNG imports, Southeast Asia, 2018 to 2050

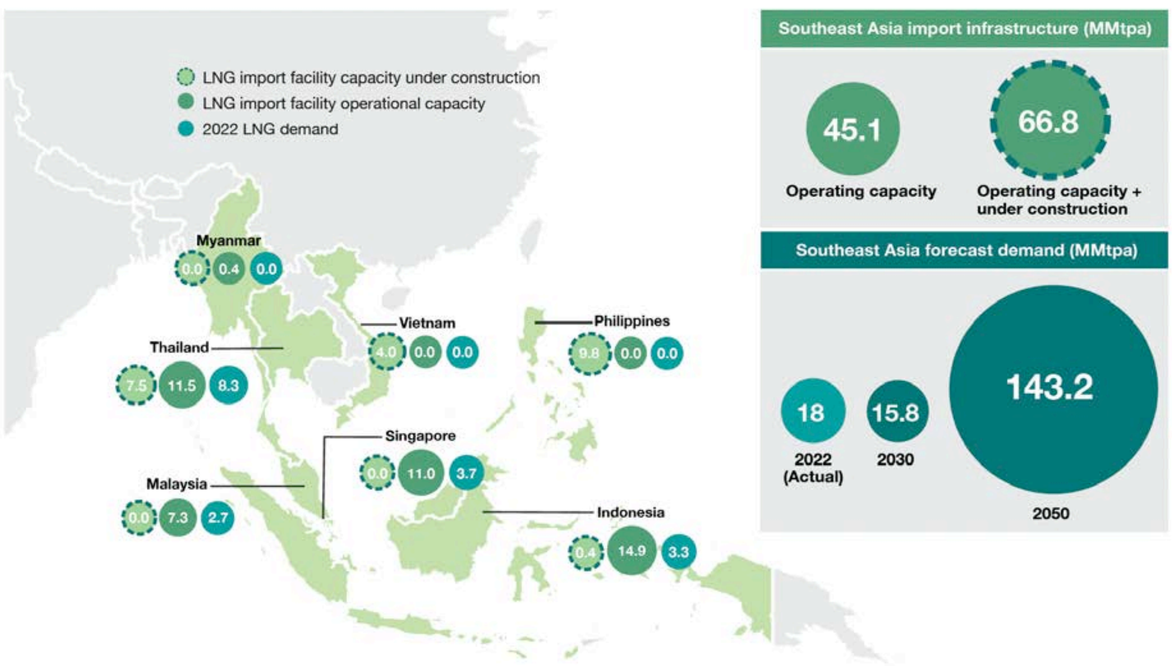


The negative value of LNG net import means that the region is a net LNG exporter. Source: EFI Foundation with data from Wood Mackenzie, Global Gas Asia Regional Market Report, November 2023.

Southeast Asia also faces substantial barriers to reducing its carbon footprint given the region's significant dependence on coal. The affordability of LNG is the most significant constraint to such a transition. In the EFIF Asia roundtable, one expert from the region stated that an affordable price point in emerging markets is about $8/MMBtu, which is much lower than the producers' offer of $12/MMBtu, and that Southeast Asian countries will continue to use coal if the costs of LNG do not come down. The affordability of LNG is especially critical in this region since many people struggle with energy poverty.

Another challenge to using LNG in Southeast Asia is the import infrastructure gap. To meet the growing need for LNG, the region would need to start building LNG import infrastructure around 2030, in addition to those LNG import facilities already in operation and under construction. The existing capacity in operation, 45 Mmtpa, would be sufficient to meet forecast demand of 16 Mmtpa by 2030. The region's LNG demand is forecast to reach 143 Mmtpa by 2050, requiring more than double the capacity of LNG import infrastructure. Additional infrastructure should be built to meet rapidly increasing LNG/natural gas demand between 2030 and 2050 (Figure 33). [103,104,105]

Figure 33. LNG import infrastructure in operation and under construction, Southeast Asia, 2022 (MMtpa)



Source: EFI Foundation with data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023).

Table 1 summarizes these data for the four regions.[106,107,108,109] It illustrates the earlier point made by the IEA in its 2023 World Energy Outlook (WEO): "Alongside gas contracted on a longer-term basis to end-users, we estimate that more than one-third of the new gas will be looking to find buyers on the short-term market. However, mature markets—notably in Europe—are moving into stronger structural decline and emerging markets may lack the infrastructure to absorb much larger volumes if gas demand in China slows." This illustrates the potential for oversupply in key regions and suggests that volumes of LNG supplies could become available for regions in Asia to support coal-to-gas fuel switching in key Asian markets, assuming adequate planning for infrastructure and future supply needs.

Table 1. LNG import infrastructure capacity in development and LNG demand in 2050, Asia and Europe

Region	LNG import infrastructure capacity (in operational and under construction)	LNG Demand in 2050	Gap in 2050 without additonal capacity
South Asia	98.2	187.7	-89.5
Southeast Asia	66.8	143.2	-76.4
China and Northeast Asia	534.2	187.7	+346.6
Europe	206.2	77.7	+128.5
Total (Europe and Asia)	905.4	596.3	309.2
Note: Data from Global Energy Monitor, World Energy Review 2023, and Wood Mackenzie			

Source: EFI Foundation with data from data from Global Energy Monitor, https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/, Eni (2023), https://www.eni.com/en-IT/strategic-vision/global-energy-scenarios/world-energy-review.html, Wood Mackenzie (2023)

Finally, of importance to all of Asia, as of December 2023, approximately 43,000 miles of natural gas transmission pipelines were under construction worldwide, an 18% increase over 2022; 82% of those miles are in Asia. Over 142,000 miles of natural gas transmission pipelines are in development, with an estimated cost of almost three-quarters of a billion dollars.[110] Policies are needed to make certain these assets are not stranded and to help ensure the energy security of the countries and regions where these assets are being developed.

Supply Risks

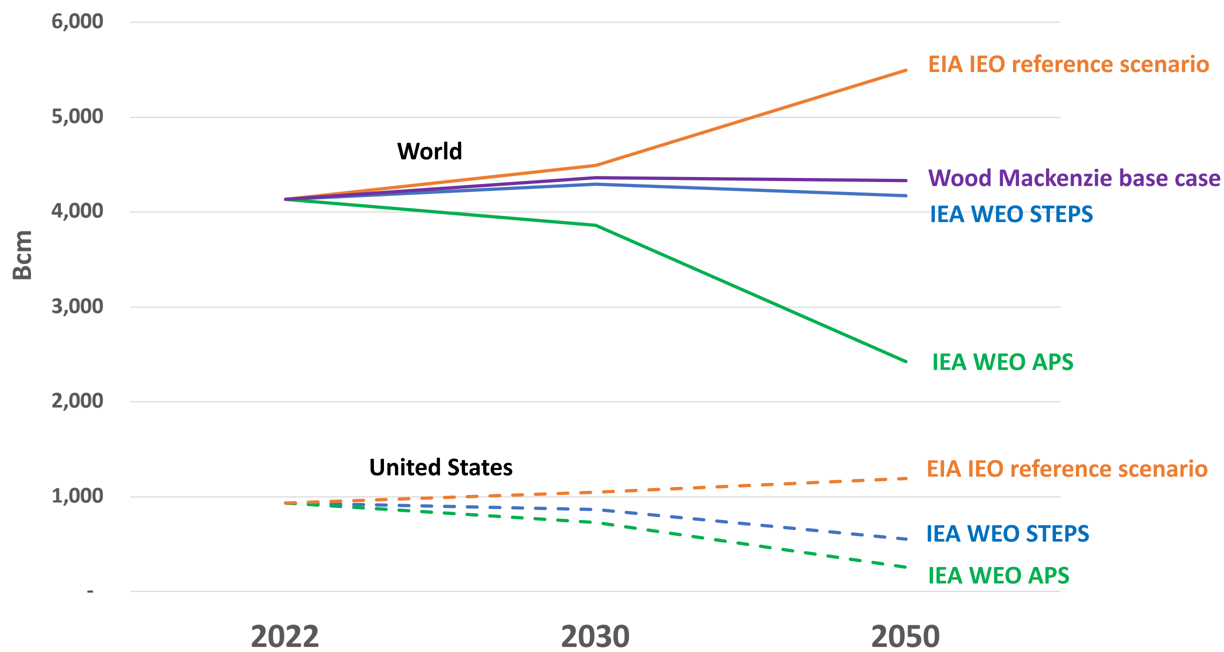
As noted, global natural gas and LNG supply and demand in the longer term are far from certain and there is significant variation in long-term forecasts for global natural gas supply. Even reference scenarios assuming existing policies show substantial gaps in supply projections to 2050.

The EIA's International Energy Outlook 2023 Reference Case shows continued growth in global natural gas supply by 2050 to meet growing international demand, while the IEA WEO 2023 Stated Policies Scenario (STEPS) forecasts a small decline in supply by 2050 (Figure 34).[111,112,113]

Under the IEA's WEO 2023 Announced Pledges Scenario (APS), which assumes that countries implement announced climate ambitions and targets, the global natural gas supply would drop by 40% from 2022 actuals.

The uncertainties surrounding long-term global natural gas demand discourage investments in building the natural gas and LNG infrastructure needed for stable and affordable long-term supply. Policies that support near- to midterm demand could reduce this uncertainty on both the demand and supply sides.

Figure 34. Natural gas supply forecasts by scenario, world and the United States



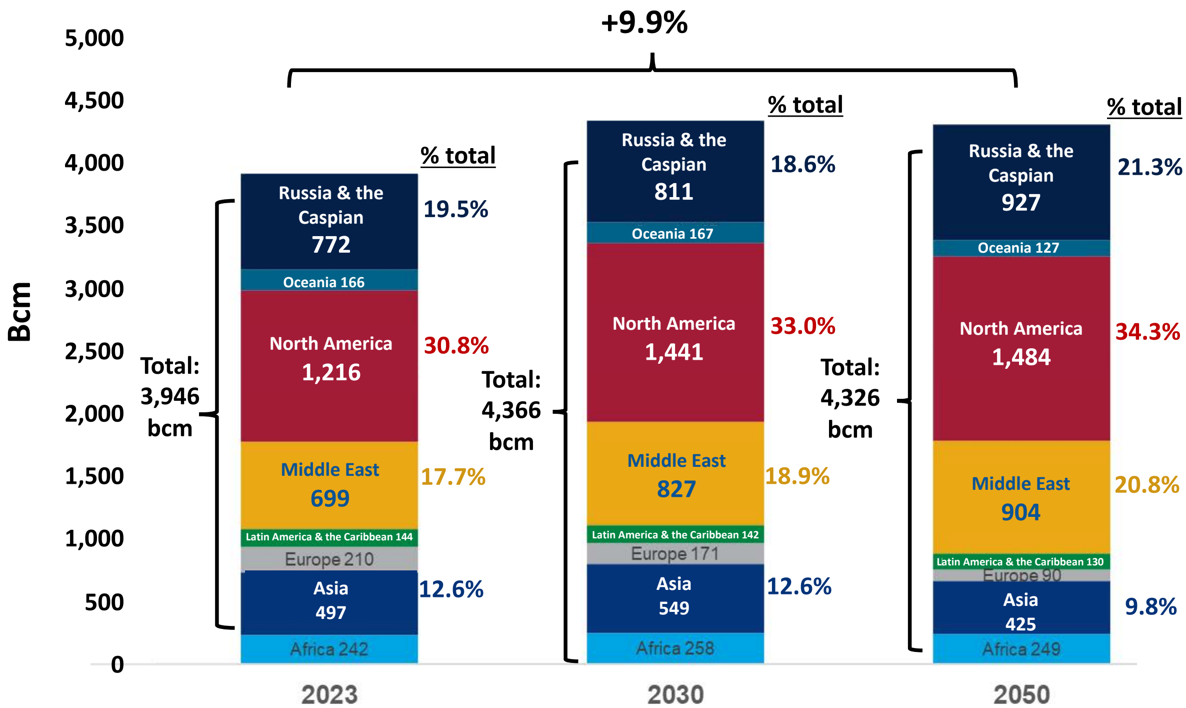
Source: EFI Foundation with data from IEA (2023), https://www.iea.org/reports/world-energy-outlook-2023, EIA (2023), https://www.eia.gov/outlooks/ieo/pdf/IEO2023_Narrative.pdf), and Wood Mackenzie (2023).

Despite the differences in long-term forecasts, it is generally agreed that North America and the Middle East will continue to lead in supplying global natural gas markets. The growth rate of natural gas production would be highest in the Middle East. In the WEO 2023 STEPS scenario, the share of the Middle East in total natural gas production would rise from 15% in 2022 to 25% by 2050. IEO 2023 forecasts that the Middle East's natural gas exports would grow in all scenarios.

A Wood Mackenzie forecast concludes that by 2030, the Middle East would replace Russia and the Caspian Sea region as the world's second-largest supplier of natural gas (including both pipeline and LNG exports), following North America, but that the Russia/Caspian region would return to global markets as the second-largest supplier by 2050 (Figure 35).[114] In this scenario, North

America would remain the largest supplier of natural gas in 2050, with the Russia/Caspian region at a distant second. Overall natural gas supply increases by 9.9% between 2023 and 2050.

Figure 35. Global natural gas supply by region, 2023 to 2050

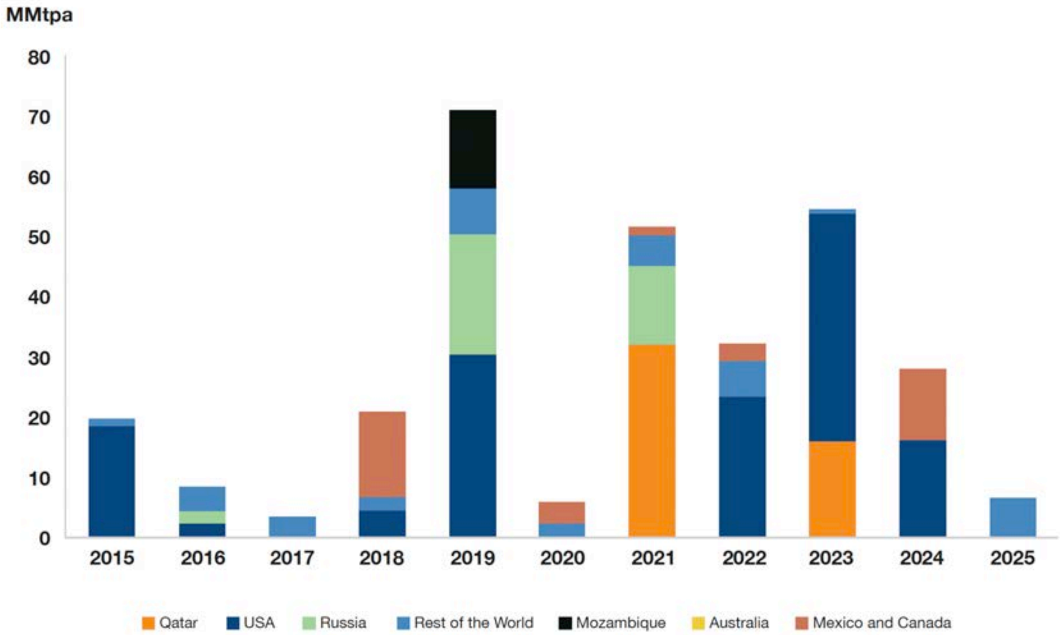


Source: Wood Mackenzie, Global Gas Supply, June 2023

Different energy scenarios generally forecast a well-supplied global LNG market up to 2030 but diverge on the need for additional supply after 2030. IEA's WEO 2023 STEPS scenario forecasts that the global LNG market would have adequate supplies from existing facilities and facilities under construction through 2040. In IEA's APS scenario, the LNG capacity in operation and under construction would be sufficient to meet demand beyond 2040.

Wood Mackenzie forecasts, however, show a possible supply shortage starting around 2030, indicating that global markets will need 60 MMtpa of new LNG supply by 2033.[115] The expansion of liquefaction capacity in the United States and Qatar from 2021 to 2023 will substantially increase LNG supplies between 2026 and 2029 (Figures 36 and 37).[116]

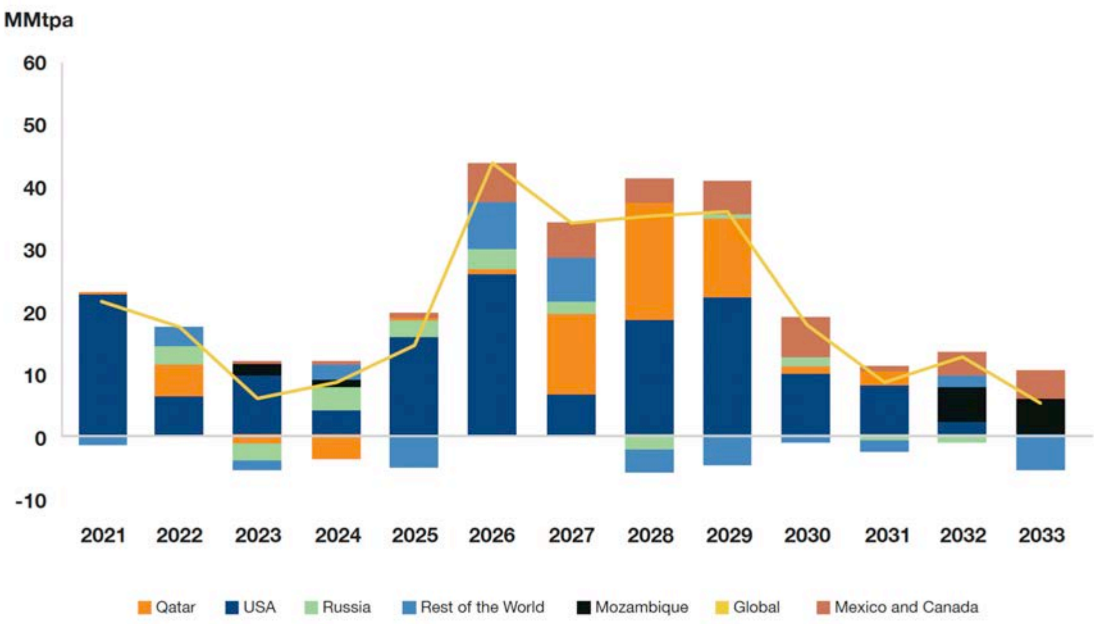
Figure 36. Capacity of LNG projects taking final investment decisions by country, 2015 to 2025



2024 and 2025 are projections. Source: Wood Mackenzie, Global Gas: LNG Supply Report, November 2023.

In the Wood Mackenzie forecasts, U.S. LNG supply would grow from 78 MMtpa in 2022 to more than 200 MMtpa by 2033. However, since less capacity for projects is expected in 2024 and 2025, global LNG supply growth could slow in the early 2030s (Figure 37).

Figure 37. LNG supply growth by country, 2021 to 2033



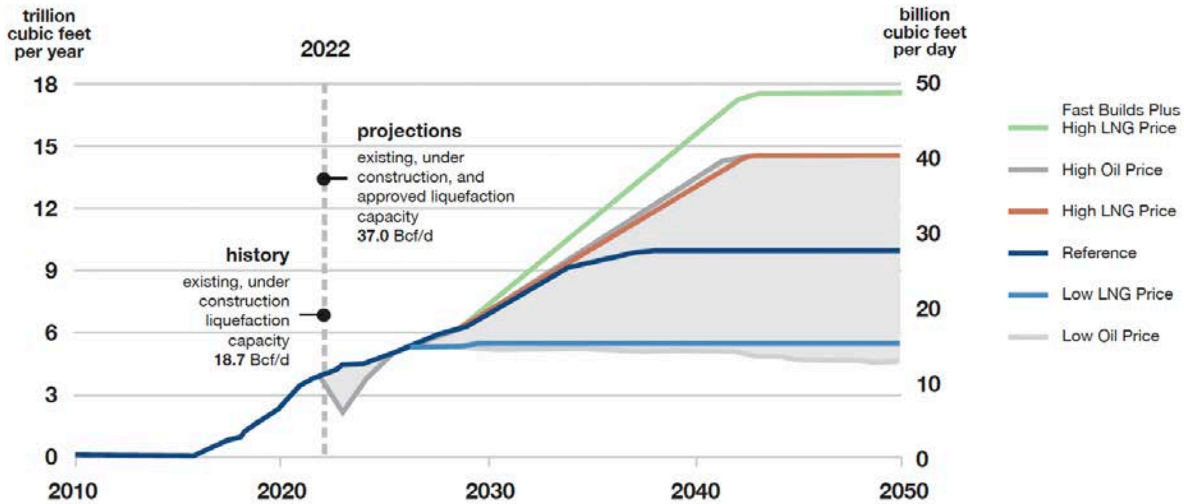
Source: Wood Mackenzie, Global Gas: LNG Supply Report, November 2023.

In sum, longer-term natural gas and LNG supply projections are far from certain as they depend on various factors, such as climate commitments and policy changes, the degree of LNG infrastructure expansion, and energy pricing. In addition, each nation and region's geopolitical, economic, environmental, and social changes influence the globalized LNG market, as shown in the energy crisis sparked by the war in Ukraine. This uncertainty challenges the LNG suppliers who should make investment decisions in LNG export infrastructure.

The United States' Role in Meeting Global Energy Security Challenges

The EIA expects that the longer-term growth of U.S. LNG exports will depend on international LNG prices and how quickly both export and import infrastructure can be built.[117] Underpinning contracts and financing are driven largely by the price of natural gas. In the EIA's reference case U.S. LNG exports are stabilized at 27.3 Bcf/d in the mid-2030s (Figure 38).[118] Under the High LNG Price scenario, exports increase to 39.9 Bcf/d, a 46% increase. With a relaxed limitation of liquefaction capacity build, exports could reach 48.2 Bcf/d, a 76% increase, as project developers have incentives to add U.S. LNG export capacity into existing, under construction, and approved liquefaction capacity.

Figure 38. AEO 2023 projection of U.S. LNG exports



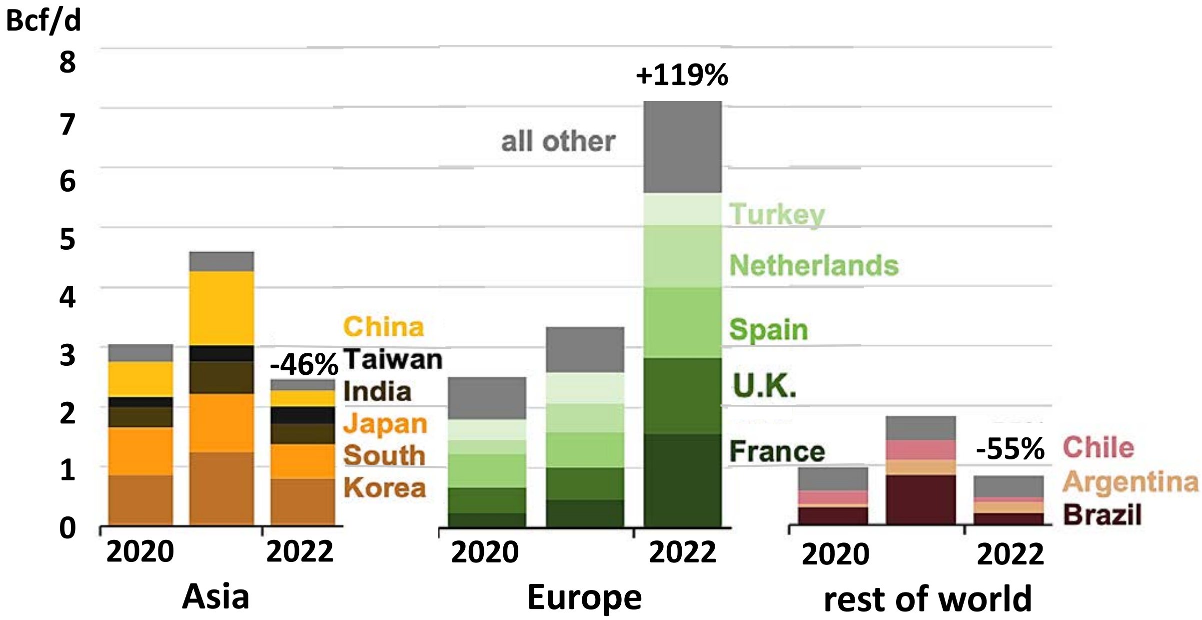
The High LNG Price Case assumes that LNG prices in Europe and Asia are higher by an average of 25% relative to the Reference Case. The Low LNG Price Case assumes that LNG prices in Europe and Asia are lower by an average of 20% relative to the Reference Case. Source: EIA, Annual Energy Outlook 2023, March 2023, https://www.eia.gov/outlooks/aeo/.

The United States can deliver significant quantities of LNG, but U.S. government policies need to do more to acknowledge and address the geostrategic and energy security value of U.S. LNG exports to U.S. allies and trading partners. U.S. natural gas producers and LNG exporters should increase actions to address the climate impacts of natural gas production, transport, liquefaction, and shipping.

While there is an ongoing need to reduce LNG and natural gas supply chain emissions, the United States, as a natural gas exporter, plays a significant leadership role in maintaining energy security and global stability. Although the United States does not have any formal or contractual obligations to provide LNG to global allies and trading partners, geopolitical issues such as energy and food security, trade balances, affordability, and geopolitical strategies and relationships are critical considerations and underscore the value of U.S. natural gas exports. In addition, the United States is a party to several treaties and agreements that carry implications for U.S. exports. Some examples of such obligations may be by treaty, by agreement, or through membership in the following: the IEA, NATO, OECD, the Energy Charter Treaty, G7, bilateral agreements on energy security with Canada and Mexico, and the U.S.-E.U. Energy Security Taskforce.

As noted, Russia's invasion of Ukraine and its weaponization of its energy supplies created an energy crisis in Europe. The U.S. government aided the supply gap, through the lack of destination clauses in many U.S. LNG export contracts, by diverting cargoes to Europe, after consulting with Asian allies and other recipients of U.S. LNG supplies. The United States also asked key Asian buyers to assist in managing the crisis by reselling their cargoes under contract to European buyers (Figure 39).[119] As one workshop expert observed, "This was a lot more government intervention in the market than we would have been comfortable with, or Europe was comfortable with, and it took cutting off supply from Russia to get there."[120]

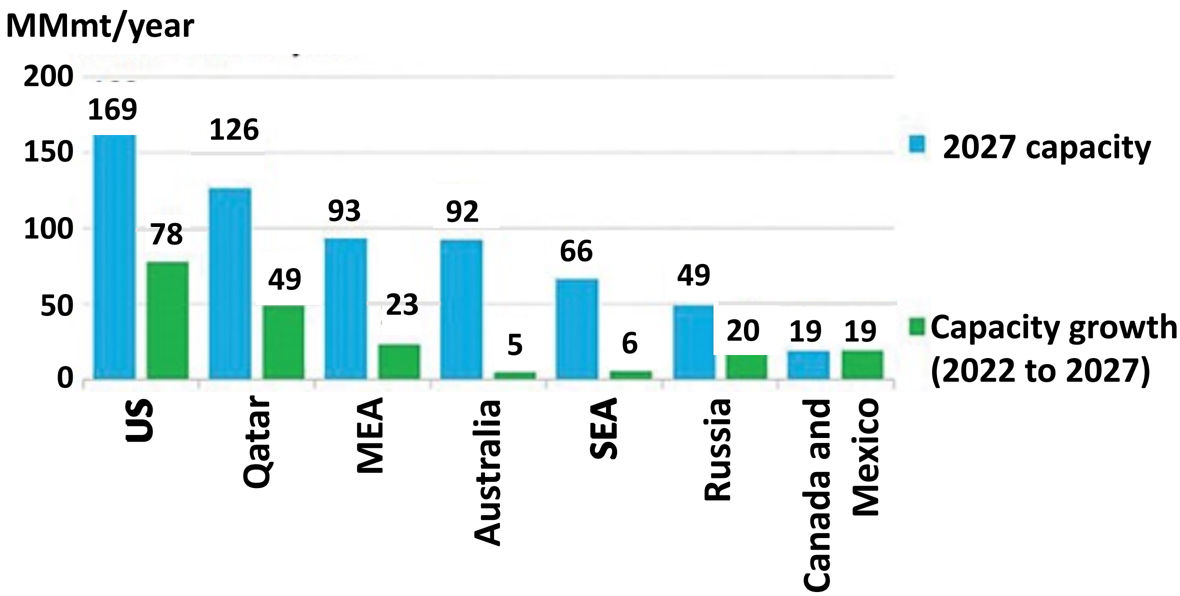
Figure 39. Annual U.S. liquefied natural gas exports by destination, 2020 to 2022



Source: EIA, "Europe Was the Main Destination for U.S. LNG Exports in 2022," Today in Energy, March 22, 2023, https://www.eia.gov/todayinenergy/detail.php?id=55920.

The United States will need to produce more natural gas if filling the vacuum created by sanctions on Russia becomes a national security priority. Other producer/supplier countries, such as Mozambique, face political uncertainties that raise reliability concerns. These and other geopolitical issues and actions underscore the critical energy security role played by the United States as the world's largest exporter of natural gas. In the EFIF's workshop in Washington, D.C., an expert noted that "North American gas supply is hugely, hugely important to the world, and the world knows it and views it as such" (Figure 40). [121,122] While supply from Qatar competes with U.S. suppliers, the United States still "stands out in terms of market access," which has prompted investment flows into the United States, even before the passage of the Inflation Reduction Act of 2022 (IRA).[123]

Figure 40. Global LNG export capacity growth

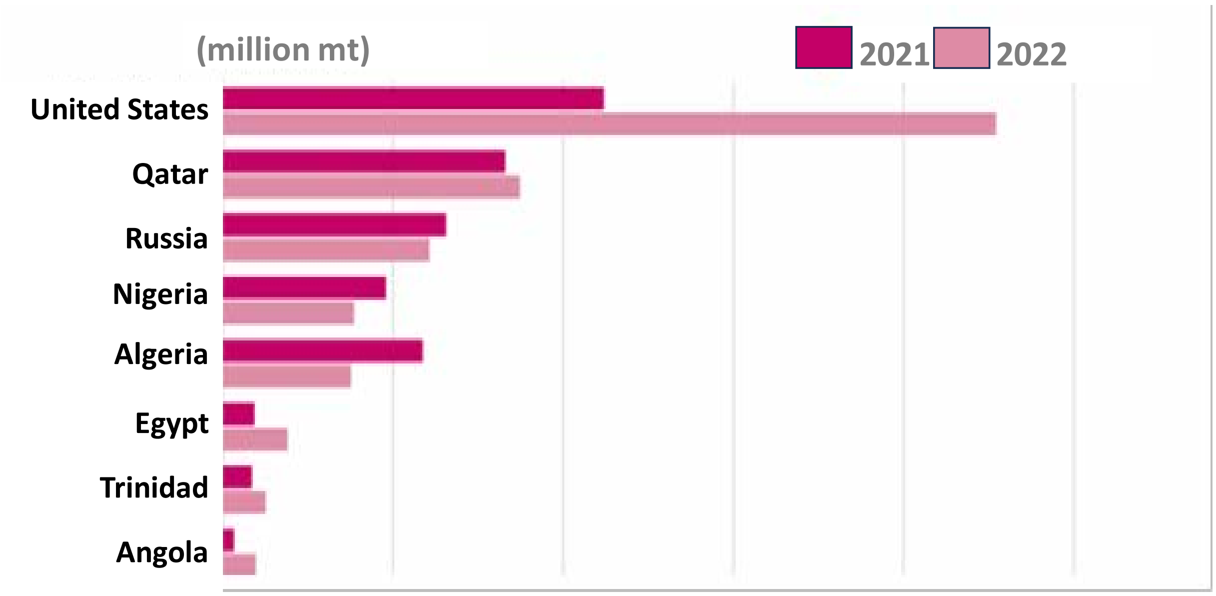


Capacity includes Bloomberg NEF's top picks for final investment decision in 2023, assumes no decommissioning, and full capacity of Arctic 2. MEA is Middle East and Africa. SEA is Southeast Asia. Source: Bloomberg NEF, "US to See Dramatic Growth in LNG Export Capacity," January 24, 2023, https://about.bnef.com/blog/us-to-see-dramatic-growth-in-lng-export-capacity/.

While Europe's long-term use of natural gas is uncertain as it weighs competing climate and security priorities, the region has been the primary consumer of LNG because it has more expendable capital to meet its energy needs than developing nations. At a workshop held to inform this analysis, one expert stated that Europe is "getting the gas they need because they're rich and can afford to pay whatever the highest price is on the global market to keep their economy running, and other countries simply cannot compete with that."[124]

As a result of the war in Ukraine, U.S. LNG exports to Europe doubled from 2021 to 2022 (Figure 41).[125] In 2022, Europe accounted for 64% of all U.S. LNG exports, and the United States represents 43% of total European LNG imports.[126,127] When Russian pipeline deliveries to Europe fell in 2022, the region increased its imports of Russian LNG by a third to 19 Bcm to help fill the shortfall.[128,129] Most of the Russian LNG came from Novatek, which is privately owned and is the country's second-largest natural gas producer after Gazprom.[130] Europe has not yet implemented sanctions aimed at limiting LNG imports from Russia, and it is unclear how the EU will meet its energy security needs without a diverse supply of LNG.[131]

Figure 41. Change in European LNG supply sources from 2021 through October 2022



Source: Ciaran Roe, "Europe to the Fore, Elsewhere Through the Floor: How LNG Flows Were Turned on Their Head in 2022," S&P Global Commodity Insights, October 26, 2022, https://www.spglobal.com/commodityinsights/en/market-insights/blogs/lng/102622-europe-lng-russian-gas-ukraine-war.

The economic downturn brought on by the COVID-19 pandemic enabled countries in Asia and elsewhere to resell surplus gas to Europe. Specifically, China exported diesel and natural gas to Europe because in 2022 and 2023 prices for both commodities in Europe increased after the Russian invasion of Ukraine, but as China's economy rebounds from the pandemic as its industrial activity ramps back up, it is likely to consume those resources domestically.[132,133]

During the EFIF workshop in Washington, a discussion focused on points surrounding the complexity of fuel pricing and trade dynamics and how this asymmetric information leads to surges in the supply of either diesel or LNG. As a result of supply shortages, many European countries shifted their consumption of gas from their industrial sectors to meet residential needs. It was observed that European governments have prioritized the use of natural gas for residential heating, and European heavy industry output has declined in areas such as cement, fertilizer, and steel.

Even at $20/million Btu, gas is too expensive to produce ammonia and smelt metal, causing an "incredible exodus of energy-intensive industries that will never come back."[134] Several experts in a breakout session concurred and concluded that "Europe is now proceeding through what you can only describe as a sort of revolutionary change in its energy system from all standpoints."[135] The crisis has accelerated Europe's move away from natural gas and, as noted by an expert in the workshop, in the long term, Europe's LNG consumption could decline by 40% by midcentury because of the decrease in industrial activity, climate goals, and a 70% reduction in ammonia production for agricultural use.[136]

Other experts were also uncertain about Europe's long-term demand for U.S. natural gas due to energy insecurity, LNG market structures, and decarbonization goals. Europe needs U.S. LNG to meet short-term energy demand, but its nationally determined contributions (NDCs) require it to aggressively reduce fossil fuel consumption and increase power generation from renewables. One expert noted that Europe's midcentury NDCs could conflict with its ability to purchase affordable gas in the short term because LNG market structures historically depend on long-term, 20-year contracts (LTCs). Some exporters will not build capacity without long-term contracts "because lenders will not put in the money without a guaranteed revenue stream."[137]

Experts agreed that this dilemma presents an opportunity to rethink the structure of contracts and LNG markets to find creative solutions where short-term demand can be met without making long-term commitments. One emerging strategy is LNG contracts with destination flexibility, a unique feature of U.S. LNG contracts. In 2022 and 2023, more than 40% of the total volumes contracted were contracts with destination flexibility, a significant increase from the average of 23% in 2020 and 2021. European buyers were dominant in destination-flexible volumes, while Asian buyers were dominant in destination-fixed volumes.[138]

In the long term, natural gas in Europe may be replaced by hydrogen as a fuel used largely for industrial purposes, but for now, natural gas will be needed as the primary feedstock for hydrogen production through steam methane reformation. Some experts also thought that some natural gas infrastructure could be repurposed for hydrogen, but there are limitations on blending which, if exceeded, could embrittle pipelines and raise safety concerns. Further analysis must be done to fully understand the implications of using natural gas infrastructure for hydrogen. Although U.S. LNG to Europe may not be a long-term option, several experts thought that natural gas would still play a critical role in U.S.-EU energy trade relationships for both hydrogen production and nitrogen-based fertilizers. The relationships also would be central to Europe's energy security.

U.S. LNG has supported energy security, the energy transition, and economic development worldwide, and many regions will continue to rely on the United States for meeting these needs. In addition to resource availability, political stability and leadership make the United States a reliable supplier of LNG in the global market. Moreover, the United States is well positioned to lead the effort to decarbonize the supply chain of natural gas, as it has been a leader in the development of decarbonization technologies, such as CCUS, methane abatement, and hydrogen.

U.S. LNG has supported energy security, the energy transition, and economic development worldwide, and many regions will continue to rely on the United States for meeting these needs. Although the United States does not have obligations to provide LNG to global allies or trading partners, energy and food security, trade balances, energy affordability, and geopolitical strategies and relationships underscore the leading role the United States has taken in handling the vast uncertainty in the global natural gas market.

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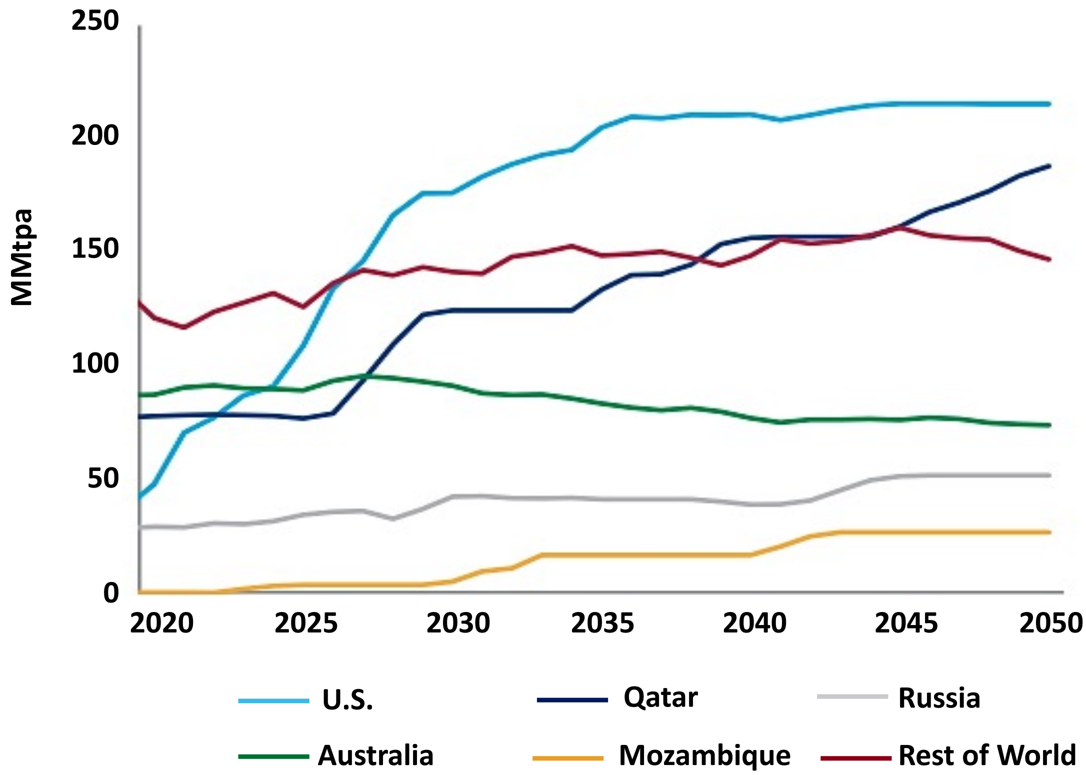
The demand for LNG is forecast to grow, and the United States is the world's top exporter of LNG. EIA forecasts suggest that the United States and the Middle East will be the world's largest gas exporters through 2050 in meeting growing international demand, especially as Europe continues to move away from importing Russian natural gas.[139] The U.S. LNG supply would be driven mainly by the growing LNG demand in Europe until 2030 and by the demand in Asia thereafter (Figure 42).[140]

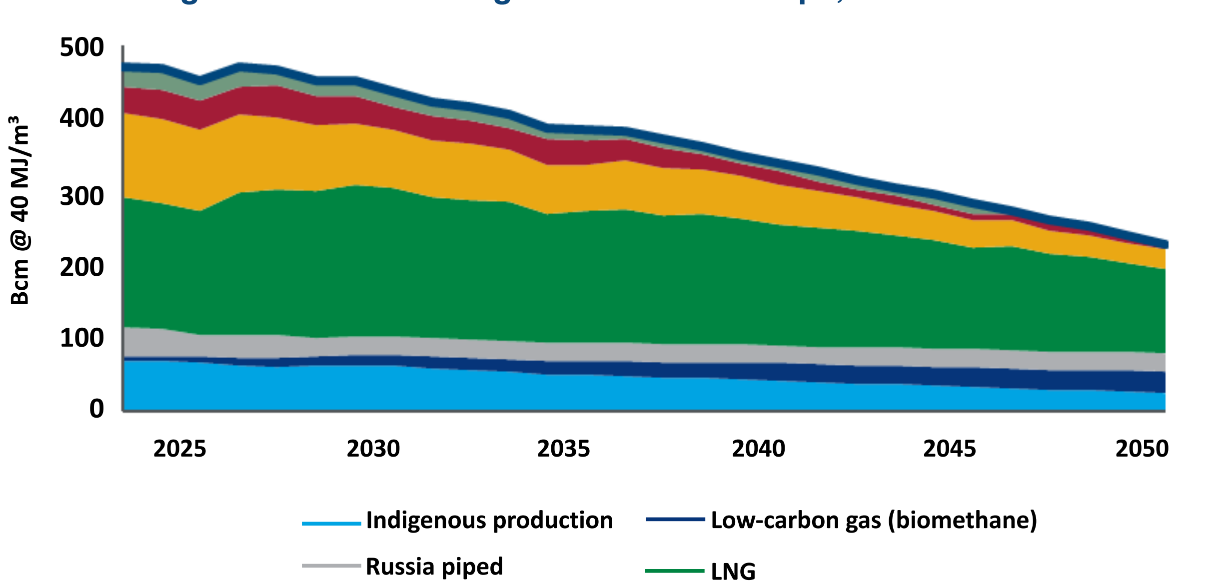
Figure 42. Projection of LNG supply by region, 2020 to 2050



Source: Massimo Di Odoardo et al., "Global Gas Strategic Planning Outlook," Wood Mackenzie, March 2023.

As noted, in Europe, the total natural gas demand is expected to decrease, but the demand for LNG will likely remain stable through 2050 (Figure 43). A recent analysis by Wood Mackenzie showed that even under the scenario of global net-zero emissions by 2050, global LNG demand would be resilient through 2050. Global LNG demand is projected to grow by 18% by 2050 compared with 2023.[141]

Figure 43. Forecast of gas sources in Europe, 2023 to 2050[142]



Indigenous production excludes Cyprus production. Source: Massimo Di Odoardo et al., "Global Gas Strategic Planning Outlook," Wood Mackenzie, March 2023.

The United States is well positioned to lead the greening of the natural gas supply chain as the federal government has put effort into reducing GHG emissions in the natural gas value chain. The methane fee included in the IRA has motivated the industry to reduce methane emissions across the value chain. In December 2023, the EPA finalized new rules to reduce methane emissions and other harmful air pollution from new and existing oil and gas operations. The Department of Energy has been developing an international measurement, monitoring, reporting, and verification framework that enables verification of GHG emissions across the international natural gas supply chain through collaboration with natural gas importing and exporting governments. These efforts are on top of current life cycle emissions from U.S. LNG that are 13% lower than those from

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Russian natural gas imports, even considering the additional emissions from liquefaction, shipping, and regasification.[143]

The United States, through environmentally focused legislation, is also poised to be a leader in CCUS technology, which has much potential to reduce natural gas life cycle emissions (see Chapter 4 for further discussion of BIL incentives and IRA of 2022 tax provisions). Lastly, the United States has invested in research, development, and demonstration of hydrogen infrastructure, which could help integrate the pathway of natural gas into the pathway of clean fuels.

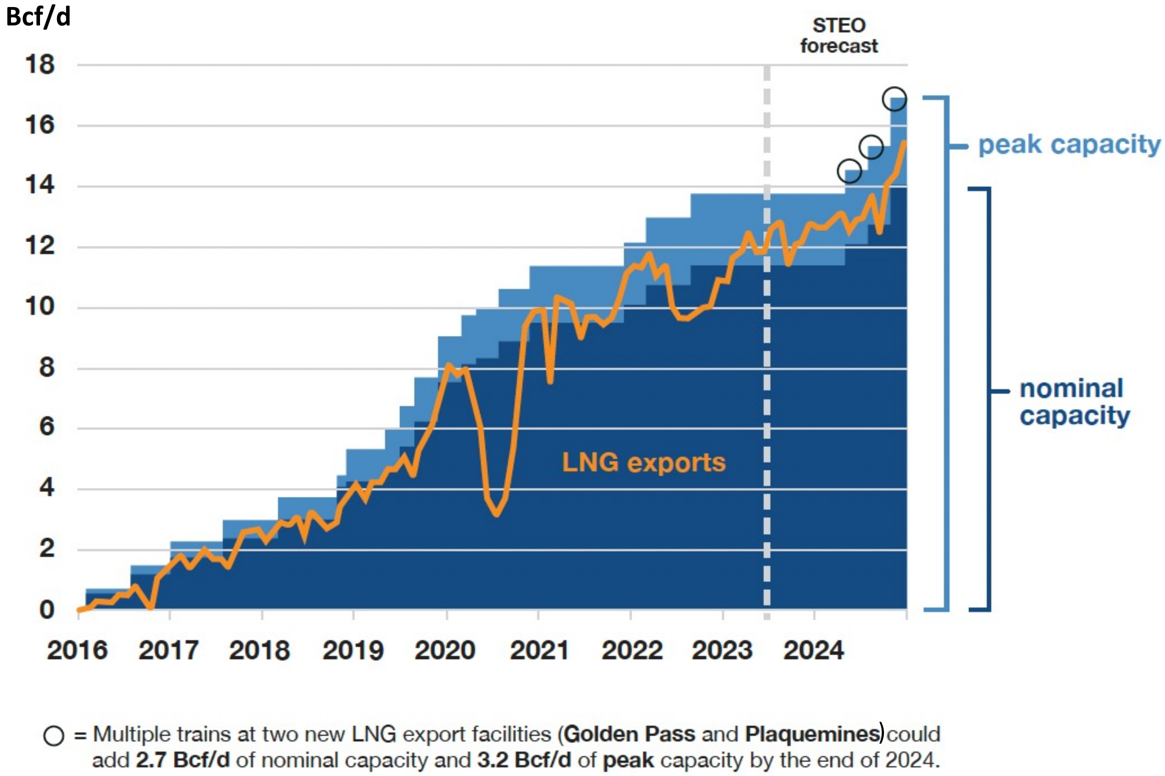
Challenges to U.S. LNG suppliers

U.S. LNG suppliers will continue to face numerous challenges in building export infrastructure, including uncertain forecasts of global LNG/natural gas demand, legal and regulatory issues, and reduction of GHG and environmental impacts of new infrastructure. A shortage of LNG liquefaction capacity is possible in the early 2030s. The average time to build an LNG liquefaction facility is seven years, so meeting demand in the early 2030s means that project developers need to start now.

Building LNG Export Terminals

The capacity of LNG export terminals has increased to meet rising global demand for U.S. LNG since the United States started exporting LNG in 2016. As shown in Figure 44, U.S. LNG exports have generally operated at nominal capacity and have exceeded nominal capacity during peak demand periods.[144] In 2022, U.S. LNG exporters used 98% of their nominal capacity, and they are expected to use 105% and 108% of nominal capacity in 2023 and 2024, respectively. Therefore, given a growing international LNG demand in the near and midterm, the United States will need additional capacity for LNG export terminals.

Figure 44. U.S. LNG gross exports and capacity, January 2016 to December 2024



STEO = Short-term energy outlook. Source: EIA, "Short-term Energy Outlook," April 9, 2024, https://www.eia.gov/outlooks/steo/report/BTL/2023/07-LNG/article.php

To build LNG infrastructure, project developers go through a lengthy permitting process. Many stakeholder concerns about GHG and other environmental impacts of an LNG export infrastructure could introduce more thorough environmental reviews, leading to a longer lead time for LNG export terminals. Building out the pipeline infrastructure needed to enhance both domestic and natural gas supply for export could face immense challenges from states, landowners, and environmental groups.

To address some of these issues, new gas infrastructure projects should be prepared to demonstrate that they minimize GHG and environmental impacts across the natural gas value chain. Projects should also, in their proposed and actual development, highlight the energy security implications of and need for the supply and its associated infrastructure.

DOE and the Federal Energy Regulatory Commission (FERC) authorize LNG export licenses under the Natural Gas Act (NGA). DOE determines whether LNG exports to the countries with which the United States does not have a free trade agreement (FTA) are in the public interest by reviewing the economic and environmental impacts of exports and the effects on U.S. energy security.[p] FERC authorizes the siting and construction of LNG export facilities. A major part of the process is an environmental impact assessment of the proposed project according to the National Environmental Policy Act (NEPA). When FERC approves a project, DOE completes the review, then grants a license to export.

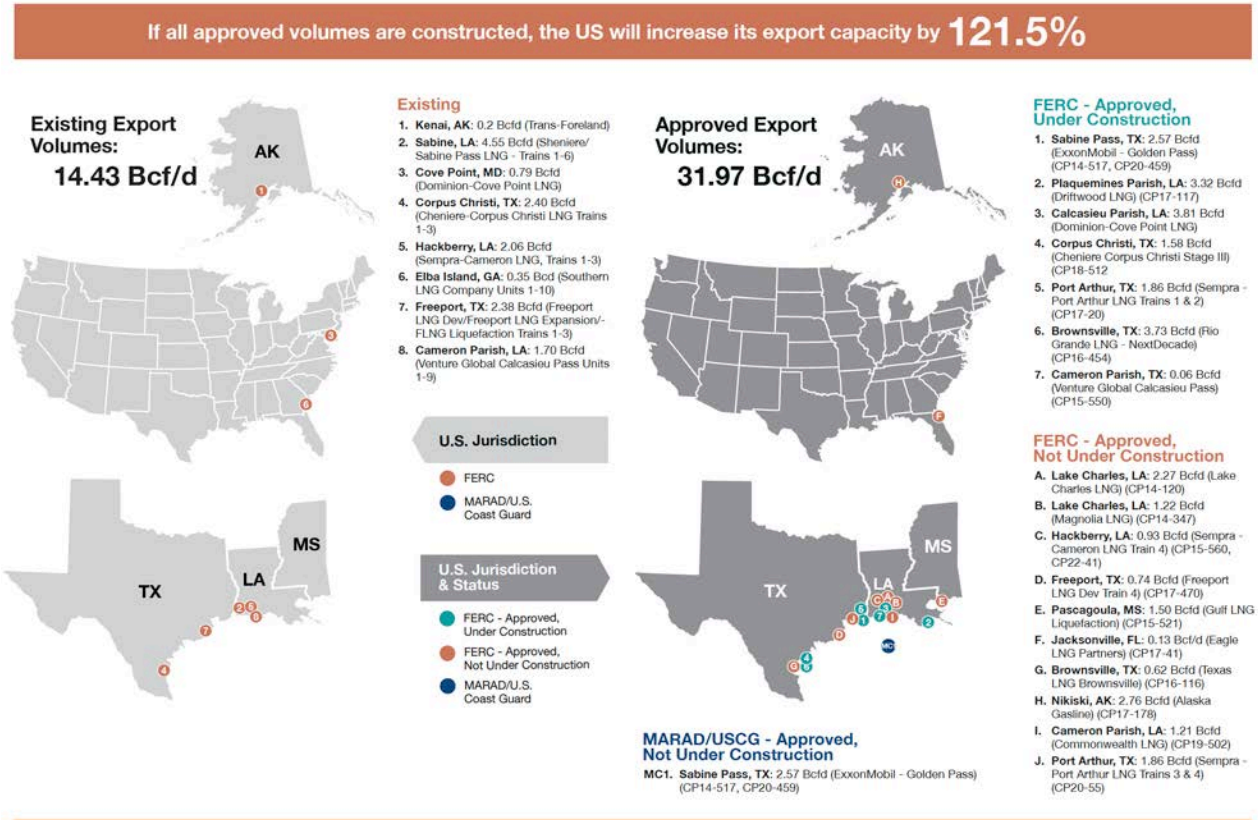
The time it takes to obtain an export license has been a concern of project developers. Historically, the average time to get approval for export to non-FTA countries was 3.9 years, with a range of 1.9 to 6.9 years.[145] This has led to long lead times for building LNG export terminals. Some cases have had an extremely long review process; some applications submitted in 2013 are still under review.[146]

Also, on January 26, 2024, the United States announced a temporary pause on pending decisions on new LNG exports to non-FTA countries while DOE updates the underlying analyses for authorizations.[147] This decision reflects the concerns about the climate and environmental impacts of LNG export infrastructure that have been raised by some lawmakers and environmental groups. Following this review, DOE is expected to review the impacts of LNG exports for several months and hold a public comment period.[148] This pause does not affect LNG facilities that have already been permitted.

Important to the need for more LNG export capacity in view of the pause, Figure 45 shows existing LNG export facilities by volume, permitted facilities under construction, and permitted facilities not yet under construction.[149] As the figure shows, if FERC-permitted facilities are completed, volumes of U.S. LNG for export will increase by over 121% and these facilities will not be affected by the pause.

[p] On December 13, 2018, DOE eliminated the end use reporting provision in authorizations for the exports of LNG. According to this policy change, authorization holders are not required to report the country of destination into which their exported LNG was "received for end use." The authorization holders report the country into which the exported LNG "was actually delivered."

Figure 45. U.S. LNG export facilities and volumes as of March 12, 2024



Source: EFI Foundation with data from FERC, "U.S. LNG Export Terminals – Existing, Approved Not Yet Built, and Proposed," accessed March 12, 2024, https://www.ferc.gov/media/us-lng-export-terminals-existing-approved-not-yet-built-and-proposed.

Despite the potential for the doubling of U.S. LNG export volumes that are excluded from the pause, U.S. allies and trading partners have expressed concerns about its potential impacts. An example: Tatsuya Terazawa, chairman and CEO of the Institute of Energy Economics, Japan (IEEJ), noted in IEEJ's March newsletter that "the announcement came as a big shock to LNG importing countries such as Japan." He stressed "the need to incorporate concerns of allies, LNG users, and market players, [as this issue] is much broader than election year politics." He also called for an investigation of the varying opinions on the pause expressed in the United States and highlighted some major points for consideration, including the following:

- Current LNG capacity and projected supply are not enough to meet global LNG demand in 2040.
- Authorization does not automatically translate into investment.
- The pause disrupts the business activities of many market players.
- Inconsistency with the policy to reduce dependence on Russia.
- Uncertainty about the future role of the United States as the largest LNG exporter.

Global LNG supply and demand projections support Chairman Terazawa's concern on insufficient LNG supply capacity around 2040. As shown in Figure 46, the expected additional U.S. LNG supply is sufficient to meet the LNG supply gap in 2030 but is insufficient to meet the gap in 2040.[150,151] The LNG supply gap is expected to be 167 MMtpa in 2040, but the additional U.S. LNG supply potential—which is the total capacity of the LNG export terminal projects approved by the U.S. government and not yet under construction—is only 115 MMtpa. Therefore, to meet the 2040 demand, the proposed U.S. LNG export capacity needs to be approved. If the five U.S. LNG export terminal projects proposed to FERC are approved, it would add 63 MMtpa of LNG supply in the market, which would fill the supply gap of 52 MMtpa in 2040.

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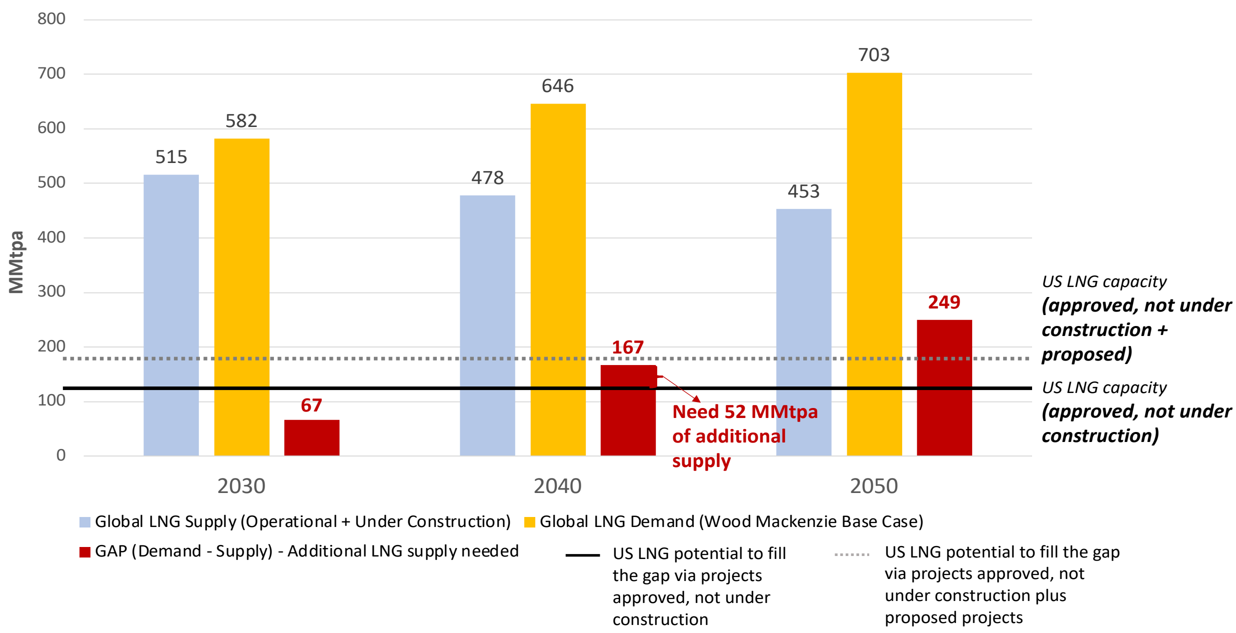
Figure 46. Global LNG supply gap and potential of U.S. LNG to fill the gap



The LNG supply gap was calculated based on the Base Case of Wood Mackenzie. The additional supply potential of U.S. LNG was calculated based on the total capacity of the U.S. LNG export terminal projects approved/not under construction and proposed as of March 12, 2024.
Source: EFI Foundation with data from FERC (2024), https://www.ferc.gov/media/us-lng-export-terminals-existing-approved-not-yet-built-and-proposed, and Wood Mackenzie (2023).

Before the January 2024 pause, some members of the U.S. Congress had been working to expedite the LNG export permitting process. For example, the Natural Gas Export Expansion Act, introduced in February 2023, proposes to amend the NGA to expedite non-FTA export permits by treating exporting LNG to certain non-FTA countries the same as exporting to FTA countries.[152] The American Gas for Allies Act, introduced in March 2023, would support expedited export approvals for NATO member countries.[153] The House recently passed a bill, the Unlocking Our Domestic LNG Potential Act, that would eliminate DOE's role in authorizing LNG exports. This has strong opposition from the Biden administration and would likely result in a veto if the Senate passed the bill.

Obtaining FERC's approval of the siting and construction of LNG facilities, which must be completed before DOE's final approval, is also challenging to project developers.[154] The lack of clarity and specificity in the regulations creates legal challenges that can add substantial delays to projects. Proponents of LNG exports have argued that FERC's approvals should be expedited. For example, the proposed Building American Energy Security Act of 2023 would establish new deadlines to review the environmental impacts of energy projects, including LNG terminals.

Other stakeholders have argued that the environmental impacts of LNG facilities should be more thoroughly reviewed. In May 2023, 44 House and Senate Democrats argued for greater scrutiny of the LNG supply chain in the U.S. Council on Environmental Quality's (CEQ) NEPA Guidance on GHG Emissions and Climate Change. The group asked the CEQ for a specific process for LNG exports, starting with the assembly of an interagency team, including DOE, the EPA, the Department of Transportation, the Department of State, and FERC, to assess the comprehensive climate and environmental justice impacts of the entire value chain of proposed LNG facilities.[155]

Obtaining a social license to operate has also been challenging for project developers. For example, a project to build an LNG export facility in South Texas has faced opposition from residents concerned about its environmental and health impacts.[156]

Another challenge to building LNG export terminals is changing market conditions. After 2015, LNG buyers demanded flexible and short-term contracts as global LNG prices stabilized. This created a predicament for LNG suppliers, which need long-term contracts for financing infrastructure buildout. Recently, however, buyers have exhibited a preference for long-term contracts. This would help LNG suppliers secure financing, but inflation and higher interest rates could pose additional challenges for project finance.

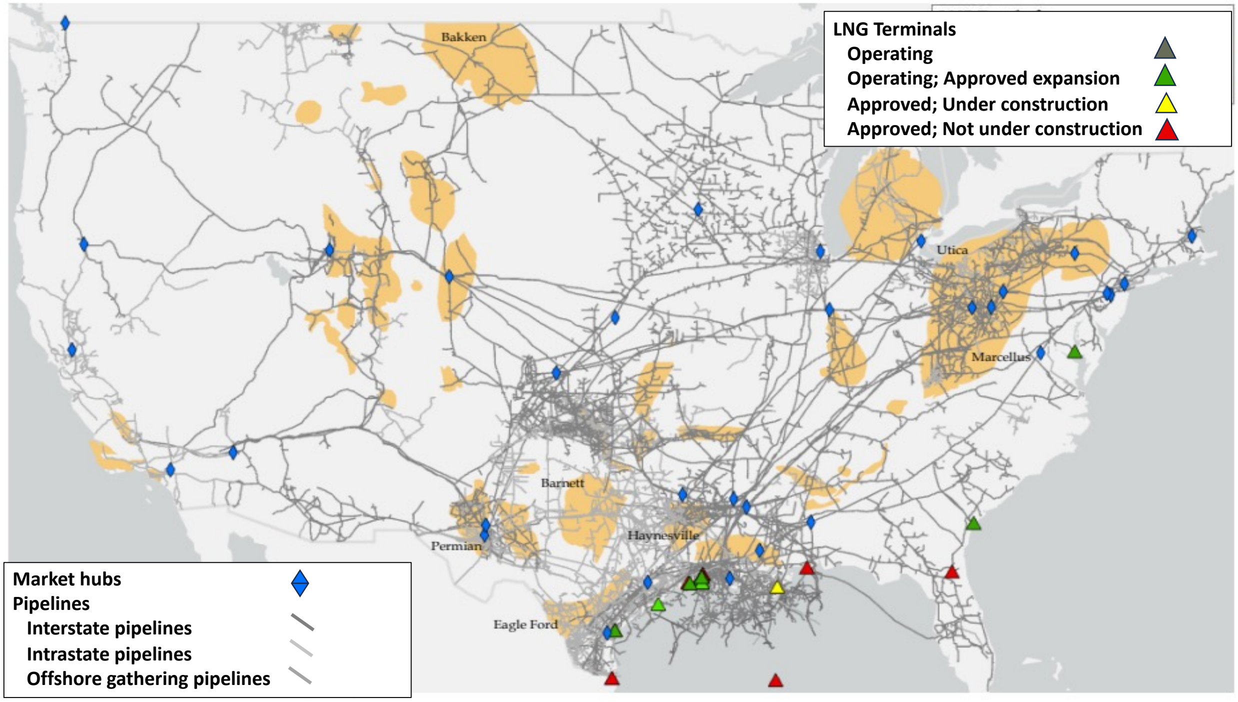
The U.S. government does not control companies, production, investment, or income, and per an expert participating in the Washington workshop, "at the end of the day, this is ultimately a market-driven direction of traffic."[157] However, some Asian consumers worry that the United States may intercede in LNG markets again, as it did with the pause in export approvals or to keep natural gas flowing to Europe in winter 2022, especially if another energy crisis emerges. Some experts suggest that in the long term, the United States should, through better forecasting of LNG flows, avoid bidding wars that could strip developing nations of their ability to import natural gas to meet energy needs.

Building Natural Gas Pipelines

Meeting domestic demand while increasing exports requires new production and transport to market centers via pipelines. If there are constraints on building new pipeline capacity from regions producing low-cost natural gas, it could reduce the competitiveness of U.S. LNG exports and the ability to meet domestic demand. There are growing concerns, however, about stranded investments and assets as the United States and other countries transition to net-zero economies.

Pipeline constraints are most notable in the Marcellus and Utica shales in the mid-Atlantic region, which are the fastest-growing sources of natural gas production in the United States (Figure 47).[158] This rapid growth in production has led to the need for additional pipelines to move supplies to other regions or to LNG liquefaction facilities. The U.S. Gulf Coast has less difficulty accommodating production growth from shales because LNG production facilities and export terminals are relatively close; however, negative natural gas prices in the Permian Basin suggest there might also be other constraints.

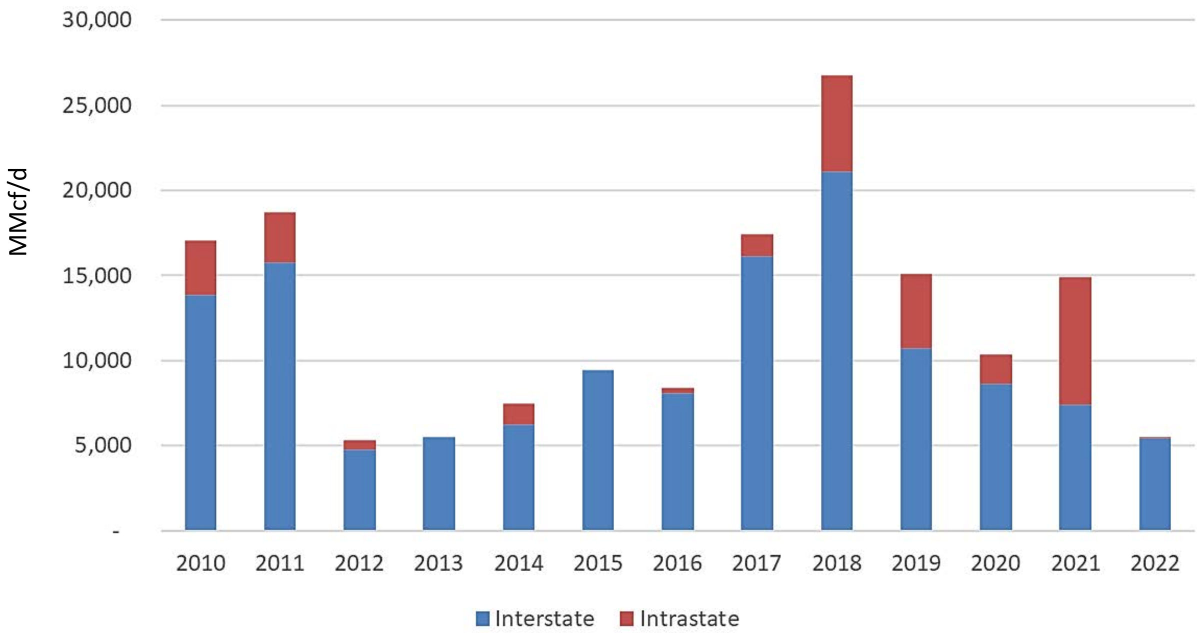
Figure 47. U.S. lower-48 pipelines, market hubs, shale plays, and operating and approved LNG export terminals



Source: Kenneth Medlock, "U.S. LNG Exports: Supply, Siting, and Bottlenecks: The U.S. Natural Gas Market in a Global Setting," January 2023, [*https://efifoundation.org/wp-content/uploads/sites/3/2023/05/White-Paper_Session-2_FINAL.pdf.*](https://efifoundation.org/wp-content/uploads/sites/3/2023/05/White-Paper_Session-2_FINAL.pdf)

The capacity of gas pipelines rapidly increased in 2017 and 2018 but has slowed since then (Figure 48).[159] In recent years, gas pipelines have faced increasing legal challenges by states, property owners, and environmental groups, often leading to the cancellation of projects. For example, the Atlantic Coast Pipeline faced protests from landowners and environmental groups concerning the project's impact on water quality. These protests and subsequent lawsuit increased the project cost to $8 billion from the initial estimate of $4.5 billion to $5 billion.[160] The project developers ended up canceling the project in 2020 because of the legal uncertainty and rising costs. In 2021, 10 gas pipeline projects were canceled, and five projects were put on hold.[161]

Figure 48. U.S. natural gas pipeline capacity additions



Source: EFI Foundation with data from EIA, "U.S. Natural Gas Pipeline Projects" spreadsheet, October 2023.

Under the Natural Gas Act, FERC has the authority to issue a Certificate of Public Convenience and Necessity (CPCN) to interstate natural gas pipeline projects, considering factors such as project need, impacts on existing customers and pipelines, environmental impacts, impacts on landowners and communities, and public benefits. According to FERC, "Section 7 of the NGA authorizes the Commission to issue certificates of public convenience and necessity for the construction and operation of facilities transporting natural gas in interstate commerce. Under section I, the Commission shall issue a certificate to any qualified applicant upon finding that the construction and operation of a proposed project 'is or will be required by the present or future public convenience and necessity.' The public convenience and necessity standard encompasses all factors bearing on the public interest."[162]

If FERC approves a CPCN, the project developer may also need to secure approvals from multiple states and other federal agencies. FERC leads the federal interagency in NEPA compliance for natural gas pipeline projects. Depending on project location and other specifics, other federal agencies that could be involved in the process include: the U.S. Army Corps of Engineers; the U.S. Forest Service; the Bureau of Land Management (BLM); the U.S. Fish and Wildlife Service; and the National Park Service. As required by the Clean Water Act and the Rivers and Harbors Appropriation Act, the project developer must receive a permit from the Army Corps of Engineers to cross streams and wetlands and discharge materials into the waters. The Clean Water Act requires the project developer to obtain a water quality certification from each state and tribal government.

Under the Mineral Leasing Act and the National Forest Management Act, the project developer must apply for a right-of-way (ROW) permit from the BLM if it builds across lands within the BLM's jurisdiction. To grant a ROW, the BLM must complete a NEPA analysis and confirm that the project complies with federal and state laws, regulations, and local ordinances. For a project crossing lands under the jurisdiction of multiple federal agencies, the BLM must receive records of decisions issued by the relevant agencies to grant a ROW. In addition, the project developer must consult with the Fish and Wildlife Service for projects that may affect threatened or endangered species under the Endangered Species Act.

To provide more clarity on FERC's permitting procedures to stakeholders, FERC issued two policy statements updating its procedures for permitting interstate natural gas pipelines in February 2022. These statements were intended to establish a new policy to provide a comprehensive analytical framework and to establish a policy for evaluating the GHG impacts of a proposed natural gas pipeline project.

In response to reactions to these statements from Congress and other stakeholders, FERC then issued an order redesignating the statements as drafts and invited additional comments in March 2022. The final policy statements are yet to be released.

CEQ's interim guidance, "National Environmental Policy Act (NEPA) Guidance on Consideration of Greenhouse Gas (GHG) Emissions and Climate Change," has implications for FERC's permitting of interstate gas pipelines and LNG terminals. The guidance could help FERC revise and finalize the policy statement on GHG emissions. For example, the guidance recommends that federal agencies quantify "reasonably foreseeable" direct and indirect GHG emissions and use additional natural gas production and consumption created by natural gas pipeline infrastructure as an example of indirect emissions. The guidance also provides recommendations that FERC can act on to better address environmental justice concerns as part of the NEPA NEPA process.

LNG Infrastructure Financing Challenges

The conflict between increasing short-term demand and declining long-term demand for LNG raises concerns about potential stranded assets. As was highlighted earlier in Figure 24 as of 2022, Europe's LNG import infrastructure capacity in operation is 175 MMtpa, and the capacity is expected to increase to 206 MMtpa if the entire capacity under construction is added. Since this total capacity far exceeds the projected LNG demand in 2030 and 2050, there could be a substantial amount of stranded assets in Europe.

Some governments are reluctant to permit 20- to 40-year projects because their climate ambitions require a decrease in fossil fuel consumption, not the addition of capacity. To balance these climate ambitions with short-term energy security needs, an expert suggested that "we need 20-year projects, given the capital intensity of liquefaction and capital intensity of regasification."

Traditional timelines for financing infrastructure projects that require large amounts of capital do not meet today's energy security and decarbonization needs; this discrepancy poses a challenge for both the natural gas industry and governments.

Some governments are reluctant to permit 20- to 40-year projects because their climate ambitions require a decrease in fossil fuel consumption, not the addition of capacity. To balance these climate ambitions with short-term energy security needs, an expert suggested that “we need 20-year projects, given the capital intensity of liquefaction and capital intensity of regasification.”[163] Natural gas infrastructure projects are capital-intensive and require operations that span a project’s useful life to ensure investor confidence in returns.[164]

Some have argued that the United States should support long-term natural gas projects to meet global demand and ensure that projects remain friendly for investors. One expert noted that “we need more infrastructure here in the United States, because it’s good globally,” alluding to the fact that fuel switching from coal to natural gas could decrease carbon dioxide emissions and support both global decarbonization and energy security goals.[165]

However, local opposition from environmental and other groups who have concerns about meeting domestic supply either prevents infrastructure from being built or increases the cost of infrastructure due to higher risks and even long timelines to get to final investment decisions. Ironically, the lack of infrastructure and associated permitting can actually diminish options for meeting environmental goals because projects cannot be built to address venting and flaring of natural gas, which amounted to over 286 Bcf in 2021.[166]

One expert said, “The cost of capital that is raised for the pipeline industry is just going to keep driving up the cost of the infrastructure that could reduce the amount of flaring that’s going on here in the United States.”[167] The passage of the IRA creates incentives for investment flows to come back to the United States for energy projects, but it is important to ensure that projects from a diverse range of energy sources are built.

Financing LNG infrastructure in foreign markets is challenging due to investor uncertainty and insufficient funding mechanisms. Integrated projects can be difficult in emerging markets because, unlike the relationships that can form between a seller and a utility in advanced markets, emerging markets do not have reliable partners “to get capital formation and get capital returned in that 20-year horizon that is necessary to get a project underway.”[168] Regardless of the maturity of a nation’s economy, “the [global] financial sectors are very cautious about financing natural gas projects because future demand is uncertain.”[169]

For the emerging markets, one solution for financing may be through multilateral development banks (MDBs). Most MDBs have limited the financing for oil and gas projects since 2021 when the United States called on MDBs to end international financing of carbon-intensive fossil fuel-based energy and support investments that prioritize clean energy, innovation, and energy efficiency, to achieve a clean and sustainable future that is consistent with member countries’ development goals and the goals of the Paris Agreement.[170]

Specifically, the United States issued guidance stating that it would oppose new coal-based projects and oil projects (with some exceptions), narrow support for natural gas projects (i.e., oppose upstream and support only midstream and downstream natural gas projects if certain criteria are met), and remain open to support CCUS and methane abatement projects. Many MDBs, including the European Investment Bank (EIB), European Bank for Reconstruction and Development (EBRD), World Bank Group, Inter-American Development Bank, Asian Development

Bank (ADB), and African Development Bank, have created or are creating policies to stop financing upstream natural gas projects (Table 2).[171] Some MDBs, however, remain open to financing midstream and downstream projects; only EIB and EBRD have committed to ending financing for midstream and downstream projects.

Table 2. MDB policies and commitments to ending support to natural gas

		Ending natural gas midstream and downstream		
		Policy or strategic framework	Commitment	No commitment
Ending natural gas upstream	Policy or strategic framework	European Investment Bank		Inter-American Development Bank, World Bank Group, Asian Development Bank, African Development Bank
	Commitment		European Bank for Reconstruction and Development	
	No commitment			Asian Infrastructure Investment Bank,* New Development Bank

An asterisk (*) indicates that an MDB is currently reviewing or updating its policy. Source: Cecilia Springer et al., "Who Funds Overseas Gas Projects?" Boston University Global Development Policy Center, June 2022, [*https://www.bu.edu/gdp/files/2022/06/GEGI_PB_020_EN.pdf.*](https://www.bu.edu/gdp/files/2022/06/GEGI_PB_020_EN.pdf)

Some MDBs do not rule out support for midstream and downstream natural gas projects, recognizing the role of natural gas in the energy transition. The World Bank Group has stated support for natural gas as a "flexible energy source that can help countries make the transition more quickly to renewables, expand access to energy for the poor, and displace carbon-intensive coal."[172] However, some MDBs offer limited and conditional support because of the concerns about environmental impacts. For example, the ADB announced that it will be "selective in its support for midstream and downstream natural gas initiatives" and will finance natural gas projects "subject to strict criteria," recognizing the role of natural gas as a transitional fuel.[173]

Although investors and regulators were concerned about the risks of building infrastructure, one expert at the U.S. workshop suggested that "the [oil and gas] industry is pretty well capitalized and pretty capable" of financing natural gas projects and is willing to take on the potential risk of stranded assets.[174] Rather, the risk of building infrastructure was attributed to the permitting issues and uncertainty. Because the industry is so constrained by permitting requirements, financiers don't have anywhere to spend available pools of capital.

Another expert at the same workshop disagreed and pointed out that "there is enough U.S. government support to build additional infrastructure, but the U.S. government is not going to supply the [final investment decisions] or contracts. … That's the industry's job."[175] This statement suggests that the financial sector is indeed the missing link for getting projects built, likely due to the riskiness of stranded assets in the context of global energy transitions. Numerous experts shared the sentiment that the industry faces barriers to infrastructure development because of community opposition, which often imposes higher costs, longer timelines, and greater risks for projects.

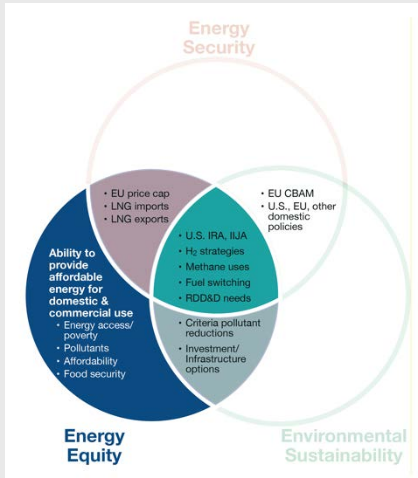
Energy security associated with natural gas, the first of the three competing priorities of the energy trilemma, has been greatly affected by the war in Ukraine as seen by the ability of countries and regions to reliably meet current and future energy demand. This chapter considered the risks and uncertainties in the global demand for natural gas, focusing on energy security issues in Europe and Asia. Given the disparity between developing and developed countries within the regions, how these two large natural-gas-consuming regions develop and decarbonize creates uncertainties in the trajectory of global natural gas markets.

As is demonstrated by the analysis, energy security is paramount to many countries but must be considered in the context of the complicated geopolitical, socioeconomic, and environmental issues in these regions and globally.

3. Energy Equity

Findings in Brief

- Rising global energy demand, driven by population growth and economic development, highlights the importance of abundant, affordable, and clean energy sources that are available to all nations, including developing countries.
    - A continuous growth of global primary energy consumption is expected for the long term, especially in emerging markets and developing countries.
    - Emerging markets and developing economies account for over two-thirds of global growth in electricity demand in IEA's scenarios.



- Population in the Asia-Pacific region is projected to increase by almost half a billion in the next 26 years and account for 25% of the total increase in global population. Population increases in the developing parts of Asia will require significant amounts of energy and electricity to support economic and social development.
- In addition to meeting rising energy demands, developing countries face other energy-related development challenges, such as providing universal electricity and energy access, reducing air pollution, or establishing infrastructure in urban areas. In 2022, the number of people without access to electricity reached 760 million worldwide, the first increase in decades.
- Affordability of clean energy sources is critical for developing countries to choose cleaner energy sources over coal to meet growing energy demands.
- While climate change raises existential concerns, air pollution and air quality are also significant issues, affecting health and quality of life, especially in regions and countries that lack air quality standards. It is estimated that long-term exposure to particulate matter (P.M. 2.5) was responsible for 4.1 million deaths worldwide in 2019.
- Natural gas has numerous attributes that could help improve energy equity. These include providing reliable power generation and backup generation for intermittent renewables; supporting cleaner air relative to coal; industrialization; lower CO_2 emissions than other fossil fuels, important for power generation, heat, and industry; and the potential for access to global markets and the associated economic benefits.

- The recent energy crisis has posed challenges to energy equity worldwide as it increased natural gas prices and brought significant market volatility.
    - Europe's reductions of Russian natural gas negatively impacted European consumers; Europe spent 400 billion euros more on natural gas imports in 2022 than in 2021, a 300% increase.
    - Developing countries are affected more severely by changes in international energy trade flows and price fluctuations as many are more reliant on energy imports. Liquefied natural gas (LNG) volumes not under long-term contracts are more often tied to spot market prices, exposing those consumers/importers in these countries to price/market fluctuations.
    - High LNG prices in Asian spot markets reduced demand for LNG in price-sensitive parts of Asia in 2022. Asian LNG demand decreased to 250 million tons in 2022 from 270 million tons in 2021.
- India and other developing Asian countries are likely to use more coal to meet their rapidly growing energy demand due to its affordability and availability.
- The increase of U.S. LNG exports to Europe after the Russian invasion of Ukraine in 2022 had unanticipated consequences in Asia. Reducing gas availability to Asian countries meant increased emissions from coal, higher prices for industrial uses of natural gas, and increased energy security concerns for energy import-dependent nations in Asia.
- Energy equity must be considered in the context of energy security and environmental sustainability where overlapping issues (e.g., LNG prices and affordability, pollutant reductions, and coal-to-gas fuel switching) must be considered in the larger context.

For purposes of this analysis, energy equity includes access to energy including clean energy, energy affordability, and food security. This chapter briefly discusses all aspects of energy equity with a specific focus on affordability as it relates directly to access to energy in developing nations. Most recently, energy equity issues were raised by Russia's invasion of Ukraine.

The invasion created a fundamental shift in natural gas markets and the associated trade flows. The war in Ukraine has greatly complicated the global energy security, affordability, and decarbonization landscape, forcing the nations of the world to simultaneously consider each of these imperatives in their policy responses to the crisis. Reduced Russian gas flows to Europe contributed to record high natural gas prices in Europe and to Asian spot prices for LNG in the third quarter of 2022. Related to this, natural gas prices in the United States last summer reached their highest levels since 2008. The invasion of Ukraine, subsequent sanctions on Russian energy exports, and the ensuing energy security challenges in Europe and Asia have caused high energy price volatility, which limited active market participants.[176] The recent decline in natural gas prices underscores the issue of volatility in natural gas markets with a range of implications for future supply and demand.

The increase in prices has also had global impacts on energy equity. The ability of consumers to purchase affordable energy is directly affected by a change in energy flows. Developing countries typically lack the financial capability to secure long-term contracts and thus are disproportionately affected by energy flow changes and price fluctuations as they are more heavily reliant on energy imports tied to the spot market. Since the war in Ukraine began, wealthier countries have been able to afford higher-priced natural gas supplies to make up for a loss of Russian supplies; developing countries were forced to use locally produced alternatives or less expensive energy imports despite the environmental concerns.

From a wider perspective, rising global energy demand, driven by population growth and economic development, highlights the importance of abundant, affordable, and clean energy sources globally. Population in the Asia-Pacific region is projected to increase by almost half a billion in the next 26 years and account for 25% of the total increase in global population. Population increases in the developing parts of Asia will require significant amounts of energy and electricity to support economic and social development. The International Energy Agency (IEA) projects that over two-thirds of the global growth in electricity demand will come from emerging markets in all World Energy Outlook (WEO) 2023 scenarios.[177] In addition to meeting rising energy demands, developing countries face other energy-related development challenges, such as providing universal electricity and energy access, reducing air pollution, and building infrastructure. In 2022, the number of people without access to electricity reached 775 million worldwide, the first increase in decades.[178]

The Importance of Energy Equity

To understand the range of energy equity issues, it is important to understand some of the trends and issues that affect the regions that are the focus of this analysis. These include energy demand growth, air quality, energy access, and energy poverty (affordability).

As noted, high-income LNG-importing countries in Europe and Asia were able to absorb the shock of high energy prices after Russia's invasion of Ukraine, but in many countries, especially developing nations, affordability was and is a significant issue. Energy prices are important for economic stability and growth, but emerging markets and developing countries are the most vulnerable to increased energy prices. High and volatile prices of natural gas are a critical challenge for LNG importing countries, especially for developing nations. Comments from a July 2022 World Bank communication on energy market developments underscore the impacts of global instability and the associated market disruptions. It noted that:

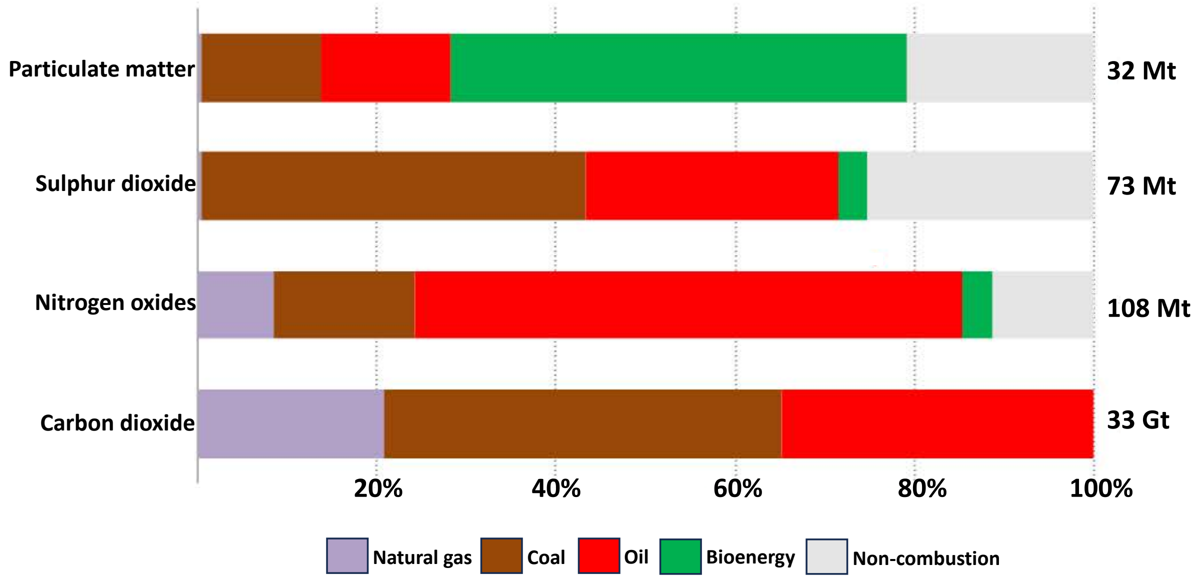
> *The recent surge in natural gas and coal prices has been so swift that the main benchmarks were roughly three times higher in 2022 Q2 compared to a year earlier. European natural gas and South African coal prices reached all-time highs in March and April, while U.S. natural gas prices reached their highest level since 2008. The surge in prices partly reflects the impact of the Russian invasion of Ukraine; in 2020, Russia accounted for one-quarter of global exports of natural gas and just under one-fifth of coal exports. Beyond the impact of the war, demand for natural gas and coal has been robust, rising by about 5% and 6% respectively in 2021 amid a strong post-pandemic recovery, with both reaching record highs. ... Because the coal (and natural gas) shortages have persisted, additional policy measures were introduced earlier this year. India, for example, announced plans to reopen 100 coal mines that had previously been considered uneconomic.*[179]

Given that energy demand has risen rapidly to support economic development, securing abundant and affordable energy supplies is a priority for developing countries. If natural gas prices are higher and more volatile than coal prices, for example, developing countries will have little motivation for building new natural gas power generation plants or implementing coal-to-gas fuel switching at existing generation facilities, and for high-heat industrial uses. Moreover, as building new LNG import infrastructure is capital intensive, developing countries with less developed capital markets may struggle with securing sufficient financing for the infrastructure needed for regasification, particularly in those with strict net-zero targets.

Air Quality

In the face of growing populations, higher or rising prices, developing countries tend to choose affordable energy sources such as coal and biofuels over lower carbon intensity options such as natural gas and renewables. This has had negative impacts on decarbonization efforts, particularly in Southeast Asia. In addition to carbon intensity concerns, emissions from coal, oil, and biofuels are much larger contributors to air quality problems. Figure 49 shows the contributions of natural gas to selected energy-related air pollutants, relative to oil, coal, and bioenergy.[180]

Figure 49. Share of natural gas in total energy-related emissions of selected air pollutants, including CO_2



Note: Non-combustion emissions are process emissions in industry and non-exhaust emissions in transport.
Source: IEA, The Role of Gas in Today's Energy Transitions, July 2019, https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions.

While climate change raises existential concerns, air pollution and air quality are also significant issues, affecting health and quality of life, especially in regions and countries that lack air quality standards. The relative emissions from fuels as shown in Figure 55 raise significant equity issues and concerns in this regard and underscore the value of natural gas in the context of air quality. It is estimated, for example, that long-term exposure to P.M. 2.5 was responsible for 4.1 million deaths worldwide in 2019.[181]

According to the World Bank, 37 of the 40 most polluted cities in the world are in South Asia, and 60% of the region's population lives in areas with significant pollution where "concentrations of particulate matter surpass even the most lenient air quality guidelines established by the World Health Organization (WHO). … This leads to an estimated two million premature deaths annually."[182] Also, 2.3 billion people, largely in sub-Saharan Africa and Asia, use solid biomass, kerosene, or coal as cooking fuels, which has resulted in 3.7 million premature deaths.[183]

In several reports, the UN spotlights how gender inequality and climate change are connected, thereby putting women and children at greater risk of chronic diseases, and in situations that escalate social, political, and economic tensions in fragile and conflict- affected settings.[184,185]

As shown in Figure 49, natural gas combustion emits no particulates and emits significantly lower SOx and NOx (and CO_2) than other fuels. Increased use of natural gas in lieu of coal, oil, and bioenergy, for both power generation and cooking, could not only address the need for deep decarbonization, but also improve air quality in the region, reduce household exposure to pollution from cooking fuels, and lower the associated premature deaths for both.

Energy Access

Energy poverty, in the context of this analysis, refers to the lack of access to modern energy services, including electricity. In 2022, the number of people who lived without electricity reached nearly 775 million.[186] The World Bank cites progress in electricity access in Asia, saying, "The number of people without electricity access plummeted in Central and Southern Asia, falling from 414 million in 2010 to 24 million in 2021, with much of the improvement occurring in Bangladesh, India, and other populous countries. The number without access to electricity in Eastern and Southeastern Asia declined from 90 million to 35 million during the same period. In Northern Africa and Western Asia, the unserved population decreased less markedly—falling from 37 million in 2010 to 30 million in 2021."[187]

Despite continued disruptions in economic activity and supply chains, renewable energy was the only energy source to grow through the pandemic. However, these positive global and regional trends in renewable energy have left behind many of the countries most in need of electricity.[188] This has resulted in an access gap to electricity that has grown across multiple regions. According to the IEA, "The 20 countries with the least access to electricity are home to 76% of the global population left in the dark. Nearly 90 million people in Asia and Africa who had previously gained access to electricity, can no longer afford to pay for their basic energy needs."[189] In developing countries, energy poverty is a critical issue for not only the well-being of the population but also economic growth. According to the Center for Strategic and International Studies (CSIS), "Energy poverty undermines efforts to advance socioeconomic development. Research shows that it negatively impacts economic growth, educational enrollment, health outcomes, life expectancy, and access to water, sanitation, and hygiene services."[190]

Figure 50 shows the percentage of total and rural populations in Asian countries with access to electricity and with net-zero commitments.[191,192] As can be seen in the figure, most countries in Asia have 100% access to electricity, with some notable exceptions.

Figure 50. Percentages of total and rural populations in Asia with access to electricity and countries with net-zero commitments

Percentages of total and rural populations with access to electricity are in the most recent and available year by country, which was mostly 2021. Source: EFI Foundation with data from The World Bank, World Bank Open Data, [https://data.worldbank.org,](https://data.worldbank.org) and Net Zero Tracker, Data Explorer, [https://zerotracker.net/#data-explorer.](https://zerotracker.net/#data-explorer)

In Southeast Asia, energy poverty directly impacts rapidly growing populations and economies. Growing populations will also mean increased electrification and energy needs to support the associated industrial development. Efforts to address energy poverty and decarbonization involve not only providing access to clean energy but also encouraging industries to adopt more sustainable practices. However, many developing countries lack the infrastructure, financing, and overall distributed energy systems required for renewables and other low-emissions technologies to proliferate. Natural gas can play a pivotal role in helping developing countries transition to a low-carbon society while also allowing for socioeconomic growth.

- In addition to analyzing electricity costs, the World Bank, the IEA, the UN Statistics Division, WHO, and the International Renewable Energy Agency (IRENA), in their *Energy Progress Report 2023,* concluded that 2.3 billion people, largely in sub-Saharan Africa and Asia, use solid biomass, kerosene, or coal as cooking fuels, which has resulted in 3.7 million premature deaths.[193] This analysis noted, "This continues to put household members, particularly women and children, at greater risk of chronic diseases, while also contributing to climate change, perpetuating gender inequity, and compromising actions for sustainable development." Replacing these cooking fuels with natural gas is an area where natural gas could make a major contribution to global health.

Energy Affordability

Rising energy prices directly affect a country's ability to provide energy for citizens and industries. Elevated prices negatively affect price-sensitive buyers, specifically buyers in developing countries. When prices are high, many developed countries will look for cheaper but higher emissions-based fuels, such as coal. These high prices have resulted in many countries and regions focusing on affordable energy sources instead of on low-carbon fuels and decarbonization strategies.

The cost of electricity by generation type is critical to providing affordable access to electricity. It is also an important consideration for replacing existing power generation, either because of age of a power plant or to meet national/regional climate targets or objectives (see Figures 15 and 16 for countries focused on in this analysis with goals or climate targets). Table 3 shows the levelized costs of generation and storage by $/MWh (megawatt-hour) for the range of generation technology options entering service in the United States in 2027.[194] Onshore wind, solar photovoltaic, geothermal, and natural gas combined cycle generation provide the lowest levelized costs of electricity, which are very important for the developing world, industrial competitiveness, and climate change mitigation.

Table 3. Levelized cost of electricity and storage for plants entering service in 2027

Levelized cost of electricity (LCOE) and storage (LCOS) for plants entering service in 2027	Capacity factor	Levelized capital cost	Total system LCOE or LCOS (2020 $/MWh)
DISPATCHABLE			
Natural gas combined cycle	**87%**	**$9.36**	**$39.94**
Advanced nuclear	**90%**	**$60.71**	**$88.24**
Geothermal	**90%**	**$22.04**	**$39.82**
USC coal	**85%**	**$52.11**	**$82.61**
RESOURCE CONSTRAINED TECHNOLOGIES			
Offshore wind	**44%**	**$103.77**	**$136.51**
Onshore wind	**41%**	**$29.90**	**$40.23**
Solar stand-alone	**29%**	**$26.60**	**$36.49**
Hydroelectric	**54%**	**$46.48**	**$64.27**
CAPACITY RESOURCE TECHNOLOGIES			
Battery storage	**10%**	**$64.03**	**$128.55**
Combustion turbine	**10%**	**$53.78**	**$117.86**

Source: EFI Foundation with data from EIA, Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022, March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

Several issues should be considered, however, when looking at the data in Table 3. Hydropower, geothermal, and offshore wind, while emissions free, are generally location specific and expensive compared with other options. Also, offshore wind and nuclear, while zero-emitting generation technologies, have costs per MWh that are, respectively, 3.4 and 2.5 times more expensive than natural gas combined cycles.

In addition, capacity factors in the table are important for the actual MW of generation that must be built compared with the MWh of electricity generated. Natural gas combined cycles entering service in 2027, for example, will have a capacity factor of 87% compared with onshore wind with a capacity factor of 41%.[195] This means that a 250 MW natural gas combined cycle plant would provide 217 MWh of electricity compared with 102.5 MWh from an onshore wind generation plant.

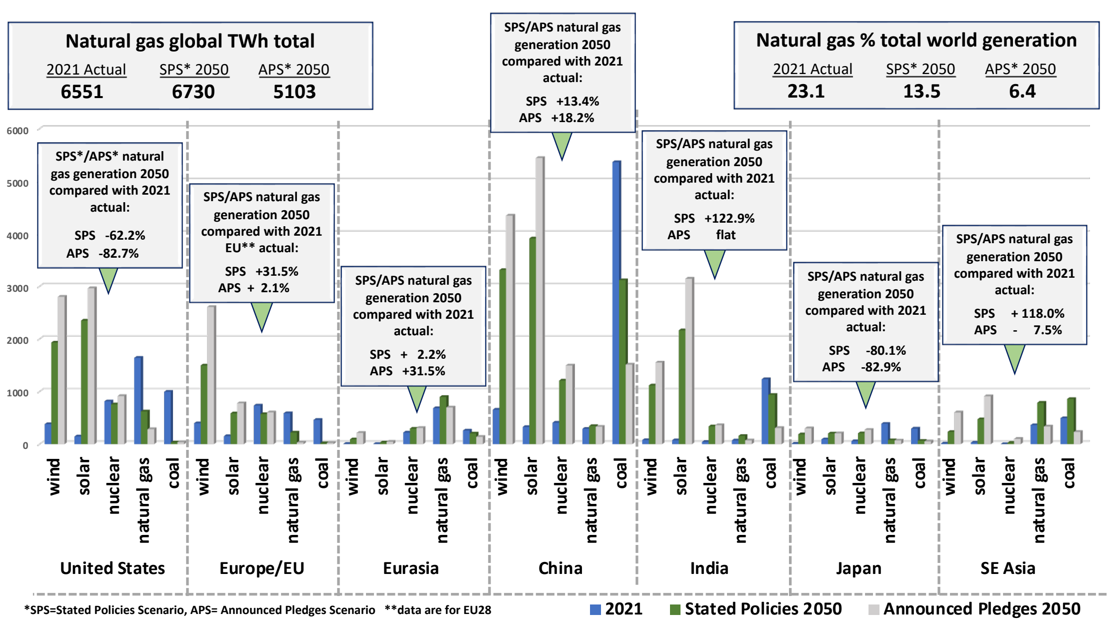
Finally, data in Table 3 shows the costs of battery storage that would be needed for wind and solar with a total LCOS system cost of $128.55/MWh (note that EIA analysis this year shows it to be approximately $124/MWh, but the data was incomplete for all generation technologies); these costs need to be added to the LCOE for intermittent renewables. Analysis by EFI and Stanford University showed that California had 90 days with little to no wind in 2017, sometimes for 10 days in a row.196 The duration of battery storage is currently around four hours, although the DOE Long Duration Storage Shot Initiative, part of its Energy Earth Shots Initiative, has a target of 10 hours, and technologies are in the development/deployment stage for batteries with storage as long as 100 hours.

Also, this data does not show the cost of CCUS needed to capture the carbon from fossil fuel generation. According to the U.S. Energy Information Administration (EIA), a natural gas combined cycle unit with 90% CCUS entering service this year has a cost of $2,845/kW. Onshore wind entering service this year has an overnight cost of $1,718/kW, substantially lower than the NGCC costs. Onshore wind, however, needs battery storage, the cost of which, according to EIA, is $1,316 per kW,197 and, as noted, current battery storage options provide about four hours of backup.

The cost of electricity is more critical in the developing world since many developing countries lack the funds for an energy transition and the new infrastructure required to deploy renewable or natural gas generation technologies. Less developed countries, when faced with costlier alternatives, may continue to use or expand coal generation, particularly in countries like India that have abundant coal resources. Higher prices and lack of infrastructure and resources could cause some countries to use cheaper but higher-emitting energy sources such as coal. When considering power generation and the phaseout of coal, replacing that generation with renewables or other low-emissions energy sources can leave gaps for developing nations that lack the infrastructure or ability to procure these at economically reasonable rates.

As shown in Figure 51, in IEA's Stated Policies Scenario (STEPS), there is a decline in natural gas power generation globally in 2050, but the natural gas demand for power generation is still substantial.[198] Natural gas power generation would increase in Eurasia, China, India, and Southeast Asia under the STEPS by 2050. Europe, Eurasia, and China show increasing demand for natural gas power generation even under the Announced Pledges Scenario (APS). The IEA's Q1-2024 gas market report also sees increased demand for gas, noting that "Natural gas markets are expected to see a return to strong growth in 2024, primarily driven by the industrial and power sectors in fast-growing economies in Asia and gas-rich countries in Africa and the Middle East."

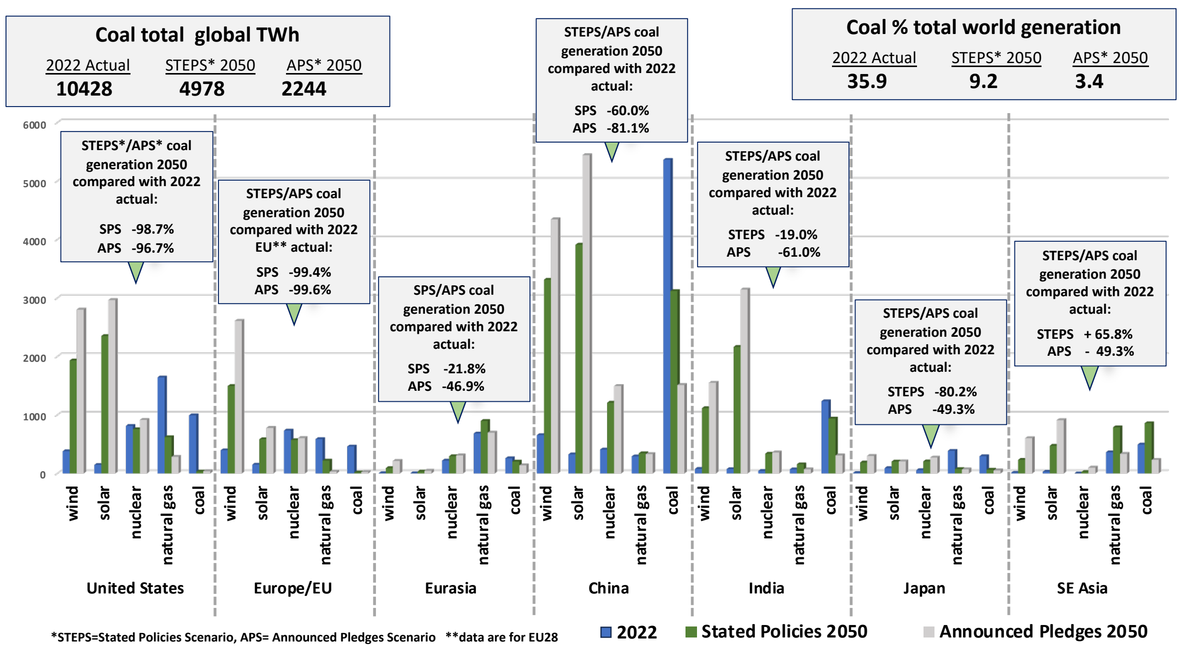
Figure 51. Natural gas generation by country/region relative to other fuels: 2021 actuals compared with 2050 IEA Stated Policies, Announced Pledges scenarios (TWh)



Source: EFI Foundation with data from IEA, World Energy Outlook 2023, October 2023, [https://www.iea.org/reports/world-energy-outlook-2023.](https://www.iea.org/reports/world-energy-outlook-2023)

In Figure 52, from the STEPS scenario, coal generation is decreasing in all regions except for Southeast Asia.[199] When considering a switch from coal to gas, emissions go down even with an increase in overall natural gas generation. During this switch, developing nations are at risk due to the prevalence of more developed countries taking excess supplies off the market during times of crisis or high prices. This purchase of excess supply perpetuates the issues associated with energy poverty, and these issues are predominantly felt in developing nations.

Figure 52. Coal generation by country/region relative to other fuels: 2021 actuals compared with 2050 IEA Stated Policies, Announced Pledges scenarios (TWh)



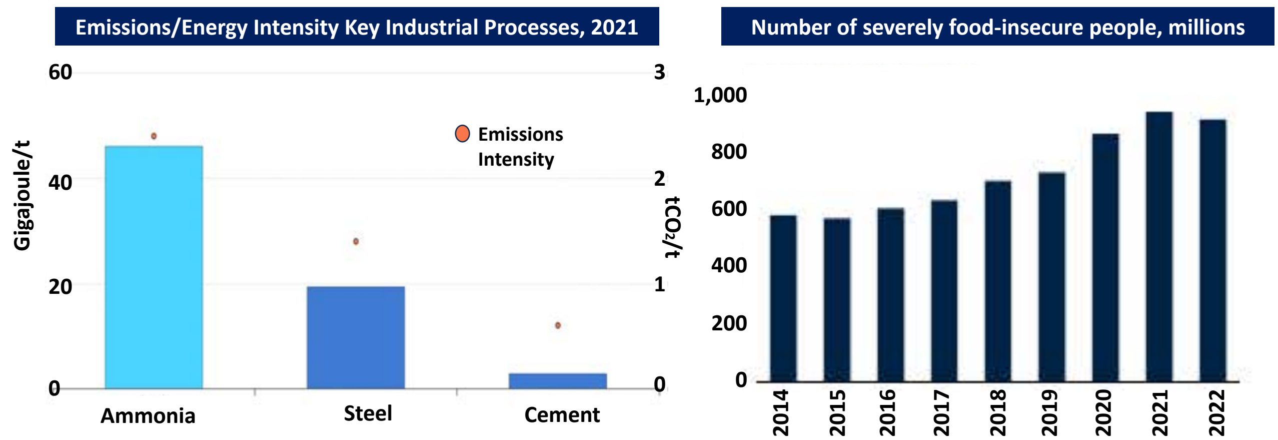
Source: EFI Foundation with data from IEA, World Energy Outlook 2023, October 2023, https://www.iea.org/reports/world-energy-outlook-2023.

While both the STEPS and APS scenarios show significant declines in coal generation, the story on the ground is different. In 2023, 69,545 MW of new coal generation was added globally; 68% of that is in China alone. As of January 2024, Asia had 193,654 MW of coal generation under construction; of that total, 142,244 MW was in Eastern Asia and almost 36,000 MW was in Southern Asia.[200]

Food Security

A final issue important to energy equity is food security. According to the IEA, about 70% of ammonia is made from natural gas, via steam reforming; most of the rest is made via coal gasification.[201] Around 70% of ammonia is used for fertilizers, and natural gas is a key ingredient in ammonia. Figure 53 shows IEA data on the emissions and energy intensity of ammonia relative to other industrial processes.[202,203] The IEA analysis concludes that there are 2.4 tons of CO_2 per ton of ammonia, compared with 1.4 tons for steel and 0.6 ton for cement.

Figure 53. Emissions intensity of ammonia production 2021; global number of food-insecure people, 2022



Sources: IEA, Ammonia Technology Roadmap, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap; World Bank, Commodity Markets Outlook: Under the Shadow of Geopolitical Risks, October 2023, https://openknowledge.worldbank.org/entities/publication/0e4e7e1e-6db9-4011-b179-806d28aa0b91?cid=pub_fb_wbpublications_en_ext.

As shown in Figure 53, more than 800 million people faced food insecurity in 2022, up from less than 600 million in 2014.[204] Natural gas is currently essential for ammonia production, ammonia is critical for fertilizer, and fertilizer is necessary for increasing food security until new, affordable options are developed. Reducing CO_2 emissions from ammonia production is essential for both climate change mitigation and food security. Developing and deploying affordable technologies to reduce these emissions is critical for both.

The Contributions of Natural Gas to Energy Equity

Natural gas has numerous attributes that could help improve energy equity. These include providing reliable power generation and affordable backup generation for intermittent renewables; supporting cleaner air relative to coal; and emitting less CO_2 than other fossil fuels, important for power generation, heat, and industry access to global markets and the associated economic benefits. In the United States, natural gas generation has been supporting and complementing intermittent renewables, enabling reliable and clean energy, essential components of energy equity, and the ability to meet midcentury emissions reduction targets.

To enable these benefits, construction and development of natural gas facilities and associated infrastructure are needed. In countries that lack a stable grid network to use renewables, natural gas can be used to support high energy-consuming industries and at times of high residential demand, which can result in blackouts when grid capacity is overloaded or unavailable. Additionally, investing in and building natural gas infrastructure (LNG terminals, storage facilities, pipelines, and distribution networks) can create local jobs, thereby stimulating economic development and growth, which can alleviate poverty.

The development of natural gas infrastructure also supports access to global markets by supporting the flow of goods. This access can allow developing countries to diversify their energy sources and reduce dependence on a single energy supplier. This can enhance energy security and stability as well as give countries more options based on prices.[205] Energy prices are important for economic stability and growth, but emerging and developing countries are the most vulnerable to increased energy prices. With the recent spike in energy prices, the hardest-hit nations include oil-importing countries in Africa, Asia, and Latin America because of higher import prices and weaker currencies.[206]

Natural gas can also replace more polluting cooking fuels. As of 2020, 2.8 billion people still cook with higher-polluting fuels, costing the world more than $2.4 trillion each year due to negative impacts on human health and the environment.[207] This challenge hit the poor communities, especially women and children, the hardest.[208]

Switching from coal to gas can also contribute to significant reductions in air pollutants. Reducing air pollutants contributes to lowering health risks of nearby communities and increasing crop yields. The negative impacts of air pollutants on crop yields have been demonstrated by a growing number of studies.[209] For example, in the United States, analysis suggests that decommissioning coal-fired power plants saved about 22,563 lives and increased corn production by 329 million bushels in nearby communities by reducing pollution from 2005 to 2016.[210] In the cities that implemented a coal-to-gas switching policy in China, on average, SO_2 and P.M. 2.5 dropped by 5.9% and 1.2% per year, respectively.[211]

People living near coal-fired power plants have higher rates of all-cause and premature mortality; increased risk of respiratory disease, lung cancer, and cardiovascular disease; higher infant mortality; and poorer child health.

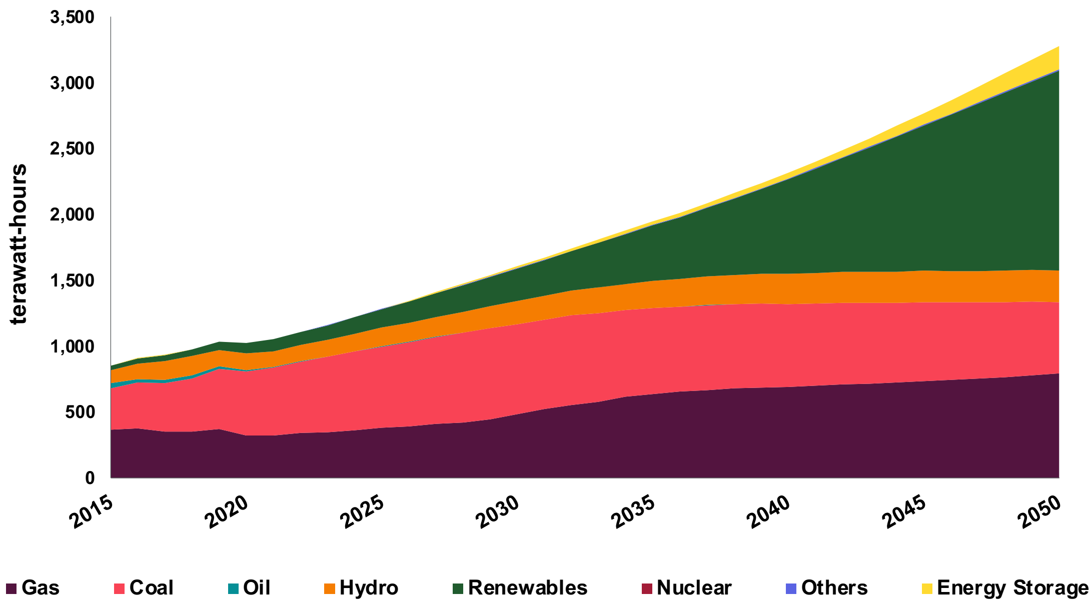
A review of 113 peer-reviewed studies spanning 30 years identified that people living near coal-fired power plants have higher rates of all-cause and premature mortality; increased risk of respiratory disease, lung cancer, and cardiovascular disease; higher infant mortality; and poorer child health.[212] However, the study notes that the specific components associated with exposure to toxic elements of coal combustion are still not fully known, as different countries use unique coal resources. As another study noted, "Each global localization has distinct coal composition according to peat depositional environments. For example, Indian and Chinese coal-fired power plants release high mercury (Hg) content into the atmosphere; in addition, the negligence of Sulfur Dioxide (SO2) and Nitrogen oxides (NOx) control makes India one of the main countries responsible for global coal combustion health impacts."[213]

As noted above, the health implications of closing or converting coal plants to gas in the United States have been extremely positive. Some coal-to-gas fuel switching is taking place in Asia. A total of 6,656 MW of coal-to-gas plant conversions are in development, with 1,835 MW under construction, 1725 MW in the preconstruction phase and 3,096 MW announced for conversion.[214] While this is an extremely small percentage of coal generation, additional policy support and data indicate the potential for switching. Such information could be very valuable for policymakers in the region who are focused on both environmental targets and equity needs, and for investors that would benefit from clear policy direction.

Southeast Asia's Evolving Energy Landscape

An examination of Southeast Asia's evolving energy landscape provides specific examples of how natural gas development can be integrated into the economic development of a country even while transitioning to a low-carbon economy. Southeast Asia appears to be more sensitive to price and reliability of supply when it comes to how countries in the region are affected by rapid economic and population growth. Southeast Asia has seen rapid economic and population growth, which has, in turn, significantly increased energy demand in the region (Figure 54).[215] From 2000 to 2020, energy demand in the region almost doubled, natural gas consumption increased by over 80%, and the region maintained around a 20% share of the total Asian energy mix over that period.[216]

Figure 54. Electricity demand in Southeast Asia, 2015 to 2050



Source: Wood Mackenzie, Global Gas: Asian Market Report, March 2023.

Despite ambitious decarbonization goals, coal is expected to be a crucial energy source for Vietnam. Forecasts suggest, for example, that coal will still account for 20% of Vietnam's energy consumption in 2030, albeit a decrease from 31% in 2020.[217] Natural gas, largely in the form of LNG, will grow in importance in Vietnam as a means of decreasing carbon emissions from coal. LNG imports, including regasification infrastructure in Vietnam, can fill an important role as baseload fuel while supporting industrial expansion and phasing out coal. If Vietnam can switch a portion of its coal use to LNG while addressing the challenges with its electricity grid infrastructure, it could help balance its decarbonization and economic development to be one of success rather than stagnation and slow, incremental progress. However, LNG has significant financial and physical bottlenecks to overcome to be successful in Vietnam, as foreign direct investment there is focused more on renewable energy projects.[218]

Indonesia is phasing out coal and replacing it with renewables; at the same time, it is expanding consumption of natural gas.[219] With the growth in domestic consumption of natural gas, Indonesia will change from a net exporter to a net importer of LNG while adding more renewable energy sources to its energy mix. Indonesia will also continue to build out a domestic mining industry as well as infrastructure for processing nickel. This growth in energy-intensive mining and processing of nickel—a critical metal for electric vehicles, for example—is likely to increase the demand for both coal and natural gas.

In countries like Indonesia and Vietnam, coal use for power generation is still significantly higher than natural gas generation. Natural gas can play an important role in enabling decarbonization in Southeast Asian countries by switching from coal to natural gas with the associated air quality and climate benefits, as well as meeting the rising energy demands of growing populations and economies.

As the region's energy portfolio evolves, supporting economic growth of respective industrial and manufacturing sectors, while also making the necessary infrastructure changes to support decarbonization, will be dependent on affordable and reliable sources of energy. In this regard, the buildout of natural gas infrastructure is important. In Southeast Asia, as of December 2023, the region had 9,936 kilometers of natural gas pipelines either proposed or under construction, with 1,087 kilometers of that total under construction. This network would significantly increase the region's existing natural gas pipeline infrastructure of 17,665 km.[220] More analysis is needed to assess the age of existing coal plants, which ones might be switched to natural gas generation, and whether additional infrastructure is needed to enable such conversions.

It is expected that Southeast Asia will become a net natural gas importer by 2025, and volatile prices and geopolitical factors may have more significant long-term consequences for natural gas utilization in the region. Changing perceptions of resource affordability and policy attitudes toward investments in gas-import infrastructure could follow. Fossil fuels will continue to play a significant role in the region for the foreseeable future. However, financing for new coal projects in the future will likely receive greater scrutiny if climate pledges are to be met, so it would behoove countries in the region to initiate decarbonization of energy generation by replacing coal with natural gas while simultaneously developing more low-carbon technologies.

Impacts of Natural Gas Market Volatility on Energy Affordability

As noted, Russia's invasion of Ukraine resulted in a significant increase in global and regional energy prices, circumstances that placed a major burden on less-developed countries that are ill-equipped to manage high energy prices. Emerging and developing countries are the most vulnerable to increased energy prices; the hardest-hit nations include oil-importing countries in Africa, Asia, and Latin America because of higher import prices and their weaker currencies.[221]

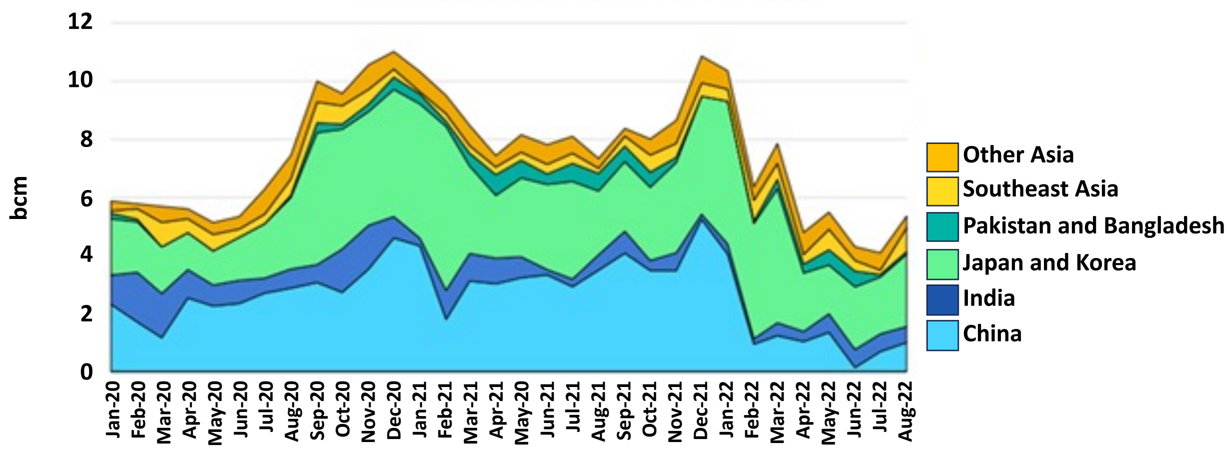
The volatility and high spot prices of LNG have a corresponding impact on affordability. Europe's move to replace Russian piped gas with LNG caused prices to hit record levels in 2022. The United States doubled LNG exports to Europe to support Europe's transition from Russian gas. However, support of European countries come at a cost, since Asian LNG importers had to deal with the full impact of volatility in gas markets and struggled to secure LNG in the market at an acceptable price.

Asia

LNG prices in Asian spot markets in 2022 averaged $34, more than double the annual average in 2021.[222] These high prices depressed demand for LNG in price-sensitive parts of Asia, and gas demand fell from 270 million tons (Mt) in 2021 to 250 Mt in 2022.[223] In billion cubic meters, the Asian decline in LNG imports is greater than the year-on-year change in European natural gas imports from Russia, a decline of 22 Bcm, during the same period.

During the first eight months of 2022, Asian spot LNG imports decreased by 28% on a year-over-year basis (Figure 55).[224] The largest decreases occurred in China, Japan, Pakistan, and India. Despite their continued interest in securing LNG shipments, the Asian LNG importers could not secure the product they needed at an acceptable price due to excessively high bid prices in the spot market.[225]

Figure 55. Collapse of Asian spot LNG imports in January-August 2022



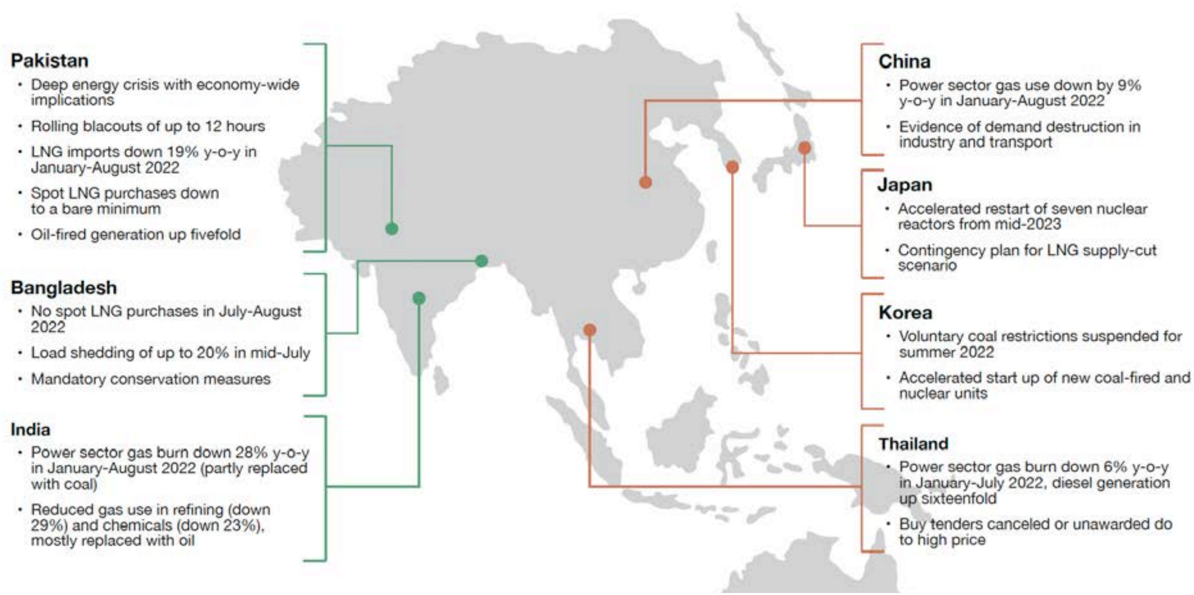
Source: IEA, Gas Market Report, Q4-2022 including Global Gas Security Review 2022, https://www.iea.org/reports/gas-market-report-q4-2022.

China was an exception. Due to domestic LNG demand reduction, driven by mild winter temperatures, decreased economic activities, COVID-related lockdowns, and strong coal and renewable generation growth in the power sector, some Chinese buyers had excess LNG that they attempted to resell on the spot market. LNG reloads in Asia were at an all-time high and increased by 48% on a year-over-year basis.

Except China, most Asian LNG importers changed their energy mix or energy strategies because of high LNG prices (Figure 56). Some countries increased their use of coal and oil. As shown in Figure

56, in Pakistan, spot LNG purchases decreased to minimum volume, a 73% decline on a year-over-year basis, and oil-fired generation increased fivefold.[226] The power sector in India used 28% less natural gas from January to August 2022, which was partially replaced with coal. In Bangladesh, there were no spot LNG purchases in July and August 2022. South Korea suspended coal restrictions for the summer in 2022, and Japan accelerated the restarting of nuclear reactors. In Thailand, diesel generation was up sixteenfold from January to July 2022 as the power sector used less natural gas.

Figure 56. Impacts of high spot LNG prices across Asia



Source: IEA, Gas Market Report, Q4-2022 including Global Gas Security Review 2022, https://www.iea.org/reports/gas-market-report-q4-2022.

Some buyers of LNG in Asia have been somewhat protected by these price spikes because they had long-term LNG contracts. However, it is estimated that 180 Bcm of LNG contracts will expire between 2022 and 2025, followed by an additional 135 Bcm between 2026 and 2030. Asia will account for 40% of the 2025 contracts.[227] Additionally, some current projections see LNG markets remaining tight until new supply comes on the market, which is unlikely before 2026. Also, long-term global LNG export project contracts starting before 2026 are already sold out.[228] How the countries that prefer long-term contracts and the producers of LNG come to an agreement on new contracts could decide the future of LNG demand in Asia.

Natural gas, however, is not as fungible as oil due to the complexity of the liquefaction process, shipping, and regasification associated with LNG, making gas markets regional and not truly liquid; these complexities invite both price volatility and the rebalancing of global markets. Natural gas procurement methods are seen as maturing, and the contract environment is still recalibrating from the aftershocks of the Russian invasion of Ukraine. Most of the Russian natural gas supply goes through pipelines; those pipelines have fixed endpoints, and Russia does not have the ability to divert supplies to China easily or quickly.[229]

As markets stabilize, importers of LNG in Asia are looking to diversify their sources and continue to build in price stabilization via long-term contracts. Also, the growth of LNG demand in Asia could be driven by some countries that are proposing a buildup of stockpiles of gas to mitigate price volatility and provide additional time to adjust energy consumption by sourcing from other sources. For example, Japan launched the Strategic Buffer LNG (SBL) ahead of the 2023-24 winter season, in which designated operators of the SBL are instructed to sell their LNG cargoes to Japanese buyers to avoid supply disruptions. India has been considering the establishment of strategic gas reserves, and China has been focused on natural gas storage development as strategic to gas market growth strategy.

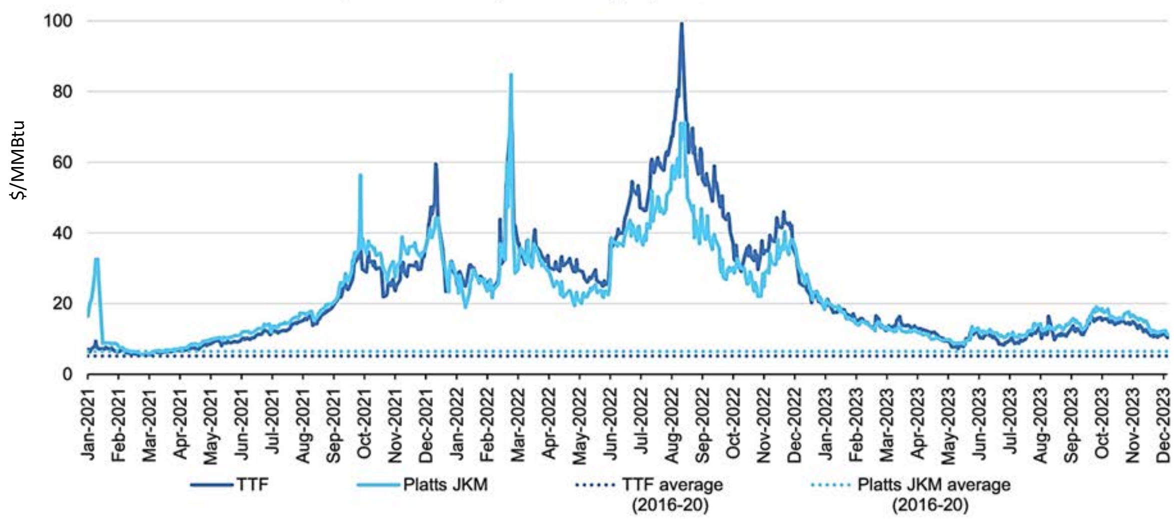
Although some countries have moved forward with strategies and investments to protect domestic markets from supply and price disruptions, not all Asian countries are well positioned to invest in strategic gas reserves and associated infrastructure. As discussed in Chapter 2, South and Southeast Asia need to build substantial LNG regasification facilities to meet their growing long-term LNG demand. As they need to invest in meeting increasing LNG demand, securing reserves is not likely to be a priority for these countries. Therefore, the countries in South and Southeast Asia could be more vulnerable to LNG price risks.

Europe

Since natural gas plays a key role in European energy systems, increased prices and costs have a range of equity/affordability issues. In 2020, natural gas accounted for about 25% of its energy consumption. More than 80% of natural gas volumes were imported in 2020, mainly from Russia. In 2020, Russia supplied 43% of gas imports in Europe. Since Russia's invasion of Ukraine, piped gas imports from Russia have been replaced with LNG imports. Europe's LNG imports rose by 70% in 2022 compared to the previous year.

As noted, the natural gas market in Europe was already tightening in 2021, starting about 10 months before Russia's invasion of Ukraine. Due to various independent events in the summer of 2021, European gas storage started the winter at an all-time low level, which was not immediately noticed by governments or the public. European pipeline supply of natural gas was further reduced by the early curtailment of production from the Groningen gas field, due to environmental concerns stemming from earthquakes. As noted, natural gas prices spiked after the Russian invasion of Ukraine (Figure 57).[230]

Figure 57. Gas prices in Europe and Asia, 2021 to 2023



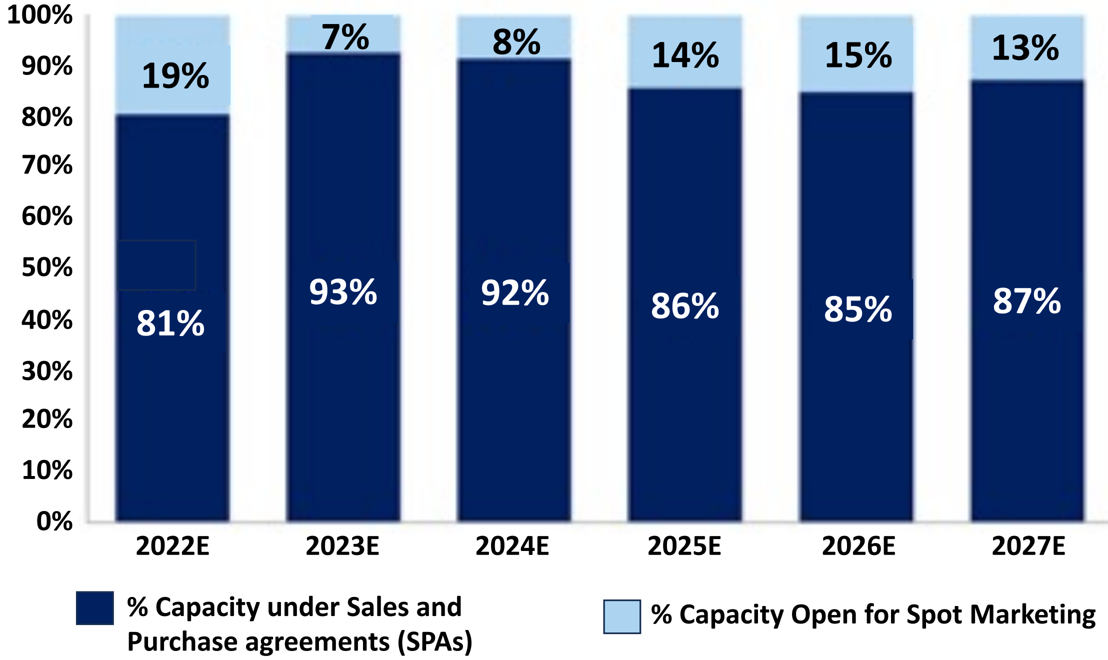
Source: IEA, Gas Market Report, Q1-2024,
https://iea.blob.core.windows.net/assets/601bff14-5d9b-4fef-8ecc-d7b2e8e7449a/GasMarketReportQ12024.pdf.

After the first spike in March 2022, prices largely stabilized, although at much higher levels than pre-2021—basically since the price collapse in 2014. However, by May, European governments saw the reduction in gas supplies from Russia and wanted to stop the purchases of Russian gas, not wanting to be accused of financing Russia's operations in Ukraine.

Alternative supplies were needed for near-term consumption and to refill natural gas storage facilities to prepare for the coming year. This was most notable in Germany and the Netherlands, which were outpricing other European countries, including those in southern Europe. Many Asian countries had ample natural gas supplies due to COVID-19-related economic slowdowns and were willing to sell—notably American LNG—to Europe.

Qatar was also an important supplier and rerouted large volumes of LNG to Europe. However, when it became known that Europe had bought enough gas to fill 90% of its storage, prices dropped between September and November 2021. Furthermore, mild weather, energy efficiency measures, and slowing economic development contributed to an overall price drop, with only a temporary rise stemming from cold weather in early December. In this regard, Cheniere, the United States' largest LNG exporter, on average has approximately 11% of total volumes available for spot sales (Figure 58).[231] Spot LNG volumes (2024 estimate) are relatively small, meaning that perturbations could significantly increase prices.

Figure 58. LNG volumes breakout: contracts vs. spot



"E" after a year indicates an estimate.
Source: Jan-Hein Jesse, The Effect of U.S. LNG Exports on U.S. Domestic Prices: A European Perspective, January 2023, *https://efifoundation.org/wp-content/uploads/sites/3/2023/05/White-Paper_Session-1_Final_edited.pdf*.

While Europe's energy security was threatened after Russia's invasion of Ukraine, Europe was concerned even before then about tight supplies of natural gas after the post-COVID surge in demand.[232] After the invasion, EU countries severely cut gas supplies from Russia. Russia's share of total EU natural gas imports fell from 40% in 2021 to below 10% by the end of 2022. However, as noted in the Foundation's workshops in Sofia and Brussels, EU sanctions in 2022 were largely ineffective and hurt European consumers. Europe ended up spending 400 billion euros more on natural gas imports than in 2021, a 300% increase in a year, with price/affordability/equity implications for its citizens and businesses.

In December 2022, European ministers approved a first-ever price cap on natural gas in response to high energy prices due to Russia's invasion and subsequent decision to halt hydrocarbon flows in retaliation for sanctions. The price cap was an emergency measure to protect consumers from high natural gas prices that saw residential heating bills skyrocket into the hundreds of euros. The price cap would be activated under two conditions: "If front-month gas contracts exceed 180 euros ($191) per megawatt-hour on the Dutch Title Transfer Facility (TTF)—Europe's main benchmark for natural gas prices—for three working days in a row; and the price is 35 euros higher than a reference price for liquid natural gas on global markets for the same period."[233] When the price cap was first announced, prices were approximately 135 euros per megawatt-hour (MWh).[234]

While the price cap was never actually triggered, in December 2023 it was extended until January 2025. On December 22, at the time of the extension, the TTF price was 34 euros.[235] "The introduction of the extraordinary measure became the dividing line between countries who favored forceful market intervention, like France, Spain, and Belgium, and those who, like Germany, the Netherlands, and Estonia," opposed the price cap, fearing it would discourage foreign suppliers.[236]

In the near term, LNG demand in Western Europe is likely to remain resilient to compensate for the loss of Russian piped gas and declining domestic natural gas production. A recent analysis by Wood Mackenzie projected that LNG imports in Northwest Europe will reach peak levels around 2028-2030 and decline thereafter as accelerated decarbonization efforts result in a significant drop in natural gas demand.[237]

The current outlook for Europe is sustained tight natural gas supply. Specifically, U.K. natural gas production is in slow decline, the Netherlands is debating shutdown of the Groningen field, and Norway's production is expected to decline from the second half of the decade as fields mature. Only Algeria is looking to increase gas exports, though volumes will likely be inadequate to meet Europe's needs for 25 million cubic meters/day by 2023-24. The U.S. LNG pause will likely increase concerns about natural gas prices and availability as well, with potential affordability and equity impacts.

Last summer, it was estimated that the increase in European energy bills from high gas prices amounted to nearly 2 trillion euros, or approximately 15% of the EU's GDP. This and other indicators underscore concerns that high European gas prices could continue to drive industrial demand destruction, an impact of the region's efforts to ensure adequate storage through 2024.[238]

At the same time, the unexpected fall in natural gas prices over the last several months has improved the outlook for European imports, storage levels, and consumer prices, helping to address the equity issues raised by high prices. The approximately 75% fall in gas prices coupled with the regulatory measures introduced last year, suggests a much more modest increase in bills (less than 0.5 trillion euros). This suggests that most European consumers may have already seen the bulk of energy bill increases.[239]

Environmental Justice and the Energy Transition

In addition to the price cap on natural gas, in response to high energy prices due to Russia's invasion and subsequent decision to halt hydrocarbon flows in retaliation, the EU reaffirmed its commitment to phase out fossil fuels. As developed nations, countries in Europe face a different challenge associated with the energy transition as it relates to energy equity.

While decision-makers have not historically considered equity and justice when making decisions on energy, environment, and climate, these concepts have recently come to the forefront of discussions around energy policy design and implementation. Energy justice, as defined by the U.S. Department of Energy (DOE), is "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system." Environmental justice, or "eco-justice," is a social movement to address environmental injustice, which occurs when poor or marginalized communities are harmed by hazardous waste, resource extraction, and other land uses in an area where they reside.

The clean-energy transition is a chance for nations to rethink the way that energy is generated, distributed, and consumed, and how these steps can be done in an equitable manner that will minimize adverse impacts on the climate, environment, and people. Without bringing communities into a dialogue early and often, clean-energy projects could be stalled or canceled. Corporations are starting to follow suit as a part of the growing importance of environmental, social, and governance (ESG) standards. For example, Shell has made explicit commitments to community engagement and equity in its current and future projects.

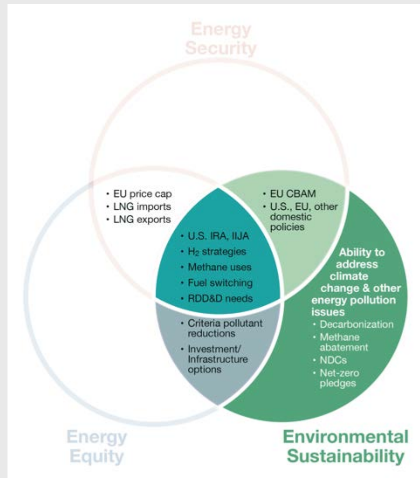
As an example of commitment to a just energy transition by a developed country, the Biden-Harris administration has emphasized equity and justice as a key focus. One such example of these concepts as an administrative priority is the Justice40 initiative, which states that "40% of the overall benefits of certain federal investments flow to disadvantaged communities that are marginalized, underserved, and overburdened by pollution." Investments within the scope of Justice40 include those related to climate change, clean energy and energy efficiency, clean transit, affordable and sustainable housing, training and workforce development, remediation and reduction of legacy pollution, and the development of critical clean-water and wastewater infrastructure. Similarly, recently passed legislative efforts (BIL, IRA, and the CHIPS and Science Act) all specifically authorize funding for justice considerations as a part of the policy implementation process.

For example, in White Plains, New York, a plan to create a lithium-battery recycling plant was canceled after three years because of an organized community movement that was concerned that the processing would include incineration and lead to environmental pollution. In contrast, the Good Neighbor Agreement at the Stillwater Mine in Montana has managed to keep up its goodwill with the local community because it has built trust and kept promises. These two examples show that consideration of community engagement is crucial when thinking about how clean-energy projects will be implemented and deployed. Examples such as these can be a road map for policymakers and industry alike on how developed nations can address energy equity and achieve a just energy transition.

From an international perspective, a key element of justice is that "nations at various levels of economic development adopt different approaches to the energy transition."[240] Thus, the role of natural gas should be considered depending on each region or country's context. Each country uses natural gas for different reasons. For example, China's use of natural gas was driven by natural gas's ability to reduce local air pollution. In the United States, natural gas was used because it is affordable and contributes to CO_2 emissions reduction. Similarly, Southeast Asian countries could increase their use of natural gas to meet their climate goals, while European countries move away from natural gas to meet their climate goals. Sub-Saharan Africa could use natural gas to improve energy access and alleviate energy poverty. Therefore, countries should be allowed to develop their own energy transition pathways and define the role of natural gas in their pathways, considering their own socioeconomic realities and national priorities.

4. Environmental Sustainability

Findings in Brief

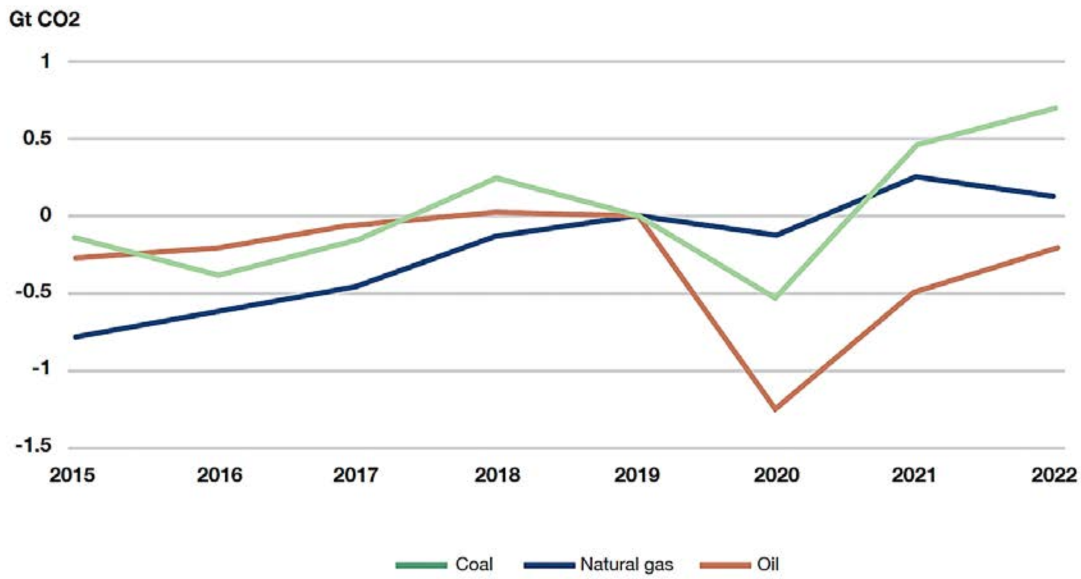


- Global GHG emissions scenarios underscore the critical need to accelerate the development and deployment of zero-emissions technologies, as well as the need for support from the developed world for decarbonization efforts in the developing world.
    - The U.S. Energy Information Administration's (EIA) Low Zero-Carbon Technology Cost scenario shows overall emissions reductions between 2022 and 2050 of around 7% globally.
    - U.S. emissions show the largest decline, Western Europe a modest decline, and Eastern Europe/Eurasia a significant increase.
    - While China shows a 17.8% decline in emissions, even in a low technology cost scenario, India's emissions almost double, and emissions from "other Asia-Pacific" increase by 62%.
- Growing international, national, and industry efforts to cut methane and CO_2 emissions from natural gas systems have not yet led to large-scale emissions reductions.
    - Global methane emissions dropped slightly because of decreased oil and gas production in 2020 but increased again in 2021.
    - The CO_2 emissions from the natural gas supply chain have continuously increased in the last decade, except a slight decrease in 2020 and 2022 due to the COVID-19 shutdowns and the supply disruptions that resulted from Russia's invasion of Ukraine.
- The CO_2 and methane emissions from natural gas supply chains infer vast opportunities for greening the natural gas supply chain. Accelerated implementation of existing commitments, and additional and strengthened policies worldwide, is needed.
- The fugitive methane emissions from upstream and midstream natural gas supply chains are highly variable and tend to be poorly measured.
    - The methane leakage from each component of the natural gas supply chain, including producing wells, processing facilities, and transmission and distribution facilities, could substantially undercut the emissions reduction benefits from lower carbon intensity of natural gas compared to coal.

- Since the Global Methane Pledge launched in 2021, there has been a proliferation of national policies and international/industry initiatives for methane abatement in oil and gas operations. However, global consensus on measurement and verification is still lacking.
    - Accurate measurement of methane leaks throughout the natural gas supply chain has been a key agenda item, and many international and industry initiatives have attempted to better measure methane emissions.
    - The United States has introduced methane policies in recent years, including the Environmental Protection Agency's (EPA) final rule to reduce methane and air pollutants from new and existing oil and gas operations, a charge on methane emitted by oil and gas companies, and financial and technical assistance to improve methane monitoring.
- The CO_2 emissions from downstream combustion are well understood and measured compared to upstream methane emissions, but the emissions vary among facilities depending on energy efficiency and type of plant.
- Carbon capture, utilization, and storage (CCUS) is an effective option for reducing CO_2 emissions across the natural gas supply chain and has already been used in upstream gas processing; however, there were no natural gas-fired power plants with CCUS in operation worldwide as of July 2023.
- Coal-to-gas switching has reduced significant CO_2 emissions and has great potential to contribute to global greenhouse gas (GHG) emissions reduction; however, high cost could be a barrier to coal-to-gas switching in many countries.
- Technologies exist for reducing CO_2 emissions from natural gas combustion, but they are at the early stages of commercialization.
    - CCUS and hydrogen need more policy support to address cost, regulatory, infrastructure, and community-acceptance barriers.
- Environmental sustainability must be considered in the context of energy security and energy equity where overlapping issues (e.g., net-zero pledges and goals, trade and industrial policies, hydrogen strategies) must be considered in the larger context.

Globally, in 2022, coal was responsible for over 44% of CO_2 emissions, oil for 33%, and natural gas for 22.7%. While global emissions from coal, natural gas, and oil all saw COVID-related declines between 2019 and 2020, emissions from coal and natural gas exceeded pre-COVID levels by 2021. CO_2 emissions from oil remained below pre-COVID levels in 2022 (Figure 59).[241] In 2020, emissions from natural gas dropped only slightly, while emissions from coal and oil sharply decreased. Natural gas emissions decreased by only 1.6% in 2022 because of the supply disruption caused by Russia's invasion of Ukraine.

Figure 59. Change in global CO_2 emissions by fuel relative to 2019 levels, 2015 to 2022

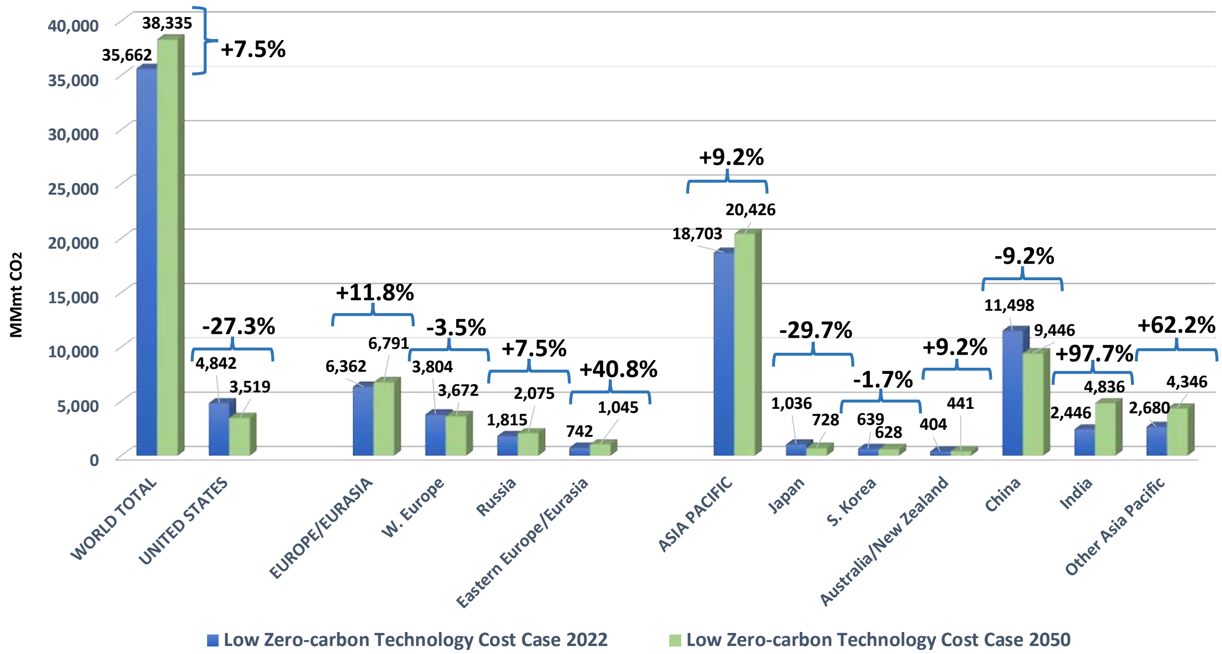


Source: IEA, CO_2 Emissions in 2022, March 2023. https://www.iea.org/reports/co2-emissions-in-2022.

For the purposes of this analysis, it is also important to understand the impact and value of emissions-reduction technologies, globally and in the regions covered in this analysis. While Chapter 1 includes data and analysis on the EIA's Low Zero-Carbon Technology Cost (Low-cost) Case by 2050 from a broader regional perspective, Figure 60 shows more specific data on the potential for CO_2 emissions reductions in this scenario that includes countries and subregions in Europe/Eurasia and the Asia-Pacific region.[q,242]

[q] The "Low Zero-Carbon Technology Cost" case assumes a more rapid capital cost decline compared with the Reference Case, achieving capital costs that are 40% lower by 2050 for these zero-carbon technologies.

Figure 60. Regional/national CO_2 emissions 2022/2050, EIA Low Zero-Carbon Technology Cost scenario



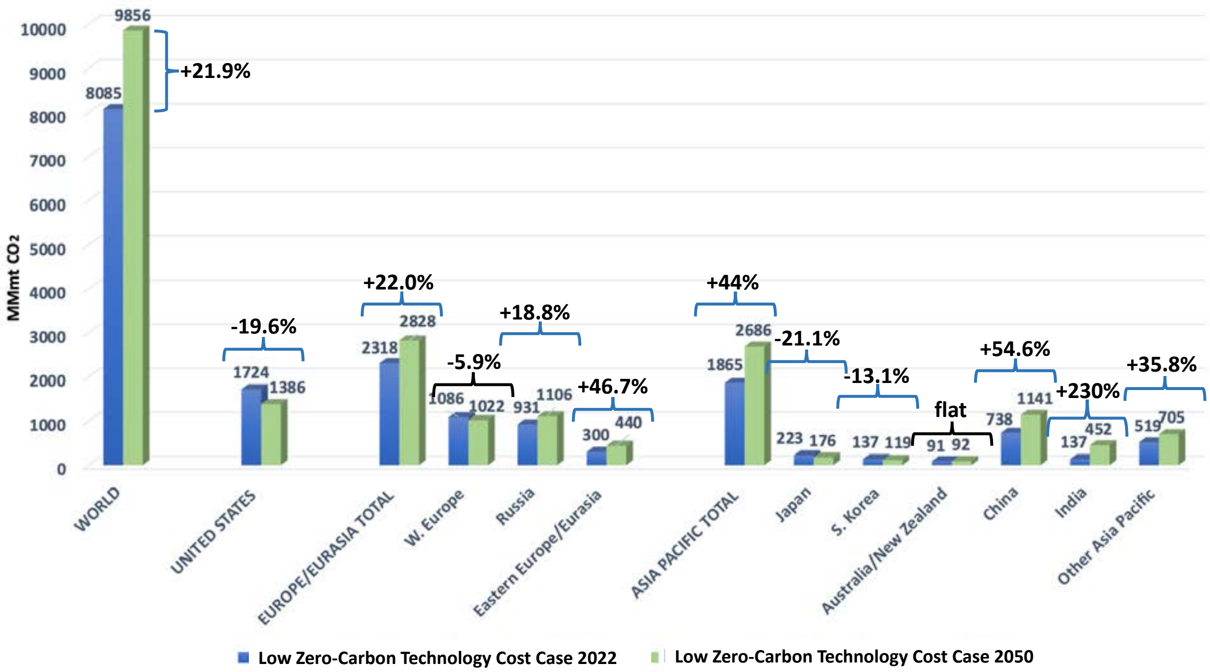
Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/

This scenario shows an overall emissions reduction in 2050 relative to the base case of 2,619 MMmt, a decrease of around 7% overall. It should be noted, however, that even in this scenario, global emissions still increase by 7.5% compared to the 2022 level. U.S. emissions show the largest decline on a percentage basis at 27.3%. In the Europe/Eurasia region, Western Europe shows a modest 3.5% decline, but Eastern Europe/Eurasia shows a 40.8% increase, more than offsetting the declines in Western Europe.

The story in the Asia-Pacific region is very different. As shown in Figure 60, in the 2050 scenario, while China shows a 9.2% decline in emissions, India's emissions rise by 97.7%, and emissions from the Other Asia-Pacific region increase by 62%. Emissions also rise by around 9% in Australia/New Zealand but are lower in Japan and South Korea by 29.7% and 1.7%, respectively. This data underscores the critical need to accelerate the development and deployment of zero-emissions technologies, as well as the need for support from the developed world for decarbonization efforts in the developing world.

Figure 61 shows CO_2 emissions from natural gas in the Low-cost Case for the same regions and countries.[243] In this scenario, total global CO_2 emissions from natural gas still increase but, importantly, the increase is lower than in the Reference Case. Also, in this scenario, global gas systems emit 9,856 MMmt of CO_2 in 2050, compared to 10,382 MMmt in the Reference Case. While this is only a 5% decrease it must be considered in comparison to the emissions from coal seen in Figure 62. In the Low-cost scenario, emissions decrease by almost 20% in the United States and by small amounts in Western Europe, Japan, and South Korea.

Figure 61. Global, country, regional CO_2 emissions from natural gas consumption, EIA Low Zero-Carbon Technology Cost Case 2022/2050

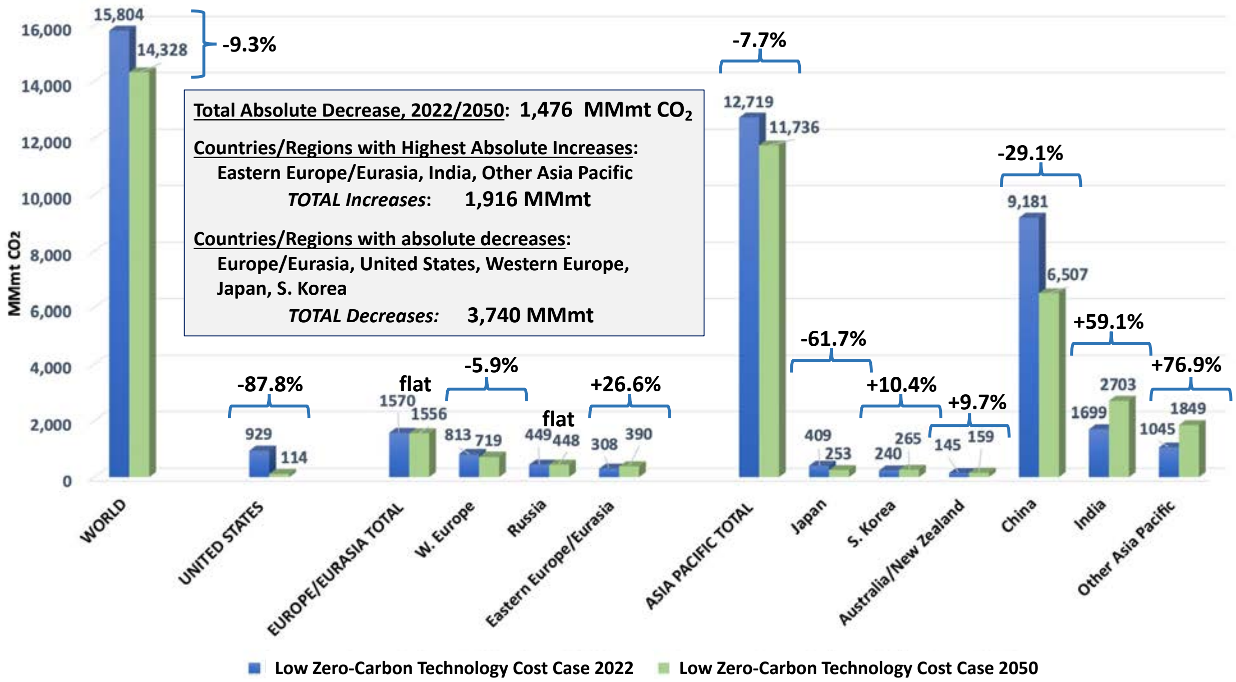


Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, https://www.eia.gov/outlooks/ieo/

CO_2 emissions from natural gas in the Low-cost scenario in the Eastern Europe/Eurasia region increase by almost 47% and in the Asia-Pacific region by 44%. In China, emissions increase by 54.6%, in India by almost 230%, and in the Other Asia-Pacific region by 35.8%. These increases largely reflect the overall increase in natural gas demand in these regions (discussed below) and need to be considered in the context of the energy sources they may displace or supplant, e.g., coal. These emissions also point to the need for emissions-reduction technologies for natural gas systems in all regions of the world. Affordability of these technologies will, however, be a critical issue, particularly for developing countries and for hard-to-abate sectors such as heavy industrial manufacturing where additional costs could affect a country's products and the affordability of key clean-energy technologies. It also underscores the importance of mechanisms such as the Loss and Damage Fund, an initiative established at the 27th United Nations Climate Change conference (COP27), as well as the general need to lower the costs of emissions-abatement technologies.

Finally, Figure 62 shows emissions from coal in these regions and countries in the EIA's Low-cost Case.[244] Globally, by 2050, there are modest decreases in emissions from coal (9.3%) compared to a small increase in the EIA's Reference Case (3.9%). In the Low-cost scenario, decreases in coal emissions in the United States are significant (87.7%), likely reflecting, in part, the availability of a significant natural gas supply as a lower-emitting alternative and a major focus on clean-energy technologies reflected in the Bipartisan Infrastructure Law (BIL) and other legislation enacted during the time frame of the EIA analysis.

Figure 62. Global, country, regional CO_2 emissions from coal consumption, EIA Low Zero-Carbon Technology Cost Case, 2022-2050



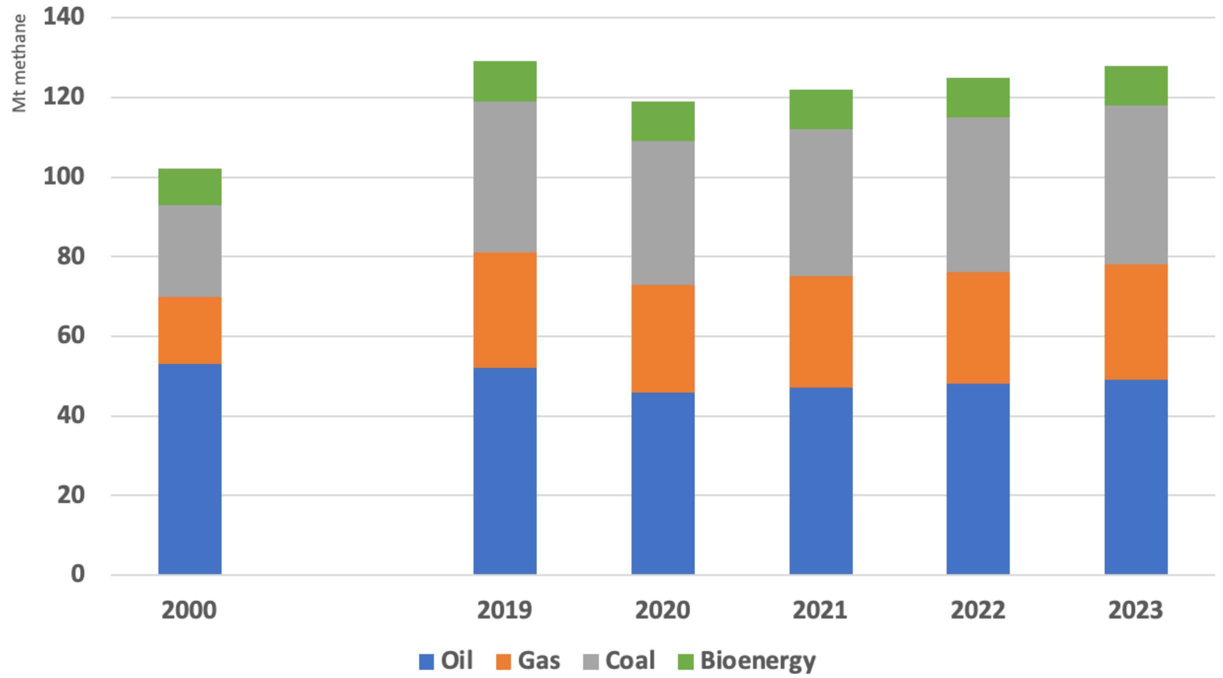
Source: EFI Foundation with data from EIA, International Energy Outlook 2023, October 2023, [https://www.eia.gov/outlooks/ieo/.](https://www.eia.gov/outlooks/ieo/)

In the Low-cost Case, the Asia-Pacific region shows an overall 7.7% decrease in emissions between 2022 and 2050, including a 29% decrease in China. Emissions in India and the Other Asia-Pacific subregion show an increase of 59% and 76.9%, respectively. Coal emissions in the Low-cost scenario decrease globally and, in the Europe/Eurasia region, are basically flat, even considering an increase of 26.6% in the Eastern Europe/Eurasia subregion. These increases, even in a Low-cost scenario, suggest a need for several actions that could help these regions and the world meet net-zero targets by 2050.

In addition to CO_2 emissions, natural gas systems emit methane, a highly potent greenhouse gas. One ton of methane is equivalent to 28 to 36 tons of CO_2 if considering its impact over 100 years, although it has a shorter atmospheric residence than CO_2—around 12 years, compared with centuries for CO_2.

Global methane emissions from the natural gas systems have not significantly declined since 2019, the record high (Figure 63).[245] Global methane emissions dropped slightly because of decreased oil and gas production in 2020, but emissions increased again in 2021. In 2023, global methane emissions decreased by less than 1% compared to the record high level of 2019.

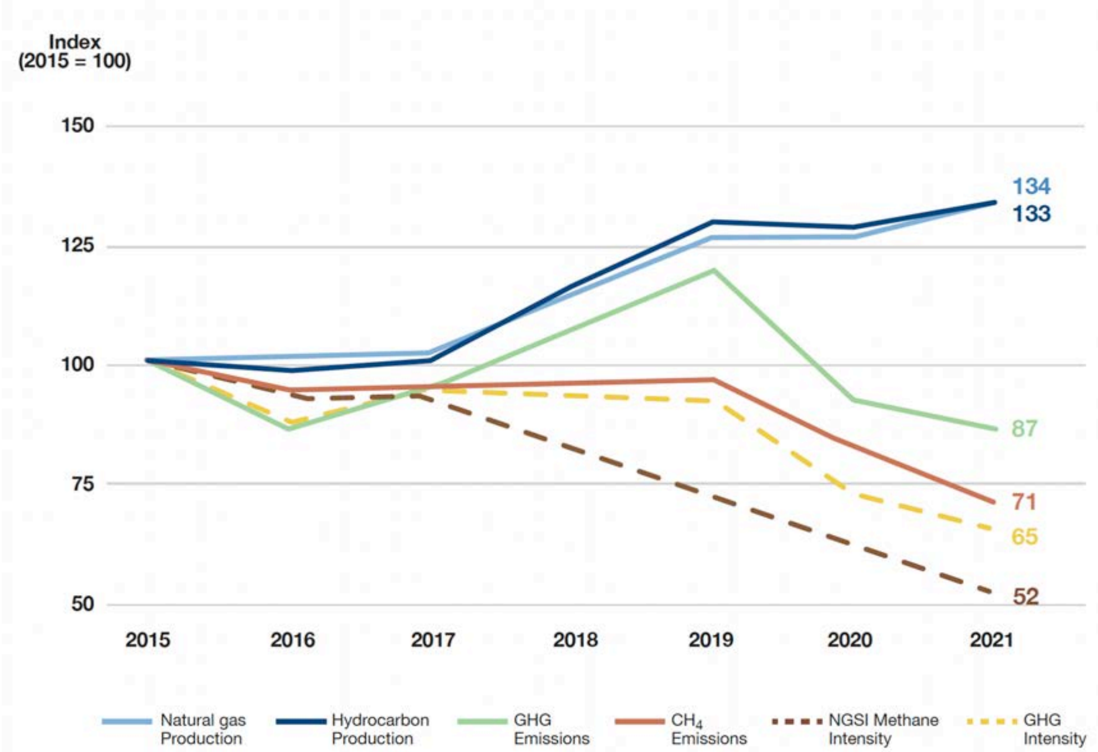
Figure 63. Global methane emissions from the energy sector, 2000 to 2023



Source: IEA, Global Methane Tracker, March 2024, https://www.iea.org/reports/global-methane-tracker-2024.

The United States is an exception in this regard. In the United States, methane emissions from oil and natural gas production significantly declined between 2019 and 2021 despite an increase of natural gas production (Figure 64).[246] This led to a substantial decrease of the methane emissions intensity; compared to the 2019 level, the methane emissions intensity declined by 28% in 2021. The decrease in methane emissions has largely been driven by a reduction of emissions from pneumatic controllers, the largest source of methane emissions from the oil and gas supply chain. However, despite this overall deceasing trend in methane emissions on average, the methane emissions intensity of natural gas production varies dramatically across the U.S. producers.[247]

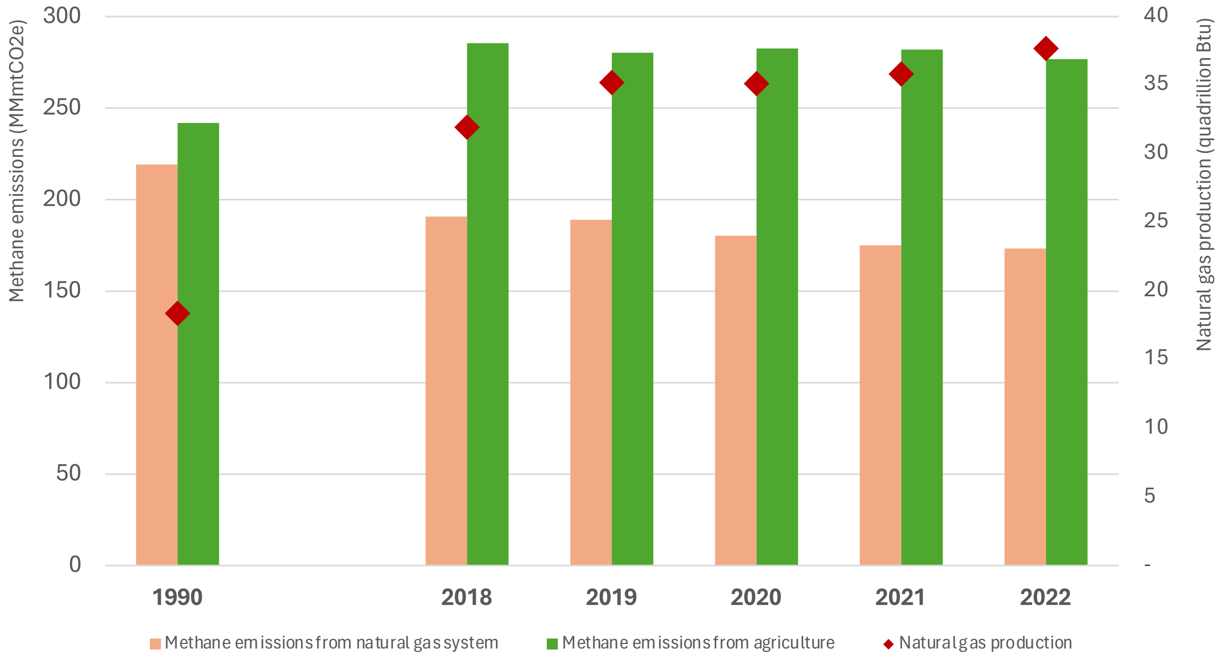
Figure 64. Natural gas production and methane emissions in U.S. oil and gas systems, 2015 to 2021



Source: Luke Hellgren et al., "Benchmarking Methane and Other GHG Emissions of Oil & Natural Gas Production in the United States," May 2023, https://www.sustainability.com/contentassets/95c6e3e4c9a440049e3533575d0b389e/oilandgas_benchmarkingreport_2023.pdf

More specifically, in 2022, U.S. natural gas systems emitted 173 MMmt CO_2e of methane, a 21% decrease compared to the 1990 level, despite a rapid increase of natural gas production since 1990 (Figure 65).[248,249] During the same period, the methane emissions from the agriculture sector increased by 15%, from 242 to 276 MMmt CO_2e. The natural gas systems account for 25% of total U.S. methane emissions in 1990 and 2022. The agriculture sector accounts for 39% of total U.S. methane emissions in 2022, compared to 28% in 1990. From 1990 to 2022, the methane emissions reduction from natural gas systems accounted for 27% of the total U.S. methane emissions reduction. High methane emissions in the agriculture sector infer a substantial potential to capture methane that could be used to increase gas supply or produce hydrogen.

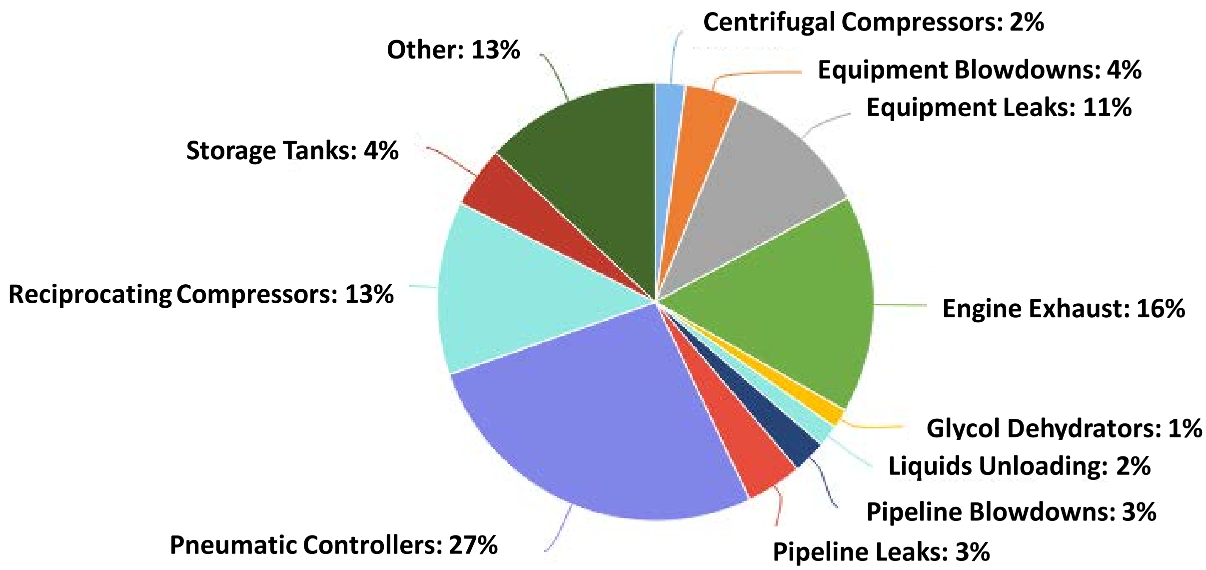
Figure 65. The U.S. methane emissions from natural gas systems and agriculture sector, 1990 to 2022



Source: EFI Foundation with data from EPA, https://www.epa.gov/system/files/documents/2024-02/us-ghg-inventory-2024-main-text.pdf, and EIA, https://www.eia.gov/totalenergy/data/annual/.

Ensuring that natural gas remains a cleaner alternative to other fossil energy sources, such as coal, is crucial from both an environmental and energy security leadership standpoint. In the United States, methane emission abatement is part of industry's "license to operate" and will impact perception of U.S. LNG as a viable, clean alternative. Figure 66 shows the sources of U.S. methane emissions from the various components of oil and gas systems in 2021.[250]

Figure 66. Share of total U.S. oil and gas methane emissions by source in domestic supply chain, 2021



Source: EPA, "Estimates of Methane Emissions by Segment in the United States," *https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states*.

While EPA data show progress on methane emissions reductions from gas systems, there is, as noted, a wide divergence of methane emissions estimates. A study indicated that the methane emissions from the U.S. oil and gas supply chain could be more than 60% higher than the EPA's estimate due to underestimation of the emissions by abnormal operating conditions, e.g., equipment malfunction.[251]

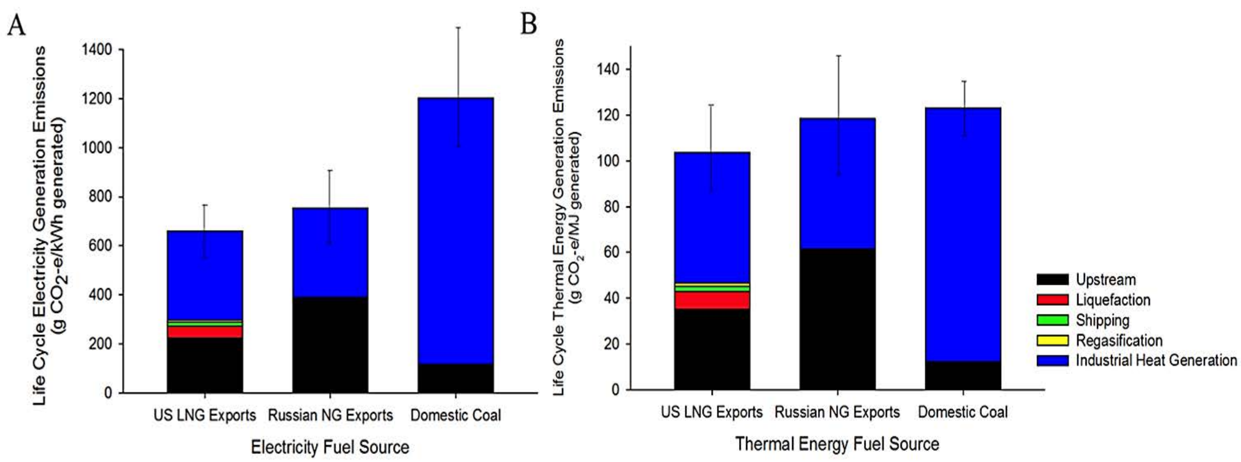
A recent study estimating the methane emissions from U.S. oil and gas systems suggested that the average methane emissions in six U.S. regions could be three times higher than the EPA inventory estimate.[252] Another study estimated that the methane emissions from oil and gas operations in Western Canada could be almost twice the reported emissions.[253] The difference between estimated emissions and what was reported is due to emissions from fugitive and unintended processes being underreported or underestimated, which demonstrates the need for consistent measurement and monitoring standards.

Experts generally agree that industry has the capability and tools to address methane fugitive emissions, but some experts voiced concerns about inadequate regulations. One suggestion is that the United States should aim to decrease life cycle methane emissions from domestically produced gas to less than 0.3% of overall gas volume by 2030, down from a current value of 1.7%, which would result in U.S. natural gas having the lowest methane emissions in the world.[254] In this context, it should be noted that, according to the EPA, "Methane (CH_4) accounted for 12% of emissions in 2021. CH_4 emissions have decreased by 8% since 2005, 16% since 1990, and 2% from 2020 to 2021. Key trends include reduced emissions from natural gas systems due to decreases in emissions from distribution, transmission, and storage, decreases in emissions from landfills due to increased landfill gas collection and fewer decomposable materials discarded in landfills, and increased emissions from livestock in line with increasing cattle populations."[255]

Higher rates of methane leakage from the components of the natural gas supply chain, including producing wells, processing facilities, and transmission and distribution facilities, could substantially undercut the emissions-reduction benefits from lower carbon intensity of natural gas compared to coal. A recent study found that a gas system with a methane leakage rate of more than 4.7% (considering a 20-year time frame or 7.6% considering a 100-year time frame) would eliminate the climate benefits of coal-to-gas fuel switching.[256] A survey of recent studies on methane leakage rates observed that the rates range from 0.65% to 66% in numerous U.S. gas systems.[257] Innovation and investments are needed to ensure more accurate assessments of methane emissions, and in ways to distinguish between methane emissions from natural gas systems and agricultural methane emissions in regions such as the Permian Basin, where these emissions sources are in proximity and mixed, and in technology options for reducing methane emissions.

Importantly, when considering future natural gas supplies to meet Asian and European demand, on average, the life cycle emissions from exported U.S. LNG are 13% lower than those from Russian natural gas export via pipelines (Figure 67)[258]; it is important to note that the data in this figure are CO_2e, so it reflects both carbon and methane emissions. A study found that higher GHG emissions from Russian natural gas exports are caused by the high leakage rate from pipeline transport.[259] This infers that the life cycle emissions from natural gas are highly dependent on the fugitive emissions rates, and the emissions from liquefying, transporting, and regasification are marginal.

Figure 67. Comparison of emissions from U.S. LNG, Russian natural gas, and coal



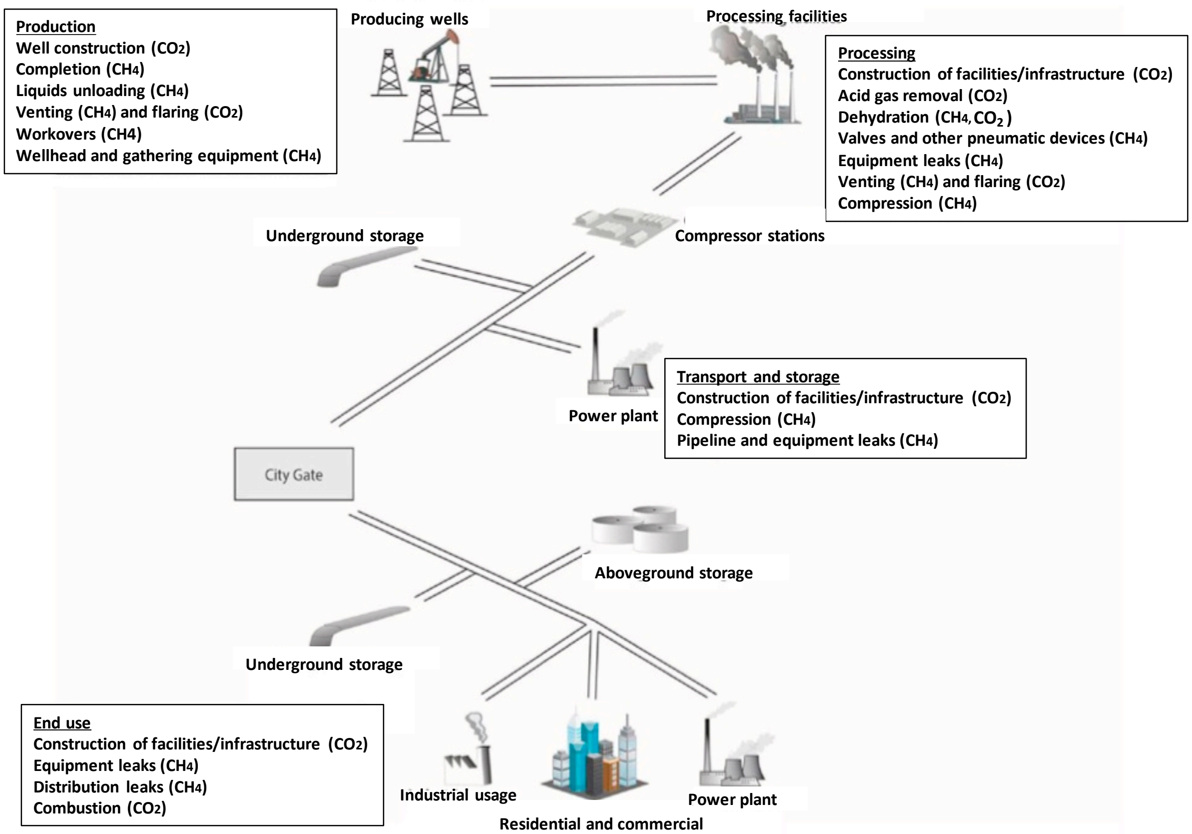
Source: Leslie S. Abrahams et al., "Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses," Environmental Science & Technology 49, no. 5 (February 4, 2015): 3237–45.

Life Cycle GHG Emissions of Natural Gas Systems

As noted, natural gas systems are a significant source of GHG emissions. Despite the broad and growing commitments to cut emissions, natural gas system GHG emissions, including CO_2 and methane, remain high. In recent years, both CO_2 and methane emissions from natural gas systems globally have dropped only modestly and temporarily, largely because of political or social disruptions rather than decarbonization efforts.

The life cycle of natural gas starts with production and ends with consumption by end users. Although there has been a great deal of focus on CO_2 reductions at power plants, the emissions from the combustion of natural gas are part of the total emissions from the natural gas system. Figure 68 shows that CO_2 and methane are emitted at numerous points along the natural gas supply chain, including the wellhead, gathering lines, compressor systems, transmission and distribution lines, and combustion at the end-use facilities.[260]

Figure 68. Natural gas supply chain with emissions sources for CH_4 and CO_2



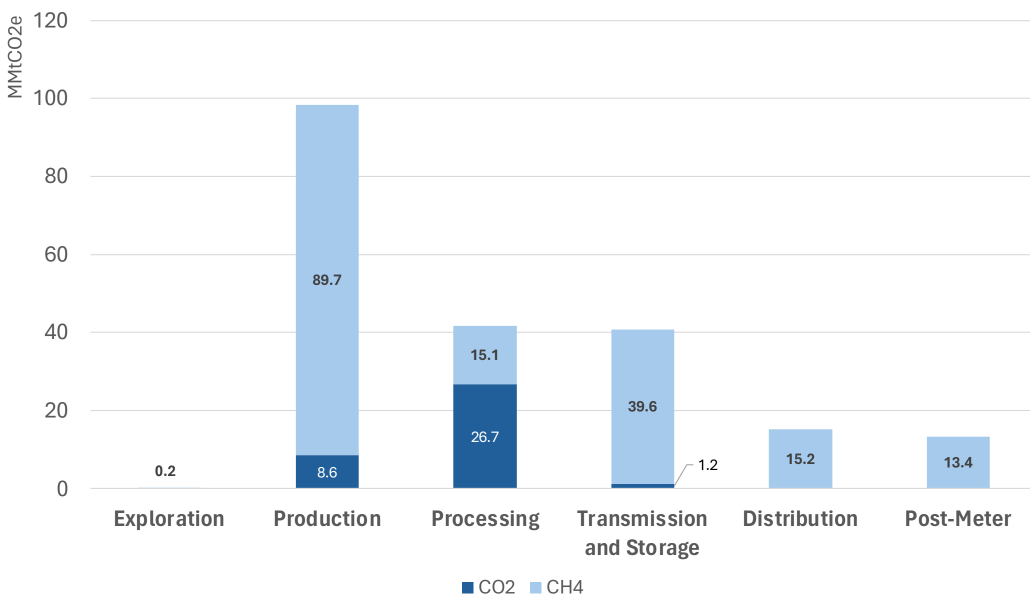
Source: Kate Konschnik and Sarah Marie Jordaan, "Reducing Fugitive Methane Emissions from the North American Oil and Gas Sector: A Proposed Science-Policy Framework," Climate Policy 18, no. 9 (2018): 1133–51.

A review of 250 papers on the natural gas supply chain emissions identified that the total GHG emissions from the natural gas supply chain range from 3.6 to 42.4 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ) of energy content of delivered.[261] The extremely large range of the emissions is due, in part, to the different processes of natural gas extraction, processing, and transport across different regions with different levels of regulations. The key emissions sources identified include well completions, liquids unloading, and equipment leaks such as pneumatic devices and compressors. In the United States, the life cycle GHG emissions from the natural gas supply chain were 19.9 gCO_2e/MJ, according to a 2019 analysis by the National Energy Technology Laboratory (NETL).[262] The key contributors to GHG emissions are compressor systems.

Upstream and Midstream Emissions

The GHG emissions from the natural gas upstream and midstream system account for approximately 27% of the life cycle GHG emissions from the natural gas supply chain in the United States.[263] In 2022, U.S. natural gas systems emitted 173 million metric tons of carbon dioxide equivalent (MMt CO_2e) of methane emissions and 36.5 MMt CO_2e of non-combustion CO_2 emissions. Figure 69 shows that methane emissions are dominant throughout the upstream and midstream natural gas supply chain, especially during production and transmission/storage phases.[264] The methane emissions from the production phase were 89.7 MMt CO_2e, accounting for 52% of the total methane emissions from U.S. natural gas systems in 2022, mainly driven by emissions from pneumatic controllers and from compressor exhaust slip, compressor venting and leaks, and tanks. In the transmission and storage phase, methane leakage from compressor stations and venting from pneumatic controllers are key contributors to the methane emissions. Similarly, in the distribution phase, the emissions result mainly from leaks in pipelines and stations.

Figure 69. GHG emissions from U.S. natural gas systems, 2022



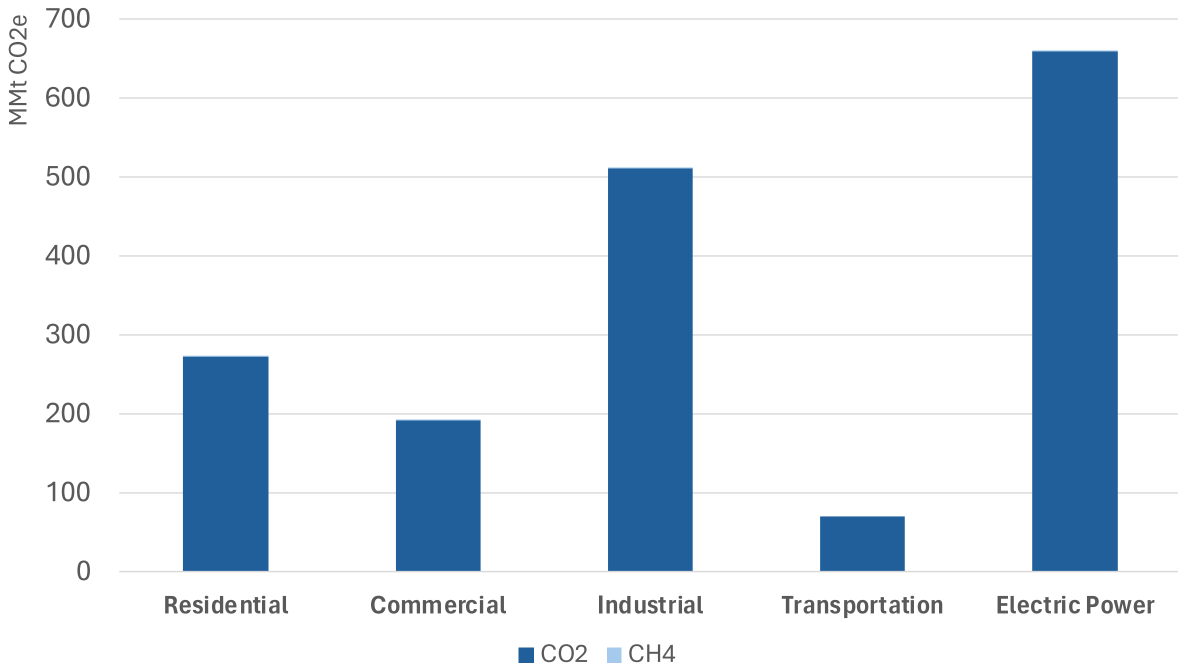
Post-meter includes leak emissions from residential and commercial appliances, industrial facilities, and power plants. The category of post-meter is not included in upstream or midstream but is included in the figure for the completion of data for the entire emissions from the U.S. natural gas systems. Source: EFI Foundation with data from EPA, Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2022, [*https://www.epa.gov/system/files/documents/2024-02/us-ghg-inventory-2024-main-text.pdf*](https://www.epa.gov/system/files/documents/2024-02/us-ghg-inventory-2024-main-text.pdf).

Compared to methane emissions, CO_2 emissions in upstream and midstream supply chain are much lower and mainly come from the processing phase. As shown in Figure 69, in 2022, the processing phase emitted 26.7 MMt of CO_2 emissions. The primary emission source is acid gas removal units that are designed to remove CO_2 from natural gas.

Downstream Emissions from Power Production

In contrast to the upstream emissions, CO_2 emissions are dominant in the downstream emissions (Figure 70).[265] More than 99% of the GHG emissions from natural gas combustion are CO_2 emissions. In 2022, the combustion of natural gas generated 1,709 MMt CO_2e of GHG emissions in the United States. As shown in Figure 70, almost 70% of the emissions were from power plants and industrial facilities. The electricity sector generated 660 MMt CO_2e of GHG emissions, which accounted for 39% of the total CO_2 emissions from natural gas combustion.

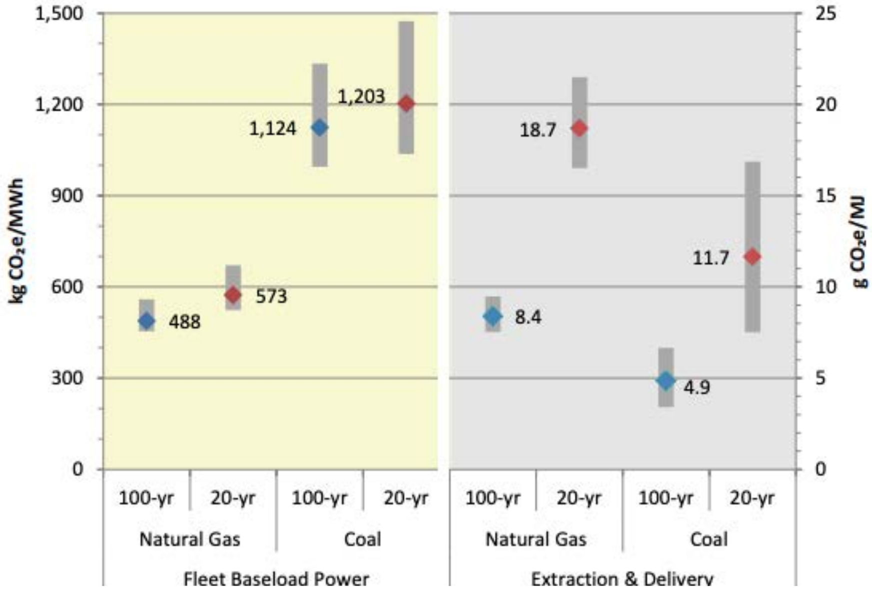
Figure 70. GHG emissions from natural gas combustion, United States, 2022



Source: EFI Foundation with data from EPA, Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2022, https://www.epa.gov/system/files/documents/2024-02/us-ghg-inventory-2024-main-text.pdf.

Natural gas-fired power generation is an effective way to reduce emissions when used to replace coal-fired power production. Due to the higher efficiency of power plants and lower carbon content of natural gas compared to coal, the life cycle GHG emissions of natural gas-fired power production is from 35% to 66% lower than those of coal-fired power production.[266] As shown in Figure 71, natural gas has higher GHG emissions than coal in the extraction and delivery phases but much lower GHG emissions in the power-production phase.[267]

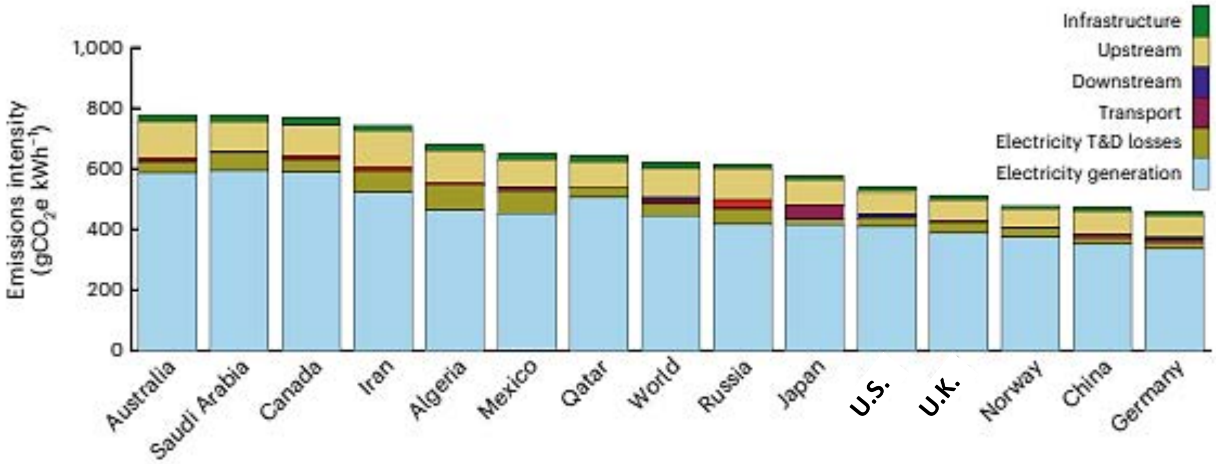
Figure 71. Natural gas and coal GHG emissions comparison



Source: Timothy Skone et al., "Life cycle analysis of natural gas extraction and power generation," National Energy Technology Laboratory, 2014, https://www.energy.gov/sites/prod/files/2019/09/f66/Life%20Cycle%20Analysis%20of%20Natural%20Gas%20Extraction%20and%20Power%20Generation%2005_29_14%20NETL.pdf

Emissions, however, vary among facilities, depending on energy efficiency and type of plant. A study on mitigation opportunities of natural gas-fired power identified a wide variance of emissions intensities from natural gas-fired power plants, ranging from 334 to 1,389 grams of carbon dioxide equivalent per kilowatt-hour (gCO_{2e}/kWh) across the 108 countries investigated (Figure 72).[268] The countries with high power-plant efficiencies and a high share of combined heat and power (CHP) plants tend to have lower emissions intensities. Many European countries, including Sweden, Finland, Estonia, and Poland, have the lowest emissions intensity of natural gas-fired plants, as all the plants are CHP plants, and the power plant efficiencies are high. The figure provides the basis for the start of a road map for areas of focus for different countries to reduce their emissions from natural gas power generation.

Figure 72. Supply chain GHG emissions of the world's largest natural gas producers and consumers

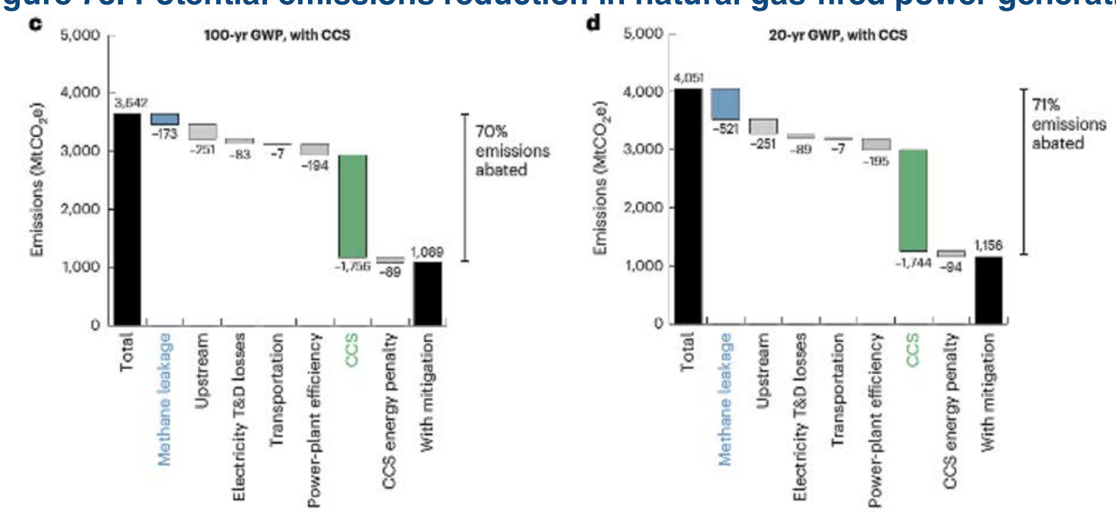


Source: Sarah M. Jordaan et al., "Global Mitigation Opportunities for the Life Cycle of Natural Gas-Fired Power," Nature Climate Change 12, no. 11 (2022): 1059–67.

Enhancing energy efficiency could be a near-term option to reduce the emissions from downstream combustion in natural gas-fired power production. The countries with plants with low energy efficiency should consider investing in energy-efficiency technologies and practices. The countries considering new natural gas-fired power plants should adopt advanced energy-efficiency technologies from the beginning of project construction.

For the midterm, an important and effective option for reducing emissions is CCUS technologies (Figure 73).[269] While energy efficiency enables about 5% of the emissions reduction, CCUS enables 43% of the emissions reduction of natural gas-fired power generation.[270] Life cycle emissions of natural gas-fired power could be mitigated, up to 71%, by deploying CCUS, efficiency upgrades, and methane abatement.

Figure 73. Potential emissions reduction in natural gas-fired power generation



GWP = Global Warming Potential. Source: Sarah M. Jordaan et al., "Global Mitigation Opportunities for the Life Cycle of Natural Gas-Fired Power," Nature Climate Change 12, no. 11 (2022): 1059–67.

Downstream Emissions from the Industrial Sector

The industrial sector is a global large consumer of natural gas. The portion of CO_2 emissions attributed to natural gas within the industrial sector has continued to expand in the United States. The substantial emissions reductions from coal-to-gas switching in the U.S. power sector have not been replicated in the industrial sector, in part because a significant percentage of industrial processes require a fuel and cannot yet be electrified. In 2022, the emissions in the U.S. industrial sector decreased by 2% because of a 3% decrease in industrial activity compared to 2021.[271]

The industrial sector is regarded as difficult to decarbonize because of the diversity of energy inputs and industrial processes and operations. In the United States, the industrial sector accounted for one-third of U.S. energy consumption and 30% of energy-related GHG emissions. Industrial-sector emissions are from four sources:

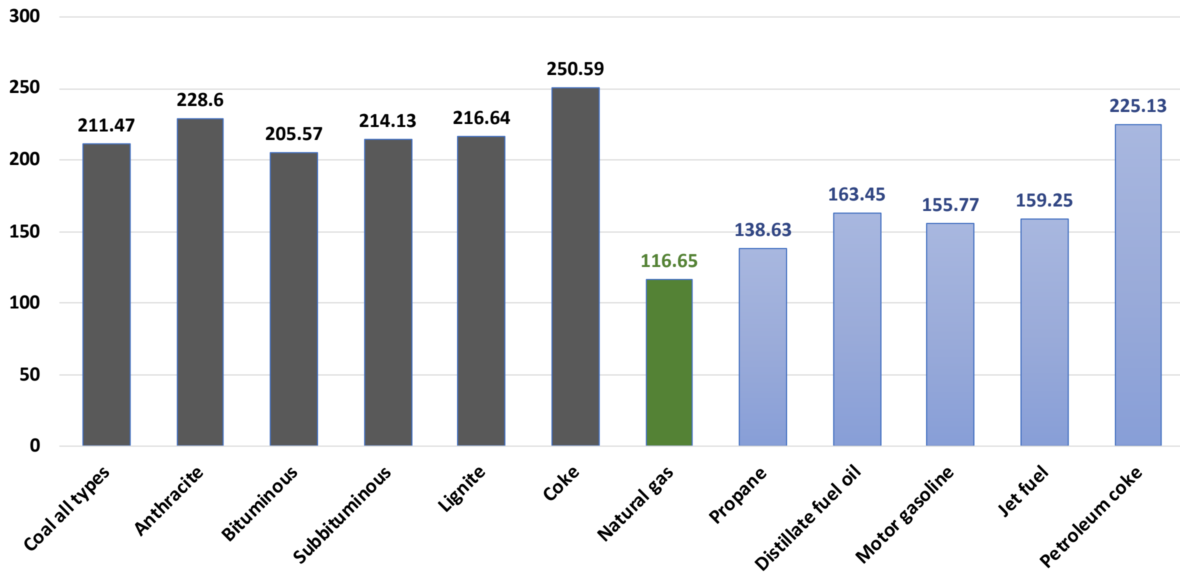
- Fuel-related emissions from the combustion and use of fuels
- Electricity generation emissions attributed to the electricity used at industrial facilities
- Industrial process emissions from industrial activities
- Life cycle emissions from manufactured products

This complexity of the emissions from industrial processes and associated challenges requires a comprehensive discussion. This is discussed in greater detail in Chapter 5.

Reducing GHG Emissions through Coal-to-Gas Fuel Switching

It is important to understand the CO_2 emissions intensity of a range of fuels. Figure 74 shows pounds of CO_2 emissions per 1 million British thermal units (Btu) across fossil fuel types/uses.[272] The differences between natural gas emissions and other fuels are stark. As seen in the figure, anthracite coal has 96% more pounds of CO_2 per million Btu than natural gas. Petroleum coke, used for industrial processes such as producing steel, graphite, and cement, has 93% more pounds of CO_2 per million Btu than natural gas.

Figure 74. Pounds of CO_2 emissions per million Btu for various fuels

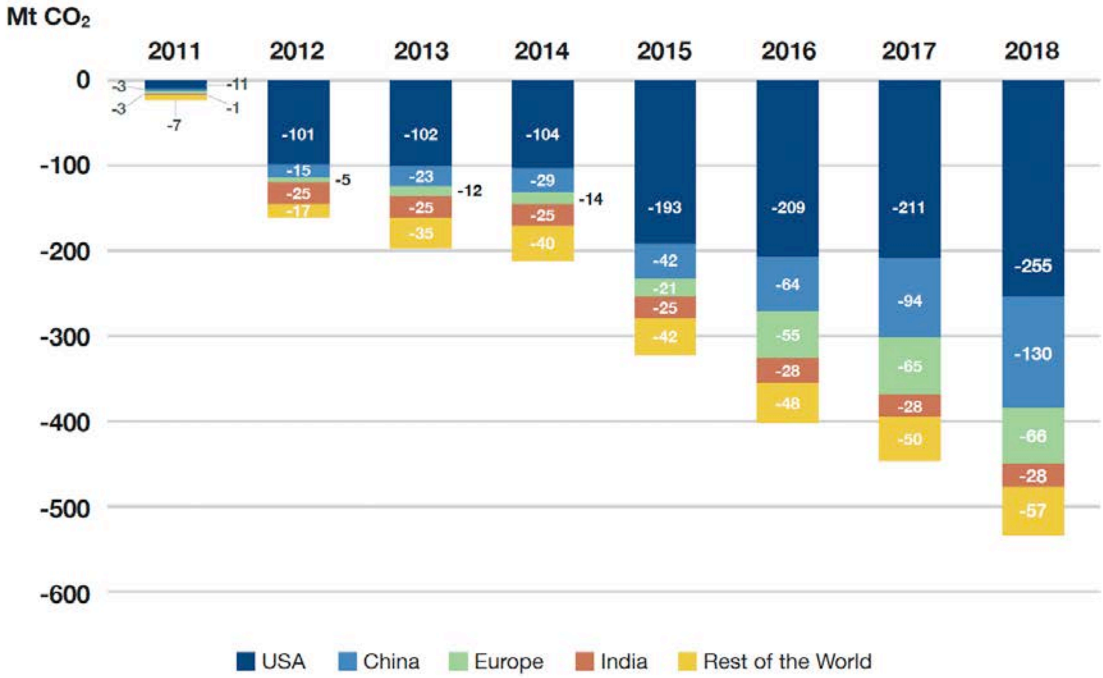


Source: EFI Foundation with data from EPA, "Emissions Factors for Greenhouse Gas Inventories," September 12, 2023, https://www.epa.gov/system/files/documents/2023-03/ghg_emission_factors_hub.pdf.

Natural gas has contributed to GHG emissions reductions by replacing coal which, as shown in Figure 75, has substantially higher CO_2 emissions than natural gas. Also as noted, on a global basis, coal emits more methane emissions than natural gas. In the United States, the CO_2 emissions from the electric power sector decreased by 32% between 2005 and 2019, largely driven by a shift from coal to natural gas in the electricity generation mix.[273] During this period, the share of coal dropped from 50% to 23%, and the share of natural gas increased from 19% to 38%.

Coal-to-gas switching has contributed to reducing CO_2 emissions worldwide, but its value (also discussed in previous chapter) has varied among different regions (Figure 75).[274] The largest emissions reduction from coal-to-gas switching occurred in the United States, whose share of CO_2 savings by coal-to-gas switching was 48% in 2018. In China, coal-to-gas switching contributed to reducing 130 Mt of CO_2 emissions in 2018. In other regions, including Europe and India, coal-to-gas switching has not yet been a main option for decarbonizing the energy system. On average, in 2018, coal-to-gas switching reduced GHG emissions by 50% for electricity generation and 33% for heat generation.[275]

Figure 75. CO_2 savings from coal-to-gas switching in selected regions compared to 2010, 2011-2018



Source: International Energy Agency (IEA), The Role of Gas in Today's Energy Transitions, July 2019, https://iea.blob.core.windows.net/assets/cc35f20f-7a94-44dc-a750-41c117517e93/TheRoleofGas.pdf.

Since many countries rely on coal for a significant percentage of their power generation, fuel switching from coal to natural gas has great potential to contribute to global GHG emissions reduction. In 2020, coal accounted for approximately 35% of electricity generation worldwide.[276] In addition, over the next several decades, coal is expected to remain a significant fuel for global power generation, especially in non-OECD Asia-Pacific countries. Fifty-five percent of all coal mines in development globally are in non-OECD Asia-Pacific countries.[277] China has 47 coal mines in development, India six, and Indonesia five.

Current State of Coal-to-Gas Fuel Switching

A global push to switch from coal to gas for power generation and industrial processes is showing how different countries will transition based on the existing energy mix and what is affordable. Two options qualify as coal-to-gas fuel-switching: The first option is "replacement"—building a new gas plant instead of a coal plant; the second option is "conversion"—converting an existing coal plant to a natural gas plant.

According to the Global Energy Monitor (GEM), the United States has more than 16.8 gigawatts (GW) of gas-fired power generation in development[r], of which 78.5% is conversion and 21.5% is replacement. The United States, however, is an outlier in this regard. According to GEM data, total

[r] GEM defines "in development" as announced, pre-construction, and construction.

global replacement of coal with natural gas is 72 GW compared to conversion, at 25.4 GW, an almost threefold difference. The United States is responsible for 52% of the total conversion globally.

Coal-to-gas fuel switching in Europe and Asia is predominantly replacement based. Asia has the largest amount of replacement-based coal-to-gas switching, at 52 GW, or 73% of the overall replacement total, of which China has 8.9 GW in development. South Korea and Taiwan have 12.8 GW and 13.9 GW, respectively, and Europe has 16 GW in development for replacement, compared to only 660 MW in development for conversion. Germany is responsible for 5.7 GW of this, with 100% being replacement. Sub-Saharan Africa had only 825 MW of conversion and zero replacement.

When comparing switching coal to gas plants, local market factors are important considerations for the cost, as gas prices and renewable Levelized Cost of Electricity (LCOE)[s] factor into this decision. As seen in Table 4, for some countries coal-to-gas switching measured by the carbon price to trigger a fuel switch decision from coal generation to gas generation is cheaper and for others, a coal-to-renewables switch is more affordable.[278,279]

Table 4. Cost comparison for coal-to-gas switching by country, as of April 2023

Country	Coal-to-gas conversion and replacement in development (GW)	Avg. Solar + Storage LCOE ($/MWh)	Avg. Onshore Wind + Storage LCOE ($/MWh)	Natural gas LRMC ($/MWh)	Carbon Price ($/tCO$_2$)	Cost for coal-to-gas switch ($/tCO$_2$)	Cost for coal-to-renewables switch ($/tCO$_2$)
China	8.9	$88	$70.40	$110.43	$10.09	$78.58	-$4.42
South Korea	12.8	$116	$165	$128.85	$11.41	$102.43	$34.49
Germany	5.8	$80.46	$86.40	$122.51	$102.04	-$7.45	-$67.45
United States	16.8	$87	$75.78	$24.67	N/A	-$2.79	$49.18

Note: The projects "in development" include the projects at announced, pre-construction, and construction phases. LRMC = long-range marginal cost.
Source: Global Energy Monitor, Transition Zero

Source: EFI Foundation with data from Global Energy Monitor (2022), https://globalenergymonitor.org/wp-content/uploads/2022/09/GEM-CoalToGas-Briefing-2022_v4.pdf, and Transition Zero (2023), https://static1.squarespace.com/static/63d1607c35efbd5cbfee1529/t/6412dbdae8b0fd509b69c59b/1678957532093/CCPI_Methodology_Doc.pdf.

In the United States, the cost of converting an existing coal plant to a natural gas plant is -$2.79/tCO$_2$, while the cost of a new plant is $14.71/tCO$_2$.[280] The cost of coal-to-gas switching is very low in the United States due to low gas prices, low cost of operating gas plants, and the project developers' use of existing electric power transmission and interconnection equipment, with an

[s] LCOE is used in this analysis as a method to determine whether to move forward with a project and to compare different energy-producing projects.

associated regulatory approval process that is faster and much less capital-intensive than building a new plant in an alternative location.[281]

The United States has a significantly higher coal-to-renewables switching cost compared to China, Germany, and South Korea, demonstrating that natural gas can be less expensive for reducing emissions in some regions relative to renewable energy resources (see Chapter 3 for a discussion of costs of NGCCs with CCUS relative to intermittent renewables with battery storage). For example, in 2022 in Indiana, a utility planned to convert two coal-fired units totaling 1,052 MW to natural gas in 2025, which was estimated to be $381 million less expensive over 20 years compared with replacing the generating station with renewable energy and storage.[282]

Ongoing Efforts for Reducing GHG Emissions

In the United States, enactment of the Inflation Reduction Act of 2022 (IRA) is a significant step for the clean-energy transition, providing financial backing for low-emissions technologies, including $5.8 billion for projects to reduce emissions in energy-intensive industries such as iron, steel, concrete, glass, pulp, paper, ceramics, and chemicals. The IRA also includes new and extensions of existing tax credits for wind, solar, and energy storage, contingent on project investment expenses and electricity generation. Additionally, it provides tax credits for local manufacturing and grid enhancements, as well as other types of support, including CCUS.

At the same time, the United States has provided tax incentives for oil and gas exploration and production. At a national level there have been discussions, however, about reducing these incentives to promote cleaner energy sources. As noted, the IRA and the expansion of tax credits have increased the interest of industry in developing decarbonization projects, primarily through CCUS.[283] First introduced in 2008, Section 45Q of the U.S. Internal Revenue Code provides a tax credit for CCUS. The tax policy is intended to incentivize the deployment of CCUS, and a variety of project types are eligible, including natural gas projects. In addition, the BIL, introduced in 2021, provides $12 billion of funding to carbon management, including $2.54 billion for demonstration capture projects and $2.5 billion in grant funding for large-scale sequestration projects.

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Also, some states incentivize renewable natural gas (RNG) production from organic waste sources and its transport via existing natural gas pipelines. RNG production costs are substantially offset by federal and state policy incentives, though scaling these sources to the equivalent scale of fossil natural gas would be a significant technical and infrastructure challenge. In addition, California's Low Carbon Fuel Standard (LCFS) program has incentivized growth in RNG projects both inside and outside the state, resulting in an uptick in RNG fuel crediting in recent years, demonstrating that local changes at least have the potential to carry past borders.[284]

Europe has also enacted various policies for the energy transition. On March 16, 2023, the European Commission introduced the Net-Zero Industry Act (NZIA), aimed at bolstering Europe's manufacturing capabilities for net-zero technologies, surmounting obstacles to scaling up manufacturing in the region, enhancing the competitiveness of the net-zero technology sector, and reinforcing the EU's energy resilience. This proposal underscores Europe's dedication to spearheading the transition toward net-zero technologies and contributing to achieving the Fit-for-55 and REPowerEU goals.[285,t] The EU has developed an Emission Trading System (ETS) that places a price on carbon emissions and encourages industries to reduce their GHG emissions, indirectly incentivizing cleaner natural gas technologies. Also, the EU has set renewable energy targets to increase the share of renewable energy sources in the energy mix, which can affect natural gas consumption within its borders.

The EU is actively working on developing and implementing a Carbon Border Adjustment Mechanism (CBAM) as part of its broader climate policy framework.[286] The CBAM, designed to go into effect in 2026, is another EU policy tool designed to specifically address carbon leakage and promote climate action by placing tariffs on certain imported goods based on their carbon content. This import tax is imposed on importers when these products enter the EU. The CBAM's goal is to help ensure that imported products are subject to a carbon pricing mechanism like those imposed on domestic products, thereby preventing companies from avoiding emissions regulations by relocating production to countries with lower environmental standards. The goods covered by the CBAM are

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[t] Fit for 55 aims to reduce GHG emissions by at least 55% by 2030. The REPowerEU plan aims to rapidly reduce dependence on Russian fossil fuels by 2027 and accelerate the green transition and increase the resilience of EU energy systems.

cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, all of which are either made or generated with substantial volumes of fossil fuels, including natural gas. Other regions and countries have also expressed interest in similar mechanisms. Notably, this mechanism involves acquiring certificates representing the carbon emissions embedded within the goods.

The pricing of these certificates will be determined by referencing the prevailing carbon price within the EU ETS.[287] On May 16, 2023, the CBAM Regulation was published in the EU's Official Journal. Over eight years, the CBAM will also gradually replace the free allowances given under the EU ETS.[288]

Other countries, and smaller administrative units, have policies on carbon pricing mechanisms and incentives for emissions reductions that affect or could affect natural gas supply and demand. These policies demonstrate the variety of approaches taken by different countries to balance natural gas development with decarbonization efforts. Canada has implemented a carbon pricing system, which includes a carbon tax in some provinces. This incentivizes industries to reduce emissions, including those from natural gas operations. California and Quebec linked their cap-and-trade systems in 2014. The system covers fossil fuel combustion and industrial emissions in power, buildings, transport, and industry. The resulting carbon trading market is now the largest in North America and has generated revenue of over $7.3 billion for Quebec.[289]

China provides subsidies for the use of natural gas in lieu of coal for heating and power generation, with a focus on improving air quality. These subsidies cover equipment installation costs and fuel prices. These incentives are projected to increase China’s natural gas imports between now and 2050. China is also on a trajectory to increase coal consumption through 2030.

Some European countries are also working on using natural gas in environmentally responsible ways. Norway has, for example, developed a blue hydrogen strategy to utilize natural gas in hydrogen production while capturing and storing carbon emissions.[290]

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Carbon Pricing

The global energy and supply chain crises from the COVID-19 pandemic and Russia’s invasion of Ukraine posed significant challenges for energy markets and the world economy in 2022. Governments have responded with measures to shield consumers from price hikes, adding to fiscal pressures accumulated during the pandemic. In this context, the political ramifications of implementing direct carbon pricing policies have become more complex.

To drive the transformational change needed to meet Paris targets and net-zero goals, analysts generally agree that carbon pricing is essential. Options that could serve as models include ETSs, carbon taxes and carbon crediting, and international carbon markets (Figure 76).[291] As seen in the figure, there is wide variation in carbon prices across the various trading systems. This could be problematic in global efforts to reach net zero. Accurate, standardized methodologies for calculating emissions are needed to ensure accurate pricing, including for international shipping and trading. The World Bank supports many countries engaged in the full range of carbon pricing policies—including through the Partnership for Market Implementation program, which provides technical assistance for domestic carbon pricing and operationalizes Article 6 of the Paris Agreement.[292]

Figure 76. Price evolution in selected ETSs from 2018 to 2023

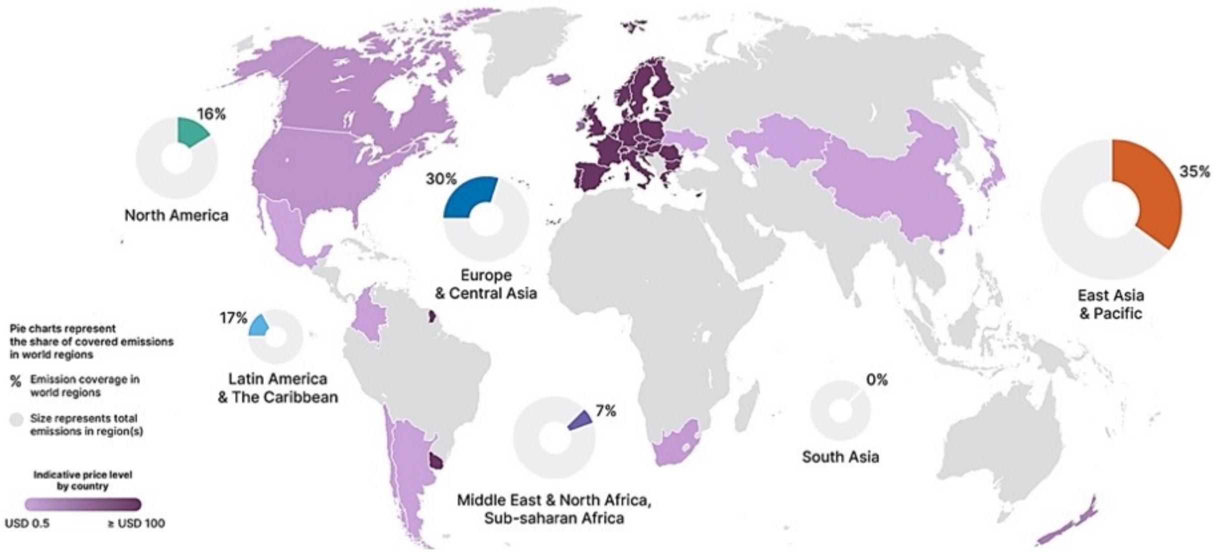
Source: World Bank Group, State and Trends of Carbon Pricing 2023, [https://openknowledge.worldbank.org/entities/publication/58f2a409-9bb7-4ee6-899d-be47835c838f.](https://openknowledge.worldbank.org/entities/publication/58f2a409-9bb7-4ee6-899d-be47835c838f)

Direct carbon pricing policies are described by advocates as efficient and effective climate mitigation policy, but their uptake and impact depend on many factors. As of April 2023, direct carbon taxes cover less than 5% of global emissions.[293] ETSs combined with carbon taxes in operation cover around 23% of global GHG emissions, a relatively small percentage of global emissions despite the expanding scope of some policies and new instruments being implemented. This is also a result of the fact that GHG emissions are decreasing in most jurisdictions that have implemented a carbon tax or ETS.[294]

A carbon price provides an economic signal, allowing investors and markets to determine where emissions can be reduced at the lowest cost. In considering these policies, governments must weigh the political and economic implications of the different options, how they will affect consumers (particularly through energy prices), how they will affect government revenue, and the urgency of reducing emissions.[295]

Also, because price reflects costs, accurate emissions methodologies are essential for providing the signals needed for markets. Figure 77 shows carbon price levels by country and both carbon tax and ETS coverage by region.[296] The pie charts in the figure represent the percentage of emissions covered by both taxes and ETS. Most of the implemented instruments exist in high-income countries in North America and Europe at the national, subnational, or regional level. However, there has been a growing interest in carbon taxes and ETSs in emerging economies, driven by the opportunity for raising revenue or preparing for the EU's implementation of the CBAM.[297]

Figure 77. Map of carbon price levels and coverage of implemented carbon taxes and ETSs

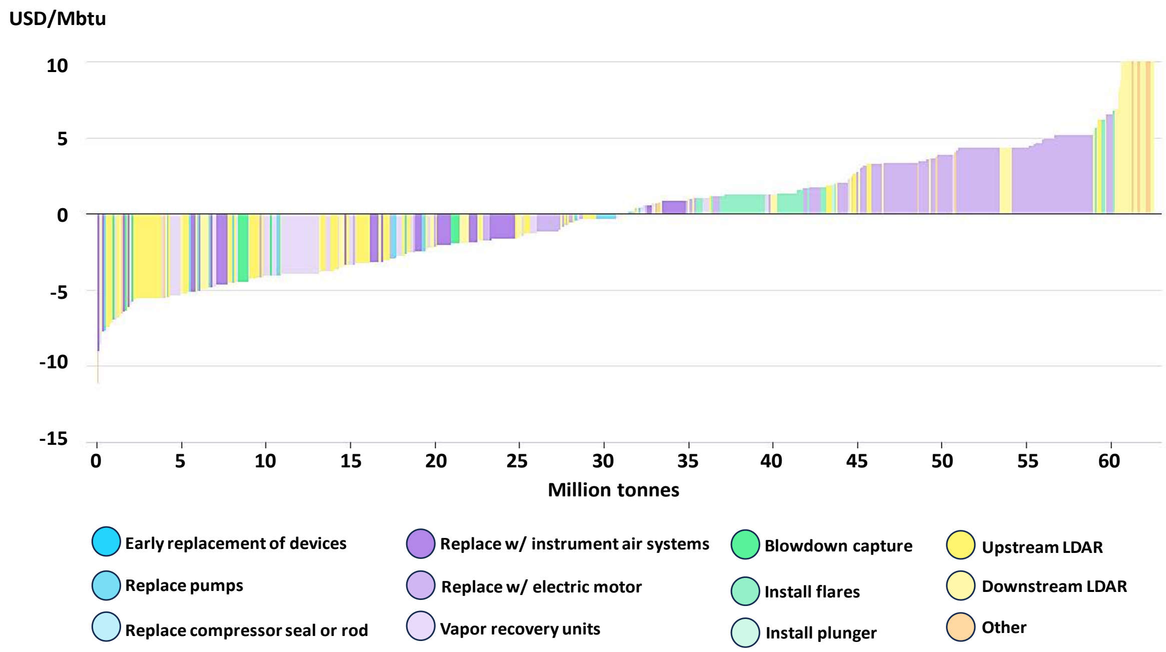


The colored section is the share of emissions in the country covered by national, regional, or subnational carbon taxes or ETSs, not necessarily national schemes only. The size of each regional pie chart represents the total emissions in the corresponding region. Source: World Bank Group, State and Trends of Carbon Pricing 2023, https://openknowledge.worldbank.org/entities/publication/58f2a409-9bb7-4ee6-899d-be47835c838f.

Methane Abatement

Capturing methane emissions could be a cost-effective option for reducing emissions in the oil and gas sectors. According to IEA, more than 75% of methane emissions from oil and gas operations could be reduced with existing technology, including, for example, leak detection and repair (LDAR). As shown in Figure 78, substantial portions of methane emissions can be reduced with a negative cost, as the additional methane recovered by adopting the technology can often be sold, and the value received for the methane sold is greater than the cost of the technology.[298,299] The IEA estimates that almost all available abatement measures would be cost-effective with a carbon price of \$20/tCO_2e.[300]

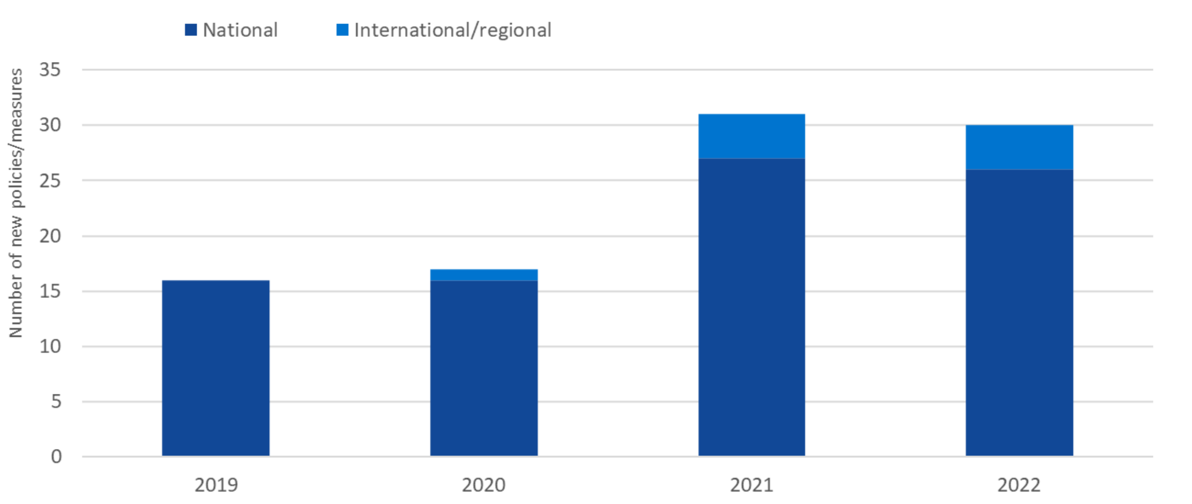
Figure 78. Methane abatement cost curve in the oil and gas sector, world, 2022



Source: *IEA, "Marginal Abatement Cost Curve for Oil and Gas Methane Emissions by Mitigation Measure," 2022,* https://www.iea.org/data-and-*statistics*/charts/marginal-abatement-cost-curve-for-oil-and-gas-methane-emissions-by-mitigation-measure-2022.

There are a growing number of initiatives, policies, and regulations to reduce methane emissions in oil and gas operations. As noted, the Global Methane Pledge, launched at COP26 in 2021, commits countries to reducing methane emissions from all sectors by at least 30% by 2030 compared to 2020 levels. The pledge has been endorsed by 150 countries and has led to diverse international, national, and industry efforts to drive methane reductions. The number of new national policies for methane abatement had increased to 27 in 2022 from 16 in 2020 (Figure 79).[301]

Figure 79. Number of new policies and measures related to methane abatement, 2019 to 2022



Source: EFI Foundation with data from IEA, "Policies Database," *https://www.iea.org/policies?topic%5B0%5D=Methane%20abatement&year=desc&page=5*.

Following the Global Methane Pledge, the Global Methane Pledge Energy Pathway was launched in 2022 by the United States, EU, and 11 other countries to catalyze methane emissions in the oil and gas sector. The United States, EU, and five other countries also committed in 2022 to creating an international market for fossil energy "that minimizes flaring, methane, and CO_2 emissions across the value chain to the fullest extent practical."[302] Countries have also introduced policies for methane abatement. For example, the United States introduced several policies in 2022, including the Methane Emissions Reduction Action Plan, the EPA's proposal to reduce methane in oil and gas operations, and funding for methane abatement (Table 5).[303]

Table 5. International, regional, and national initiatives/policies for methane abatement, 2019 to 2022

	2019	2020	2021	2022
International/ regional policies	N/A	An EU strategy to reduce methane emissions	• Global Methane Pledge • Proposal for an EU regulation on methane emissions reduction in the energy sector • Technical Regulations of the Eurasian Economic Union on the requirements for main pipelines for the transportation of liquid and gaseous hydrocarbons • U.S.-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s	• Global Methane Pledge Energy Pathway • Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels • EU external energy engagement in a changing world • European Union and Azerbaijan memorandum of understanding to increase energy cooperation
U.S. federal policies	N/A	Protecting Our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act of 2020	• Infrastructure Law funding for Abandoned Mine Land Grant Program • Advanced Research Projects Agency Energy (ARPA-E) "Reducing Emissions of Methane Every Day of the Year" (REMEDY) program	• Methane Emissions Reduction Action Plan 2022 • Inflation Reduction Act 2022: Sec. 60113 and Sec. 50263 on methane emissions reductions • Inflation Reduction Act 2022: Sec. 60105 funding to address air pollution (to the EPA) • EPA proposal to reduce methane and other harmful pollution from oil and natural gas operations • DOE funding to reduce methane emissions from the oil and gas sector • BLM proposed waste prevention rule RIN 1004-AE79

Source: EFI Foundation with data from IEA, "Policies Database," https://www.iea.org/policies?topic%5B0%5D=Methane%20abatement&year=desc&page=5.

Ongoing initiatives and policies focus on tackling two key challenges to reducing methane emissions: the gaps in actionable data on actual methane emissions and the lack of motivation to invest in emissions reduction.

Methane emissions need to be measured to be mitigated, but it has been difficult to accurately measure them. To address this challenge, the United Nations Environment Programme (UNEP) launched the International Methane Emissions Observatory (IMEO) at the G20 Leaders' Summit in 2021, aiming to provide open, reliable, and actionable data to reduce 150 Mt of methane emissions by 2030. The IMEO integrates methane data from scientific studies, satellites, national inventories, and industry reporting through the Oil & Gas Methane Partnership 2.0 Framework. Satellites are becoming critical tools for providing timely and actionable data. In 2022, IMEO launched the

Methane Alert and Response System (MARS), a system notifying stakeholders of large methane emissions events using existing satellites.

Other initiatives include GHGSat, EnMAP, Carbon Mapper, SBG, CHIME, EMIT, and MethaneSAT. For example, GHGSat, a satellite-based emissions monitoring company, has detected, monitored, and measured methane emissions from oil and gas facilities using its nine satellites. Recently, GHGSat, with OGCI and Carbon Limits, conducted a pilot study in six oil fields in Iraq from late 2021 to 2022, resulting in observing 175 sources of methane emissions and quantifying emissions rates for more than 80% of the satellite observations. They plan to expand this pilot project to 20 more sites. MethaneSAT, a subsidiary of the Environmental Defense Fund, launched its own satellite in March 2024 to track methane emissions from oil and gas operations worldwide, including thousands of smaller sources of methane emissions. The data collected by MethaneSAT will be accessible to the public free of charge; thus, operators worldwide could find and fix problems in their operations quickly, and the stakeholders could monitor the progress of emissions reduction in each operation.

After accurate measurement the next step should be mitigation. Many countries in recent years have introduced or have planned policies and regulations to mitigate methane emissions. These include the United States, where there has been a proliferation of methane policies in recent years. In December 2023, the EPA finalized new rules to reduce emissions of methane and other harmful air pollution from new and existing oil and gas operations, requiring oil and gas production facilities to stop venting and flaring methane, capture the methane, or be required to monitor and report. The rule also includes stricter standards on oil and gas production equipment and compressor stations, especially for methane leak detection. The IRA includes an introduction of a charge on methane emitted by oil and gas companies that report emissions under the Clean Air Act, starting at $900 per metric ton of methane for 2024 and increasing to $1,500 per metric ton from 2026. The IRA also includes a $1.55 billion fund for financial and technical assistance to improve methane monitoring and to reduce GHG emissions, including methane, CO_2, and air pollutants. Following this, the EPA and DOE announced that they would provide up to $350 million in funding to eligible states to assist the industry in reducing methane emissions from low-producing conventional wells in July 2023.

Since LNG is globally traded, a number of countries have committed together to reducing GHG emissions across the global LNG value chain. In August 2023, the U.S. and 10 other countries affirmed their commitment to support international public-private coordination on GHG reduction, especially methane reduction, across the LNG value chain.[304] A month earlier, Japan and South Korea launched the Coalition for LNG Emission Abatement toward Net-zero (CLEAN). The EU and Japan will support CLEAN by creating a globally aligned methane emissions assessment of LNG projects and facilitating the collection of information on methane leakage and methane reduction targets.

In this regard, it should also be noted that there are methane emissions associated with LNG shipping. A recent study that measured both CO_2 and methane emissions on a single LNG tanker concluded that using a global warming potential (GWP) of 100 years equivalent, methane accounted for 35% of the total GHG emissions; when a 20-year GWP was used, methane represented 56% of the emissions from the ship. Total methane emissions from the shipping accounted for 0.1% of the delivered LNG.[305]

Industry or multistakeholder initiatives have also been accelerated. In December 2023, the Oil and Gas Decarbonization Charter (OGDC), a voluntary commitment launched at COP28 to accelerate climate action in the oil and gas sector, was signed by 50 leading oil and gas companies, pledging to eliminate routine flaring and reach near-zero methane emissions by the end of the decade. The signatories include several international companies, including ExxonMobil, BP, and Shell, and several national oil companies, such as Saudi Aramco, ADNOC, Petrobras, and Petronas. In total, these companies represent about 40% of global oil and gas production. On the data front, UNEP has led the Oil & Gas Methane Partnership (OGMP), a program that has been setting standards for methane emissions reporting, since 2014. In 2020, OGMP became OGMP 2.0 pursuing a more ambitious and comprehensive reporting framework. More than 130 companies representing almost 40% of the world's oil and gas production have joined OGMP 2.0.

In August 2023, the U.S. and 10 other countries affirmed their commitment to international public-private coordination on GHG reductions, especially methane reduction, across the LNG value chain. A month earlier, Japan and South Korea launched the Coalition for LNG Emission Abatement toward Net-zero (CLEAN). The EU and Japan will support CLEAN by creating a globally aligned methane emissions assessment of LNG projects and facilitating the collection of information on methane leakage and methane reduction targets.

Reducing CO_2 Emissions

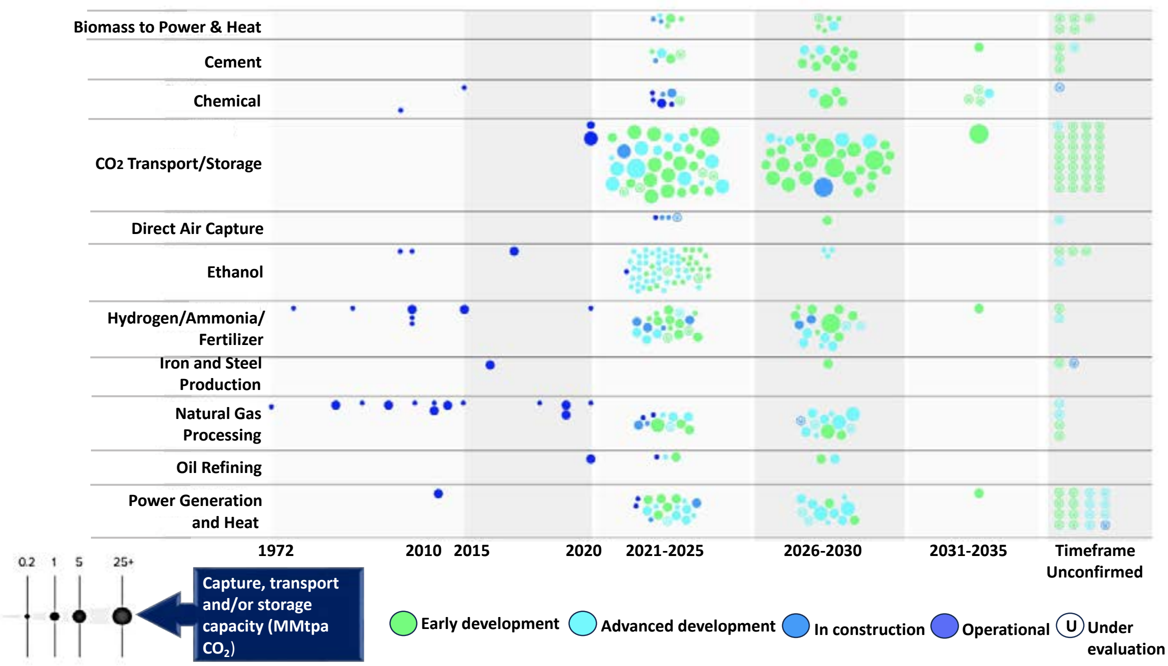
Deploying CCUS, electrifying operations, and alternative fuels such as hydrogen are the possible ways to mitigate CO_2 emissions from the natural gas supply chain. Among these options, CCUS has been regarded as an option with the most significant potential to reduce CO_2 emissions throughout the natural gas supply chain.

CCUS can be applied across the natural gas supply chain. It has already been used in upstream gas processing. As of July 2023, 15 CCUS projects in natural gas processing were in operation worldwide. Separating impurities, including CO_2, from the produced gas results in a concentrated stream of CO_2, which is easy to capture, transport, and store. The IEA estimates that capturing and storing the CO_2 in natural gas processing would cost \$15/tCO_2 to \$30/tCO_2. No LNG liquefaction facility has used CCUS, but potentially, CCUS could reduce about 90% of emissions from a liquefaction facility, with an average cost of \$40/tCO_2.[306]

Also, 95% of the hydrogen produced in the United States is made via natural gas reforming. Natural gas reforming is regarded as a critical near-term pathway for hydrogen production. Among the seven U.S. regional hydrogen hubs announced in October, three plan to use natural gas to produce hydrogen. Producing hydrogen from natural gas requires significant mitigation of methane and CO_2 in the production process. To meet DOE's definition of clean hydrogen, the emissions from hydrogen production should be less than two $kgCO_2e$ per kilogram of hydrogen produced. This standard requires hydrogen production from natural gas to emit almost zero methane and capture and sequester more than 90% of CO_2 emissions.[307]

There are, however, higher barriers to CCUS. Most CO_2 emissions in the natural gas system come from combustion in gas-fired power plants or industrial facilities. As of July 2023, there were no natural gas-fired power plants with CCUS in operation worldwide. Sixteen CCUS projects in natural gas-fired power plants are at the advanced development phase with one coal-fired power plant with CCUS in operation (Figure 80).[308] A key barrier is high costs. According to EFI's analysis, the cost of the first-of-a-kind CCUS in a natural gas-fired power plant would be around $120/metric ton, which is much higher than the current baseline level of 45Q tax credit, $85/metric ton; the costs of CCUS applications in heavy industries, including cement, pulp and paper, steel, refineries, and ammonia, are also much higher than the value of 45Q tax credit.[309]

Figure 80. CCUS projects pipeline by industry and year of operational commencement



MMtpa is million metric tons per annum. Source: Global CCS Institute, Global Status of CCS 2023: Scaling Up Through 2030. https://www.globalccsinstitute.com/resources/publications-reports-research/global-status-of-ccs-2023-executive-summary/.

Currently, the 45Q tax credit is the only federal cost reduction option for CCUS in the United States. Without additional support or a mandate, including a carbon tax or price, industry will not be motivated to invest in deploying CCUS in natural gas-fired power plants or industrial facilities. In addition, CCUS also faces infrastructure, regulatory, and community-acceptance barriers, which are amplified because of the complex supply chain of CCUS.

The possibility of electrifying upstream gas operations is another option for mitigating life cycle CO_2 emissions from gas systems. Diesel- and pneumatic-powered equipment is commonly used to provide the energy needed for extraction. The IEA estimates that electrifying facilities could technically reduce 400 $MtCO_2$, almost three-quarters of the emissions from upstream energy use, in 2030.[310] The remainder includes operations that are impractical for full electrification. However, no large-scale actions of electrifying upstream operations have been observed worldwide except for a couple of examples. Unlike methane emissions reduction, most electrification options are costly; thus, additional policy measures are required to motivate the natural gas industry to invest in electrification.

Differentiated Natural Gas and Carbon Neutral LNG

Differentiated natural gas (DNG) is natural gas that has undergone independent certification to verify its environmental attributes. It is also referred to as certified natural gas or responsibly sourced natural gas. DNG is verified using standards developed by independent third parties to measure GHG emissions or other environmental attributes. Since the first DNG transaction in 2018, the certified volume of gas has grown in the United States. As of mid-2023, multiple certification providers have certified 42 Bcf/d of U.S. natural gas production.[311] The major certification providers include two nonprofit organizations—Equitable Origin and MiQ—and one for-profit organization—Project Canary.

DNG has yet to contribute to substantial mitigation of the environmental impacts of natural gas for two reasons. First, certification programs have been developed on an ad hoc basis without standard certification requirements. Less-rigorous certification enabled a broader participation but, at the same time, has raised concerns about DNG as a “greenwashing” tool.[312] For the certification programs to be credible, standardized measurement, reporting, and verification methodologies of GHG emissions—including direct measurement of methane emissions rather than using emissions factors—are required.[313] Second, natural gas buyers have not been strongly motivated to purchase more-expensive DNG, as no incentives or regulations motivate them to select DNG over non-DNG.[314]

LNG producers have started to offer customers carbon-neutral LNG cargo, which neutralizes the emissions from LNG production by purchasing carbon offsets, which mean reduction or removal of GHG emissions to compensate for emissions made elsewhere.[u] The first carbon-neutral LNG cargo was transacted in 2019, and as of January 2022, 35 transactions have been made.[315] Many LNG suppliers, including Shell, Total, Jera, Mitsui, Gazprom, PWE, and Vitol, have started or planned to offer carbon-neutral LNG. In March 2021, 15 Japanese companies launched an alliance of carbon-neutral LNG buyers.

The mechanisms of carbon-neutral LNG vary. The scope of offsets could be the life cycle emissions, from wellhead to end use, or partial life cycle emissions, from wellhead to delivery. It could be a single-cargo transaction or term contract. The carbon credits used also vary from afforestation to renewable energy.

One of the challenges to scaling up carbon-neutral LNG is the lack of robust and transparent GHG emissions accounting practices. To offset the emissions, the emissions of each cargo should be calculated using detailed accounting methodologies since the emissions intensity varies widely by

[u] Carbon offsets are tradable rights linked to activities lowering the amount of CO_2 in the atmosphere. The types of offsets include renewable energy development, energy efficiency, reforestation, and carbon-storing agricultural practices.

supply chain. The LNG industry started developing and publishing detailed methodologies for emissions accounting, but they are not yet common practice in the industry.[316]

A more fundamental challenge is that using carbon offsets from technologies such as carbon dioxide removal, including direct air capture, is eventually a secondary option rather than an actual emissions mitigation option. The natural gas industry still needs to prioritize reducing methane and CO_2 emissions in its supply chain over purchasing offsets. The Monitoring, Reporting, Verification and GHG Neutral LNG Framework developed by the International Group of Liquefied Natural Gas Importers (GIIGNL) clarified that the use of offsets compensates for "residual" emissions that cannot be reduced.[317] Offsetting the emissions from natural gas assets requires a tremendous number of offsets, and current carbon offset markets cannot supply them. Moreover, offsetting emissions by purchasing carbon credits produced far from the infrastructure would not help garner local social acceptance of natural gas infrastructure. Communities' health concerns due to methane or NOx emissions from natural gas infrastructure in their communities cannot be addressed by purchasing carbon credits.

Turning Potentials and Commitments into Actions

Despite the proliferation of initiatives and commitments described above, global methane and CO_2 emissions reductions from natural gas systems are not substantial yet. Global methane emissions from natural gas systems have decreased only marginally since the record high in 2019. Global CO_2 emissions from natural gas have consistently increased in the past few years except for a slight decrease due to decreasing energy demand under the COVID-19 pandemic and supply disruption sparked by Russia's invasion of Ukraine.

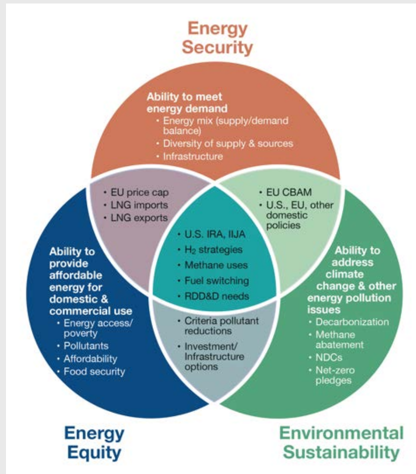
As noted, since most international commitments, national policies, and industry initiatives to reduce methane emissions were introduced after the launch of the Global Methane Pledge in 2021, it may take time for them to result in significant methane mitigation. Given the urgency for methane reduction, however, the commitments and action plans should turn into detailed policies and regulations to provide a clear signal to the natural gas industry.

Industry has also been supporting direct regulations to reduce methane emissions. In response to the EPA's announced regulations to address methane emissions in the oil and gas industry, many companies, including Exxon, BP, and Oxy, showed support for direct federal methane regulation.[318] As well as accelerating the implementation of domestic policies or regulations, countries should continue to collaborate with one another for methane abatement to accelerate the implementation of international commitments and planned actions.

Reducing CO_2 emissions from natural gas systems also remains a major concern. Technologies exist for reducing CO_2 emissions from gas systems—CCUS and hydrogen—but deployment of the necessary infrastructure, and associated regulations, are at the early stages and need more policy support. The United States has been making investments in both pathways recently via BIL and IRA. The goal is for these investments to aid in scaling up CCUS and hydrogen infrastructure through detailed policies, regulations, and incentives that are positive signals for increased private-sector investments. Building upon these efforts, the United States could lead dissemination of knowledge, technology, and lessons learned from the demonstration of CCUS and hydrogen worldwide.

5. Industrial Decarbonization

Findings in Brief



- The industrial sector is a major contributor to the global gross domestic product. In 2022, the steel, aluminum, and pulp and paper markets had a combined value of over $2.2 trillion; and in 2017, the chemical industry's contribution to global GDP was almost $6 trillion, the equivalent of 7% of global GDPA continuous growth of global primary energy consumption is expected for the long term, especially in emerging markets and developing countries.
- Concrete, steel, aluminum, and iron are essential materials for construction and building renewable generation technologies (e.g., wind turbines), as is glass. Ammonia, as a key component of fertilizer, is essential for food security.
- The industrial sector is a major energy consumer and accounts for nearly one-quarter of global carbon emissions. Absent enhanced policies, actions, and affordable technologies, the industrial sector will remain one of the leading sources of increases in CO_2 emissions.
- Natural gas could play a continued and evolving role in decarbonizing the industrial sector since many industrial decarbonization options are in the early phases of commercialization.
- Over 30% of industrial processes require high-temperature process heat which, in turn, requires a fuel for economic operation.
- While technical challenges remain for decarbonizing high-heat industrial processes, lower-temperature process heat needed in certain segments of industrial manufacturing shows promise for near-term opportunities for potentially zero- and low-carbon heat sources such as low-carbon electricity. It is, however, important to consider full life cycle emissions in qualifying reductions in emissions.
- No single option enables deep decarbonization of the industrial sector. The U.S. Industrial Decarbonization Roadmap, the path to net-zero industrial emissions for five U.S. carbon-intensive subsectors, identified that CCUS, industrial electrification, low-carbon fuels/feedstocks/energy sources (including hydrogen), and enhancing energy efficiency should be adopted altogether to decarbonize the U.S. industrial sector.
- Coal-to-gas switching can serve as an intermediate step to decrease the carbon footprint in the industrial sector while more advanced technologies are developed to further reduce the sector's carbon footprint.

- Many industrial decarbonization options are in the early phases of commercialization.
    - Technologies for electrifying industrial manufacturing processes requiring high-temperature heat are mostly in the research or pilot phases and have significant economic challenges.
    - The costs of electrification could be high since electricity is significantly more expensive than natural gas in many regions and countries. These cost differentials could affect the competitiveness of industrial products globally.
    - Hydrogen is not yet available in volumes sufficient to meet large-scale supply or demand needs, and green hydrogen costs are high.
- CCUS, in combination with natural gas use, could be one of the most effective ways to reduce a significant amount of the emissions from industrial facilities. Realization of this technology is also in development, with multiple barriers to overcome in scaling up use.
- Possible technology development timelines vary (20 to 40+ years) for several of the options (electrification, green hydrogen, CCUS) listed in this chapter to be realized commercially and applied widely.
- Green steel projects could have a higher impact on emissions if China and India focus on decarbonizing production of high-volume, low-margin structural steel products. This contrast of business with Western low-volume, high-margin steel business highlights that cost will be a major issue with implementing a change to green steel in the near term.
- This section includes case studies of four industry subsectors—glass, cement, steel, and ammonia—that highlight the immense challenges to decarbonizing the industrial sector and the importance of navigating multiple decarbonization pathways, including an evolving use of natural gas.

According to the U.S. Energy Information Administration (EIA), “The industrial sector consists of all facilities and equipment used for producing, processing, or assembling goods.” The industrial sector includes manufacturing, agriculture, construction, fishing, forestry, and mining (which includes oil and natural gas extraction). Industry uses fossil fuels and renewable energy sources for: heat in industrial processes and space heating in buildings; boiler fuel to generate steam or hot water for process heating and generating electricity; and as feedstock for manufacture of products such as plastics and chemicals.[319]

The industrial sector is, not surprisingly, a major contributor to the global gross domestic product (GDP). In 2022, for example, the steel, aluminum, and pulp and paper markets had a combined value of over $2.2 trillion. In 2017, the chemical industry’s contribution to global GDP was almost $6 trillion, the equivalent of 7% of global GDP. Concrete, steel, and iron are essential materials for construction and building renewable generation technologies (e.g., wind turbines), as is glass. Ammonia, as a major ingredient for making fertilizer, is essential for food security.

Natural gas is a key energy source and ingredient in industrial manufacturing. Natural gas is a key feedstock (a fuel used as a chemical input to industrial processes),[320] provides affordable high heat needed for these many of these processes, and supplies electricity for industrial processes that can currently be affordably electrified.

Given the complex value chain of critical industrial manufacturing sectors, the value to national economies and jobs, and the lack of current commercialized, deployed, and affordable technologies for high-heat electrification of a significant percentage of industrial processes, it is likely that natural gas will continue to play a significant role. DOE's Industrial Decarbonization Roadmap, for example, shows that even in 2050, natural gas will continue to account for a significant share of the energy consumption of key, albeit carbon-intensive, industrial subsectors.

Industry is also a leading greenhouse gas (GHG) emitter, with around 9.2 billion metric tons (Gt) of CO_2 in 2022.[321] GHG emissions from the industrial sector are nearly one-quarter of global carbon emissions. The industrial sector will be one of the leading sources of increases in CO_2 emissions in the future, particularly for developing economies. The relative contribution of developing countries to industrial emissions has been increasing rapidly, with the highest rate of growth in industrial energy use occurring outside the Organization for Economic Co-operation and Development (OECD) countries.

In the near term, natural gas will continue to be a decarbonization option for the regions that are the focus of this analysis. Technologies for industrial processes that require high-temperature heat are either unavailable or in the early stages of commercialization. Green hydrogen could, for example, replace natural gas as the fuel used to achieve the high temperatures required for approximately 40% of key industrial processes. Green hydrogen is, however, very expensive to produce and lacks both production and distribution infrastructures needed to meet the scale of such requirements. Also, its expense would have an impact on the prices and competitiveness of key industrial products.

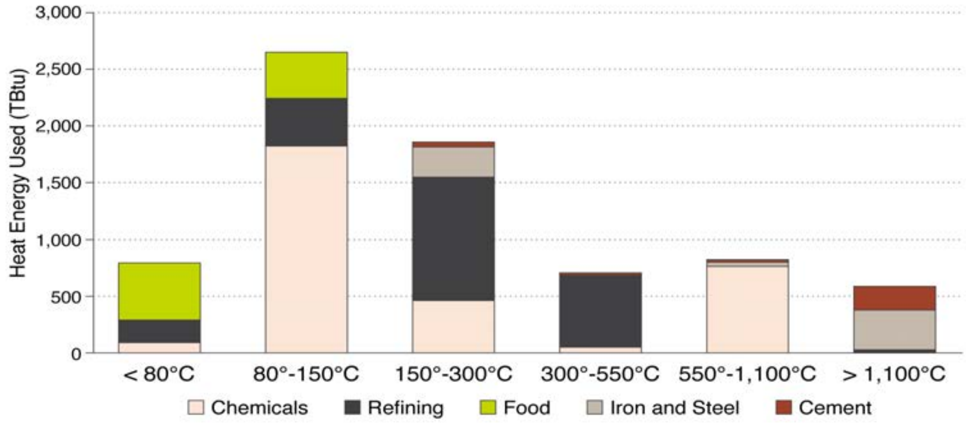
For the mid and long term, and assuming technologies are developed that affordably enable electricity to provide the high heat needed for some industrial processes, natural gas could still contribute to industrial decarbonization by providing backup to intermittent energy sources. As shown in Figure 95 (page 164), however, U.S. electricity prices, while they vary by region, are substantially higher per unit of energy than natural gas; electricity prices would need to be substantially reduced to maintain the competitiveness and affordability of a range of U.S. industrial products. In addition, natural gas could continue to serve as a feedstock of hydrogen production or be used in conjunction with CCUS at industrial facilities.

This chapter analyzes the role of natural gas in industrial decarbonization, examining the decarbonization options for the overall industrial sector, as well as case studies of four industrial subsectors—glass, steel, cement, and ammonia.

Industrial Heat Requirements

Industry processes need different levels of heat. The use of lower-temperature process heat, typically below 300 degrees Celsius, is widespread in subsectors like chemicals, food production, and refining (Figure 81).[322] This highlights the potential for low-carbon or carbon-free technologies capable of providing heat in this temperature range, including electricity generated by renewable energy sources and heat pumps. Temperature ranges between 300 C and 500 C are mainly used for refining and certain chemical processes; temperatures above 550 C are used in energy- and heat-intensive industries like iron, steel, glass, cement, and chemicals.

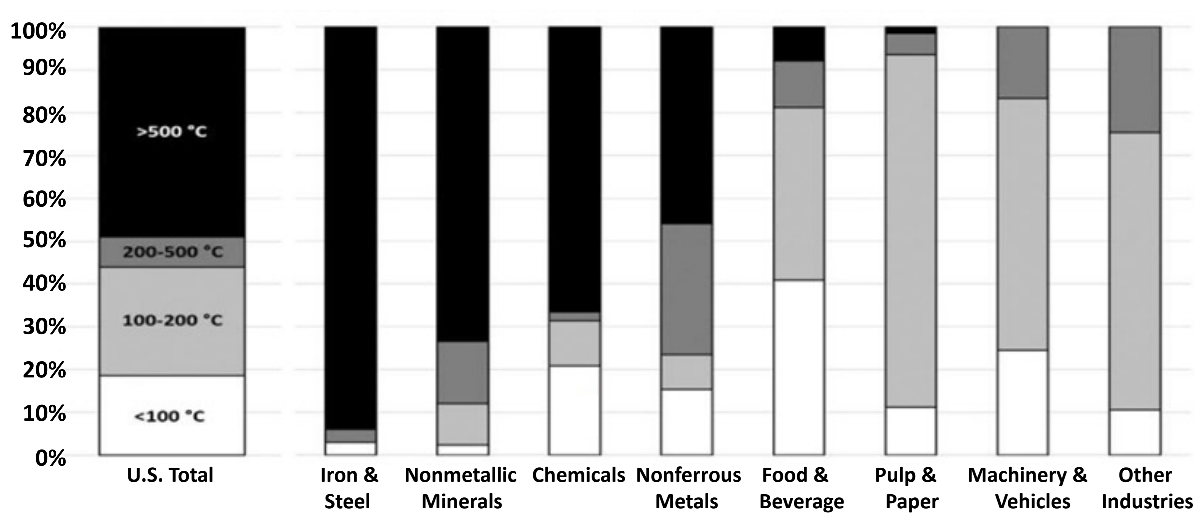
Figure 81. Distribution of process heat temperature ranges by U.S. industrial subsector



Source: Ali Hasanbeigi et al., "Electrifying US Industry." Renewable Thermal Collaborative (2021): 21-1.

Translating these volumes into percentages underscores the importance of the high heat needs of critical industries. As seen in Figure 82, around 50% of overall heat demand for these industries is over 500 C.[323] For iron and steel, it is around 93%, nonmetallic industries around 75%, chemicals around 68%, and nonferrous metals, e.g., aluminum, around 45%.

Figure 82. Percentage heat demand by temperature range in industry, U.S., 2021



Nonmetallic minerals include cement, lime, brick, glass, tile, etc. Source: Jeffrey Rissman, "Decarbonizing Low-Temperature Industrial Heat in the US," Energy Innovation Policy & Technology" (2022), https://energyinnovation.org/wp-content/uploads/2022/10/Decarbonizing-Low-Temperature-Industrial-Heat-In-The-U.S.-Report-2.pdf

Natural Gas in the Industrial Sector

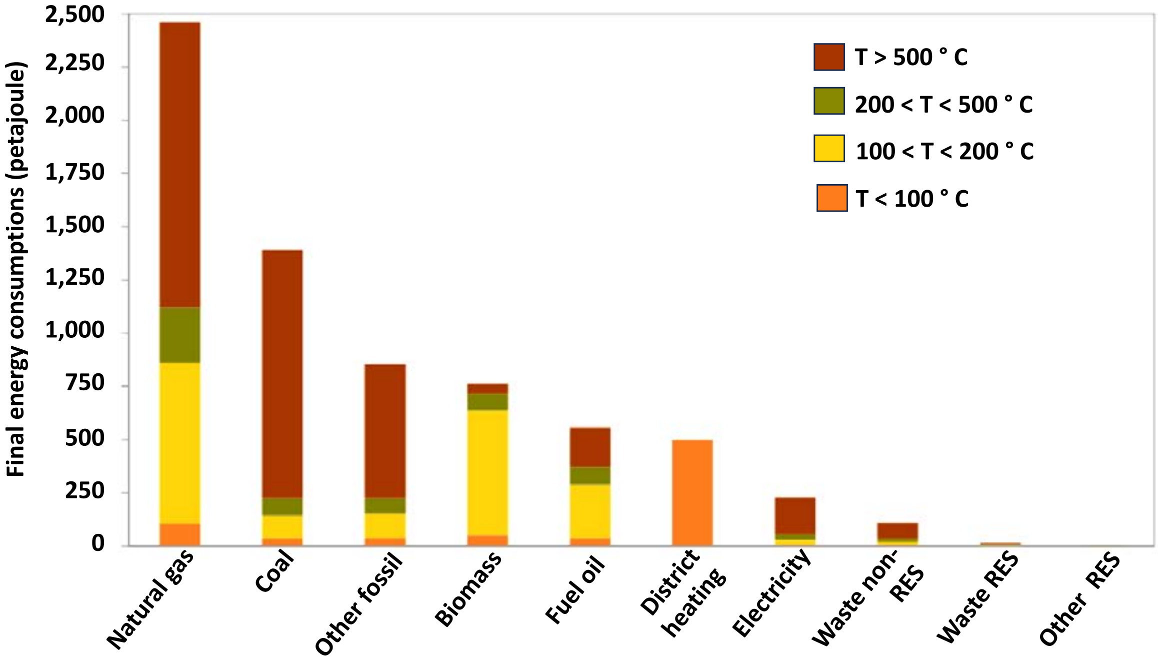
A significant amount of natural gas is used as an industrial heat source. It is used for industrial furnaces and kilns as it has efficient and precise temperature control. Burning natural gas can also provide the very high temperatures that are needed to manufacture steel, cement, and glass, as well as in some chemical manufacturing processes.[324] A summary of principal natural gas industrial usage by category of use (fuel, furnaces, feedstocks, steam) includes:

- Furnaces: metal smelting, glass production including for silicon chips, ceramic manufacturing
- Steam generation: power generation, heating, sterilization
- Feedstocks: ammonia, methanol, hydrogen, carbon fiber
- Fuel: cement, brick, and blocs kilns

Approximately 70% of ammonia used in fertilizers is produced via natural gas-based steam reforming. Ammonia production accounts for 20% of industrial natural gas demand and is more emissions-intensive than the steel and cement industries combined.[325] Natural gas is also a raw material input, serving as a feedstock in the production of chemicals and plastics.[326] Other industrial subsectors that use natural gas include waste treatment, petrochemicals, mining and smelting, metal processing, food processing, and textiles.

Figure 83 shows the final volumes of energy consumption for industrial heat by source and volumes associated with the temperatures needed for key industrial processes in the EU-28.[327] As suggested by the figure, natural gas plays the most significant role in all temperature ranges but especially in temperatures greater than 500 C. Coal, a very close second to natural gas, combined with "other fossil" and fuel oil, however, substantially exceed the amount of natural gas used by the EU's industry for high-heat processes. Depending on costs and other infrastructure issues, changing carriers for high-heat processes to natural gas could provide an option for reducing emissions from the industrial sector. This option is discussed later in this analysis.

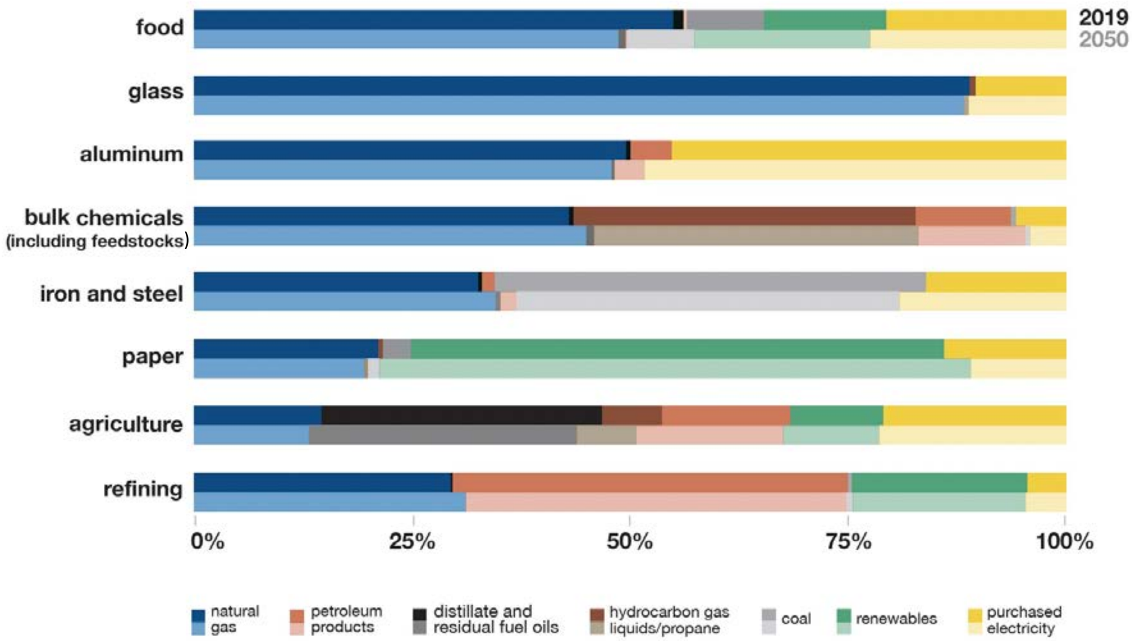
Figure 83. Energy carriers used for industrial heat in the EU-28, categorized by temperature levels, 2020



"RES" refers to residential waste.
Source: Olle Olsson and Fabian Schipfer, Decarbonizing Industrial Process Heat: The Role of Biomass, 2021, [*https://www.ieabioenergy.com/wp-content/uploads/2022/02/Role-of-biomass-in-industrial-heat.pdf*](https://www.ieabioenergy.com/wp-content/uploads/2022/02/Role-of-biomass-in-industrial-heat.pdf)

Figure 84 shows natural gas use by various industries' total energy consumption.[328] It should be noted that purchased electricity is its own category in this figure, in addition to the range of fuel sources depicted in the graph. In 2021, natural gas generated 39% of power in the United States, and this would add to the percentage of natural gas used for the key industrial subsectors depicted in the figure. Thus, through increased electrification, a portion of the carbon footprint could shift from industrial processing to the power sector dependent on the source of fuel.

Figure 84. U.S. energy consumption by fuel in industry subsectors, 2019/2050, AEO2020 Reference Case



Source: U.S. Energy Information Administration, Annual Energy Outlook 2020 with Projections to 2050, January 29, 2020. [*https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf.*](https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Full%20Report.pdf)

The range of industries that use large volumes of natural gas for heat, as a feedstock, or for purchased power generation have significant value to the U.S. economy. In 2022, examples of the economic value of and jobs associated with key U.S. industrial subsectors supported by natural gas include:[329]

- Glass and glass products: $20.5 billion, approximately 82,000 jobs
- Iron, steel, and steel products: $99.1 billion, approximately 136,000 jobs
- Aluminum: $32.4 billion, approximately 60,200 jobs
- Plastics: $200.8 billion, approximately 618,800 jobs
- Chemicals: $707.8 billion, approximately 905,500 jobs
- Agricultural chemicals: $31.9 billion, 36,900 jobs

Collectively, these sectors represent approximately $1.09 trillion in value to the U.S. economy and around 1.8 million U.S. jobs. Again, this data underscores the critical role that natural gas plays in the industrial sector and the overall economy. This highlights critical drivers and needs, such as preserving industrial competitiveness, jobs and affordability, while meeting the need for deep decarbonization of energy systems. These industries are essential for global economic development. Especially in the developing world, the affordability of fuels in industrial subsectors is a key consideration in economic development.

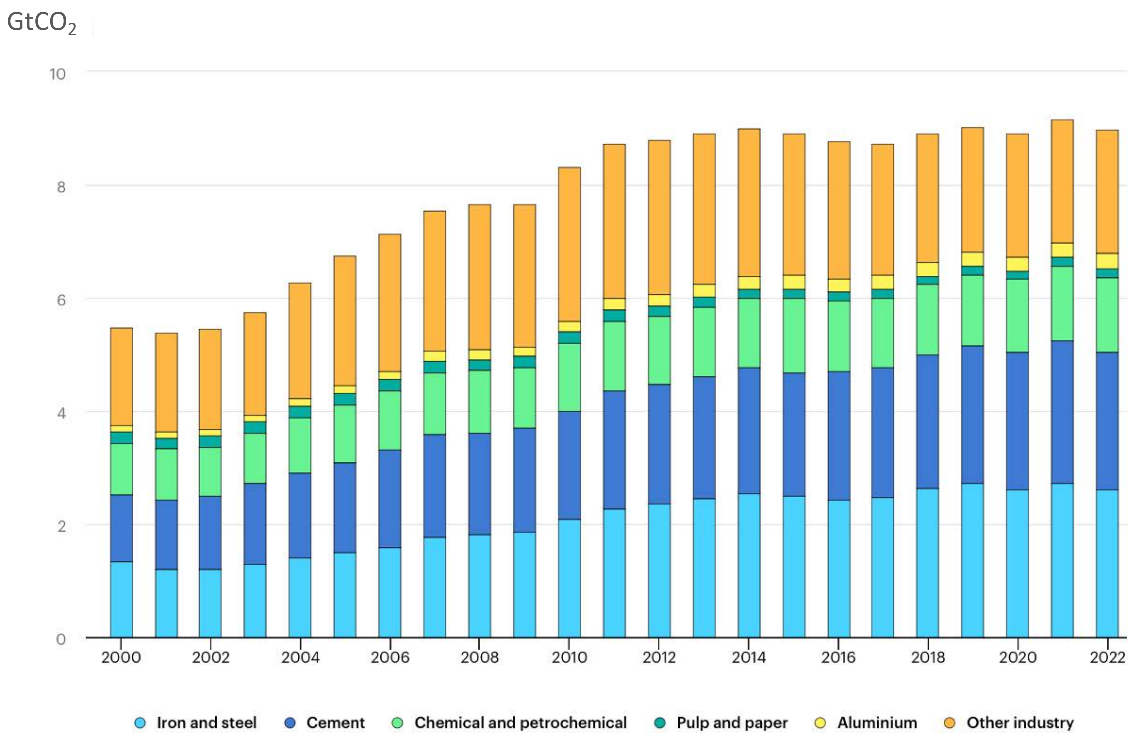
In addition, the industrial sector—and natural gas by virtue of its significant uses within the sector—supports the deployment of renewable energy through the manufacture of key technologies, including wind turbines and solar arrays. Industry, supported in part by natural gas, also produces the steel, carbon fiber, concrete, and glass needed for these and other key renewable technologies.

Challenges to Decarbonizing the Industrial Sector

In 2022, approximately 25% of global energy-related CO_2 emissions came from the industrial sector. There have been some emissions reductions due to improvements in energy intensity of GDP and carbon intensity of energy used, but these reductions were less than the overall increase in emissions from the global use of fossil fuels.[330]

Since 2000, global industrial CO_2 emissions have rapidly grown, which has been driven by increased basic materials extraction and production. The direct CO_2 emissions from industry, including both fuel combustion and industrial process emissions, have increased by 64% from 2000 to 2022 (Figure 85).[331]

Figure 85. Direct CO_2 emissions from industry, 2000 to 2022

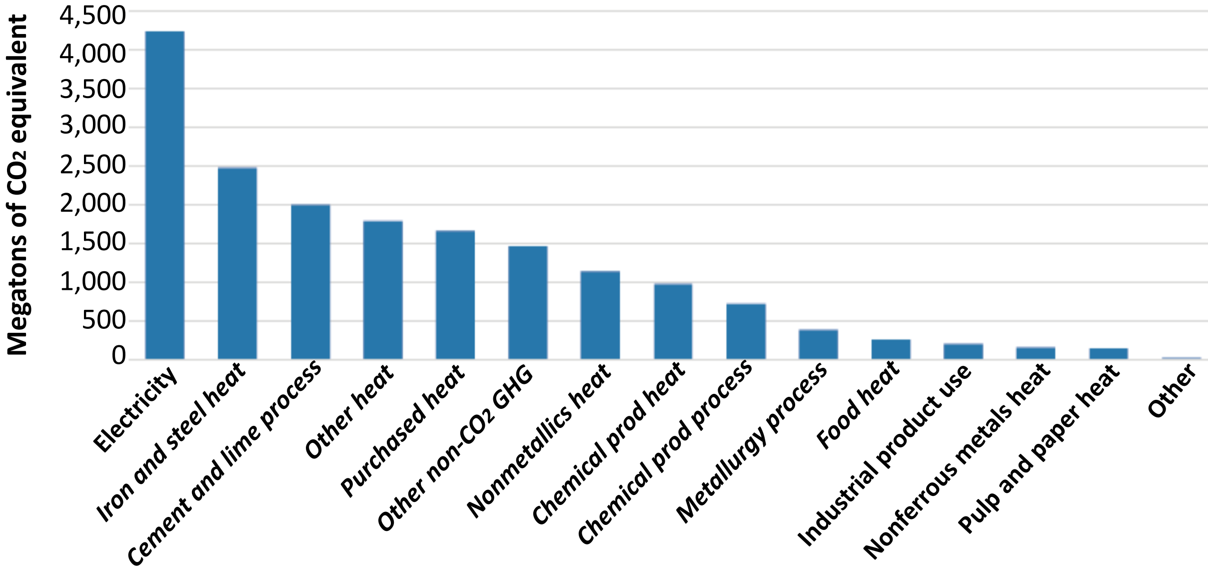


Source: IEA, "Direct CO2 emissions from industry in the Net Zero Scenario, 2000-2030," last updated June 15, 2023, https://www.iea.org/data-and-statistics/charts/direct-co2-emissions-from-industry-in-the-net-zero-scenario-2000-2030-2.

Emissions from the industrial sector are primarily related to energy consumption, a wide range of industrial heat requirements spanning from 50 degrees to 1,600 degrees Celsius (122 degrees to

2,912 degrees Fahrenheit), and the release of CO_2 during several industrial processes, including those for producing cement, lime, hydrogen, and other products. The largest contributors to industrial emissions in 2019 are seen in Figure 86. [332]

Figure 86. Global GHG emissions from the industrial sector by source, 2019



Source: Igor Bashmakov et al., "Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 11" (2022), https://escholarship.org/content/qt23n103jv/qt23n103jv.pdf.

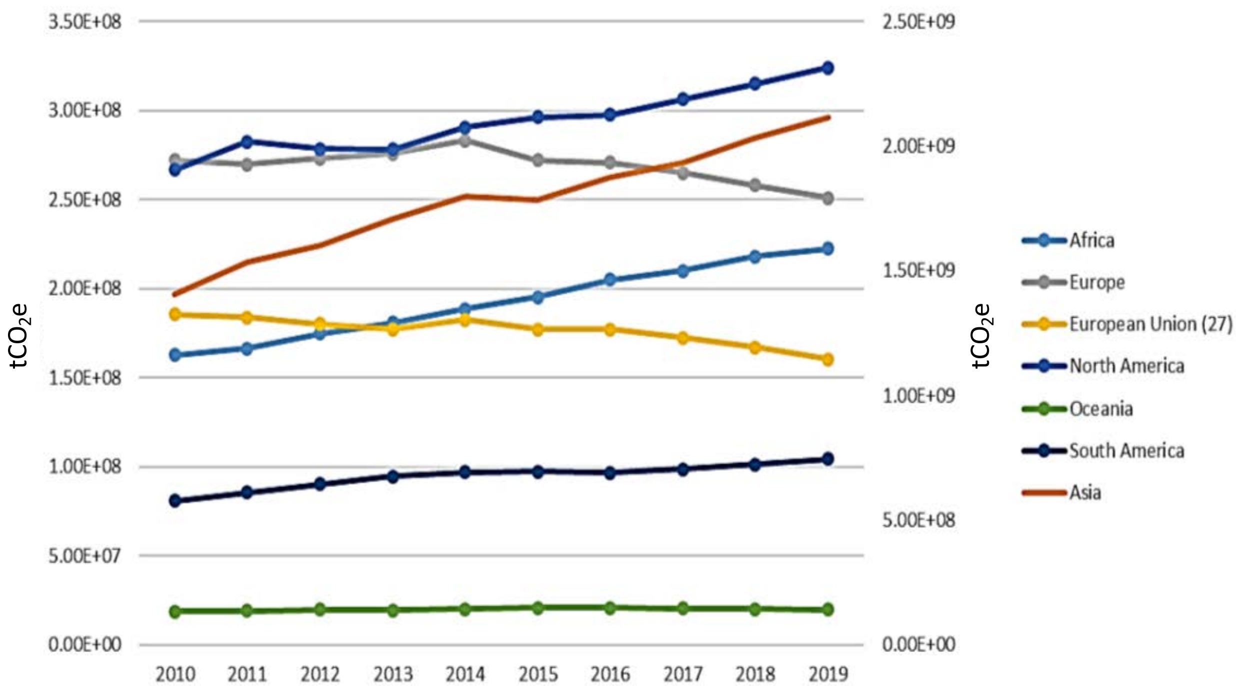
The following are percentages of global GHG emissions from some key industrial subsectors in 2016, most of which rely on fossil fuels for heat, as feedstocks, and for electricity:

- Manufacturing of iron and steel: 7.2%
- Manufacturing of cement and chemicals: 5.2% (not counting 3% for clinker in cement)
- Manufacturing of fertilizers, pharmaceuticals, refrigerants, and oil and gas extraction: 3.6%
- Manufacturing of tobacco products and food processing: 1%
- Manufacturing of nonferrous metals 0.7%
- Conversion of wood into pulp and paper: 0.6%
- Production of machinery: 0.5%
- Other industry (including mining and quarrying, construction, textiles, wood products, and transport equipment): 10.6%[333]

These emissions levels, economic value, and difficulties associated with decarbonizing many of the associated processes have received significant policy attention in the United States. On March 25 of this year, DOE announced $6 billion in awards for projects to decarbonize energy-intensive industries, with a focus on chemicals and refining; cement and concrete; iron and steel; aluminum and metals, including copper; glass; pulp and paper; and process heat. It is worth noting that in announcing its award for process heat to two companies, DOE noted that “These two projects plan to validate the use of electric boilers and electric steam production to reduce emissions associated with process heating across a wide range of industries. By demonstrating applicability across sectors, these projects will chart a path for addressing one of the biggest challenges in the industrial sector—heat-related emissions."[334] These are described by DOE as projects that will "help accelerate the commercial-scale demonstration of emerging industrial decarbonization technologies."[335]

In this regard, according to the IEA, global emissions from the industrial sector declined by 1.7% in 2022. While several regions saw manufacturing curtailments, the global decline was largely driven by a 161 $MtCO_2$ decrease in China's industrial emissions, reflecting a 10% decline in cement production and a 2% decline in steel manufacturing.[336] At the time, the IEA noted that these numbers would likely rebound, tracking patterns seen from 2010 to 2019, when GHG emissions from the industrial sector saw widespread increases (Figure 87).[337] Only the European Union saw emissions decline during this period.

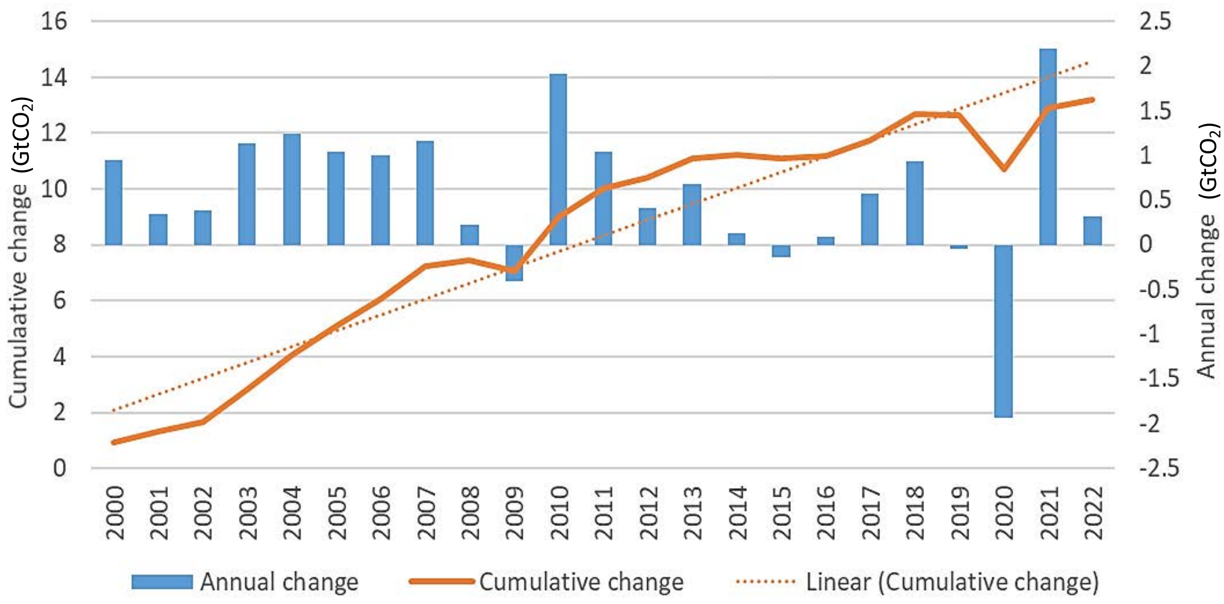
Figure 87. CO_2 emissions from industry by continent/global region, 2010 to 2019



Source: Bob Balch et al, "Industrial Decarbonization and the Role of Natural Gas," December 2023.

Emissions declined by more than 5% in 2020, as the COVID-19 pandemic cut energy demand. Per the IEA's forecast, emissions in 2021 rebounded past pre-pandemic levels, growing more than 6% as the global economy recovered and grew post-COVID lockdowns (Figure 88).[338]

Figure 88. Annual and cumulative change in global CO_2 emissions from energy combustion and industrial processes, 2000 to 2022



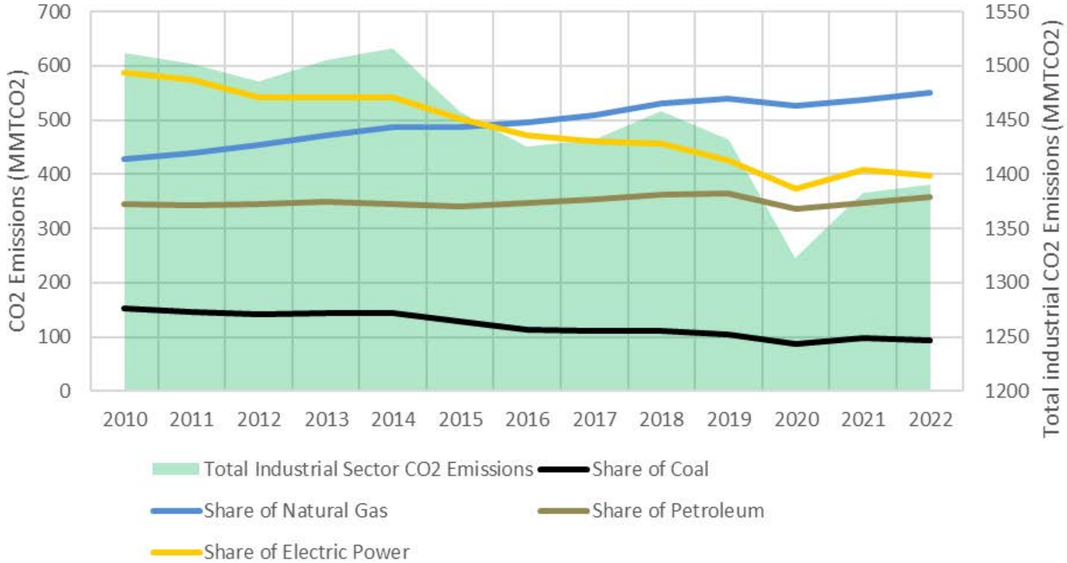
Source: Bob Balch et al., "Industrial Decarbonization and the Role of Natural Gas," December 2023.

Simulations and modeling suggest that the trajectory of industrial emissions heavily depends on the broader assumptions about emissions pathways. In all cases reviewed for this analysis, industry is set to become the largest emitting sector by 2035.[339]

While OECD countries are switching from coal and oil to lower-carbon-intensive energy sources, the same is not true for non-OECD countries, where the least expensive sources of energy and power will continue to dominate.[340] The investments needed to accelerate the clean-energy transition could be significant in both OECD and non-OECD countries. The affordability and timescales for deployment of these emissions-reduction technologies, however, could also limit their uses in non-OECD countries, as these countries tend to be more focused on energy prices, industrial development, and the associated buildout of energy systems.

This shift toward decarbonizing electricity generation in some countries and regions has had a notable impact on global CO_2 emissions from the industrial sector. It's worth noting, however, that the portion of CO_2 emissions attributed to natural gas within the industrial sector continues to expand (Figure 89)[341] This underscores the ongoing imperative to aggressively pursue decarbonization efforts within the natural gas industry.

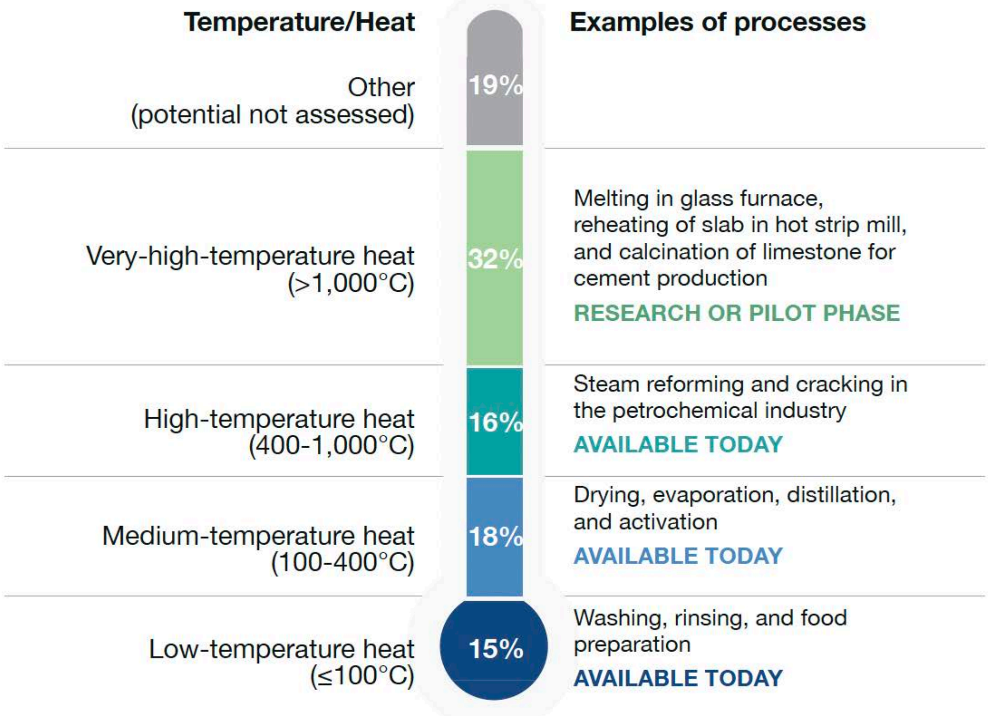
Figure 89. CO_2 emissions from the U.S. industrial sector and energy/electricity shares, 2010 to 2022



Source: Bob Balch et al, "Industrial Decarbonization and the Role of Natural Gas," December 2023.

Understanding the specific heat requirements for a range of key and crosscutting industrial processes where natural gas plays a significant role is important for developing decarbonization pathways for industry. Figure 90 shows the percentages of temperatures needed for many of these processes.[342]

Figure 90. Percentage share of heat requirements for key/crosscutting industrial processes



Source: Occo Roelofsen et al., "Plugging in: What electrification can do for industry," March 28, 2020, https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry.

The analysis accompanying this figure concluded that most processes under 500 degrees C could be electrified with today's technologies. The figure also shows that approximately 32% of key industry processes require very high temperatures that currently can only be achieved using a fuel; many related electrification technologies are still in research or pilot phases or are expensive and could affect the affordability and competitiveness of many industrial products. The conclusion is that for manufacturing competitive products, these processes currently require a fuel such as natural gas to affordably achieve the levels of heat needed for manufacturing of many products.

Approximately 32% of key industry processes require very high temperatures that can currently only be achieved using a fuel; many related electrification technologies are still in research or pilot phases or are not affordable. The conclusion is that for manufacturing competitive products, these processes currently require a fuel such as natural gas to affordably achieve the levels of heat needed for manufacturing of many products.

Also, energy-intensive industries may face higher energy costs from the shift toward renewable energy sources and the implementation of carbon pricing. In addition, the costs associated with decarbonization efforts, such as subsidies and energy-efficiency upgrade requirements, would be passed on to consumers. Concerns have been raised that this cost transfer could make some industrial manufacturing products less competitive in global markets, potentially leading to a loss of market share for some subsectors in certain countries and eventually a loss of jobs.

Industrial Decarbonization Options

IEA has identified a range of technologies, processes, and associated policies that could abate emissions from the industrial sector, delineating the options for the different components of industrial processes, i.e., fuel use, process emissions, and emissions from the use of the product (Table 6).[343] This list is extensive but does not identify the status of the options (available, in development, early stage, etc.) nor does it address the costs or timescales associated with the deployment or use of these technologies. Nevertheless, the list provides areas where additional inquiry could provide valuable information to inform pathways for industrial decarbonization.

Table 6. Overview of emission abatement options for different carbon streams in high-temperature industrial processes

Options to reduce emissions from fuel use	Options to reduce process emission	Options to reduce product emissions
• Fuel efficiency increase • Switching to biomass heat • Switching to solar thermal • Nuclear heat • Geothermal heat • Direct REN electrification (e.g. heat pumps, induction) • Indirect REN electrification (e.g. hydrogen, hydrogen derivates) • Biogenic or fossil carbon capture and storage • Providing flexibility to the electricity grid	• Process efficiency increase • Carbon switching (e.g. biogenic carbon) • Carbon capture and storage • Inter-industry material synergies • Inter-industry energy synergies	• Decreased material intensity • Material efficiency (e.g., lifetime expansion) • Reduce • Reuse • Recycling / Upcycling • Carbon utilization – secondary raw materials • Energy recovery • Substitution with other, lower-emission materials

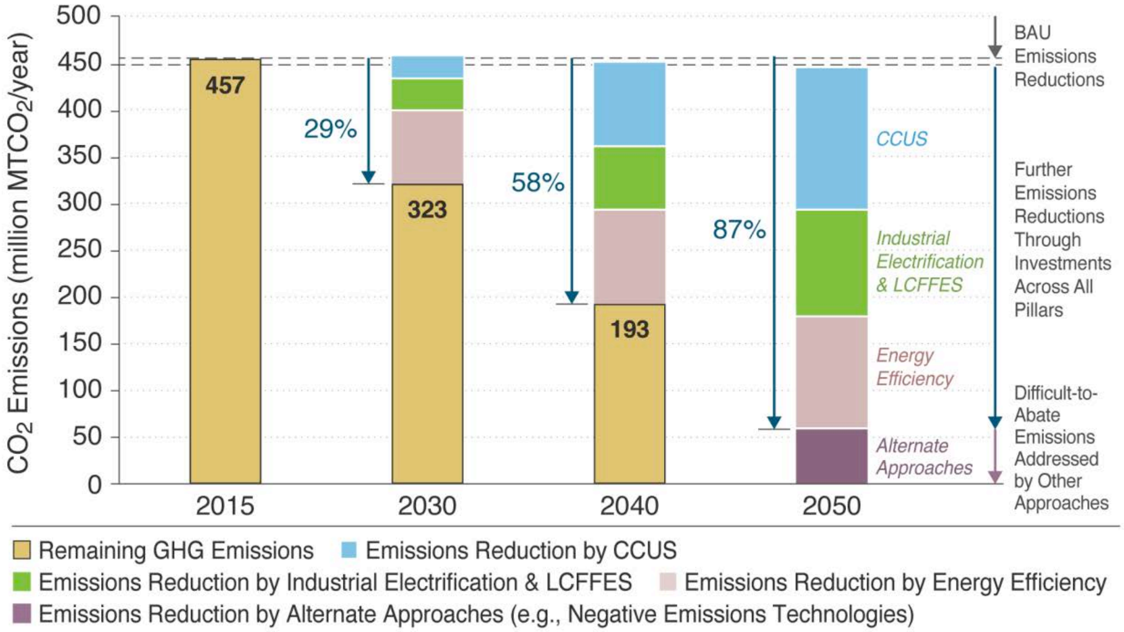
Source: Olle Olsson & Fabian Schipfer, "Decarbonizing industrial process heat: The role of biomass," IEA Bioenergy Task 4, December 2021. https://www.ieabioenergy.com/wp-content/uploads/2022/02/Role-of-biomass-in-industrial-heat.pdf.

No single option enables deep decarbonization of the industrial sector. DOE's Industrial Decarbonization Roadmap developed a pathway to net-zero industrial emissions for five U.S.

carbon-intensive subsectors by adopting several pillars of decarbonization: energy efficiency, industrial electrification, low-carbon fuels/feedstocks/energy sources, CCUS, and alternative approaches (e.g., negative emissions technologies).

Figure 91 shows that CCUS, industrial electrification, low-carbon fuels/feedstocks/energy sources, and enhancing energy efficiency should be adopted altogether to decarbonize the U.S. industrial sector; these options/technologies could be used by other regions and countries to reduce their emissions as well.[344] Even with all the options, a limit of representation of "Remaining GHG Emissions" in Figure 91, the industrial sector would not be entirely decarbonized; thus, negative emissions technologies are also necessary.

Figure 91. The path to net-zero industrial CO_2 emissions in the United States for five carbon-intensive industrial subsectors



BAU = business as usual. Source: DOE, Industrial Decarbonization Roadmap, DOE/EE-2635, May 2023. https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

As seen in Figure 91, efficiency provides the most significant emissions reduction in the near term and over time. CCUS and low-carbon fuels, feedstocks, and energy sources (LCFFES) provide relatively similar and small shares of reduction in 2030, but CCUS outpaces LCFFES in both the 2040 and 2050 time frames where, by 2050, it supports the largest percentage of emissions reductions of the three categories analyzed in those time frames. Efficiency and LCFFES, while smaller percentages of emissions reductions in 2050, are still significant. DOE identifies several key challenges associated with LCFFES that help identify both technology and policy innovation needs. These include:

- Lack of process equipment to address alternative fuel-specific phenomena such as pre-treatment and conversions process

- Lack of auxiliary equipment to address industrial infrastructure needs such as hydrogen (H_2) compressors for lower volumetric energy density
- Industry hesitation toward adopting new energy sources, such as product quality concerns, potentially high capital costs, and longer paybacks
- Mitigation of other harmful impacts, including water scarcity, nuclear waste, and high NOx emissions
- Inadequate supply chain for materials and fuels, such as the availability of clean hydrogen, seasonal variation for biofuels, or lack of manufacturing capacity in support of renewables

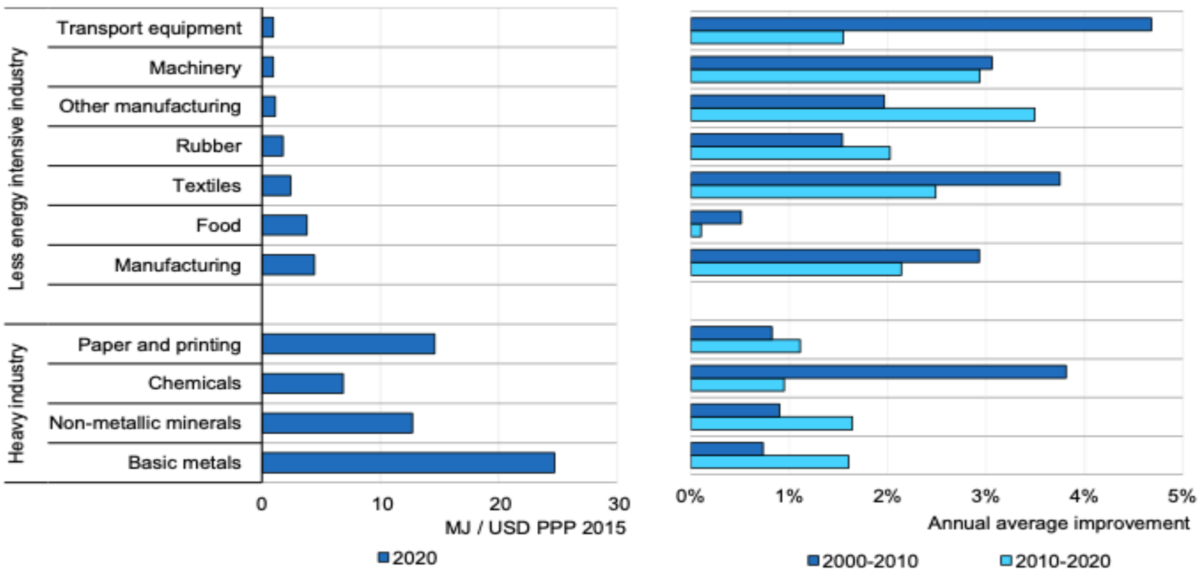
These options, and technology and investment needs, while focused on the United States, could provide guidance for other regions included in this analysis, particularly for those countries with net-zero targets. Choices will vary depending on costs, energy supplies, and policy and regulatory differences, but it is likely that to some degree, most of these options and issues will figure into industrial decarbonization pathways for all regions globally.

Increasing Energy Efficiency

Increasing energy efficiency is a foundational decarbonization strategy and is the most cost-effective option for emission reductions in the near term. The efforts for increasing energy efficiency include both technology deployment and strategic management of operations, such as strategic energy management approaches to optimize industrial processes, tools and technologies for systems assessment and optimization, and smart manufacturing and advanced data analytics.

Globally, energy efficiency has been continuously increased, but the progress has not been fast enough to meet the net-zero emissions goal. The IEA recommended a 3% annual improvement of energy efficiency in the industrial sector to meet the milestones in the Net Zero Emissions to 2050 scenario.[345] While addressing energy efficiency in IEA countries has shown promise (Figure 92), addressing energy efficiency in developing countries' industrial sector is a significant challenge.[346] Within IEA countries, the energy efficiency in chemicals, nonmetallic minerals, and basic metals sectors had improved 1% to 2% annually on average from 2010 to 2020, while less energy-intensive manufacturing showed 2% to 4% improvement over the same period.

Figure 92. Average energy intensity of major industrial subsectors in IEA countries, 2000 to 2020



PPP = purchasing power parity. Source: IEA, Energy Efficiency 2022, https://iea.blob.core.windows.net/assets/7741739e-8e7f-4afa-a77f-49dadd51cb52/EnergyEfficiency2022.pdf.

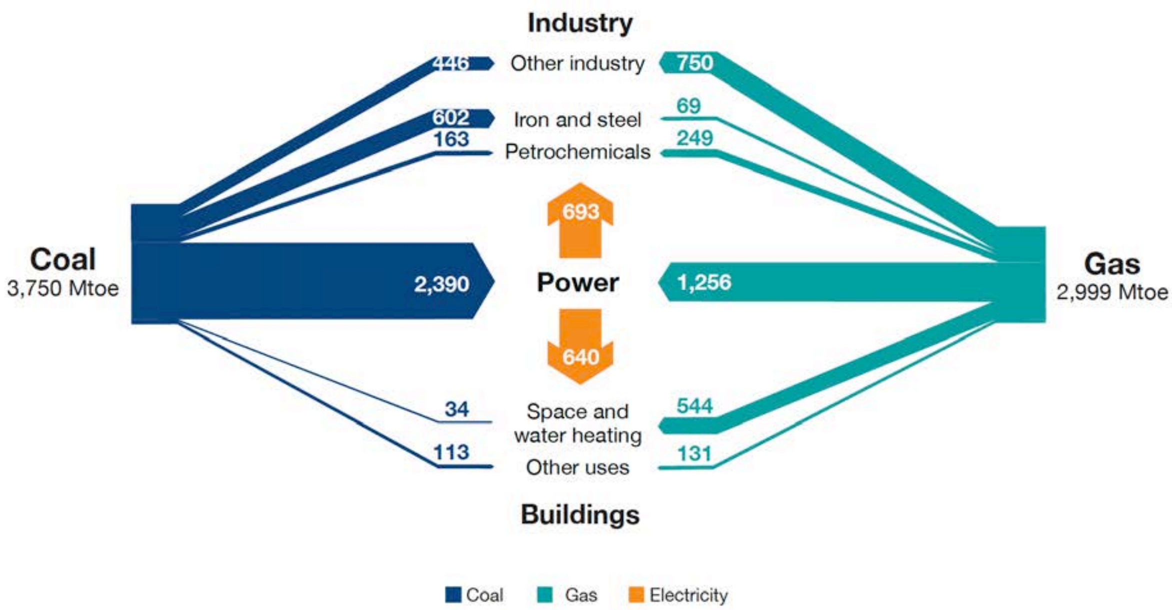
Since increased energy efficiency also leads to cost reductions, many industry organizations have been motivated to invest in energy efficiency. A global survey of more than 2,200 companies in 13 countries showed that 97% of them were investing in energy efficiency or efficiency planning.[347] U.S. manufacturers are also investing in energy efficiency. To support the industry effort for energy efficiency, DOE has initiated the Better Plants Program to reduce energy intensity by 25% over a 10-year period across all U.S. operations. Through this program, DOE supported 3,600 facilities, accounting for 14% of the U.S. manufacturing footprint, cumulatively saving 2.2 Btu of energy and $10.6 billion by 2022.[348]

The IEA notes that before the COVID-19 pandemic, advanced economies saw an energy intensity reduction of around 1.8% per year between 2000 and 2019, slightly less than in developing economies. “In emerging markets and developing economies (EMDE), energy intensity improved at a slightly higher annual rate of 1.9% on average between 2000 and 2019, with average GDP growth of 6% per year requiring 3.6% more energy per year. Behind this energy growth story is the catch-up in living standards, with an average person in an EMDE using three times less energy in their home and four times less for transport compared with a person in an advanced economy.”[349]

Coal-to-Gas Fuel Switching

Fuel switching can serve as an intermediate step to decrease the carbon footprint while more advanced technologies are developed to further decrease the carbon footprint of industry. Coal-to-gas fuel switching could reduce industrial sector emissions, especially in subsectors using significant amounts of electricity in manufacturing processes. As seen in Figure 93, the global iron and steel industry used 602 million metric tons of oil equivalent (Mtoe) of coal in 2017, nine times the amount of natural gas used in the industry subsector; this creates siginifcant opportunities for emisisons reductions via coal-to-gas fuel switching, although process changes would require additional analysis.[350] Also, around 40% of the fuel used in the petrochemicals industry is coal, presenting another opportunity for emissions reduction from coal-to-gas fuel switching. Finally, 52% of electricity for these select processes is for industrial uses; depending on how that electricity is generated, there are also opportunities for coal-to-gas fuel switching, and there may be opportunities for using fuels like natural gas in lieu of electricity, which could lower overall costs, as electricity tends to be more expensive per unit of energy than natural gas (see Figure 94 below).

Figure 93. Selected flows of coal and gas for industry in the global energy balance, 2017



Mtoe = million tons of oil equivalent. Source: IEA, The Role of Gas in Today's Energy Transitions, July 2019, https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions.

Electrification

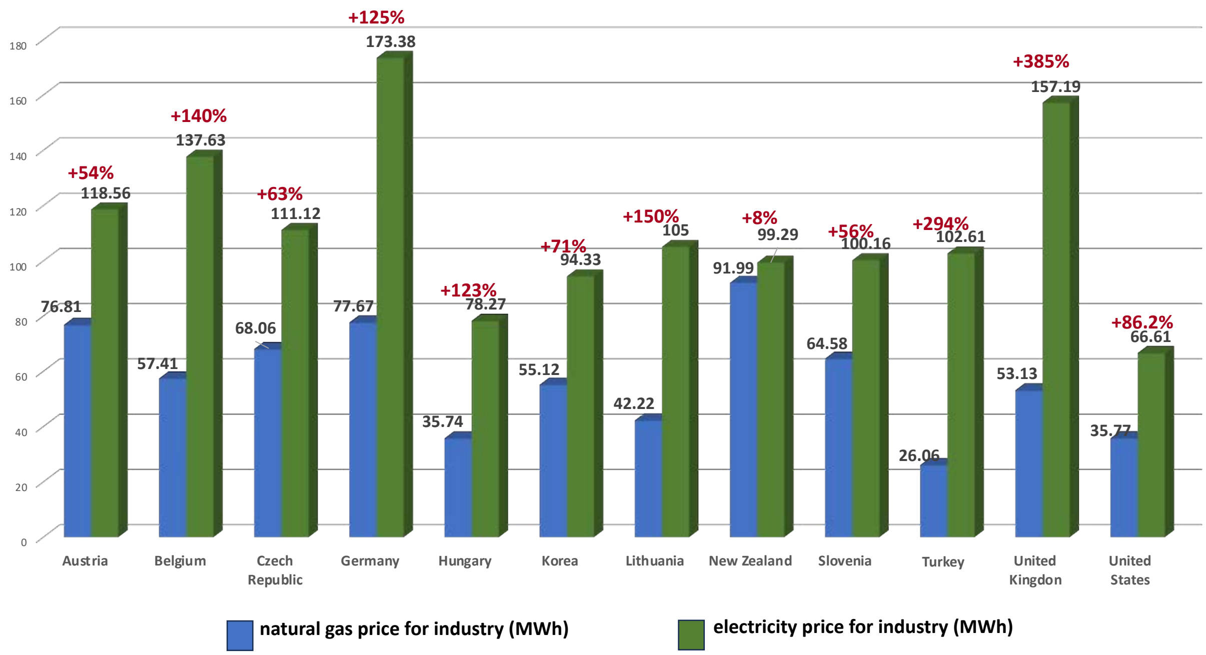
Electrification can play a crucial role in decarbonizing the industrial sector by replacing carbon-intensive processes and energy sources with cleaner and more sustainable alternatives. In the United States, process heat is the largest energy consumer in manufacturing, accounting for 51% of total on-site manufacturing energy consumption in 2018, with a corresponding 31% share of energy-related GHG emissions.[351] As seen in Figure 90, 32% of key industrial processes require very high heat and most technologies for providing this heat, other than the current use of a fuel, are in the research or pilot phase or are expensive.

Technologies in development for high heat from electricity and the temperature levels those technologies can achieve include resistance heating (up to 1,200 degrees Celsius); induction heating (up to 2,500 C); infrared heating (up to 1,000 C); microwave heating (up to 3,000 C);

graphene heating (up to 2,000 C); and carbon nanotube heating (up to 3,000 C).352 Process needs/changes, timescales for replacing existing systems, and costs are issues with these new technologies. As noted in an article about these options, "Obviously, the cost of electricity is a critical factor in the economic viability of advanced electric heating technologies. … If electricity is expensive or generated mainly from fossil fuels, then the operating costs of advanced electric heating technologies will be higher than fossil-based heating systems. However, if electricity is inexpensive or generated from renewable energy sources, then advanced electric heating technologies can be more cost-effective."[353]

Considering the rapid development and implementation of electrification technologies, data shows the price differential between natural gas and electricity for industry in select OECD countries, several of which are included in the regions on which this study is focused, e.g., Germany, the United States, and Korea (Figure 94).[354] These cost differentials could affect the competitiveness of industrial products globally.

Figure 94. Natural gas and electricity prices per million cubic feet of energy, select OECD countries, 2021

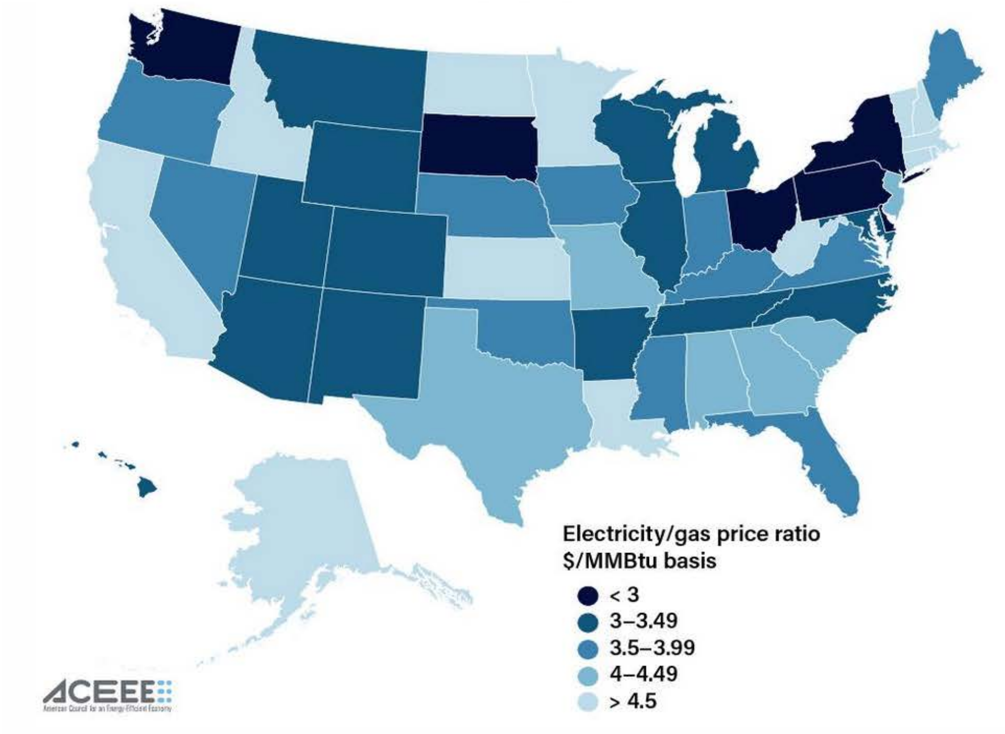


Source: EFI Foundation based on data from IEA, Key World Energy Statistics 2021, September 2021, *https://www.iea.org/reports/key-world-energy-statistics-2021*.

In 2021, electricity prices compared to natural gas prices in the 12 countries shown were 96.3% higher. In Western European OECD countries (Austria, Belgium, Germany, United Kingdom) electricity versus natural gas prices in 2021 were 121.1% higher. In Eastern European countries (Czech Republic, Hungary, Lithuania, Slovenia, Turkey) electricity prices were 110.1% higher than natural gas prices. Turkey had the highest percentage difference between electricity and natural gas prices at 294% in 2021, and New Zealand had the lowest at 8% higher.

In the United States, electricity prices overall are 86% higher than natural gas prices in the IEA data for 2021 but there are significant regional differences between electricity and natural gas prices as well. Figure 95, from an American Council for an Energy-Efficient Economy (ACEEE) analysis on the value of industrial heat pumps, shows that electricity prices compared to natural gas prices in 2022 are less than three times greater in only five states.[355] Electricity prices are three to four-and-a-half times greater in all other states.

Figure 95. Electricity to gas price ratios in the United States, 2022



Source: ACEEE, "Decarbonizing Industry with Heat Pumps," March 2022, [*https://www.aceee.org/sites/default/files/pdfs/ihp_fact_sheet_final.pdf.*](https://www.aceee.org/sites/default/files/pdfs/ihp_fact_sheet_final.pdf)

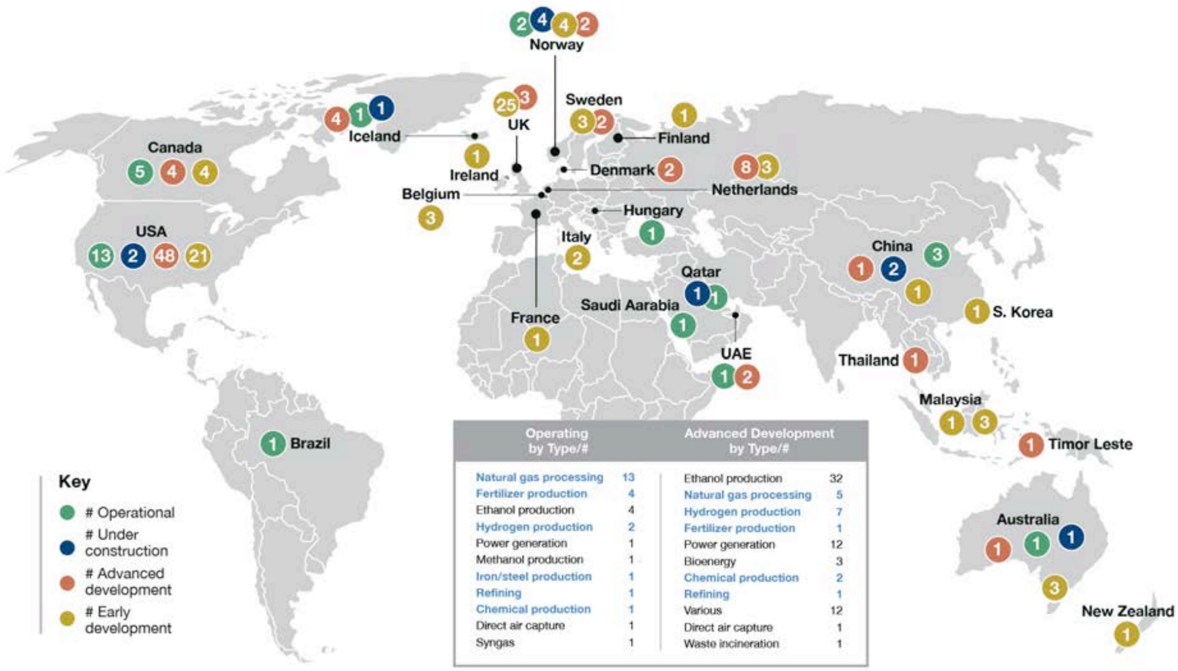
Additionally, regulatory requirements or incentives for the electrification of industrial processes may not exist or may be insufficient. Also, there are likely to be significant expenses associated with switching technologies for high heat production. Finally, industrial electrification faces the challenge of economic viability.

The electrification of industrial processes will require additional investments to convert machinery, equipment, and processes in addition to the construction of new or modified infrastructure. For example, scaling up direct reduced iron (DRI) technologies to process 1 million tons of steel annually would be uneconomical, even considering successful pilot projects.[356] The consequences of process change will have cost implications on other sectors as well, including renewables, which use industrial products manufactured at high temperatures as building blocks (i.e., carbon fibers, steel, concrete, and other metals). Thus, incremental costs from industrial decarbonization will flow down through to the products and materials needed for the construction of renewable energy resources.

Carbon Capture, Utilization, and Storage

CCUS is one of the most effective ways to reduce a significant amount of the emissions from industrial facilities. There are many operating CCUS projects around the world, as well as many projects in the advanced development stage in the industrial sector; these are highlighted in blue type, where 26 of 30 operational projects are highly relevant to natural gas uses and emissions for natural gas use in the industrial sector (Figure 96).[357] There is also significant momentum for CCUS. Between 2019 and 2022, operating projects increased by 58%. Over that same period, the number of projects in development increased from 10 to 77, a 670% increase in three years.

Figure 96. Carbon capture, utilization, and storage projects by type, 2022

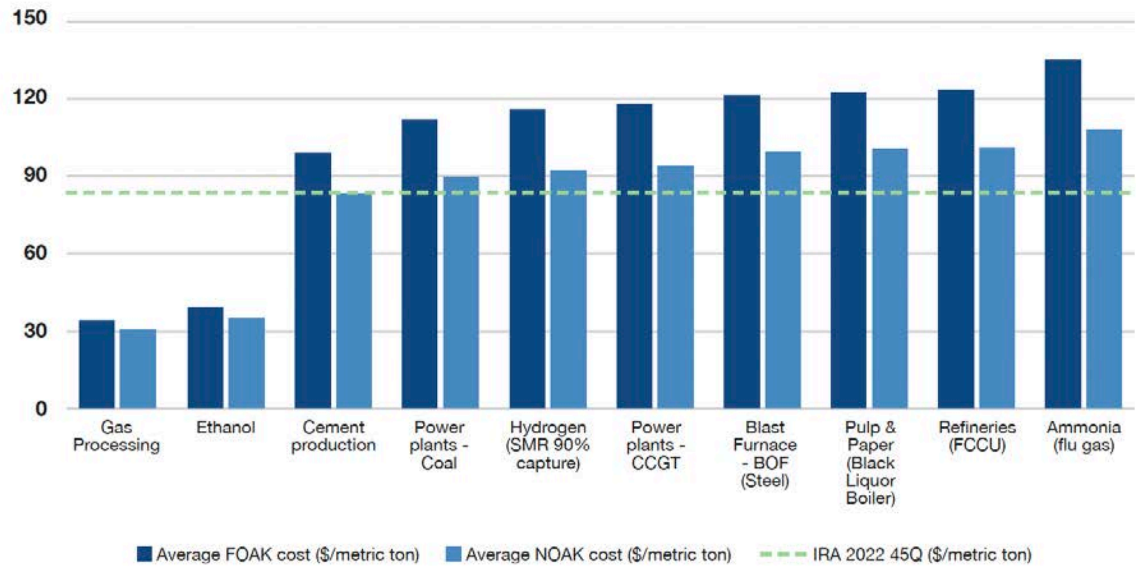


Operating by Type/#		Advanced Development by Type/#	
Natural gas processing	13	Ethanol production	32
Fertilizer production	4	Natural gas processing	5
Ethanol production	4	Hydrogen production	7
Hydrogen production	2	Fertilizer production	1
Power generation	1	Power generation	12
Methanol production	1	Bioenergy	3
Iron/steel production	1	Chemical production	2
Refining	1	Refining	1
Chemical production	1	Various	12
Direct air capture	1	Direct air capture	1
Syngas	1	Waste incineration	1

Source: EFI Foundation with data from Global CCS Institute, Global Status of CCS 2022, https://www.globalccsinstitute.com/resources/global-status-of-ccs-2022/.

Technology is maturing; however, CCUS faces economic, financial, infrastructure, regulatory, and reputational barriers to scale up. In the United States, most CCUS applications in the industrial sector cost more than the current level of the 45Q tax credit. Figure 97 shows that CCUS applications for cement, steel, pulp and paper, refineries, and ammonia sectors are more costly than the value of the 45Q tax credit.[358] The companies in these industrial subsectors would, absent a price on carbon, likely not invest in CCUS because they would lose money on the investment.

Figure 97. Industry comparison of calculated first-of-a-kind (FOAK) and nth-of-a-kind (NOAK) dollars per metric ton cost of CCUS to the U.S. Inflation Reduction Act tax credit incentive



BOF = basic oxygen furnace, CCGT = combined cycle gas turbine, FCCU = fluidized catalytic cracking units. Source: EFI, Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments, February 2023, https://efifoundation.org/reports/turning-ccs-projects-in-heavy-industry-into-blue-chip-financial-investments/.

In addition to addressing cost barriers by offering additional incentives, scaling up CCUS deployment requires significant additional effort, such as accelerating the construction of CO_2 pipelines and sequestration infrastructure, lowering federal and state regulatory barriers, and offering data and knowledge to project developers and communities. CCUS projects may create social, economic, and environmental impacts for the host communities, and as such, trade-offs of benefits and costs and the communities' preferences should also be considered. In the United States, substantial policy support has been provided to help accelerate CCUS deployment, mostly via the U.S. Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act of 2022 (IRA). Building on these foundational laws, additional policy and regulatory changes would likely be needed for CCUS deployment in industrial subsectors.[v]

Offsets via Carbon Dioxide Removal

Carbon dioxide removal (CDR) can be used as an offset to complement mitigation strategies to achieve science-based climate targets, depending on a wide range of factors, including the scale and cost of mitigation programs, rate of technological innovation, and willingness to accept uncertainty in modeling projections. Technological CDR can reduce atmospheric CO_2 concentrations, which have been increasing at a rate of 2 to 3 parts per million (ppm) per year with

[v] For details, see EFI's report *Turning CCS Projects in Heavy Industry and Power into Blue Chip Financial Investments* for details of recommended actions to scale up CCUS deployment, https://efifoundation.org/reports/turning-ccs-projects-in-heavy-industry-into-blue-chip-financial-investments/.

a commensurate rate of warming of 0.2 C per decade. Modeling studies by the Intergovernmental Panel on Climate Change (IPCC) indicate that the range of technological CDR to complement mitigation measures and natural carbon absorption to meet a 1.5 C target is between 100 and 1,000 $GtCO_2$ removed from the atmosphere (cumulative) by 2100. A National Academies of Sciences, Engineering, and Medicine (NASEM) report from 2018 stated that technological CDR will need to be deployed at a scale to achieve CO_2 removal at a rate of 20 $GtCO_2$/yr by the end of the century to achieve the target.

This scale is daunting when considering that a CDR deployment program at a gigaton scale will place it in the same size as the domestic petroleum industry or the global steel industry. Consequently, nations may commit to a lower temperature target of 1.5 C by as early as 2030. Achieving net zero emissions is technoligicaly infeasible and cost prohibitive, if onlny utilizing only the mitigation technologies and strategies commercially available today. The following sections on direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) provide examples of offset options via CDR deployment.

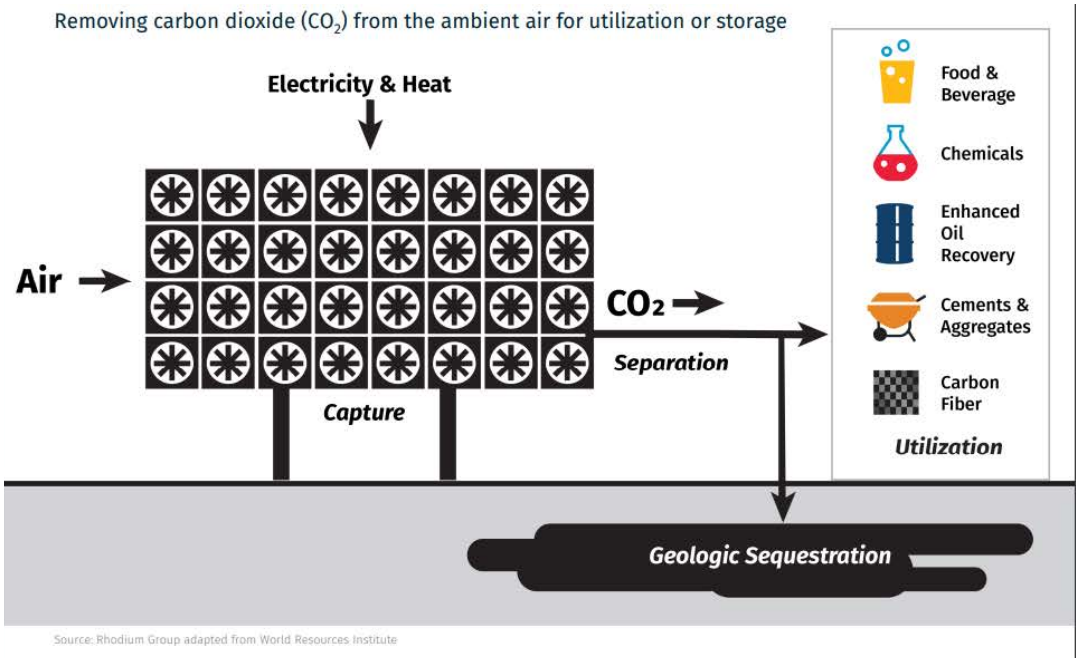
Direct Air Capture

DAC technology uses heat and electricity to separate ambient air into a concentrated stream of CO_2 and a stream of CO_2-depleted air. By itself, this is not a complete carbon removal system and must be coupled with a disposition pathway, either utilization or sequestration of the removed CO_2. The life cycle impacts of these options can be different, so the overall potential removal of DAC needs to be evaluated in combination with CO_2 disposition.

While DAC with storage (DACS) results in the largest net CO_2 removal, DAC with utilization is attractive because of revenue from the sale of utilization products, and it has thus been the focus of most commercial DAC activity to date. In the EIA's Net Zero Emissions by 2050 Scenario, DAC is scaled up to capture more than 85 $MtCO_2$/yr by 2030 and ~980 $MtCO_2$/yr by 2050. This level of deployment will require several more large-scale demonstrations to refine the technology and reduce capture costs.[359]

There are three main categories of DAC: cryogenic, membrane, and chemical. Cryogenic DAC takes advantage of the fact that CO_2 has a different freezing temperature than other gases in the air and can be separated by cooling air below this temperature, as occurs during the operation of cryogenic oxygen separation facilities. Membrane DAC uses ionic exchange and reverse osmosis membranes to separate CO_2 from air and seawater, as occurs during typical seawater desalination. To date, these two categories have received limited research attention as pathways for CDR. Chemical DAC (as seen in Figure 98) uses various sorbents to remove CO_2 from the air in a process that can be reversed using heat, pressure, or moisture, and is the most utilized form of DAC technology.[360] Chemical DAC systems operate on a capture-regenerate cycle in which CO_2 is removed from ambient air and later released in concentrated form for utilization or storage. There are currently two primary techniques under development: low-temperature solid sorbent (LTSS) and high-temperature liquid solvent.

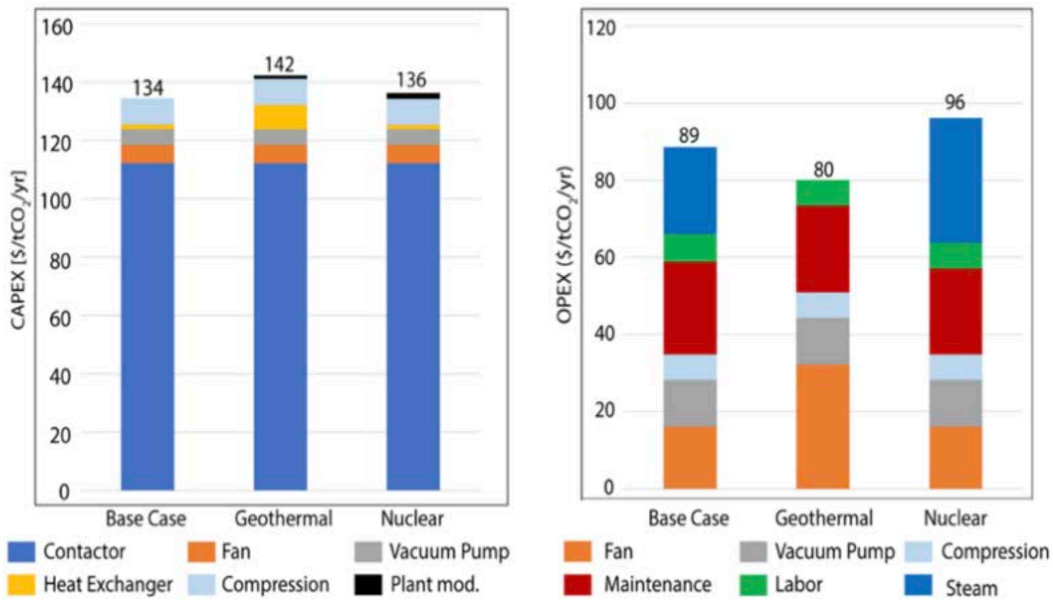
Figure 98. Direct air capture illustration



Source: John Larsen et al., "Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology," May 9, 2019, Rhodium Group, [*https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/.*](https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/)

The cost analysis presented in Figure 99, in terms of DAC capacity or the amount of CO_2 captured per year, provides a breakdown of annualized capital cost (left) and annual operating and maintenance costs (right) per ton of CO_2.[361] Costs are calculated for a system capable of processing 100 kilotons (kt) of CO_2 per year. Total cost of capture (capital and operating) is $223/t$CO_2$, $205/t$CO_2$, and $233/t$CO_2$ captured for the base, geothermal, and nuclear cases, respectively. Given the similarity in capture costs, there are no apparent cost savings to offset the apparent risks in engineering these systems; thus, for illustration purposes, this study will utilize a DAC cost of $223/t of CO_2 captured, equivalent to the base DAC case.

Figure 99. Breakdown of annualized capital cost and annual operating and maintenance costs per tCO_2



Source: Amelia Meyer et al., "A Critical Analysis of the Ocean Effects of Carbon Dioxide Removal via Direct Air and Ocean Capture–Is it a Safe and Sustainable Solution?" The Ocean Foundation Report (2021), https://oceanfdn.org/wp-content/uploads/2021/04/Direct-Carbon-Removal-Strategies-TOF-1Apr21-.pdf.

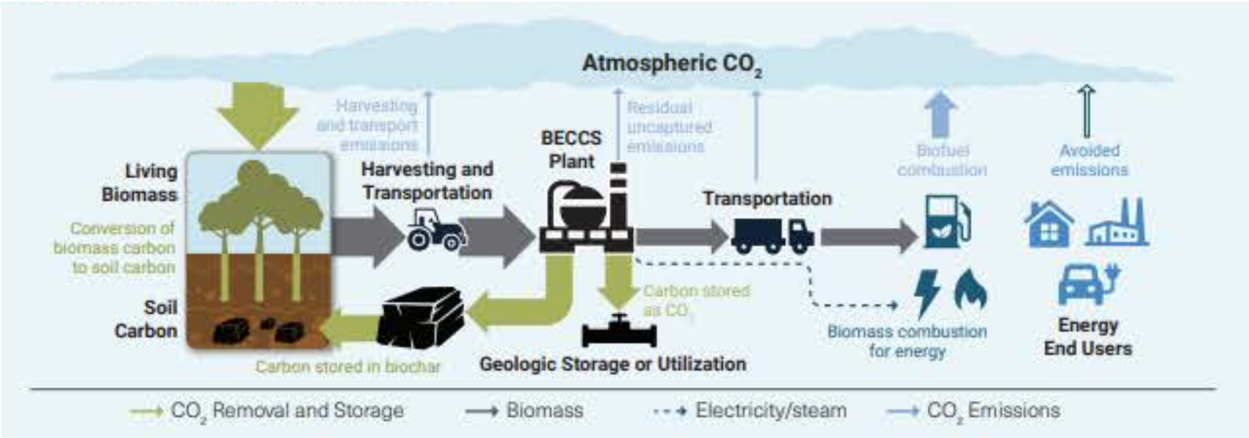
According to the IEA, 19 DAC plants are currently operating worldwide, capturing more than 0.01 $MtCO_2$/yr, and a 1 $MtCO_2$/yr capture plant is in advanced development in the United States.[362] In September 2021, the world's largest DACS plant opened in Iceland with an initial capacity to capture 4,000 tCO_2/yr. The plant comprises eight air collection containers, each holding several dozen cylindrical fans, which suck in ambient air and filter CO_2 from it. What is trapped is heated, mixed with water, and pumped deep underground. Climeworks, owner of the Orca plant in Iceland, recognizes their current technology sits at the high end of the cost range for carbon removal with a reported cost of $775/t of CO_2 removed, but as with any new technology, they expect the cost to decrease over time with a long-term price target of $100/$tCO_2$ to $200/$tCO_2$.[363]

In March 2022, Occidental Petroleum Company (Oxy) released an investor presentation titled "Stepping Up to Bring Emissions Down," in which Oxy provided their carbon management vision, provided an overview of the low-carbon business opportunity, and highlighted their "1PointFive" business strategy.[364] While current estimates for DAC are $425/$tCO_2$, according to Oxy's analysis, DAC technology can be de-risked and scaled up to 500,000 tCO_2 removal per project by 2030, with a cost between $200/t and $250/t as part of integrated projects, such as the Permian DAC-1 Project. Further, Oxy is targeting 70 DAC projects by the 2030-to-2035 time frame, which they estimate is 2.5% of the addressable market, with a goal of reducing the cost associated with DAC of CO_2 to less than $150/t.

Bioenergy with Carbon Capture and Storage

BECCS refers to a set of distinct systems that share common features: a biomass feedstock, biomass-to-energy conversion, and creation of a useful energy product, carbon capture, and carbon storage or utilization. BECCS is a set of systems that use biomass to produce energy and capture and store the embedded carbon, which can result in a net removal of greenhouse gases (GHGs) from the atmosphere. Plants (e.g., trees, crops) naturally absorb atmospheric CO_2 through photosynthesis and convert it into biomass carbon. BECCS involves harvesting these biomass "feedstocks" and converting them into useful energy (e.g., electricity, biofuels), while also capturing some of the carbon that would otherwise be released back to the atmosphere as GHGs (Figure 100).[365] This carbon is then used or permanently stored, either underground or in soil.

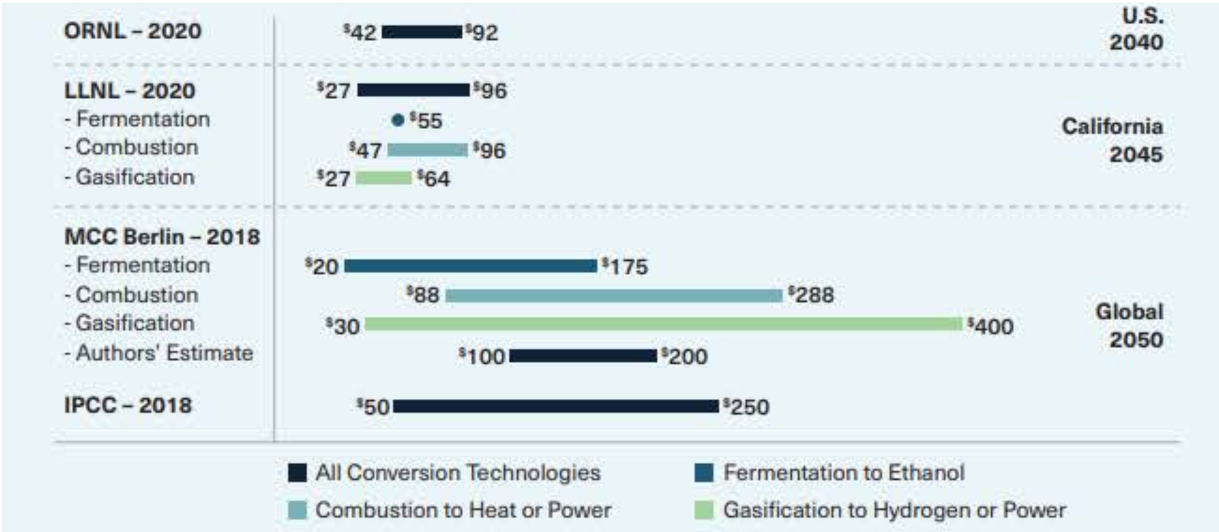
Figure 100. Carbon flows from BECCS



Source: EFI, Surveying the BECCS Landscape, January 2022, https://efifoundation.org/wp-content/uploads/sites/3/2022/03/Survey-the-BECCS-Landscape_Report-v2.pdf.

While BECCS technologies build on a well-established foundation of fully commercialized bioenergy and CCUS technologies, a legacy of many non-technology barriers to deployment means that BECCS projects are at an earlier stage of demonstration and deployment. Current estimates for BECCS carbon removal costs range widely from \$20/tCO_2 to \$400/tCO_2; estimates vary for different feedstocks, conversion and capture technologies, and system configurations (Figure 101).[366] Projects with access to abundant, cheap biomass, feedstock production co-located with energy conversion, and proximity to geologic storage can achieve lower cost and could be currently economically feasible.

Figure 101. BECCS technology CO_2 abatement cost estimates ($/t$CO_2$)



LLNL = Lawrence Livermore National Laboratory, MCC Berlin = Mercator Research Institute on Global Commons and Climate Change, Berlin, ORNL = Oak Ridge National Laboratory. Source: EFI, Surveying the BECCS Landscape, January 2022, https://efifoundation.org/wp-content/uploads/sites/3/2022/03/Survey-the-BECCS-Landscape_Report-v2.pdf.

The cost of capturing carbon depends on the concentration of carbon in the flue stream. Many sources anticipate carbon capture costs for BECCS projects to be on par with or less than those for fossil fuel generation sources. As significant as these technologies are (CDR, DAC, and BECCS), wide-scale commercial application requires governmental incentives to be economically viable. Also, as noted, both BECCS and DAC of carbon require CCUS. Critical areas of inquiry and analysis for the regions of the world focused on in this study are the value of BECCS and DAC; the potential for coordinating CCUS infrastructure and disposal sites; the innovation and investments needed for DAC and the associated CCUS; the development of trading systems needed for such offsets; and the policies needed to support this range of activities.

Hydrogen

Hydrogen is a possible substitute for natural gas and coal to achieve the high levels of heat needed for many industrial processes. Hydrogen shares several key characteristics with natural gas. It is transportable, storable, and has high energy density. A notable advantage of hydrogen is its capacity to combust without directly emitting pollutants or greenhouse gases.[367]

In discussing industrial decarbonization, it is important to consider the unique characteristics of hydrogen as an energy carrier and to address challenges related to infrastructure, cost, safety, and scalability.[368] At present, in nascent market development stages for use as an energy commodity, hydrogen is not yet available in volumes sufficient to meet large-scale supply or demand needs. Also, its costs are high, which could impact the competitiveness of industrial products. The cost of using hydrogen would be more than 30% higher compared to directly using natural gas. Therefore, transitioning to low-carbon or zero-carbon hydrogen from natural gas will be complex and require careful planning, technological innovation, strong policy support, and significant infrastructure.

Pipelines are the most cost-effective way to transport significant volumes of hydrogen. Above certain levels of blending, hydrogen embrittles pipelines. So, pipelines would require retrofits to transport pure hydrogen, not to mention the possible end-of-pipe refining challenges that could come from mixing hydrogen with natural gas. Some North American midstream transportation companies have stated concerns about the lack of clarity in existing regulations for hydrogen pipeline infrastructure. This, in turn, has made investors hesitant to invest in hydrogen pipelines, especially because future hydrogen demand is uncertain.

Some technical reports have cited the possibility of 10% or greater blending of hydrogen in natural gas lines.[369] Research by the National Renewable Energy Laboratory and the Gas Technology Institute states that blending relatively low concentrations of hydrogen—from 5% to 15% by volume—is viable without increasing risks to end-user devices (such as household appliances), overall public safety, or the durability and integrity of the existing natural gas pipeline network. The United Kingdom initially said its pipelines would be ready to blend up to 20% hydrogen into gas networks across the country starting in 2023. However, that goal was quickly revised to 2025.[370,371] Beyond this goal, the United Kingdom has ambitious goals for converting household boilers, which is the main constraint on higher blending ratios at present, according to utility company National Grid.[372]

Blending hydrogen with natural gas in existing pipelines could support additional hydrogen demand and possibly reduce emissions, depending on the method of hydrogen production. Blending hydrogen in these pipelines creates near-term demand for hydrogen. If blue or green hydrogen is used, it could reduce the carbon intensity of end uses while satisfying the ongoing need for a fuel for industrial processes.

Hydrogen, however, affects the safety of pipelines and equipment. The highest possible (i.e., safe) hydrogen blending ratio with natural gas has reached 20%. Some countries in Europe have set allowable blending limits between 1% and 10%.[373]

Overall, the following challenges need to be addressed to develop a hydrogen economy:

1. The infrastructure supporting hydrogen as an energy commodity as opposed to a specialty chemical: Some existing natural gas pipelines can potentially be repurposed to transport hydrogen, but modifications would be needed as hydrogen can embrittle material and escape more easily than natural gas. International transport of hydrogen also faces the same barriers of safety and cost.
2. Hydrogen storage solutions to ensure adequate and reliable supplies: For example, storage solutions are needed to balance the intermittent nature of renewable energy sources used to produce green hydrogen.[374]
3. High costs: In terms of cost and needed investments, green hydrogen is currently more expensive to produce compared to gray hydrogen. The cost of green hydrogen could decrease as renewable energy becomes more affordable, though this would require faster growth in renewables than is currently projected through 2050.
4. The lack of global safety standards: Hydrogen has different safety characteristics and transportation pressure profiles than natural gas, so safety standards and regulations need to be adapted.

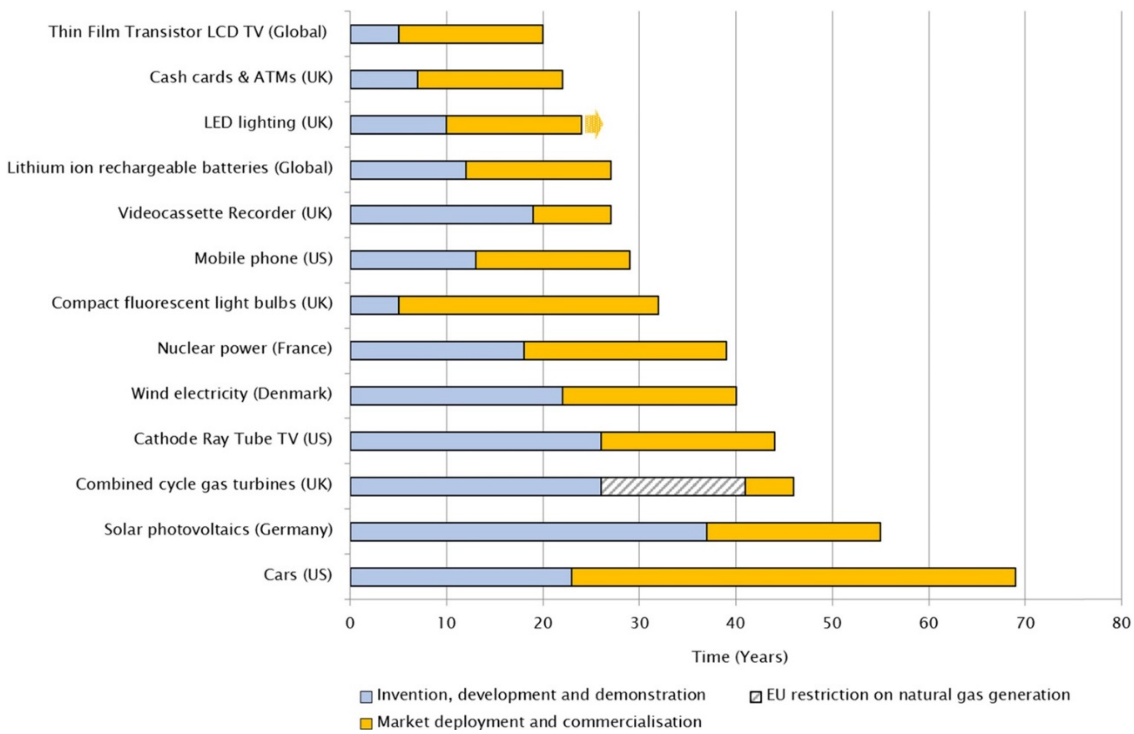
5. Demand: Hydrogen demand from new sectors such as transportation and power generation may create additional competition for natural gas.

Technology Innovation Timelines

As noted, hydrogen is a new and emerging substitute for natural gas, but the infrastructure needed for using hydrogen as an energy commodity, as opposed to a specialty chemical, is not yet developed. Another aspect that needs to be considered with any new decarbonization technology is the time frame from innovation to commercialization. These timelines can span anywhere from 20 to 60-plus years. Figure 102 shows technology development timelines, including those of many energy technologies.[375] Combined cycle gas turbines, for example, took approximately 45 years from invention to commercialization, and lithium-ion batteries took close to 30 years for full commercialization.

When considering decarbonization strategies and technological advancements in hard-to-abate sectors, these aspirations and realistic timelines of R&D need to be compared against net-zero goals for the most effective utilization and investment of capital.

Figure 102. Technology development timelines: From innovation to commercialization



Source: Robert Gross et al., "How Long Does Innovation and Commercialisation in the Energy Sectors Take? Historical Case Studies of the Timescale from Invention to Widespread Commercialisation in Energy Supply and End Use Technology," Energy Policy 123 (2018): 682-699.

For any industrial sector to take up a new technology, significant R&D is required. Also, once these technologies are proven to be market viable, it still takes investment and scaling for them to reach full maturity, i.e., market deployment and commercialization. While net-zero goals and emissions reduction targets serve as a driving force for new decarbonization technologies, there is still a delay between technological feasibility and the full industry uptake of new technologies. While these challenges are daunting, the case studies provide examples of new and emerging technologies for decarbonization in these sectors.

Case Studies: Decarbonizing Industrial Subsectors

Case Study 1: Glass

Findings in Brief

- Glass manufacturing is a significant industrial subsector. It contributes to various economic sectors and is a critical component in many industries, including renewable energy technologies.
- Glass manufacturing is an energy-intensive process that requires high heat. Decarbonization of the subsector represents a significant challenge.
- Electrification of high-capacity furnaces is an important—but not yet fully developed or deployed—technology for furnaces exceeding a high volume of work or very high temperatures.
- Glass manufacturers will remain focused on total costs when making technology and investment choices.
- For near- to midterm decarbonization, technology options must be commercially viable and accommodate technical needs for glass quality, coupled with country-specific regulations. These considerations will significantly impact the decision-making process for specific glass production methods.

Glass is a versatile material with numerous uses across various industries and in everyday life. Glass manufacturing plays a significant role in the industrial landscape. It contributes to various economic sectors and is a critical component in many industries. Industrial glass manufacturing is a complex process that transforms raw materials into products that are used in numerous quotidian applications. Glass plays a vital role in modern society, from windows in homes and screens for smartphones to bottles for food and beverages. Environmental concerns have, however, played a pivotal role in shaping glass market dynamics. Glass manufacturing is energy-intensive and a significant source of GHG emissions. Both the fuels and the processing of raw materials used in glass manufacturing emit CO_2 when heated in glass-melting furnaces.

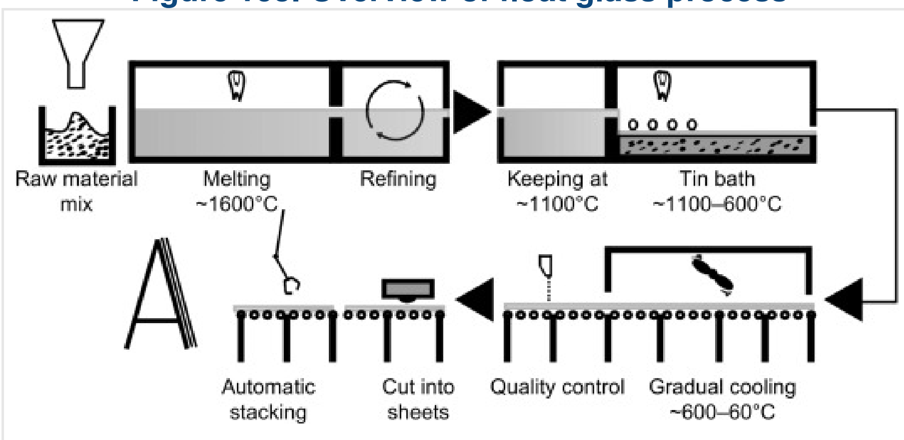
Natural gas is primarily used for two critical processes in making glass: melting raw materials and providing heat for temperature control during various stages of production. Electricity is also used at stages in glass manufacturing, including for powering equipment, conveyors, and lighting. The primary advantage of electric melting compared to fossil-fueled melting is higher efficiency. Additionally, electric melting furnaces potentially have lower investment costs due to their smaller furnace volumes, the absence of regenerators, and the elimination of expensive high-temperature crowns. They also significantly reduce combustion-induced gaseous emissions like CO_2 and NO_x, as well as dust, reducing the need for costly filter systems.

Glass Manufacturing Processes

The production process of glass can be categorized into four stages. First, in the batch preparation and mixing stage, raw materials—including silica, limestone, soda ash, borosilicate, additives, and recycled glass—are blended, ground, and mixed before entering the melting furnace. Second, these prepared materials are added to glass-melting furnaces of various sizes and designs in the melting, refining, and conditioning steps. The required temperatures can range from 600 degrees Celsius to 1,600 C (Figure 103).[376] The resulting melted glass is refined to remove bubbles and is homogenized and heat conditioned. Regulating temperature ensures that the glass is at the optimal temperature for forming and shaping.

The third stage, forming, involves shaping the refined glass into the desired product. Finally, in the finishing stage, the formed glass is subjected to processes designed to meet specific product characteristics.[377] The float glass process—making sheets of glass—requires a substantial amount of heat, resulting in significant energy consumption. Glass melting represents 87% of energy consumption for float glass and around 80% for other types of glass.[378]

Figure 103. Overview of float glass process



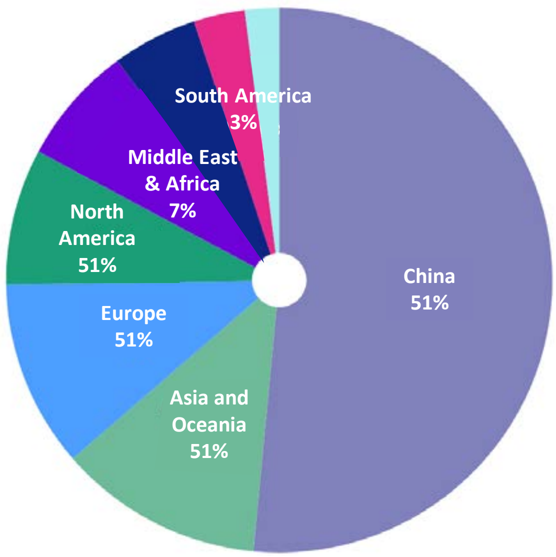
Source: Mithila Achintha, "Sustainability of Glass in Construction," in Sustainability of Construction Materials, 2nd edition, ed. Jamal Khatib, Cambridge, MA: Woodhead Publishing, 2016, p. 79-104. https://www.researchgate.net/profile/Mithila-Achintha/publication/307584942_Sustainability_of_glass_in_construction/links/59e72e6aaca2721fc2308383/Sustainability-of-glass-in-construction.pdf.

Heat and power are critical for the glass industry, which typically uses a combination of energy sources to meet the high temperatures required to power its production processes. Coal has historically been used because of its high heat-generation capabilities, and this use has been driven by access and affordability. While coal consumption has declined at an average rate of 3.9% in OECD countries, non-OECD countries have seen coal consumption grow at an average rate of 1.4%, emphasizing additional challenges for decarbonizing industrial sectors in developing countries.[379]

With coal use decreasing in OECD countries because of environmental impacts, a shift toward less carbon-intensive energy sources, including natural gas, has taken place. Modern glass manufacturing facilities often incorporate heat recovery systems to improve energy efficiency. While natural gas combustion generates a considerable amount of waste heat, this can be captured and reused by the facility for various purposes, including preheating raw materials, heating incoming combustion air, or providing heat for other industrial processes.

Most of the float glass production, however, happens in China (see Figure 104).[380] As with steel in Case Study 3, in many regions of the world significant decarbonization of the sector to reach net-zero commitments will require an ongoing and major effort by China. Additionally, the capacity of China's glassmaking industry dwarfs that of the United States: "The United States now has only 23 plants with 31 lines, while China, by far the world's largest glass producer, has more than 50 factories and 190 lines. ... Even in population-adjusted terms China tops such formerly dominant glass powers as Germany, France, and Italy. Only Poland, the Czech Republic, and Luxembourg are 'glassier' than China on a per capita basis."[381]

Figure 104. Float glass production worldwide, 2019



Source: Stephen Cousins, "The 75 Per Cent Problem: Making Greener Glass," Modus, RICS, September 15, 2021, https://ww3.rics.org/uk/en/modus/natural-environment/renewables/the-75-percent-problem--making-greener-glass.html.

There are also major regional/country differences in the fuels used for making glass. Simulations of CO_2 emissions from China's container glass industry were substantially higher than those in Europe. This difference was attributed to the fuel mixes. In China, the industry used 44.3% coal, 13.1% fuel oil, 15.5% natural gas, and 27.1% electricity and other sources. According to this same analysis, the U.S. glass industry uses 80% natural gas, and the European industry uses 90% natural gas.[382]

Decarbonization Strategies for Glass

There are a few options for decarbonizing glass manufacturing, including electrification, the use of low-carbon fuels, and technology innovations (e.g., CCUS).

Electrification

In the industrial sector, over the lifespan of the equipment, fuel costs are over 10 times greater than the initial capital investment in the equipment. In medium- and high-temperature heat applications, electric furnaces require a comparable capital investment and exhibit similar efficiency levels as their conventional counterparts. Therefore, the investment required to transition to electric equipment must consider the difference between the ongoing operational energy costs for electric furnaces and those for conventional fuel-based ones.[383] As such, electricity to natural gas price ratios are highly relevant and could impact the overall cost and price of the glass and, at a minimum, need to be compared to the costs of making glass with conventional furnaces and fuel with CCUS.

Electrification of high-capacity furnaces is an important—but not yet fully developed or deployed—technology for furnaces exceeding a daily capacity of 200 t. To develop this technology, the European Container Glass Federation launched an initiative called the Furnace of the Future,[w] which gathers major packaging glass manufacturers with aims to achieve a 50% reduction in CO_2 emissions and the development of a high-capacity hybrid furnace.[384]

However, there are technical and economic drawbacks. These include low volume capacity, dependence on electricity prices that can vary regionally relative to natural gas prices, and the critical necessity of a reliable electricity grid. Additionally, the high heat requirements for making glass limit the viability of electricity in the process, as electricity can typically produce heat at a maximum temperature of about 400 C. In addition, as was seen in Figure 94 (gas vs. electricity costs), the differences between costs of natural gas and electricity for industry are substantial and could affect affordability and competitiveness in national, regional, and global markets.

Low-Carbon Fuels

Substituting fossil fuels with biogas or hydrogen, electrifying large-capacity furnaces, and implementing carbon capture represent additional techno-economic challenges, even though all are viable solutions for reducing carbon emissions. For example, biogas would generate additional costs, and the source and availability of biogas pose challenges. Hydrogen would require furnace replacements because current furnaces can only use up to 20% hydrogen with natural gas due to differences in thermal and radiative properties.[385]

CCUS Technology Innovation

Technological innovations are one method by which the glass industry is trying to decarbonize. One company, C-Capture, is working with glass manufacturer Pilkington to assess the possibility of using its unique and relatively inexpensive CCUS technology. The company claims the approach uses 40% less energy than other commercially available technologies and addresses the difficulties associated with capturing CO_2 emissions. The emissions in glass production are caused by high levels of impurities from nitrogen oxides and sulfur oxides.[386]

Glass manufacturers will, however, continue to focus on total costs when making technology and investment choices. With rising renewable energy adoption, energy efficiency and operational

[w] Furnace for the Future is a European glass industry project that fosters electric melting technology that will allow the switch to renewable electricity and dramatically reduce CO_2 emissions, https://www.glass-international.com/content-images/news/F4F-in-short-FINAL.pdf.

adaptability will gain greater significance, accompanied by an increased emphasis on energy security. Simultaneously, the decarbonization solutions chosen must possess the necessary technological maturity and technical considerations—such as glass quality, coupled with country-specific regulations—and these considerations will significantly impact the decision-making process for specific glass production methods.[387]

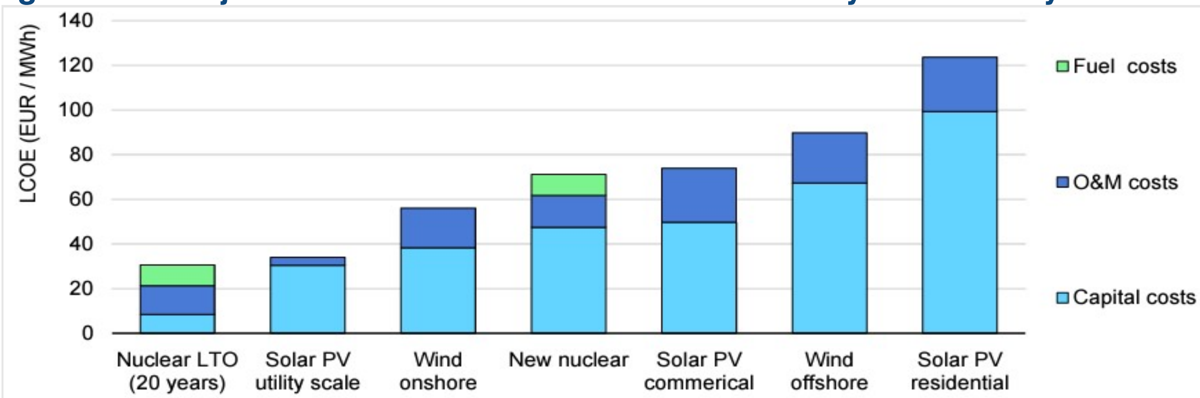
Example: Glass Industry in France

To illustrate these and other issues, this subsection examines the evolution of the glass industry in France and the effect that decarbonization efforts and France's energy makeup have had on the industry.

France is the second-largest glass producer in Europe, with an annual output of approximately 4.6 million metric tons. Importantly, in France, the thermal energy necessary for glass fusion comes mainly from natural gas (85%) and only 10% from electricity.[388] The French government has a target of reducing GHG emissions by 50% by 2030, with glass playing a significant role in the clean energy transition. According to the French Glass Federation, glass production in France resulted in 2.7 million metric tons of CO_2 equivalent emissions, constituting 0.6% of the nation's total emissions and 3.3% of emissions from the French industrial sector. Approximately 20% of these emissions can be attributed to using raw materials, while the remaining 80% is attributed to using fossil fuels from production. Importantly, in 2019, the EU's Emissions Trading System allowances cap covered 85% of declared emissions from the French glass industry. In the absence of these quotas, glass production costs could rise by approximately 5%, with a cost of 25 euros ($26.67) per metric ton of CO_2.[389]

In 2019, approximately half of France's total energy supply was domestically generated, and 79% of this generation was zero-emissions nuclear power. France's operating of nuclear power plants for extended periods while adhering to strict safety standards represents an economically efficient approach to generating environmentally friendly, low-carbon electricity. According to the 2020 edition of the IEA/NEA publication titled "Projected Costs of Electricity," France is projected to incur costs of approximately $30/MWh for maintaining these plants in operation for either a minimum of 10 or 20 years (Figure 105).[390]

Figure 105. Projections for the levelized cost of electricity in France by technology



LCOE = levelized cost of electricity, LTO = long term operation, MWh = megawatt hour, O&M = operating and maintenance, PV = photovoltaic, Data are based on a 7% discount rate and costs are projected for the year 2025 based on data submitted by the Ministry of the Ecological Transition. Source: IEA, Projected Costs of Generating Electricity 2020, 2020, https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, License: CC BY 4.0.

Nuclear generation gives France an advantage for the electrification of the glass industry, where electricity costs for nuclear generation are competitive with natural gas and where industrial processes do not require high levels of heat. Nuclear power in France, however, faces several challenges, including enriched uranium supply risks, public perception, capacity factors, and the age of its nuclear plants.

The versatility and adaptability of glass make it a critical material for a wide range of applications, aligning with the diverse needs of French industries and climate objectives. French glass manufacturers contribute to the country's sustainability efforts by producing eco-friendly packaging solutions and promoting recycling initiatives. France is well positioned for electrification of many of the steps in the glass-making processes as 79% of its domestic electricity generation is zero-emissions nuclear power.

Case Study 1 Summary

The decarbonization of glass manufacturing, an energy-intensive process that requires high heat, faces numerous challenges and opportunities. The industry's high energy demand—primarily met by fossil fuels—has significantly contributed to GHG emissions. To align with sustainability goals and meet the demands of environmentally conscious consumers and clients, glass manufacturers are actively pursuing decarbonization strategies.

Addressing the critical challenges in the sector involves decarbonizing energy inputs for glass production and reducing emissions related to raw materials. Europe is actively exploring technologies like hydrogen, biomass, and decarbonized electricity, but these options come with significant infrastructure and investment challenges and costs, underscoring the importance of long-term planning and thoughtful, sequenced policies.

Case Study 2: Cement[x]

Findings in Brief

- The cement industry is responsible for a substantial share of global CO_2 emissions due to the chemical process of calcination and the energy-intensive nature of cement production.
- The GHG emissions in the cement industry are hard to abate since mitigation measures are insufficient, expensive, or inadequate for final production.
- Electrification is only a partial option to decarbonize the cement industry. Multiple additional approaches are needed, including the use of alternative, lower-carbon binders; supplementary cementitious materials; improving energy efficiency; reducing the amount of clinker in cement; and CCUS technologies.
- The decarbonization options must be cost-effective because the cement industry is cost-sensitive due to the high-volume and low-margin nature of the industry.

Industrial subsectors, particularly the cement industry (and steel, as discussed in Case Study 3), play a pivotal role in the global economy, providing essential materials for construction, infrastructure, and manufacturing. Cement and other industrial subsectors are, however, among the largest contributors to hard-to-abate CO_2 emissions, which pose significant challenges in achieving global, regional, and national climate goals. Cement accounts for around 7% of global emissions.[391]

In 2021, China, India, Vietnam, the United States, and Turkey were the world's largest cement producers, although there are substantial differences in volumes of production. In 2021, China produced 4.1 billion metric tons (Gt) of cement and India produced 2.1 Gt.[392] That same year, the U.S. produced 92 million tons (Mt) of portland and masonry cement and 79 Mt of clinker.[393] Decarbonizing cement production is critical around the world but is essential in Asia, as three of the top five producers are in that region.

These emissions are considered hard to abate because mitigation measures like electrification from low-carbon generation sources are expensive, insufficient, or inadequate for final production. Both concrete and steel production are inherently energy-intensive processes. The use of raw materials and the processes for their use in manufacturing require exceptionally high temperatures, the generation of which generally relies on fossil fuels.

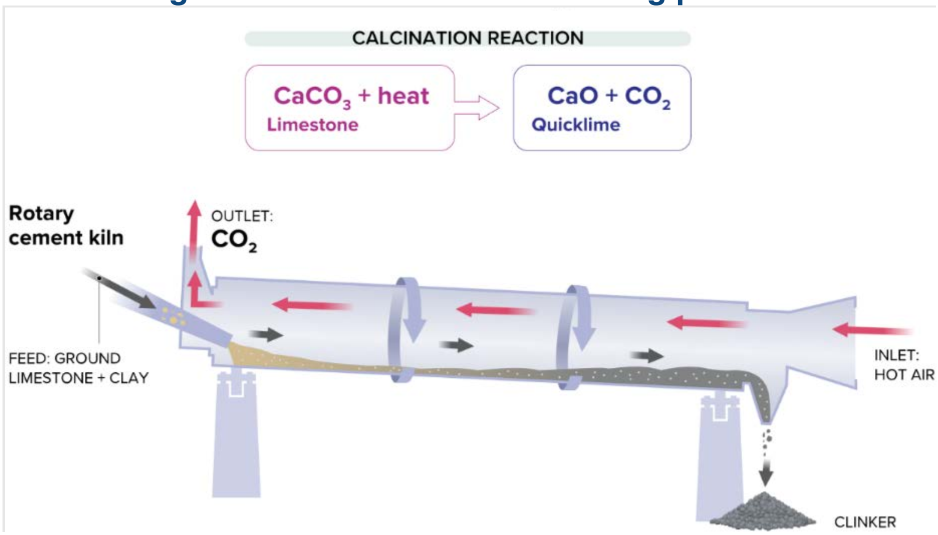
Cement Manufacturing Process

The cement industry is fundamental to construction and is the most widely used construction material globally. It is crucial for buildings, roads, dams, and various infrastructure projects, providing durability and structural integrity to buildings. The production of concrete involves cement, which is a primary source of CO_2 emissions. The chemical process of making cement, known as clinker production, is extremely carbon intensive.

[x] Concrete is a composite made from several materials, one of which is cement.

As noted, the cement industry is responsible for a substantial share of global CO_2 emissions, primarily due to the chemical process of calcination, where limestone is heated to produce clinker, the primary ingredient in cement (Figure 106).[394] Moreover, the energy-intensive nature of cement production further exacerbates its carbon footprint.

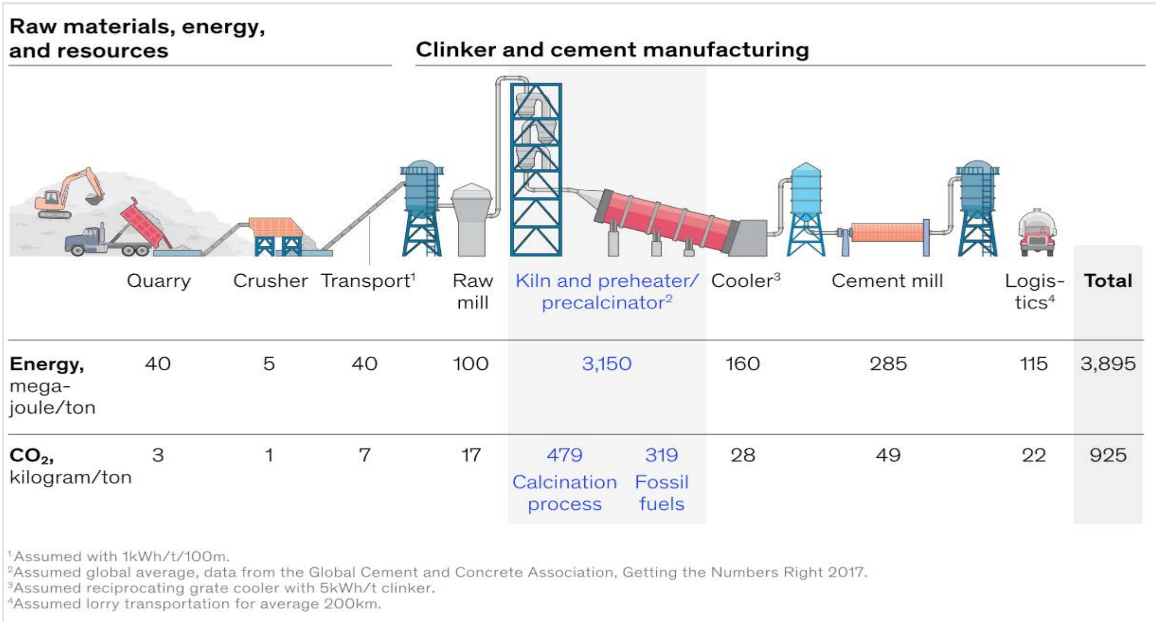
Figure 106. Cement manufacturing process



Source: Mitchell Waldrop, "The Road to Low-Carbon Concrete," Knowable Magazine, November 16, 2022, [*https://knowablemagazine.org/content/article/technology/2022/low-carbon-concrete*](https://knowablemagazine.org/content/article/technology/2022/low-carbon-concrete).

Traditional decarbonization solutions, like electrification, may reduce emissions from energy use, but they cannot fully address approximately 50% of the emissions associated with cement manufacturing (Figure 107).[395,396] Emissions mitigation strategies for the cement industry include the use of alternative, lower-carbon binders and supplementary cementitious materials, improving energy efficiency, reducing the amount of clinker in cement, and CCUS technologies.[397]

Figure 107. Cement production and calcination reaction are the sources of CO_2 emissions



Source: Thomas Czigler et al., "Laying the Foundation for Zero-Carbon Cement," McKinsey & Company, 2020, https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement.

Implementing decarbonization strategies in the cement industry has several challenges. In the United States, for instance, the added cost and scale of retrofitting production facilities and the rural location of concrete facilities make natural gas from pipelines inaccessible. Technological innovation will play a pivotal role in the transition to more sustainable production processes, yet developing and deploying these technologies at the scale required for these industries is a challenge. Innovations such as electrification processes, low-carbon fuels, advanced CCUS, and recycling need substantial research, development, and capital investment.

Decarbonization Strategies for Cement

The following are decarbonization strategies for cement: electrification, use of low-carbon fuels, and other innovations.

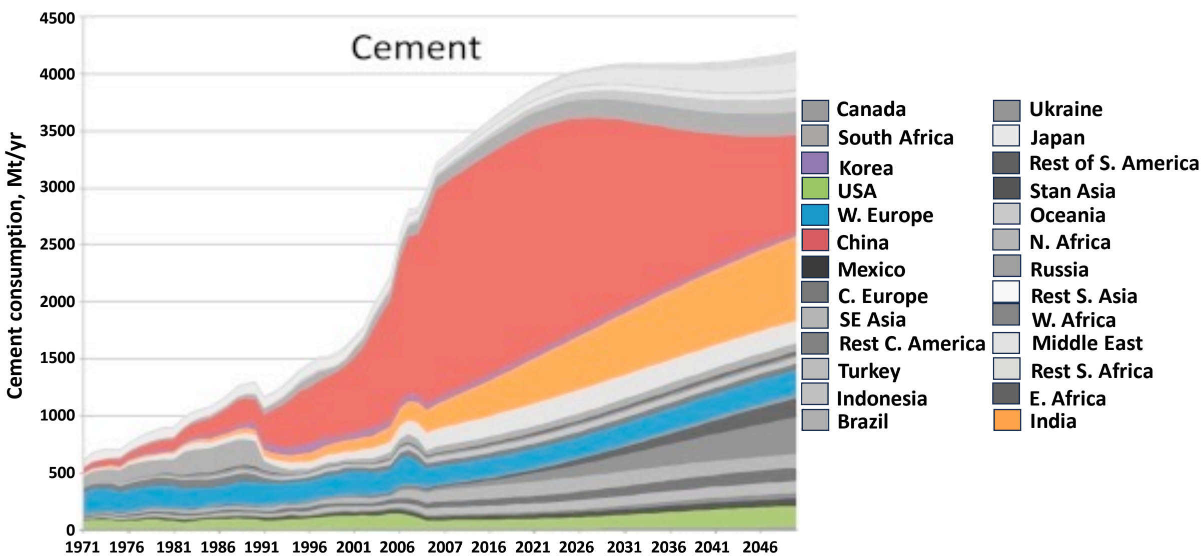
Electrification: Electric Kilns

As seen in Figure 107, the main source of CO_2 emissions in cement manufacturing is the clinker and the associated fossil fuel use at this stage of the production process. The segment encompassing the kiln, the preheater, the pre-calcinator, and the cement mill accounts for more than 94% of the CO_2 emissions. The calcination process accounts for around 52% of the CO_2 emissions and the kiln for 34%. Electrification of the kiln can contribute significantly to the decarbonization of the cement industry. Some examples of electric kilns in operation are described below.

VTT, a Finish research organization, conducted successful experiments using an electric kiln for cement production. This electric kiln, powered by low-emissions electricity, offers the potential to significantly reduce carbon emissions in the cement industry. VTT's electric kiln, which was operational between November 2021 and October 2022, demonstrated that it could make cement production nearly carbon-neutral and capture pure CO_2 during the pre-calcination phase. This captured CO_2 can be used for various industrial applications or permanently trapped in concrete. VTT is seeking partnerships with major industrial players to scale up this solution. This innovative approach could revolutionize the cement industry, making it more environmentally friendly and contributing to global decarbonization efforts.[398]

China and increasingly India are the largest consumers of cement in the world (Figure 108).[399] This is only expected to grow with urbanization efforts underway in both countries. Current data suggests that "Cement manufacturing emissions in India have experienced a steep climb in recent decades. In 2022, figures reached a high of 164 million metric tons of carbon dioxide ($MtCO_2$), up from some 149 $MtCO_2$ in the previous year. India is the second-largest polluter from cement manufacturing across the globe."[400] Efforts to decarbonize the cement industry will need to be targeted in these countries if they are to have a significant impact on emissions.

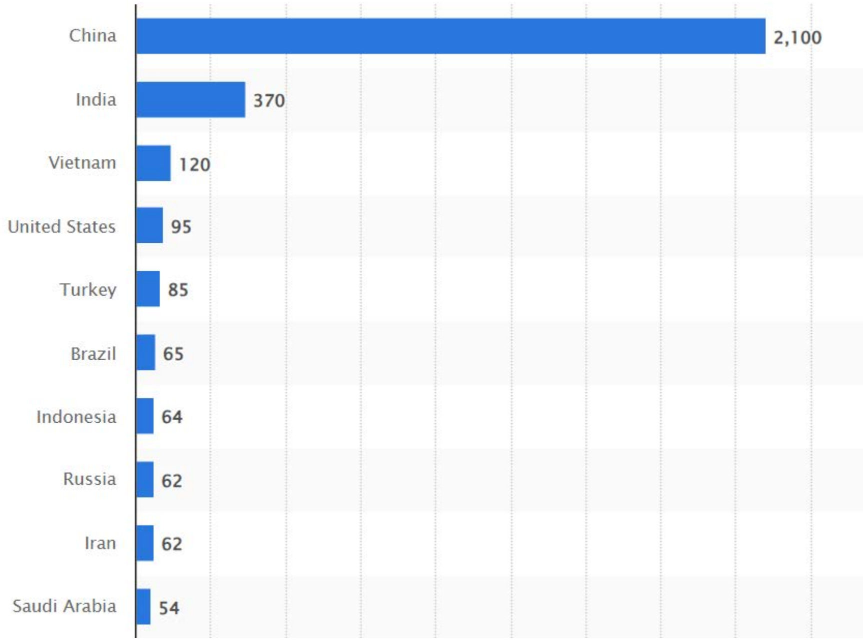
Figure 108. National/regional consumption of cement, 1971 to 2046



Source: Bas J. van Ruijven et al., "Long-Term Model-Based Projections of Energy Use and CO2 Emissions from the Global Steel and Cement Industries." Resource, Conservation and Recycling 112, (September 2016): 15–36.

Like with green steel, the cement industry's decarbonization will largely depend on China's (and India's) production and decarbonization efforts. Since China vastly outproduces cement compared to every other country combined (Figure 109), China's policies will decide whether global CO_2 emissions from cement manufacturing are adequately mitigated.[401]

Figure 109. Worldwide cement production in 2022 (Mt)



Source: Oluwafemi Ezekiel Ige et al., "Carbon Emissions Mitigation Methods for Cement Industry Using a Systems Dynamics Model," Clean Technologies and Environmental Policy (2024): 1–19.

Low-Carbon Fuels

Hydrogen and biomass could be alternative and lower-carbon fuels for the cement industry, but much progress would be required to commercialize these options. CCUS can play a critical role in decarbonizing the cement industry, and corporations have started exploring the feasibility of CCUS deployment in their manufacturing facilities.

Hydrogen

Hydrogen is emerging as a versatile and clean energy carrier. The adoption of hydrogen, particularly green hydrogen produced using renewable energy, can significantly contribute to decarbonizing industries. Hydrogen holds the potential to transform clinker production. It could be used as a reducing agent, replacing traditional fossil fuels in the clinker production process, thereby reducing CO_2 emissions.

Green hydrogen or hydrogen, coupled with CCUS, offers a solution for a more sustainable cement production process. However, considerable progress would be required to commercialize these options and enable them to affordably compete with alternatives. Also, hydrogen technologies would address energy but not process emissions from cement production.

Biomass

Biomass, sourced from organic materials like wood and agricultural residues, represents a renewable, carbon-neutral fuel option. When used in cement production, biomass could theoretically replace fossil fuels, thereby reducing carbon emissions. Co-firing biomass in cement kilns leads to a reduction in the carbon footprint.

Carbon Capture, Utilization, and Storage

CCUS technologies can play a pivotal role in capturing and managing CO_2 emissions in the cement industry. CCUS involves capturing CO_2 emissions at the source, preventing them from being released into the atmosphere. In the cement industry, CO_2 capture technologies can be used with cement kilns, where the chemical conversion of limestone into clinker generates significant CO_2 emissions.

Captured CO_2 could be used in various ways. In the cement sector, CO_2 could be used to produce construction materials like aggregates or in the formation of low-carbon cement, which could further reduce emissions. Electrification could facilitate the deployment of CCUS technologies. The electricity required to operate these CCUS processes can be sourced from renewable energy, making the capture and storage of carbon emissions more sustainable. CO_2 that is captured but not immediately utilized can be safely stored underground in geological formations, preventing its release into the atmosphere. Below are examples of CCUS in the cement industry:

- Heidelberg Cement and its Swedish subsidiary, Cementa, have shown positive results from a pre-feasibility study for the Slite CCUS project, a significant step toward the industry's sustainability targets. The project is located at the Slite cement plant in Sweden and aims to capture up to 1.8 $MtCO_2$ annually, equivalent to 3% of the country's total emissions, and is the largest CCUS project for the cement industry. The technology used for carbon capture is amine capture, and the full-scale implementation will require plant modifications and increased power demand. It builds on the experience gained from the Brevik CCUS project in Norway, set to be operational in 2024.[402]
- Air Liquide, a French company, has secured EU funding to develop two CCUS projects at cement factories in Poland and France. The first project, called Go4ECOPLANET, aims to completely decarbonize cement production at a Lafarge plant in Kujawy, Poland. The technology captures and liquefies CO_2 emissions, capturing 100% of the plant's CO_2 emissions and storing them in the North Sea. This project is expected to result in 105% GHG emissions avoidance compared to a reference scenario. It is expected to start operation between late 2027 and early 2028.[403]
- Air Liquide's second project, known as the K6 Program, will transform a cement plant in Hauts-de-France into the first carbon-neutral cement plant in Europe. The plant has a significant capacity and utilizes local waste materials, providing jobs and serving a regional market. The K6 Program will employ an innovative combination of an airtight kiln and cryogenic carbon capture technology to capture and store CO_2 emissions in the North Sea. Over the first decade of operation, it is expected to avoid 8.1 MtCO2e emissions. Additionally, the project will support the development of the nearby port of Dunkirk as a European CO_2 hub. Both projects aim to contribute to decarbonizing the construction industry and are set to commence operations in the late 2020s.[404]

Innovative Solutions: Clinker-to-Cement Ratio

Cement remains one of the more difficult industrial sectors to decarbonize because of the GHG emissions produced through the production process and the high global demand for a key building block for construction and renewable technologies such as wind power.[y]

One avenue for decarbonization focuses on the clinker-to-cement ratio, as about 60% of emissions from cement manufacturing come during the clinker process.[405] The emissions from manufacturing clinker—the main component of cement—result from chemical reactions and fuel combustion in the process. Measures to reduce emissions include reducing the clinker-to-cement ratio by adopting supplementary cement materials, adopting low-carbon fuels, and capturing residual CO_2 emissions.[406]

The IEA notes that the "global clinker-to-cement ratio has increased at an annual average of 1.1% since 2015, from 0.66 increasing to 0.71 in 2022." However, regional differences can skew this overall percentage. The IEA also says that "China, despite having one of the lowest clinker-to-cement ratios globally, saw an increase from 0.57 in 2015 to 0.65 in 2022. In contrast, countries with high ratios, such as the United States and Canada, have decreased their ratios from 0.90 and 0.87 in 2015, respectively, to 0.89 and 0.86 in 2022."[407]

Technology Innovation

CO_2 from industrial sources can be used to produce building materials, notably through CO_2 curing in concrete production and by reacting CO_2 with waste materials (e.g., iron slag, coal fly ash) to create construction aggregates. CO_2 curing in concrete production involves using CO_2 as a curing agent to enhance concrete properties. These approaches offer CO_2 storage within the building materials, potentially reducing costs and avoiding conventional waste disposal expenses. However, energy-intensive processes, especially in pre-treatment and post-treatment steps, are associated with producing building materials from waste.[408]

Carbon dioxide sequestration in carbonates offers semipermanent CO_2 storage options and potential cost reductions in concrete production. It requires effective carbon capture technologies to achieve emissions reductions, but if CO_2 is sourced from non-cement industrial sources, it doesn't directly reduce CO_2 emissions from cement production.

Current projects include Carbon8 in the U.K., which uses high-purity CO_2 to convert air pollution control residues into carbon-negative aggregates for building materials. They have conducted successful demonstration projects in Canada, the United States, and France and are piloting a waste and CO_2 aggregate production system in the Netherlands. Another is CarbonCure, a Canadian company that offers a commercial CO_2 curing process available in numerous concrete plants, claiming improved compressive strength and cost-effectiveness. Finally, a commercially available option in Japan, CO_2-SUICOM, developed by Kajima Corporation and others, uses a powder to reduce CO_2 emissions in concrete with practical applications in construction.

[y] A typical slab foundation for a 1 MW turbine is around 15 m in diameter and 1.5 to 3.5 m deep. The foundation for turbines in the 1 to 2 MW range typically uses 130 to 240 m^3 of concrete. For details, see https://www.utilitysmarts.com/renewables/wind-power/how-much-concrete-in-a-wind-turbine-foundation/.

Recycling

Several methods have been developed to recycle concrete, with one approach focusing on producing crushed concrete fines, which are fine particles ranging from 0 to 4 mm in size. This method allows for the recovery of calcium oxide (CaO) from these fines, which can then be employed in cement kilns to substitute a portion of the limestone ($CaCO_3$) typically used as an input. This substitution significantly reduces process emissions, estimated to be around three times less.[409] Additionally, the recovered CaO can serve as a filler in blended cements.

Also, when concrete is crushed into its individual components, it yields old cement powder. This powder can initially replace lime flux in steelmaking and subsequently be used as a zero-emissions clinker in cement production. In the steelmaking process, lime flux is a chemical substance (typically CaO) that is added to the furnace or vessel where steel is being produced.

Another method to recycle cement is unhydrated cement recycling. During the concrete curing process, a portion of the cement may not interact with water and remains unhydrated. Some estimates indicate that as much as 50% of the cement might stay unhydrated. Researchers are working on innovative concrete crushing methods that could potentially retrieve this unhydrated cement from old concrete, allowing it to be reused directly as new cement.

Case Study 2 Summary

The cement industry plays a vital role in shaping global infrastructure and fostering development, including being a key building block for renewable implementation, e.g., for wind turbine bases. Yet, concrete stands out as an energy-intensive sector with notable environmental consequences. The challenges are further exacerbated by the energy-intensive manufacturing processes, coupled with the inherent chemical reactions that release CO_2 as a significant byproduct. Additionally, like steel, concrete represents high-volume, lower-margin manufacturing that could be more sensitive to added costs of production.

Electrification is only a partial solution to the challenge of abating emissions in the production of concrete, and several other approaches and technologies are needed for decarbonization of this sector. The increasingly energy-efficient CCUS technologies utilize lower-carbon binders and supplementary cementitious materials. Further development and scalability of these technologies will be vital in effectively decarbonizing the cement industry.

Case Study 3: Steel

Findings in Brief

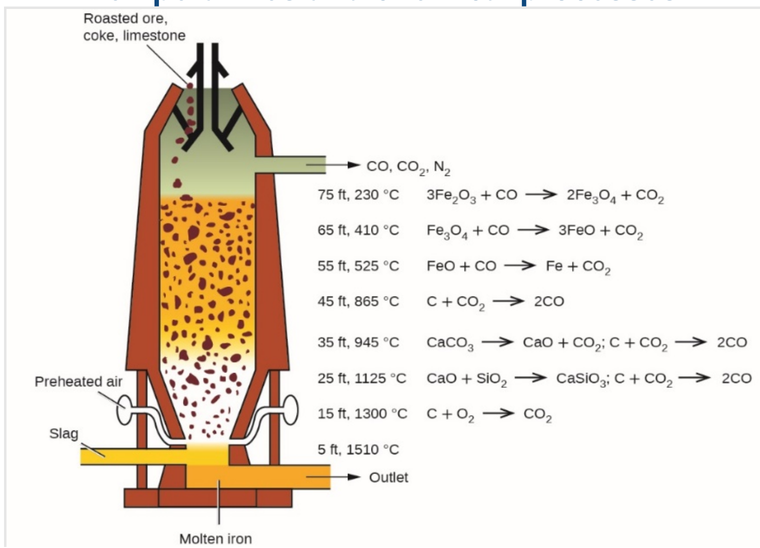
- The energy-intensive steel industry is strategic for development and production of component products used as the basic building blocks in renewable energy projects, but steel's contribution to global CO_2 emissions is a critical issue.
- As developing countries continue to progress, the demand for steel is expected to increase, especially in China and India.
- Balancing the need for steel with sustainability goals is challenging, necessitating emissions reduction while maintaining steel's essential role in development. Green steel is an option, but costs and process changes will be issues for its near-term use.
- Emissions mitigation can be achieved through changes in manufacturing processes, technological advancement, fuel switching, and advancements in commercial CCUS.

Steelmaking, like cement production, is an inherently energy-intensive process. The use of raw materials and the processes for their use in manufacturing require exceptionally high temperatures, the generation of which generally relies on fossil fuels. But most importantly, because the production of steel involves chemical reactions that release CO_2 as a byproduct, it remains one of the hard-to-abate sectors. To achieve a low-carbon future, mitigating these emissions will be essential.

Manufacturing Processes

Steel can be manufactured using two main approaches: (1) integrated or (2) all-electric. In an integrated approach, steel is produced from iron ore and coal or coke in a blast furnace (BF) and a basic oxygen furnace (BOF) (Figure 110).[410,411] This method, while highly energy-efficient, results in significant CO_2 emissions. The integrated approach is the dominant global crude steel production method, accounting for nearly 71% of total crude steel production. In European steel production, the BF-BOF approach constitutes approximately 56% of total steel production, whereas in the United States, only 31% of steel is produced through the integrated approach.[412]

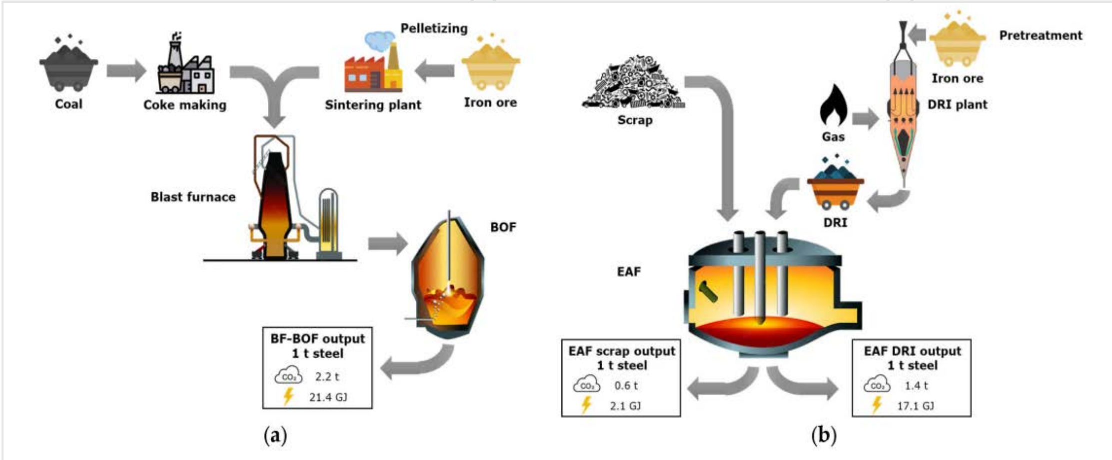
Figure 110. Blast furnace process for producing molten iron with associated temperatures and chemical processes



Source: LibreTexts Chemistry, "19.1: Occurrence, Preparation, and Properties of Transition Metals and Their Compounds," https://chem.libretexts.org/Bookshelves/General_Chemistry/Chemistry_2e_(OpenStax)/19%3A_Transition_Metals_and_Coordination_Chemistry/19.01%3A_Occurrence_Preparation_and_Properties_of_Transition_Metals_and_Their_Compounds.

As seen in Figure 111, the CO_2 emissions amount to approximately 2.1 tCO_2 per ton of crude steel produced from a BF and 0.6 tCO_2 per ton from an electric arc furnace (EAF).413 The emissions vary from country to country, with most countries falling within the range of 1.8 tCO_2 to 4.0 tCO_2 per ton of crude steel.414 Notably, China and the EU report lower CO_2 emissions, at 1.84 tCO_2 and 1.81 tCO_2, respectively, while South Africa and India generate more than 3.8 tCO_2 per ton of steel.[415]

Figure 111. Energy consumption and CO_2 emissions in steel manufacturing for blast furnace (a) and electric arc furnace (b)



Source: Josué Rodríguez Diez et al., "Decarbonization Pathways, Strategies, and Use Cases to Achieve Net-Zero CO2 Emissions in the Steelmaking Industry," Energies (2023).

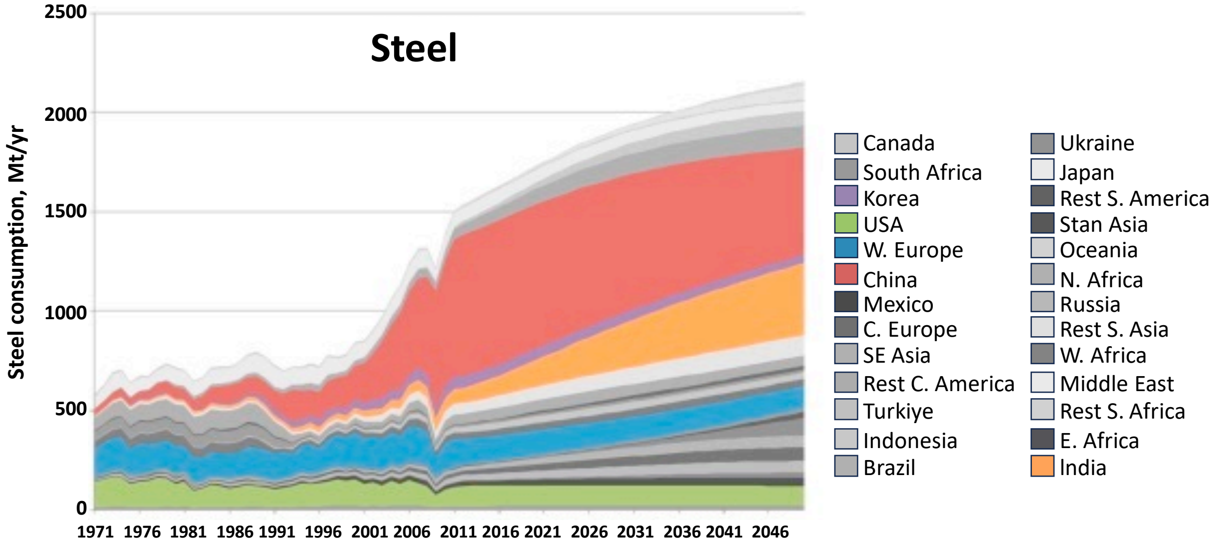
Efforts to mitigate CO_2 emissions are growing in the steel manufacturing industry. Decarbonizing the steel industry hinges on assessing the availability of energy and materials crucial for steel production. Decarbonization initiatives must be accompanied by considerations regarding technological maturity, supply aspects, infrastructure availability, energy and raw materials, plant-specific investment cycles, and financial/cost and legislative conditions.

Steel decarbonization could be facilitated using natural gas in lieu of coke gas, transitioning to a hydrogen-based steel industry, adapting fossil-fuel-based steel processes for CCUS, and increasing the use of scrap and steel byproduct recycling. Energy, feedstock, and carbon storage emerge as the pivotal elements in addressing this formidable challenge.[416]

The quality of steel products is closely linked to the availability of high-grade steel scrap. When such scrap is scarce, the integration of direct reduced iron (DRI) into the production process becomes essential to guarantee specific product qualities. It is worth noting that the production of DRI relies on the availability of economical and easily obtainable natural gas or coal. As a result, regions with lower natural gas prices, such as the Middle East or North America, have become significant producers of DRI, while its utilization is less common in Europe. In some European steelmaking operations, a derivative of DRI known as hot briquetted iron (HBI), which is a more transportable form of DRI, is imported. HBI is incorporated into the steelmaking process either in the traditional BF method to optimize the mix of materials or in the EAF method, where it is blended with scrap to enhance the quality of the steel product. This approach aligns with the objective of improving steel production's efficiency and environmental sustainability.

As with cement and glass, a significant and growing percentage of steel consumption is in China and India, where the corresponding manufacturing is done predominately with coal (Figure 112).[417] Any decarbonization efforts in this sector need to be targeted in these regions.

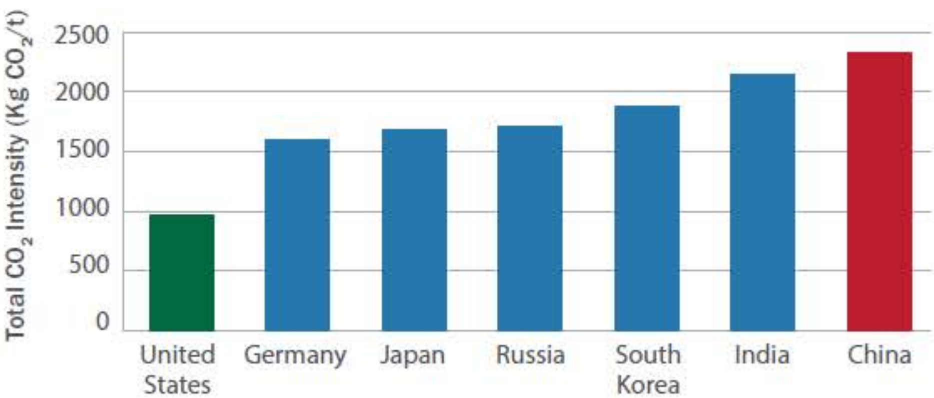
Figure 112. National/regional consumption of steel, 1971 to 2046 (projected)



Source: Bas J. van Ruijven et al., "Long-Term Model-Based Projections of Energy Use and CO_2 Emissions from the Global Steel and Cement Industries," Resource, Conservation and Recycling 112 (September 2016): 15–36.

Both India and China, the top two producers of steel in the world, expect significant economic and urbanization growth over the next 30 years, increasing the likelihood of needing larger amounts of steel. Figure 113 shows the CO_2 emissions intensity of some of the largest steel-producing countries.[418]

Figure 113. Total CO_2 emissions intensity of the seven largest steel-producing countries



Source: Short Span Steel Bridge Alliance, "Facts About American Steel Sustainability," [*https://www.shortspansteelbridges.org/american-steel-sustainability/*](https://www.shortspansteelbridges.org/american-steel-sustainability/).

Decarbonization Strategies

There are a range of options for reducing CO_2 emissions from steel and iron. These include electrification; the use of natural gas in lieu of coal for key processes in iron and steel manufacturing; the use of hydrogen and biomass in lieu of coal for key processes; CCUS; and recycling.

Electrification: Electric Arc Furnaces and Direct Reduced Iron

Globally, steel production is highly reliant on coal, which currently meets around 75% of the energy and feedstock demand of the sector, and has remained roughly the same over the past decade.[419] Coal is primarily used as a reducing agent to extract iron from iron ore and to provide the carbon content needed in steel.

Electrification in the steel industry can mitigate emissions, particularly by using EAFs, but the global manufacturing process still poses challenges for decarbonization. In the United States, most crude steel production (around 69%) uses the all-electric approach. In the EU and worldwide, the EAF approach accounts for 44% and 30% of total crude steel production, respectively, according to 2021 data.[420]

An all-electric approach involves melting scrap in an EAF, which could significantly reduce CO_2 emissions compared to the BF-BOF approach. Another method to reduce CO_2 emissions from the integrated approach is by using an alternative iron source in the EAF, such as DRI produced with natural gas.[421] The emissions from the scrap-EAF and DRI-EAF processes generally range from 0.6 tCO_2 to 1.4 tCO_2 per ton of crude steel, depending on the raw materials used.[422]

The steel industry has made substantial progress in decarbonization through the development of EAFs. Nearly 71% of the steel produced in the United States was from EAFs, compared to only 26% globally in 2020.[423] EAFs use electricity to melt scrap steel, eliminating the need for traditional blast furnaces that rely on coal or coke and eliminating significant amounts of $C0_2$. However, EAFs and blast furnaces are two distinct methods for producing steel. Whether EAFs can replace BFs depends on various factors, including the type of steel production, the desired end products, environmental considerations, and economic factors (Table 6).

Table 7. Comparison of blast furnace (BF) and electric arc furnace (EAF)

	Raw Materials	Environmental Impact	Product Quality	Economic Factors	Operation
BF	Iron ore, coke, limestone	Higher carbon footprint	High-quality steel	Requires significant capital investment	Hard to replace or shut down
EAF	Scrap steel	Lower carbon footprint	Scrap steel quality	More cost-effective	More flexible

EAFs are well-suited for recycling scrap steel and producing certain types of steel products, especially in regions where environmental regulations are strict or clean energy sources are abundant. However, BFs are still necessary to produce primary steel from iron ore, and in some cases, a combination of both methods may be employed to meet different steel production needs while addressing sustainability goals.

EAFs can be combined with the utilization of DRI to enhance the efficiency and sustainability of steel production. DRI is a form of iron that is produced by reducing iron ore in a process that emits significantly less CO_2 compared with the conventional integrated steelmaking process. Direct reduction methods can use either gas or coal. In both instances, the primary goal is to eliminate the oxygen present in the iron ore. This is done to transform the ore into metallic iron without the need for melting, and the process operates at temperatures below 1,200 degrees Celsius (2,190 degrees Fahrenheit). This approach facilitates the production of high-quality steel products within the EAF.[424]

The Use of Natural Gas in Lieu of Coal for Iron and Steel Manufacturing

According to the U.S. Iron and Steel Institute, the use of natural gas by the industry increased from 29% in 1998 to 39% in 2018. It also noted that U.S. emissions reductions in steel manufacturing have been achieved by using natural gas in lieu of coal in the production of pig iron.[425]

An analysis of the use of natural gas in lieu of coke gas for reheating furnaces in a Turkish facility concluded that this was possible, economic, and would result in substantial reductions in CO_2 emissions of around 50%. The analysis developed information for a “renovation project” of an iron- and steelmaking facility. Its broader conclusions about such a renovation stated: “Using natural gas improves output by 914 tons and allows the firm to generate an additional 5,979,334 kWh of electric power from metallurgical gases per month. In the economic analysis, a positive return for each month demonstrates the feasibility of the renovation investment. The investment’s payback period is a short term of 11 months. The process renovation reduces health and safety risks during manufacturing, storage, and distribution. The project decreases the global warming potential of blast furnace gas constituents and carbon emissions by 0.84% per month.”[426]

In this context, it is worth noting the range of steel-manufacturing countries in the regions that are the focus of this analysis. Table 7 shows steel operations by volume in Asia and Europe for operating plants, plants under construction, and announced plants.[427]

Table 8. Steel capacity by development status in Asia and Europe, thousand tons per annum (TTPA)

Country in Asia	Announced	Under Construction	Operating	Country in Europe	Announced	Under Construction	Operating
Bangladesh	4,500	0	5,200	Albania	0	0	700
Cambodia	3,100	0	0	Austria	2,450	0	7,570
China	142,698	64,531	1,112,318	Belarus	0	0	3,000
Hong Kong	700	0	0	Belgium	2,500	0	8,050
India	167,491	28,415	120,573	Bosnia/Herzegovina	0	0	1,940
Indonesia	43,000	3,200	14,275	Bulgaria	0	0	1,200
Japan	0	835	115,381	Croatia	200	0	350
N. Korea	0	0	10,720	Finland	5,100	0	4,663
S. Korea	5,000	0	82,710	France	6,500	0	16,350
Malaysia	7,100	9,800	16,150	Georgia	250	0	120
Myanmar	4,000	0	0	Germany	17,600	0	50,550
Pakistan	0	1,100	4,100	Greece	0	0	3,300
Philippines	11,000	16,100	500	Hungary	0	0	2,840
Singapore	0	0	800	Italy	2,500	0	34,970
Taiwan	0	0	22,080	Luxembourg	250	0	3,000
Thailand	0	0	8,355	N. Macedonia	0	0	550
Vietnam	29,100	500	25,700	Moldova	0	0	1,000
Asia TOTAL	***417,689***	***124,481***	***1,538,862***	Netherlands	8,660	0	7,500
				Norway`	0	0	700
				Poland	1,000	0	9,690
				Portugal	0	0	1,700
				Romania	4,100	0	5,350
				Russia	3,250	2,800	86,106
				Serbia	0	0	2,700
				Slovakia	0	0	4,500
				Slovenia	0	0	726
				Spain	1,700	0	19,440
				Sweden	6,700	2,500	6,810
				Switzerland	0	0	687
				Turkey	2,500	5,400	52,080
				Ukraine	4,500	0	27,392
				United Kingdom	780	0	11,120
				Europe TOTAL	***70,540***	***10,700***	***376,654***

Source: Global Energy Monitor, "Global Steel Plant Tracker," *https://globalenergymonitor.org/projects/global-steel-plant-tracker/download-data/*.

In 2022 the United States steel production capacity was 114,926 TTPA in operation, 7,397 TTPA under construction, and 1,044 TTPA announced projects.[428] Of importance to this analysis are the announced plants, particularly in Asia and Europe. In Asia, announced projects would increase total operating volumes by 27%. In Europe, they would increase operating volumes by almost 19%.

In Asia, helping to ensure these volumes, where possible, and using natural gas as opposed to coal would help with emissions reductions in many countries, with significant opportunities in China and India. In Europe, Germany, the Netherlands, Sweden, France, and Finland have the largest production volumes of announced projects in Europe. Ensuring adequate natural gas infrastructure to enable natural gas use in Europe and Asia is an essential strategy for CO_2 emissions and criteria pollutant reductions.

Low-Carbon Fuels

Hydrogen

Hydrogen can transform the steel industry by offering a clean alternative to the carbon-intensive processes associated with blast furnaces. Green hydrogen, produced through renewable energy-powered electrolysis, can act as a reducing agent in steelmaking, significantly reducing carbon emissions. Another option is blue hydrogen, which is made via steam methane reforming with CCUS and is largely produced from natural gas. This transition not only lowers the carbon footprint but also enhances overall sustainability. Additionally, hydrogen can be utilized as a reducing agent in the direct reduction of iron ore, leading to lower carbon emissions compared to the conventional blast furnace method.

Below are some examples of how hydrogen and natural gas are revolutionizing the steel industry.

- In China, Sinosteel Engineering & Technology contracted for a hydrogen-based “ENERGIRON” direct reduction (DR) plant with a capacity of 1 Mt/yr. This plant will become China's largest hydrogen-based DRI facility and part of the global effort to reduce carbon emissions in the steel industry by replacing traditional blast furnace methods with more sustainable alternatives, particularly gas-based ironmaking technologies. The new plant will primarily use hydrogen as the reducing gas, with the option to mix it with natural gas and coke oven gas (COG). The facility can also capture and sell CO_2, further reducing emissions and generating additional revenue. The plant will produce cold DRI pellets with potential future hot DRI production and transport to an adjacent EAF mill.[429]
- Baowu Group, the world's largest steelmaker, developed a road map to reduce carbon emissions per metric ton of crude steel by 30% from 2020 to 2035 and achieve carbon neutrality by 2050. Decarbonization of the steel industry, accounting for 15% to 20% of China's annual carbon emissions, is vital to achieving these goals. Some steelmakers focus on blast furnace and converter technologies to attain carbon neutrality, while smaller mills may transition to EAFs. Some analysts predict that 50% of China's crude steel capacity will be EAFs in the future. Baowu is also testing hydrogen-rich blast furnace technology and pure hydrogen furnace technology with plans to build hydrogen-based facilities and EAFs to promote a sustainable steel industry.[430]

Box 2

Green Steel[431,432,433,434,435]

Iron and steel manufacturing accounts for 7% to 8% of global CO_2 emissions, consequently meeting net-zero targets by midcentury will be virtually impossible without deep reductions in emissions from steel manufacturing. While there is no universally accepted definition, "green steel" is generally defined as a form of sustainable production, e.g., high recycling rate, green energy usage, or manufacturing of steel without using fossil fuels. Other definitions are less manufacturing technology-specific and production-specific but instead focus on emissions.

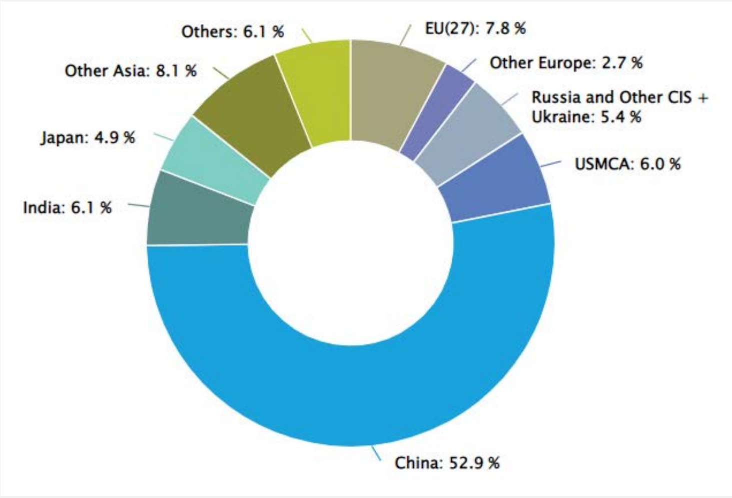
Consistent with the broader definition, emissions-reduction technologies, including CCUS, are critical for mitigating emissions from steel manufacturing. Hydrogen is also being advanced as a pathway to produce green steel, which has shown promise for decarbonization. Cost, however, is a factor, and most announced projects and companies with climate targets are in Sweden, Finland, Germany, and the United States where production is focused on a narrower band of low-volume, high-margin, high-value metal products, e.g., alloys, specialty steel, and tool steel.

Green steel projects could have a higher impact on emissions if companies, mostly in China and India (58.9% of production), focused on decarbonizing production of high-volume, low-margin structural steel products, e.g., construction materials and other carbon steel products. Therefore, the major issue with implementing a change to green steel in the near term will likely be cost.

One production pathway, and one of the few projects under construction, that can use either natural gas or hydrogen is the ThyssenKrupp tkH_2Steel® carbon-neutral project in Germany. To make this pilot project successful the EU Commission approved a 2 billion euro grant through both German national and regional governments following ThyssenKrupp's initial investment of just under 1 billion euros. This plant's estimated annual emissions reduction is 3.5 $MtCO_2$.

It is, however, critical to note that China produces more steel than the rest of the world combined. In China, almost 90% of steel is produced by the BF-BOF approach to steel manufacture. Even considering positive developments in green steel technology, for significant reductions of emissions to occur, this needs to be addressed.

China produces more steel than the rest of the world combined



The technology used for these specialty production volumes and emissions of these higher-end products is limited and may require significant government support, compared to the manufacture of cruder low-margin structural steel products. This crude steel, made predominantly in China, India, and other parts of developing Asia, is made in high quantities and uses vast amounts of natural gas and coal, producing significant emissions.

Biomass

Biomass is being considered as an optional energy source for steelmaking. This substitution would involve the use of biochar, biomass that has been burnt and broken down into charcoal-like substances. This material could potentially be substituted for coal currently used in blast furnaces. As noted by the World Steel Association, "work was undertaken to this end under the Australian CO_2 breakthrough program, which focused on substituting coal used in pulverized coal injection in the BF with sustainable biochar. Some development continues to further optimize charcoal production to improve its product specifications for steel production."[436]

CCUS for Steel Production

DRI plants, where iron ore is turned into iron without melting (usually using natural gas or coal), could be upgraded with a CO_2 capture system that relies on a chemical reaction between CO_2 and a solvent (like amine-based). This process captures CO_2 and then releases it at temperatures between 120 C and 150 C, allowing the solvent to be reused. Carbon capture can be integrated into the steelmaking process, especially in facilities using blast furnaces and other high-emissions operations. In the steel industry, CO_2 can be used to produce synthetic fuels and chemicals.

- Two plants in Tenova, Mexico, have been capturing 5% of emissions (approximately 0.15 Mt/yr to 0.20 Mt/yr combined) since 2008. Tenova DRI plants, which use natural gas, can already reduce CO_2 emissions by over 50% compared to traditional BF methods. Moreover, Tenova has implemented CO_2 absorption units that capture around 250 kilograms of CO_2 for every ton of steel produced using DRI technology, out of the total 400 kgCO_2 generated in the process. This unique feature is also present in both the Guerrero and Puebla Ternium DRI modules, and the captured CO_2 is sold to the beverage industry as an end user, contributing to the reduction of emissions.[437]
- Emirates Steel, in partnership with Al Reyadah, pioneered a CCUS project in Abu Dhabi that started in November 2016. The project is a joint venture between Abu Dhabi National Oil Company (ADNOC), Masdar and Emirates Steel Industries. It captures CO_2 from a steel production facility and uses it to enhance oil and gas recovery. It aimed to reduce carbon emissions and contribute to Abu Dhabi's sustainability goals. The project successfully captured a significant amount of CO_2, equivalent to removing emissions from 170,000 cars. This approach showcased the effectiveness of CCUS in steel production and increased oil recovery by 10%. Emirates Steel is also working on a green hydrogen project in collaboration with TAQA to achieve green steel production and further reduce energy consumption and carbon emissions.[438]

Technology Innovation

In traditional blast furnace steelmaking, carbon monoxide is primarily used as a reducing agent, typically generated on-site through partial coke oxidation. An approach to emissions reduction is capturing and reusing the carbon dioxide byproduct resulting from this process through a thermochemical CO_2 splitting process. This would create a self-contained carbon cycle, eliminating the need for additional coke consumption in the production process.

Researchers at the University of Birmingham and the University of Science & Technology Beijing conducted a study that identifies a cost-effective decarbonization approach through the coupling of a thermochemical CO_2 splitting cycle with existing BF-BOF steelmaking processes. The key element in this approach is a perovskite material that can efficiently split CO_2 into carbon monoxide (CO) at low temperatures and with high selectivity. The CO generated in this cycle can replace expensive metallurgical coke in the blast furnace for iron ore reduction. Additionally, the CO_2 produced by the blast furnace can be fed back into the thermochemical cycle to generate more CO, creating a closed carbon loop.[439]

Recycling

A team of engineers from the University of Cambridge developed a groundbreaking invention—the world's first emissions-free method to recycle Portland cement. This innovative process combines steel and cement recycling, powered by renewable electricity, and has significant implications for creating the basic materials for construction in a zero-emissions future. This new approach recycles concrete waste from demolished buildings and reuses old cement powder to eliminate emissions associated with cement production.

The process starts by taking old concrete from demolished buildings. It is then crushed to separate rocks and sand from the mixture of cement powder and water that holds them together. Then the old cement powder is used instead of using a substance called lime-flux in the process of recycling steel. When the steel is melted, this cement-like substance creates a layer on top of the liquid steel to protect it from the air. After the recycled steel is removed, it is quickly cooled, then this cement-like layer is crushed into a powder. In tests, this recycling process produces a material with the same chemical composition as that of regular cement.

Case Study 3 Summary

Steel manufacturing is essential for both developed and developing economies, including in the near-term deployment of clean energy technologies and options (e.g., wind turbines and increased electrification). Steel's contribution to global CO_2 emissions is, however, a critical issue. As developing countries continue to urbanize and industrialize, the demand for steel is expected to increase, especially in China and India. Without emissions mitigation strategies, this will likely lead to higher GHG emissions. Balancing the need for steel and the emergence of green steel with sustainability goals is challenging, necessitating emissions reduction while maintaining steel's essential role in development.

Decarbonizing the steel industry does not have a one-size-fits-all solution; instead, it requires many approaches and strategies, and there will be significant country and regional variation. While the challenges of decarbonizing the steel industry are considerable, the benefits are equally substantial. In addition to electrification, the industrial carbon footprint could be significantly reduced by using natural gas instead of coal, other low-carbon fuels, increasing energy efficiency, practicing circular economy principles, and integrating CCUS technologies into the production processes.

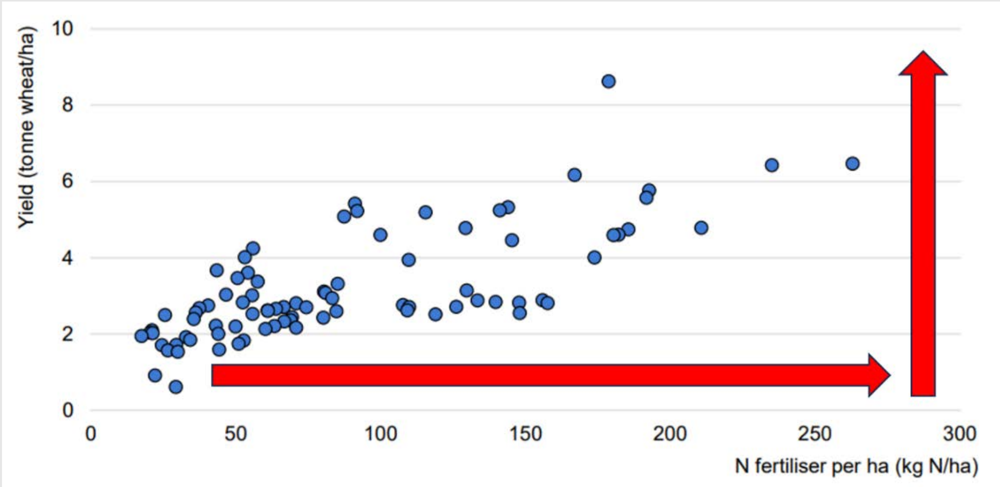
Case Study 4: Ammonia

Findings in Brief

- Made mostly from natural gas, ammonia is critical to global food security as approximately 70% of ammonia produced is used for fertilizer.
- There are two main production methods: from renewables (“green ammonia”) or from natural gas. Green ammonia is promising but expensive to produce and currently accounts for only 2% of current global production.
- Options for decarbonization include electrolysis, methane pyrolysis, and CCUS.
- Pilot projects are encouraging, but green ammonia will only be market viable when production costs come down compared to production from natural gas.
- Advancing green hydrogen will require a host of different policy options and pathways to emerge in coordination with infrastructure support for increased production.

Ammonia is a critical ingredient of fertilizer, and natural gas is a critical feedstock for making ammonia. According to the IEA, “Ammonia is the starting point for all mineral nitrogen fertilizers. … About 70% of ammonia is used for fertilizers, while the remainder is used for various industrial applications, such as plastics, explosives, and synthetic fibers. … Since the early 20th century, mineral fertilizers have formed an integral part of our food system. … Around half of the global population is sustained by mineral fertilizers.”[440] As seen in Figure 114, wheat crop yields increase with fertilizer use (arrows added for emphasis), an indicator of the significant value of ammonia for food security.[441]

Figure 114. Fertilizer use and crop yield for wheat production



ha = hectare. Each data point represents the average fertilizer use and yield of wheat fields in a specific country for the years 2006, 2007, 2010, and 2014. Red arrows added by EFI Foundation. Source: IEA, Ammonia Technology Roadmap, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.

Currently, fossil fuels are predominantly utilized as a feedstock for making fertilizer. According to the IEA, "in 2020, of the 185 Mt of ammonia produced, 72% relied on natural gas-based steam reforming, 26% on coal gasification, about 1% on oil products, and a fraction of a percentage point on electrolysis."[442] In 2021, American agriculture, which constituted over 15% of total commercial and industrial natural gas usage in the U.S., uses more than 1.7 Tcf, with natural gas accounting for approximately 70% to 80% of all energy in fertilizer manufacturing.[443]

Importantly, ammonia production is greatly influenced by feedstock and processed energy availability. In the first half of 2023, the United States emerged as the world's leading exporter of LNG, surpassing all other nations, with Australia and Qatar closely following suit. This is important for several reasons, including ammonia production.[444]

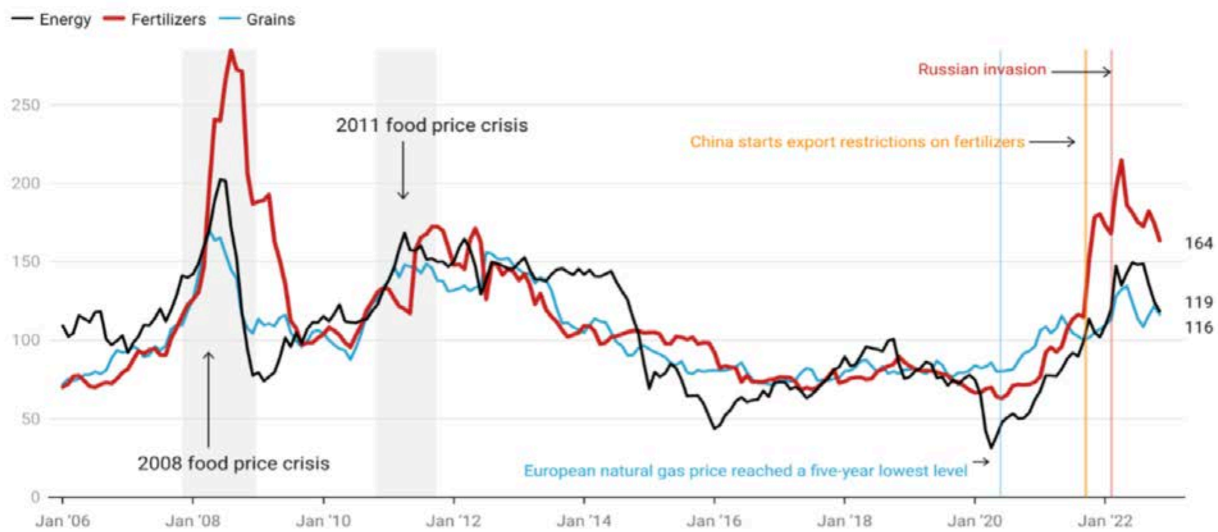
China is the largest global ammonia producer, contributing 30% to overall production. Other notable contributors include the United States, the EU, India, Russia, and the Middle East, each accounting for 8% to 10% of production. About 10% of ammonia production is globally exported, and its primary derivative, urea, is even more widely traded, representing just under 30% of total production. In short, ammonia is critical for food security and natural gas is critical for ammonia production. At the same time, the demand for ammonia is growing. The IEA, in its Stated Policies Scenario, forecasts ammonia production increases by almost 40% by 2050.[445]

Price Disruptions for Food and Fertilizer

Recent geopolitical events, such as the COVID-19 pandemic and the invasion of Ukraine, had a significant impact on energy prices and global fertilizer production. The invasion exacerbated an already challenging situation in the fertilizer market, where prices were already rising due to supply chain disruptions and transportation bottlenecks affecting the world's ability to produce and deliver fertilizer. The U.S. Department of Agriculture stated, "The Russian invasion in early 2022 led to additional transportation interruptions in the Black Sea region and the enactment of new trade restrictions. That curtailed already short fertilizer supplies, driving up prices over 50% from February to April 2022."[446] Prices have since normalized, but these steep fluctuations show how profoundly prices of natural gas can impact the global food chain.

The sharp increase in the price of natural gas, a crucial component used for both feedstock and energy in ammonia production, can significantly impact the entire food supply chain because of the critical role of fertilizer in grain production. Figure 115 illustrates the International Food Policy Research Institute's "immediate concern about the impact of high food prices on food security, especially in low- and middle-income countries," emphasizing that "fertilizer price spikes and concerns about availability cast a shadow on future harvests, and thus risk keeping food prices high for a longer period."[447,448]

Figure 115. Prices for grains, fertilizer, and energy



Index based on constant USD prices. Base 100 = Average 2010 to 2020. Source: Abdullah Mamun and David Laborde, "When Policy Responses Make Things Worse: The Case of Export Restrictions for Agricultural Products," June 30, 2023, https://www.foodsecurityportal.org/node/2467.

Food Security

Many aspects of food security are focused on the effects that climate change and changing weather patterns are having on food production and costs, which inevitably impact local or regional availability. Specifically, production disruptions can lead to local availability limitations and price increases, interrupted transport conduits, and diminished food safety.[449] Those experiencing food insecurity increased from 135 million people in 2019 to 345 million in 2022 due in large part to the "war in Ukraine, supply chain disruptions, and economic fallout of the COVID-19 pandemic that pushed food prices to all-time highs."[450] The World Bank notes that "rising food commodity prices in 2021 were a major factor in pushing approximately 30 million additional people in low-income countries toward food insecurity."[451]

Decarbonization of the ammonia industry is directly tied to food security as fertilizer production directly impacts food prices. As the IEA notes "higher energy and fertilizer prices therefore inevitably translate into higher production costs, and ultimately into higher food prices."[452]

Emissions from Ammonia

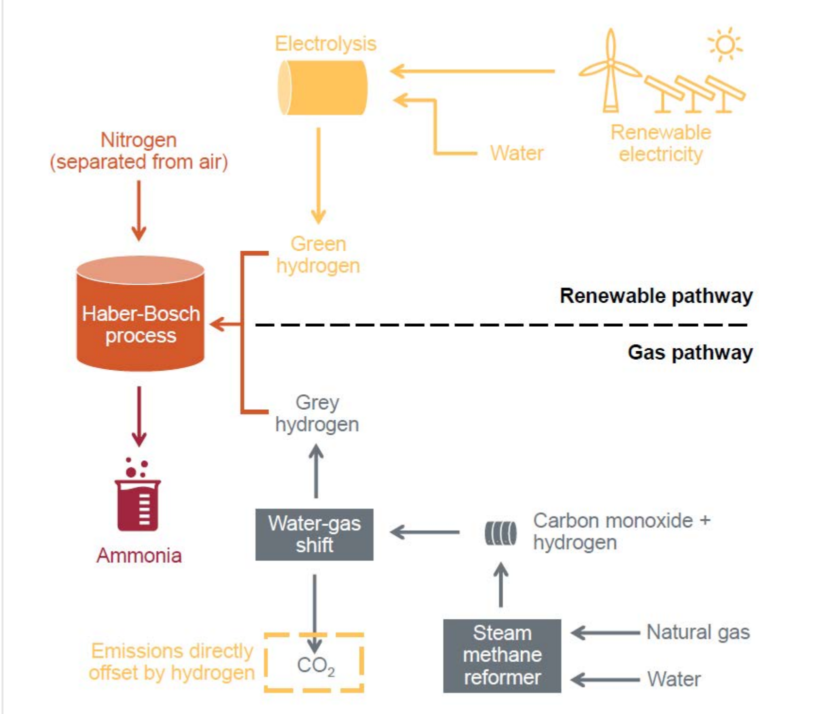
Ammonia is a vital ingredient for food security, but because it is derived from natural gas and coal, its emissions are an impediment to net-zero goals: "In 2020, global ammonia production accounted for about 450 million metric tons of carbon dioxide emissions—about 1.2% of global emissions—which is about 37 metric gigatons of CO_2 equivalent."[453] It was also the largest emitting product in the chemical section, almost doubling the amount produced from high-value chemicals (250 Mt).[454] With demand for ammonia in the form of fertilizer expected to increase significantly, decarbonization of the industry is becoming a priority.

Decarbonization of the ammonia industry can focus on low-emissions production methods such as the use of electrolysis to create green ammonia, methane pyrolysis, or CCUS. These strategies can help the ammonia industry achieve its stated goals of "27% emissions intensity reduction by 2030 and a 96% reduction by 2050."[455] Reduction of emissions intensity will be vital for the ammonia industry as it is expected that electrolysis-based green hydrogen will account for 70% of ammonia in 2050.[456]

Options for Decarbonization of Ammonia Production

Ammonia production can generally be categorized into two manufacturing methods. The first is carbon-neutral green ammonia. The other is gray ammonia, which is made with natural gas, emits carbon, and is a major air pollutant. Figure 116 shows both the green and gray ammonia production processes.[457] Most of the ammonia produced falls in the gray category, making decarbonization of the industry a challenging prospect.

Figure 116. Ammonia can be produced using gray or green hydrogen

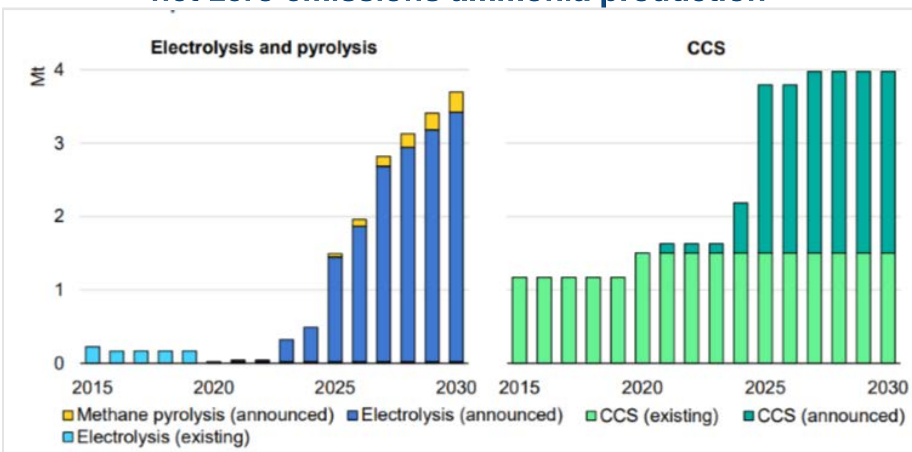


Source: Tony Wood et al., "Hydrogen: Hype, Hope, or Hard Work?" Grattan Institute, December 2023, https://grattan.edu.au/wp-content/uploads/2023/12/Hydrogen-hype-hope-or-hard-work-Grattan-Institute.pdf.

This makes reducing emissions from ammonia an important need for reaching net-zero targets by midcentury while simultaneously ensuring the food security it provides to the world's population. Options for decarbonization include electrolysis, methane pyrolysis, and CCUS. According to the IEA, for ammonia, "Near-zero-emission production methods are emerging, including electrolysis, methane pyrolysis and fossil-based routes with carbon capture and storage (CCS)."[458] These emerging routes are typically 10% to 100% more expensive per ton of ammonia produced than conventional routes, depending on energy prices and other regionally varying factors. Existing and announced projects totaling nearly 8 Mt of near-zero emissions ammonia production capacity are scheduled to come online by 2030, equivalent to 3% of total capacity in 2020.

Figure 117 shows current and announced projects as of 2020 focused on decarbonizing ammonia production and the volumes of CO_2 these projects are designed to capture.[459] As seen in the figure, the largest volumes of CO_2 already being captured from ammonia production are from CCUS plants, and more significantly, more volumes are planned to be captured by announced projects between 2023 and 2030. All pyrolysis and electrolysis capture projects were announced but not yet operational as of 2020 when this figure was released by the IEA.

Figure 117. Current and announced projects for net-zero emissions ammonia production



Source: IEA, Ammonia Technology Roadmap, October 2021,
https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.

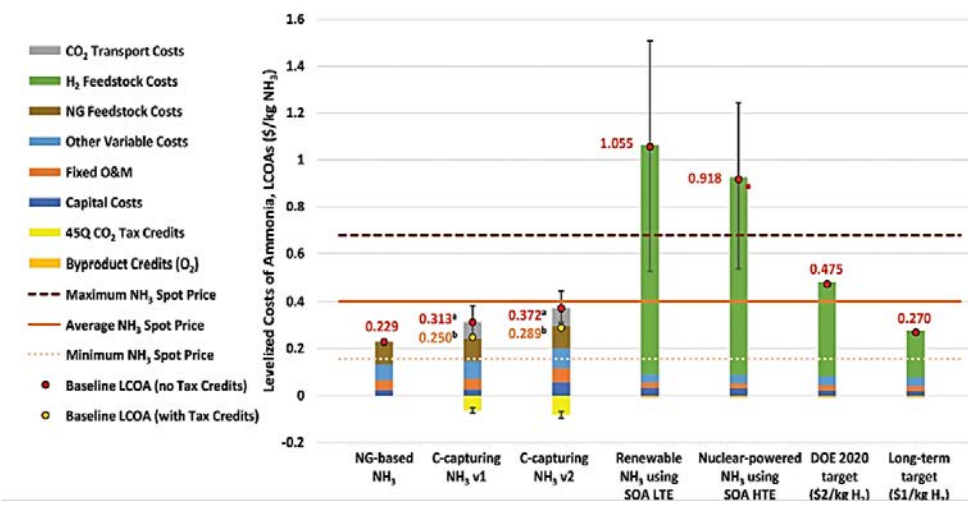
There are several fertilizer producers that are working on low-carbon production, targeting a reduction of between 20% and 50% of Scope 1 and 2 emissions. Some examples of projects already in the pipeline: "In Denmark, an industry consortium of the country's four largest agricultural companies is exploring whether more sustainable fertilizer can be produced in Denmark. In Iowa, Greenfield Nitrogen, a green hydrogen and green ammonia company, is developing a $400 million green ammonia plant to produce 96,000 tons of zero-carbon fertilizer."[460] While these projects are encouraging, the fact is that green ammonia will only be market viable once the price comes down compared to that of natural gas.

Levelized Costs

This analysis, based in part on engineering modeling using Aspen Plus, identifies levelized costs of the range of options for ammonia production from natural gas, natural gas with carbon capture, nuclear generation, and renewables generation. As seen in Figure 118, the levelized costs of ammonia (LCOA) produced with renewable and nuclear generation are significantly higher than ammonia produced from natural gas with CCUS.[461]

These data—the vital role of ammonia in feeding the world's populations, and the need to lower the costs of ammonia made with renewable or nuclear generation—suggest a range of policy and technology pathways are essential for addressing these issues in the longer term. In the near- to midterm, based on the analysis used to inform Figure 116, natural gas with CCUS appears to be the most affordable option; and affordability is key to feeding the world's population. This option needs policy support, too, however, in part to support the infrastructure and regulatory structures needed for CCUS.

Figure 118. Levelized costs of ammonia when using natural gas, carbon capture, nuclear power, and renewables in ammonia production



NH3 = ammonia. Source: Kyuha Lee et al., "Techno-Economic Performances and Life Cycle Greenhouse Gas Emissions of Various Ammonia Production Pathways Including Conventional, Carbon-Capturing, Nuclear-Powered, and Renewable Production," Green Chemistry 24, no. 12 (2022): 4830–4844.

More analysis is needed to review the status, costs, locations, and any policy support for the announced and existing projects. Such analysis is important to understand which policies and subsidies might need to be developed/implemented to decarbonize ammonia production going forward. This is important from both a cost and process perspective.

Case Study 4 Summary

Ammonia will continue to grow in importance, and its growth will need to hurdle numerous challenges along the way. As noted above, the ammonia industry has a 27% emissions intensity reduction target by 2030 and 96% reduction by 2050.[462] The only way to accomplish this would be to use electrolysis-based green hydrogen, but lack of available green hydrogen supplies puts this goal at risk. Currently, green ammonia accounts for only 2% of current global production.[463]

The use of CCUS will assist in emissions reduction from ammonia production, and with a push from government incentives, green hydrogen will proliferate and use similar methods of transportation to reduce prices to a competitive level. This will require a host of policy options and pathways, including infrastructure support for increased production.

6. Recommendations

The current market conditions; energy security needs; longer-range global and regional forecasts; technology needs and limitations; and national policies analyzed in this study suggest that natural gas will be a mainstay in the energy systems for the near and midterm—and, depending on the country/region, in the long term.

Issues analyzed in the previous chapters, however, such as energy security concerns, a growing demand for affordable energy in emerging economies, and the urgency of decarbonizing energy systems, make forecasting the future of natural gas in the global energy system challenging.

Recognizing the local and regional differences in energy mixes, including natural gas utilization, countries should embrace financial instruments that enable developing countries to implement net-zero pathways. Developed countries can afford the low-carbon energy technologies that are more expensive than conventional energy technologies, if the political will can be mustered, but developing countries are less able to do this given overall high levels of energy poverty and rising energy demands from growing economies. In general, developing nations prioritize economic development. Near-term decarbonization should be part of every industrialized country's investment choices. Countries should enhance international support for developing countries' energy transitions by balancing economic growth, energy security, and climate goals. Well-structured carbon trading markets would facilitate this, but they currently lack sufficient integrity.

Governments, international bodies, and industry initiatives have put varying emphasis on natural gas as a strategy for meeting energy security, energy equity, and environmental sustainability goals, but substantial tasks remain. Major consumers of LNG in Europe and Asia are concerned about the reliability and affordability of LNG. Many countries have committed to net-zero emissions goals, but emissions from the natural gas supply chain have not decreased significantly. As Nobel Laureate William Nordhaus stated in his recent research, "One important finding is that international climate policy has set ambitious goals but has failed to establish an architecture for implementation."[464]

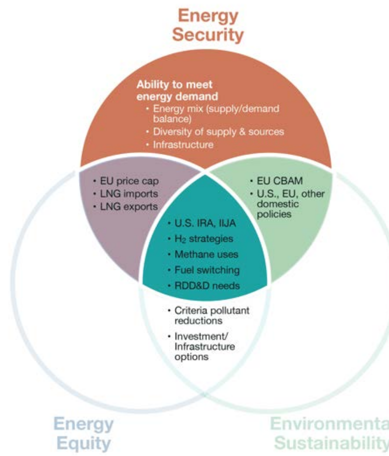
> **"One important finding is that international climate policy has set ambitious goals but has failed to establish an architecture for implementation."** -William Nordhaus

All stakeholders should accelerate efforts and turn their commitments into detailed policies and actions. This study has examined crosscutting issues associated with the energy trilemma of natural gas and formulates corresponding recommendations.

Based on the findings in this analysis, this report provides recommendations for decision-makers to clarify the role of natural gas in the global energy mix while balancing the competing priorities of the energy trilemma (energy security, energy equity, and environmental sustainability). It should be recognized that success in any element of the trilemma facilitates success in all. The recommendations are organized around the dimensions of the energy trilemma with key crossover issues highlighted in each section.

Energy Security

- **Establish a collective action mechanism to develop energy security strategies for natural gas consuming and producing nations.**



  In response to recent gas market disruptions, major natural gas consuming nations began discussing the need for internationally coordinated responses and strategic natural gas/LNG reserves. These nations have been working to ensure secure supply and have started emphasizing the criticality of international cooperation and coordination in terms of strategic gas reserves. At Japan's LNG Producer-Consumer Conference in July 2023, for example, the host proposed the idea of a global stockpile for natural gas, like the emergency reserve in the oil sector, to be used in case of market volatility. The EU also indicated the need for additional work on how some form of coordination could increase natural gas reserves globally.

  In the context of energy security, the need for cooperation is both near term and ongoing, particularly for countries that are large gas consumers/importers. This urgency suggests the need for an existing entity, such as the International Energy Agency (IEA), to provide this critical function.

  The February 2024 IEA Ministerial Communiqué focused on ensuring a secure and resilient global energy system where natural gas was prominently featured. In the communiqué, ministers welcomed a strengthened IEA role in energy security. In the context of well-functioning global natural gas markets, ministers said, "We request the IEA Governing Board, at official level, through appropriate bodies, to exchange information, explore and analyze ways to enhance flexibility, transparency, and security of supply, such as through enhanced gas storage and reserve mechanisms."[465] If the IEA was tasked by its members with this ongoing function, then the United States, as the world's largest producer and exporter of natural gas, should play a prominent role.

  Also, developing countries cannot join the IEA, as membership is restricted to OECD countries. If the IEA leads the convenings and associated strategy development, it should include the active participation of developing countries, especially those with a growing demand for natural gas. These countries should be offered “associated country status” to support energy security and advance the transition to clean energy.

- **Include an energy security determination (ESD) as a key component of the public interest determination for approving U.S. LNG export permits to non-FTA countries, with a focus on the impacts on U.S. allies and trading partners. This builds on the G7/EU 2014 commitment to energy security as a collective responsibility among allies and friends.**

  U.S. LNG exports have significant geostrategic importance for U.S. allies and trading partners, as demonstrated after Russia invaded Ukraine. Guidance by the U.S. Department of Energy (DOE) for the current LNG export approval process notes that “completed applications to export LNG to countries with which the United States has a free trade agreement (FTA countries) or to import LNG from any source are deemed automatically in the public interest. The [Natural Gas Act] directs DOE to evaluate applications to export LNG to non-FTA countries. DOE is required to grant export authority to non-FTA countries, unless the Department finds that proposed exports will not be consistent with the public interest, or where trade is explicitly prohibited by law or policy” [emphasis added].[466]

  The approval process should explicitly include an ESD. The White House National Security Council should be included at the initial and final reviews of permits to provide ESD guidance and analysis, including identifying the potential need for expediting permits in lieu of potential energy security needs of U.S. allies and trading partners. An ESD at the initial stages of review could provide the basis for expedited reviews of export permits.

- **The United States should commit to an ongoing global leadership role in meeting global energy security objectives, focused on those associated with U.S. natural gas exports.**

  Domestic policy decisions made by the United States have international implications because it is the world’s largest LNG exporter. The United States-led 2014 G7/EU energy security principles emphasized energy security as a collective responsibility among allies and friends. The United States must clarify and commit to an ongoing global leadership role in meeting the natural gas-associated energy security needs of its allies and trading partners and work with them collectively to meet critical energy security needs. It must do so, however, by advancing a balanced approach to the energy trilemma of energy security, energy equity, and environmental sustainability.

  The United States needs to reconcile domestic energy policy with international climate goals and commitments. This must be done with the recognition that global energy markets are interconnected and impacted by climate change mitigation and equity considerations.

- **Maintain market and U.S. destination flexibility, and continue to not require destination clauses in the consideration of LNG export licenses to non-FTA countries.**

  As this study and the associated analysis demonstrate, natural gas can provide energy security, facilitate economic growth, and foster CO_2 emissions reductions if managed appropriately. The United States can lead in this regard by providing reliable and affordable supply while ensuring the entire supply chain—from the upstream production to the end use—results in net GHG emissions reductions. U.S. supply can also address issues identified by IEA, for instance, “Projects that have started construction or taken final investment decision are set to add 250 billion cubic metres per year of liquefaction capacity by 2030, equal to almost half of today’s global LNG supply. … This additional LNG arrives at an uncertain moment for natural gas demand and creates major difficulties for Russia’s diversification strategy towards Asia. … The glut of LNG means there are very limited opportunities for Russia to secure additional markets.”[467]

  Also key to energy security considerations: The retention of the lack of destination clause feature of U.S. LNG export licenses was important for enabling diversification of U.S. LNG cargoes to Europe after the Russian invasion. This feature of export contracts should be retained as an essential component for ensuring and enhancing the energy security value of U.S. LNG exports.

- **Establish U.S. information-sharing requirements and a convening authority to harmonize federal, state, local, and tribal permitting requirements.**

  To ensure reliable and affordable supplies of clean U.S. natural gas, relevant federal agencies and the representatives of state governments, such as the Interstate Oil and Gas Compact Commission and the Environmental Council of the States, should establish a collaborative organization to review permitting by bringing together federal, state, local, and tribal entities under one umbrella. The mission of the coordinating body would be to create consistency between jurisdictions that allow an applicant to submit a single application that provides all required information by federal, state, and local statutes and regulations. The submitted application and information would then be consistent and accessible to all relevant regulatory bodies at federal, state, and local levels and relevant stakeholders such as host communities. This would also enable multijurisdictional reviews to occur in parallel, thus expediting the process. This transparent sharing of information would mitigate redundancies and avoid the potential risk of legal challenges or local opposition caused by insufficient information about the project. The newly created body should also lead community engagement efforts regarding the proposed infrastructure. Similar coordination efforts would be of great benefit globally, such as in the European Union.

- **Further analyze supply needs and operational implications of announced and under- construction natural gas-fired power plants and associated infrastructure in Europe and Asia.**

Announced and under-construction plants in Asia as of February 2024 totaled 235,871 MW, on top of more than 426,000 MW of operating gas plants. In Europe, there are 25,412 MW of under-construction and announced gas plants, on top of 361,328 MW of operating plants. Increasing capacity of gas plants requires infrastructure support. As of 2023, Europe had 5,569 km of natural gas pipelines under construction and 37,220 km in the proposed/construction phase.

At the same time, U.S. LNG export destinations have dramatically changed since the invasion of Ukraine. In 2021, China imported 453,304 MMcf of U.S. LNG and in 2023 it imported 173,247 MMcf. The Netherlands imported 174,339 MMcf in 2021 and 588,557 MMcf in 2023; this is a pattern seen in other U.S. LNG importers in Asia and Europe as well.

In addition, dramatically different forecasts of natural gas consumption/demand are creating uncertainty, which impacts investment decisions. A deeper analysis is needed of both regions to understand the effects of these alterations on LNG trade and implications for Europe, Asia, and the United States through the 2030-to-2050 time frame. Also, a detailed analysis is needed of gas plant retirement schedules (either lifespan or policy driven) in Europe and Asia; what the new plants will mean for additional supply and associated infrastructure; the implications of these assets for grid reliability, economic growth, and consumer needs; the harmonization of these assets with decarbonization policies; and the potential for stranded assets.

Energy Equity

- **Enhance international support for the clean energy transition in developing countries, including support for securing reliable and affordable natural gas supplies, climate change mitigation technologies, and infrastructure. This serves all three dimensions of the energy trilemma.**

Building on the agreement at the 28th United Nations Climate Change Conference of the Parties (COP28), parties should develop detailed mechanisms that support pathways for affordable energy transitions in developing nations. Natural gas plays a significant role in developing countries to achieve the dual goals of accelerating economic development and addressing climate change.[468] Developing countries have urgent needs for reliable and affordable energy sources in order to expand energy access and support industrialization. Because most multilateral development banks (MDBs) already recognize this context for natural gas, they should continue to finance natural gas infrastructure in developing countries.

This study also found that there is a need for construction of additional LNG import infrastructure in South and Southeast Asia between 2030 and 2050 to meet the rapidly increasing LNG demand. Securing an affordable energy source is critical for economic development in these regions. The high costs of building additional LNG infrastructure, including the associated natural gas distribution infrastructure, could, however, motivate the countries in these regions to consider using coal instead of LNG. MDBs should focus on financing NG and LNG distribution infrastructure in developing countries to support a more affordable clean energy transition through qualified LNG projects.

- **Support additional public and private sector funding for the implementation of the ALTÉRRA fund or similar private funds.**

  The UAE-sponsored ALTÉRRA fund is a $30 billion climate investment fund launched at COP28. The fund, with its structure, scale, scope, and focus on innovation and partnerships, is designed to steer private markets toward climate investments to transform emerging markets and developing economies. ALTÉRRA features an innovative two-part structure: $25 billion ALTÉRRA ACCELERATION is designed to steer capital toward investments at scale to accelerate the transition to a net-zero and climate-resilient global economy, and $5 billion ALTÉRRA TRANSFORMATION is designed to provide catalytic capital to incentivize private sector investment flows into the Global South's emerging market and developing economies. The fund's mission is to make climate finance more available, accessible, and affordable, and to remove barriers impeding investment. ALTÉRRA seeks to mobilize $250 billion globally by 2030. The fund and donor countries must coordinate regarding costs, financial instruments, and access.

- **Expand MDBs' financing of methane emissions reduction projects in natural gas operations.**

  The analysis of IEA identified a $15 billion to $20 billion financing gap for methane emissions reduction in low- and middle-income countries by 2030. Philanthropic initiatives, such as the Global Methane Hub, could fill part of this gap, but additional support is necessary. MDBs could help fill this gap by providing financing or catalyzing private financing with technical or regulatory assistance. Although some MDBs have stopped financing oil and gas projects, they have not entirely stopped financing methane abatement projects. For example, the World Bank's Global Gas Flaring Reduction Partnership (GGFR) provides technical and regulatory support to reduce flaring and methane emissions. The United States, Germany, and Norway intended to support the GGFR by funding $1.5 million, $1.5 million, and $1 million, respectively.

  MDBs should continue to support methane emissions reduction projects in existing natural gas operations to fill the financing gap for methane emissions reduction in developing countries. Reducing methane emissions from existing natural gas operations is critical to reach global net-zero emissions. In recognizing this importance, MDBs should not stop financing and supporting methane emissions reduction projects in existing oil and gas operations.

- **Re-establish an MDB carbon capture, utilization, and storage (CCUS) trust fund for developing countries with broader support by more donors.**

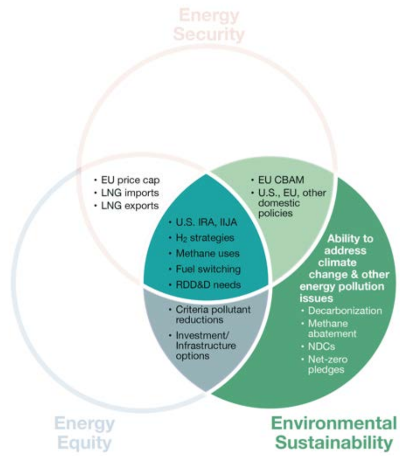
  MDBs have supported CCUS market development in developing countries. The World Bank started a carbon capture and storage (CCS) Trust Fund to help establish market conditions for CCS in client countries in 2009. The bank completed a CCS screening for 11 countries and selected Mexico and South Africa for further analysis of CCS regulations. In February 2022, the World Bank, and the International Finance Corporation started a project for Nigeria to outline policies and regulations accelerating domestic CCS market development funded through the CCS Trust Fund. This trust fund was supported by the U.K. and Norway but was completed and dissolved in December 2023.[469] Asian Development Bank (ADB) has run the Carbon Capture and Storage Fund since 2009 to support capacity development, geological investigation and environmental studies, and community awareness and support programs to accelerate CCUS deployments. Australia and the U.K. supported the fund, and several Asian countries, including China, India, Indonesia, and Vietnam, received the fund. Funds and mission of the fund expired in 2022.

  MDBs should continue to support the reduction of technological, regulatory, institutional, financial, economic, and environmental barriers to CCUS deployment in developing nations. Even in the United States, CCUS deployment has not been scaled up significantly because of these barriers. Without international support, emerging economies will not be motivated to kickstart CCUS deployments because of the lack of regulatory and institutional conditions supporting CCUS deployments and the high financial, economic, and environmental barriers. Because even developed countries are in the early phases of domestic CCUS market development, developing countries may require international technical assistance followed by funding to support larger-scale CCUS investment. Catalyzing private financing should be considered for the long term.

- **Perform an analysis of the Asia-Pacific region to develop a comprehensive energy security road map for the region through 2050.**

  An appropriate entity (e.g., the Economic Research Institute for ASEAN and East Asia [ASEAN-ERIA] or the ADB) should perform an integrated energy review, like the U.S. Quadrennial Energy Review, and analyze the Asia-Pacific region to develop a comprehensive energy security road map through 2050. This effort would provide a deep analysis of supply/demand options, infrastructure needs, and a detailed country/regional review of the implications of coal-to-gas fuel switching for industry and power generation in developing countries in the region. The review would also examine costs, affordability, energy access, and pollutants associated with the range of fuel options. As noted, Southeast Asia has experienced rapid population growth, economic growth, and energy demand. Growth doubled between 2000 and 2020, natural gas consumption increased by over 80%, and the region maintained around a 20% share of the total Asian energy mix over that period.[470] The review would be designed to specifically inform suppliers, investors, and policymakers.

Environmental Sustainability



- **Build international consensus on GHG disclosure requirements for LNG.**

  The United States should take a leadership role in defining green LNG in international fora (G7, IEA, OECD, COP, etc.) by implementing disclosure requirements for LNG export approvals with independent verification of net GHG emissions impact. This would build on the U.S. Council on Environmental Quality's (CEQ's) work and DOE studies on the life cycle analysis of the environmental impacts of the natural gas systems.

  While these studies were domestically oriented, the inclusion of the climate and environmental impacts of LNG export infrastructure (upstream, i.e., life cycle) should consider the net impact on GHG emissions by the receiving country. During the "pause" directed by the White House on January 26, 2024, officials should revisit the scenarios used in the 2018 study (1) to examine whether those scenarios reflect existing U.S. LNG trade and (2) to account for the effects of recent geopolitical, economic, and social disruptions. The scenarios should then be revised to reflect the current and expected risks and uncertainty. The study result should be used as a basis not only for permitting LNG infrastructure by DOE, the U.S. Federal Energy Regulatory Commission (FERC), and other relevant federal and state agencies, but also for building international consensus on a "green LNG" definition and associated measurements and standards.

- **Assess the potential for additional natural gas and biogas supplies associated with methane emissions and provide support for innovation in difficult-to-abate sectors, e.g. agriculture.**

  The agricultural sector produces more methane emissions than oil and gas operations. Globally, the agriculture sector accounts for around 40% of total anthropogenic methane emissions. In the United States, the agricultural sector accounted for 39% of total U.S. methane emissions in 2022, an increase from 28% in 1990. High methane emissions in the agriculture sector infer substantial potential to capture methane that could be used to increase gas supply. Also, capturing and utilizing methane from agriculture gives opportunities to lower the net cost of methane abatement as it would create revenues from energy supply. High costs for methane have been a barrier to scaling up methane abatement in the agricultural sector.

  A range of technologies for capturing and utilizing methane have been developed and are beginning to be deployed. Policy support can accelerate this effort. Such support should include assessing the potential to incorporate methane capture and utilization technologies, analyzing the technical and economic viability of technology deployment, and evaluating financial incentives. Moreover, the international community should collaborate to develop technology transfer and capacity building programs for worldwide deployment of the technologies.

- **To meet both critical climate change and energy security imperatives in a timely way, CEQ should be tasked with clarifying and routinizing the assessment criteria and guidance for emissions from U.S. LNG projects.**

  Changes in the permitting process for LNG export terminals and gas pipelines would address multiple challenges. On the one hand, the permitting process should be expedited as the current procedures are lengthy, complex, and unpredictable. On the other hand, a more thorough environmental review process is necessary to reduce the climate and environmental impacts across the proposed facility's value chain and to obtain a social license to operate. Finally, the energy security value of U.S. LNG exports was demonstrated after the Russian invasion of Ukraine. Energy security considerations should be included in the LNG export permitting process.

  To ensure expedited reviews, the CEQ should develop guidance on the assessment of GHG emissions and environmental impacts of the entire LNG value chain. This guidance should be the basis for permitting LNG export infrastructure by DOE, FERC, and other relevant federal and state agencies. The guidance should clarify requirements without extending current review and approval timelines.

  A study of more than 200 legal challenges to natural gas or liquid pipelines identified the National Environmental Policy Act (NEPA) as the statutory basis for challenging pipeline expansions between 2012 and mid-2019.[471] A flawed GHG analysis was the most frequently claimed error by the project opponents, and the number of claims due to insufficient review of upstream GHGs or downstream GHGs have increased since 2015.[472] Building on the January 2024 White House announcement to temporarily pause pending decisions on exports of LNG to non-FTA countries and CEQ's interim NEPA guidance (issued January 2023) on GHG emissions and climate change, CEQ should develop guidance to assess GHG and environmental impacts of LNG infrastructure from upstream emissions to downstream combustion.

  In parallel with the DOE's upcoming review of LNG export licenses, CEQ should focus on developing methodologies and practices for rigorous assessment of the impacts that federal agencies can use when they make decisions about permitting LNG export infrastructure. The guidance, to be implemented by DOE and FERC, should include set timelines for governmental review and approvals.

- **Accelerate the implementation of the Global Methane Pledge through biannual convenings of participating regions and nations.**

As an implementation step of the Global Methane Pledge, the United States, the EU, and 11 countries launched the Global Methane Pledge (GMP) Energy Pathway in June 2022 to catalyze methane emissions reductions in the oil and gas sector. The Pathway aims to capture the maximum potential of cost-effective methane mitigation in the oil and gas sector and eliminate routine flaring no later than 2030. Participant countries committed to implementing domestic policy actions and providing technical and financial resources to accomplish the GMP objectives. The governments and supporting organizations announced approximately $60 million in funding to support the implementation of the Pathway.

Countries should coordinate on implementation of the GMP Energy Pathway to ensure effective global methane emissions reductions. As part of the GMP Energy Pathway, many countries and organizations announced their ongoing and planned actions for methane emissions reduction, ranging from technical assistance to policy enforcement. These diverse efforts should be implemented effectively and efficiently. For example, an alert and response system for satellite-detected methane emissions under development by the United Nations Environment Programme International Methane Emissions Observatory (IMEO) should be effectively used in formulating national methane mitigation policies, regulations, and projects. In addition, the IMEO's work should be aligned with the work of other private and nonprofit initiatives to measure methane emissions using satellites. To inform these efforts, there should be a biannual convening of participating nations to share data, policies, and best practices.

- **Assess and quantify methane emissions from LNG shipping.**

  While initial data suggest that methane (and CO_2) emissions from LNG tankers are not substantial, net-zero targets require rigorous and accurate data and reductions for all emissions sources. Also, initial analysis suggests that there may be variation in methane emissions, depending on the age, size, and type of LNG tanker. Emissions reduction technologies and changes in practices will likely be needed, and these need to be informed by further analysis and data from across the LNG tanker fleet. Importantly, this could be an initial analysis of emissions from international shipping in general (around 3% of global emissions). These emissions need to be quantified and appropriately attributed/allocated to countries.

- **Enhance cooperation between allies and trading partners on developing national and regional industrial decarbonization pathways for natural gas systems and supply chains.**

  The industrial sector is responsible for almost a quarter of all CO_2 emissions and is a significant energy consumer. Natural gas is a key energy source for a range of industrial processes. Given the complex nature of industrial subsectors, natural gas is likely to play a continued and evolving role in the industrial sector in the long term.

  Natural gas currently plays a significant role in the affordability and reliability of industry globally as a feedstock and energy source to the industrial sector. There is a wide range of potential industrial decarbonization options: energy efficiency; electrification; low-carbon fuels (including green hydrogen); and CCUS. Carbon pricing and carbon dioxide removal—including direct air capture and bioenergy with carbon capture and storage—are relevant to industrial decarbonization, as is international agreement on how to measure Scope 1, 2, and 3 emissions. Accurate emissions measurement is critical to the establishment of accurate and persistent carbon pricing and its adoption in global markets. CCUS offers advantages such as addressing difficult-to-decarbonize combustion and process emissions, as well as harnessing existing infrastructure and workforces. Hubs can be an enabler for realizing the emissions reduction opportunity of CCUS because shared infrastructure can significantly decrease the economic, technical, and logistical barriers to CCUS deployment for small-to-midsize emitters.

Countries should cooperate to develop national policies and international rules for decarbonizing energy-intensive industry sectors effectively and efficiently and make it a priority for COP29. Industrial decarbonization requires investments in technology and process development, supporting mechanisms for commercialization and deployment, and rules and regulations. In addition, the effects of national policies are not restricted within borders since industrial products are heavily exposed to international trade. These complex and international contexts of industrial decarbonization require the collaboration of countries to develop national and global pathways for industrial decarbonization.

In advance of COP29, each country or region should work on developing road maps for industrial decarbonization, considering economic, energy security, social equity, and climate perspectives. In addition to emissions consideration, examining the cost of each pathway should be an essential part of the work since it leads to the competitiveness of industries and eventually to national and global economic growth. For example, each country should compare the cost of decarbonization options—such as energy efficiency, electrification, coal-to-gas switching, and hydrogen—and examine the effects of adopting certain decarbonization options on the competitiveness of their industries. These national pathways should be discussed at COP29 and lead to an agreement on how to accelerate decarbonization. The potential for significant CO_2 reductions from coal-to-gas switching, particularly in Asia, necessitates study of power systems and harmonization with national net-zero goals.

- **Incentivize and accelerate research and development in new technologies and policies to reduce the cost of electrifying industrial heat.**

  Increasing the electrification of industrial processes for which electricity can provide the levels of heat required could reduce emissions from the industrial sector. Electricity is, however, significantly more expensive than natural gas in many regions and countries. Industry will not be motivated to invest in electrifying key industrial processes if electrification is not cost-effective; even small cost differentials will affect the competitiveness of industrial products. Cost-effectiveness of electrification is a vital consideration for high-volume and low-margin industry sectors.

Countries should consider specific issues when assessing the cost of electrifying their industrial sector: energy mix, energy prices, industry structure, and climate goals. The cost for electrification will be different by country or region since each country has different opportunities and challenges in terms of energy production and consumption. Note that industrial decarbonization is closely connected to the national economy and national climate goals; thus, each country should assess the cost of electrifying the industry sector in their own contexts.

- **Accelerate international collaboration on deployment of CCUS technologies.**

  As most CO_2 emissions in the natural gas system come from combustion rather than upstream processing, it is crucial to deploy CCUS in downstream operations for natural gas-fired power plants and industrial facilities. However, CCUS is not widely deployed in downstream operations. The case studies of four industrial subsectors all concluded that CCUS is necessary for industrial decarbonization; however, the authors also identified significant barriers to accelerated CCUS deployment.

  International collaboration for CCUS deployment in industrial facilities is important because of the essential role industry plays in national, regional, and global economies. Industrial products such as ammonia are vital for food security; steel, aluminum, glass, and resin (currently made from oil) are central to the clean energy transition. For example, China and India are the top two producers of steel and cement; decarbonizing the steel and cement industries largely depends on the success of the decarbonization efforts of these two countries. International dialogue on CCUS deployment needs to include the top producers of industrial products for CCUS to be effective in decarbonizing carbon-intensive industrial sectors.

  To accelerate CCUS deployment in industrial facilities, countries need to share knowledge and best practices on CCUS deployment. There have been international efforts to collaborate on CCUS technologies, such as the Carbon Sequestration Leadership Forum, the CCUS Initiative under the Clean Energy Ministerial, and the Mission Innovation Carbon Capture Innovation Challenge. Efforts must be expanded to move beyond the current focus on RD&D to deployment. They should include sharing information on best practices, reducing barriers to deployment, policies (i.e., incentives, regulatory frameworks, knowledge sharing), and how to increase general community knowledge and acceptance of CCUS.

- **Incentivize industry to switch to low-carbon hydrogen to meet existing demand for industrial feedstocks.**

  Transitioning existing uses of hydrogen to low- and zero-carbon pathways can reduce global emissions by about 1,300 $MtCO_2e$. Fossil fuel-based hydrogen use today equates to about 3.5% of global CO_2 emissions. These emissions predominantly come from hydrogen's use in petrochemical refining, ammonia production, and methanol production. Given that these industries already use hydrogen in their regular operations, substituting clean hydrogen would function as a like-for-like fuel switch with few technical challenges. Transitioning to low-carbon hydrogen has significant implications for the future of natural gas since currently most hydrogen is produced with natural gas.

In these traditional hydrogen applications, however, it is important to recognize the investment and other business trade-offs between retrofits and new builds within these industries. In both cases, incentives or new regulations would be key components of making a widespread transition feasible. China represents the largest current user of on-purpose hydrogen in refineries. More broadly, China has the world's second-largest refining capacity globally and consumes about 8 Mt to 9 Mt of hydrogen per year. The agricultural sector accounts for nearly 24% of global GHG emissions, and ammonia production alone makes up nearly 2% of global CO_2 emissions. China is the largest producer of ammonia, encompassing roughly 30% of global production, followed by Russia, the EU, the United States, India, and the Middle East (i.e., Pakistan, Qatar, Saudi Arabia, and Iran). This distribution generally follows demand for fertilizer, where countries like China and India have some of the largest agricultural sectors in the world.

Crosscutting Needs: Cooperation in the Development and Implementation of Energy Transition Pathways

- **Identify the appropriate international entity to develop consistent, transparent, and accurate methodologies for calculating Scope 1, 2, and 3 emissions.**

  Because price reflects costs, accurate emissions methodologies are essential for providing the signals needed for markets. As noted in this analysis, there is a wide variation in prices per ton of CO_2 in various trading systems around the world.

  The need to harmonize economic needs, energy security, social equity, and climate goals with the role of transition fuels has been emphasized in recent international dialogues (COP28 and G7 2023). Subsequent agreements need national-level development and implementation of detailed policies for the effective and efficient use of transition fuels in related energy systems. Since developing countries are not equipped with sufficient resources and capacities for the energy transition, international support for developing countries is required to accelerate the global energy transition.

  Countries should also work together to set pathways for effective and efficient industrial decarbonization. The rise of green industrial policies raises concerns about increasing costs for producing industrial products. For example, the managing director of the IMF urged that green subsidies should be "carefully designed to avoid wasteful spending or trade tensions, and to make sure that technology is shared with the developing world."[473] Raising trade barriers could slow the diffusion of clean energy technologies across borders and increase the cost for global transition to a net-zero economy.

- **Through an ISO-like organization, establish and maintain accurate and comprehensive methodologies for GHG accounting across energy systems and supply chains, including those for natural gas.**

  The need for agreement on and standardization of emissions across supply chains is illustrated by the earlier discussion of differentiated natural gas, where two key points were made: (1) “Certification programs have been developed on an ad hoc basis without standard certification requirements” and (2) “Less rigorous certification enabled a broader participation but at the same time, has raised concerns about [differentiated natural gas] as a ‘greenwashing’ tool.”

  The International Standards Organization (ISO) offers a good model for addressing these issues. The ISO has brought together industry and global experts to agree on the best way of doing things, from measurement standards to managing production processes. As a nongovernmental international organization, ISO has enabled trade and cooperation for almost 80 years. ISO standards are created through a multistakeholder process, initiated by those who use them, and could bring together disparate and geographic-specific standards under a single umbrella. ISO does not decide when to develop a new standard but responds to a request from industry or other stakeholders such as consumer groups. Typically, an industry sector or group communicates the need for a standard to ISO through a national-level representative. Internally, ISO standards are developed by technical committees composed of experts from all over the world. These experts would negotiate all aspects of the standard.

  Making changes at the ISO to accommodate and carry out this mission or establishing a new organization for developing ISO-like standards for GHG emissions across supply chains (including natural gas supply chains) would provide detailed, accurate emissions accounting across sectors that would enable investors to make informed choices. It would also incentivize the industry to reduce emissions and/or utilize offsets. Transparent and consistent measurements would provide buyers with a clear differentiator—a “carrot” as opposed to a “stick” approach.

- **The IEA should add to its decarbonization modeling portfolio a scenario in which carbon emissions targets accommodate economic development metrics, e.g., different target dates for industrialized, emerging, and developing economies.**

  A decarbonization scenario that accounts for different stages of development reflects a realistic mix of objectives (e.g., the three dimensions of the energy trilemma) that are weighted according to economic circumstances; these would include different levels of infrastructure needed to support the clean energy transition. Such a scenario would inform national, regional, and global policy developments; energy supply and demand; decarbonization technology needs; and associated investments. This analysis could also inform and provide the framework for emissions trading among countries.

- **Under the auspices of the United Nations Framework Convention on Climate Change, complete a price-based climate policy economic analysis.**

The analysis of an incentive, “price-based” GHG emissions framework that studies the impact of establishing a national price on GHG emissions could serve to level the emissions reduction playing field by applying consistent penalties to emissions from all sources and all uses. This analysis would provide insight into graded economic development trajectories based on an individual country’s emissions reduction targets such as nationally determined contributions and net-zero commitments. For developed countries with aggressive near-term GHG emissions reduction targets, such policies would affect domestic energy systems and could further impact international trade. For developing countries, this study would also highlight the potential trade-offs between economic development and the timing of environmental commitments, two key elements of the energy trilemma for natural gas that are discussed in detail in this report. Finally, this analysis could inform and provide the framework for emissions trading among countries.

Appendix: Units and Conversion Factors

Table A1. Natural gas (NG) and liquefied natural gas (LNG) conversion factors[474]

	To Convert					
	1 billion cubic meters NG	1 billion cubic feet NG	1 million tons oil equivalent	1 million tons LNG	1 trillion British thermal units	1 million barrels oil equivalent
From	Multiply by					
1 billion cubic meters NG	1.000	35.315	0.860	0.735	34.121	5.883
1 billion cubic feet NG	0.028	1.000	0.024	0.021	0.966	0.167
1 million tons oil equivalent	1.163	41.071	1.000	0.855	39.683	6.842
1 million tons LNG	1.360	48.028	1.169	1.000	46.405	8.001
1 trillion British thermal units	0.029	1.035	0.025	0.022	1.000	0.172
1 million barrels oil equivalent	0.170	6.003	0.146	0.125	5.800	1.000

Source: BP, 2021.

Unit Abbreviations

Bcf = billion cubic feet

Bcf/d = billion cubic feet per day

bcm = billion cubic meters

Btu = British thermal units

Gt = gigaton

GW = gigawatt

Kt = kiloton

MJ = megajoule

MMBtu = million British thermal units

MMcf = million cubic feet

MMmt = million metric tons

$MMtCO_2$ = million metric tons of carbon dioxide

MMtpa = million metric tons per annum

Mt = megatons

$MtCO_2$ = megatons of carbon dioxide

Mtoe = million tons of oil equivalent

MW = megawatt

MWh = megawatt-hour

quads = quadrillion Btu

TBtu = trillion British thermal units

Tcf = trillion cubic feet

TTPA = thousand tons per annum

Twh = Terawatt-hour

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