U.S. Department of ENERGY | Office of Fossil Energy and Carbon Management

ENERGY, ECONOMIC, AND ENVIRONMENTAL ASSESSMENT OF U.S. LNG EXPORTS

October 7, 2025

On December 20, 2024, DOE published a notice of availability of its study entitled, *2024 LNG Export Study: Energy, Economic, and Environmental Assessment of U.S. LNG Exports* 2024 LNG Export Study (2024 LNG Export Study, *see* 89 Fed. Reg. 104,132 and https://fossil.energy.gov/app/docketindex/docket/index/30). DOE prepared the 2024 LNG Export Study as a comprehensive update of DOE's prior studies evaluating exports of natural gas, including liquefied natural gas (LNG), under section 3 of the Natural Gas Act (NGA), 15 U.S.C. § 717b. Since issuing the 2024 LNG Export Study and the related Response to Comments on May 19, 2025 (*see* 90 Fed. Reg. 21,912), DOE has determined that the environmental analysis in the 2024 LNG Export Study is not required for DOE's decision on applications to export LNG to non-free trade agreement (non-FTA) countries under NGA section 3(a), 15 U.S.C. § 717b(a).

Specifically, DOE found that its review of an export application under the National Environmental Policy Act of 1969 (NEPA)—in particular, under categorical exclusion B5.7, *Export of natural gas and associated transportation by marine vessel*—considers all relevant environmental effects from the proposed export of LNG to non-FTA countries. The environmental portions of the 2024 LNG Export Study were not limited to marine transport effects considered under categorical exclusion B5.7, but rather included the integration of potential upstream and downstream environmental effects, which are not reasonably foreseeable environmental impacts of DOE's export authorizations. Accordingly, on August 4, 2025, in *Venture Global Calcasieu Pass, LLC*, DOE/FECM Order No. 4346-B (Docket No. 15-25-LNG), DOE explained that its discussion of the 2024 LNG Export Study would focus only on the economic analysis in the Study, as well as DOE's related findings on energy security. DOE further explained that this position is informed by and consistent with the Supreme Court's holdings in *Dep't of Transportation v. Public Citizen*, 541 U.S. 752 (2004), and *Seven County Infrastructure Coalition v. Eagle County, Colorado*, 605 U.S. __, 145 S.Ct. 1497 (2025), which make clear that "agencies are not required to analyze the effects of projects over which they do not exercise regulatory authority." *Seven Cnty. Infrastructure Coal.*, 605 U.S. __, 145 S.Ct. at 1516.

DOE thus reiterates that, in pending and future export application proceedings under NGA section 3(a), DOE will not consider the environmental analysis in the 2024 LNG Export Study or the related Response to Comments. For more discussion, *see, e.g.*, *Venture Global Calcasieu Pass, LLC*, DOE/FECM Order No. 4346-B, at 12-13, 15-16, 36-38. We note that, on October 3, 2025, in DOE/FECM Order No. 4346-C, DOE denied rehearing of Order No. 4346-B.

December 2024

Summary Report

December 2024

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List of Abbreviations

AEO	Annual Energy Outlook
AR6	Sixth Assessment Report
ATB	Annual Technology Baseline
Bcf, BCF	Billion cubic feet
Bcf/d	Billion cubic feet per day
BECCS	Bioenergy with carbon capture and storage
BIL	Bipartisan Infrastructure Law
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EJ	Exajoule (10^{18} joules)
EU	European Union
FECM	Office of Fossil Energy and Carbon Management
FID	Final investment decisions
FTA	Free trade agreement
GCAM	Global Change Analysis Model
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigaton
$GtCO_2$	Gigatons of carbon dioxide
HAPs	Hazardous air pollutants
HEIDM	Household Energy Impact Distribution Model
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
LCA	Life cycle assessment
LNG	Liquefied natural gas
MAM	Macroeconomic Activity Module
MWH	Megawatt-hour
MJ	Megajoule
MMBtu	Million British thermal units
MMT	Million Metric Tons
$MtCO_2$	Million tons of carbon dioxide
$MtCO_2e$	Million tons of carbon dioxide equivalent
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
NGA	Natural Gas Act
OGSM	Oil and Gas Supply Module
PM	Particulate matter
PNNL	Pacific Northwest National Laboratory
ROW	Rest of the World
SC-GHG	Social cost of greenhouse gas emissions
SWDs	Saltwater disposal wells
Tcf, TCF	Trillion cubic feet
TTF	Title Transfer Facility
U.S., USA	United States
VOCs	Volatile organic compounds
yr	Year

Foreword

This multi-volume study of U.S. LNG exports serves to provide an updated understanding of the potential effects of U.S. LNG exports on the domestic economy, U.S. households and consumers; communities that live near locations where natural gas is produced or exported; domestic and international energy security, including effects on U.S. trading partners; and the environment and climate. Prior to this study, Department of Energy's (DOE's) most recent economic and environmental analyses of U.S. LNG exports were published in 2018 and 2019, respectively. At that time, U.S. LNG exports were just getting underway and our export capacity was 4 billion cubic feet per day (Bcf/d), less than one-third of what it is today. Since then, our world and the global natural gas sector have changed significantly: the U.S. has become the top global exporter of LNG; Russia has invaded Ukraine and used energy as a weapon to undermine European and global security; the impacts and costs of extreme weather and natural disasters fueled by climate change have increased dramatically; and the pace of the energy transition and technological innovation has itself accelerated.

These developments and others factor into a global energy system that is changing rapidly. The pace of change creates inherent uncertainty in projecting the potential pathways for U.S. LNG through 2050. Accordingly, several considerations should be borne in mind when interpreting this study and its results.

- Given the global scope and timeframe examined in this study, there should be recognition of the inherent uncertainty in conclusions, especially given their size relative to the overall global economy and energy system.
- This study is not intended to serve as a forecast of U.S. LNG exports and impacts. Rather, it is an exercise exploring alternative conditional scenarios of future U.S. LNG exports and examining their implications for global and U.S. energy systems, economic systems, and greenhouse gas (GHG) emissions. This type of scenario analysis is a well-established analytical approach for exploring complex relationships across a range of variables.
- The scenarios explored in this study span a range of U.S. LNG export outcomes. Each scenario relies on input assumptions regarding many domestic, international, economic, and non-economic factors, such as future socioeconomic development, technology and resource availability, technological advancement, and institutional change. A full uncertainty analysis encompassing all underlying factors is beyond the scope of this study.
- For the portions of this study that have modeled results, the study does not attach probabilities to any of the scenarios examined.

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) is responsible for authorizing exports of domestically produced natural gas, including liquefied natural gas (LNG), to foreign countries under section 3 of the Natural Gas Act (NGA), 15 U.S.C. § 717b. An application to export domestically produced natural gas to countries that have a free trade agreement (FTA) with the United States must be granted without delay or modification and is deemed to be consistent with the public interest by statute. For applications to export domestic natural gas to non-FTA countries, DOE must grant the application unless it finds that the proposed exportation will not be consistent with the public interest.

Since 2012, to inform its public interest determination, DOE's Office of Fossil Energy and Carbon Management (FECM) has commissioned multiple studies to help assess the various facets of the public interest that are affected by U.S. LNG exports. The purpose of the current study is to provide a comprehensive update to our understanding of how varying levels of U.S. LNG exports impact all these facets.

The study is composed of this summary and four appendices:

- **Appendix A:** ***Global Energy and Greenhouse Gas Implications of U.S. LNG Exports.*** An analysis of the global market demand for U.S. LNG exports across a range of scenarios and the global emissions impacts of increased U.S. LNG exports through 2050.
- **Appendix B**: ***Domestic Energy, Economic, and Greenhouse Gas Assessment of U.S. LNG Exports.*** An analysis of the implications of the various U.S. LNG export levels on the U.S. economy and greenhouse gas emissions.
- **Appendix C**: ***Consequential Greenhouse Gas Analysis of U.S. LNG Exports.*** An analysis of global greenhouse gas emissions in response to increased U.S. LNG exports.
- **Appendix D:** ***Addendum on Environmental and Community Effects of U.S. LNG Exports.*** A literature review of the effects of upstream, midstream and downstream natural gas production and exports on the environment and on local communities.

Appendices A and C present global scenario analyses that evaluate the impact of different levels of U.S. LNG exports. The three defining variables in the scenario design are: 1) global climate policies and policy ambition, 2) technology availability, and 3) U.S. LNG export levels. (Table ES-1). Details on the assumptions behind each variable are included in Section 3 of this summary.

This study does not attach probabilities to any of the analyzed scenarios. Rather, the study explores a range of conditions that rely on described assumptions. The primary reference for comparison in this study is the level of U.S. LNG exports as it moves from levels associated with facilities that are operating or under construction pursuant to a final investment decision (FID) as of December 2023 (referred to as *Existing/FID Exports* levels) to levels determined by the global energy model in response to policy and technology assumptions (referred to as *Model Resolved* levels).

In Appendix B, the results from the global analysis (Appendix A) are used as inputs in a domestic scenario analysis. The domestic scenario analysis also includes sensitivities on U.S. oil and gas supply, following an approach consistent with the side cases in the EIA Annual Energy Outlook 2023 (AEO 2023).

Table ES- 1. Scenario assumptions and definitions

<table>
<tr><th>Global Climate Policies</th><th>Technology Availability [a]</th><th>U.S. LNG Export Levels</th></tr>
<tr><td rowspan="3">Defined Policies</td><td rowspan="3"></td><td>Model Resolved Exports</td></tr>
<tr><td>Existing/FID Exports</td></tr>
<tr><td>High Exports</td></tr>
<tr><td rowspan="6">Commitments</td><td rowspan="3">High CCS</td><td>Model Resolved Exports</td></tr>
<tr><td>Existing/FID Exports</td></tr>
<tr><td>High Exports</td></tr>
<tr><td rowspan="3">Moderate CCS</td><td>Model Resolved</td></tr>
<tr><td>Existing/FID Exports</td></tr>
<tr><td>High Exports</td></tr>
<tr><td rowspan="5">Net Zero 2050</td><td rowspan="3">High CCS</td><td>Model Resolved Exports</td></tr>
<tr><td>Existing/FID Exports</td></tr>
<tr><td>High Exports</td></tr>
<tr><td rowspan="2">Moderate CCS[b]</td><td>Model Resolved</td></tr>
<tr><td>High Exports</td></tr>
</table>

[a] *Existing/FID Exports* stands for an expected level of exports from facilities that are operating or under construction pursuant to a final investment decision (FID) as of December 2023.

[b] In the Net Zero 2050 (Mod CCS): Model Resolved scenario, U.S. LNG exports fall below the Existing/FID Exports level. As a result, a Net Zero 2050 (Mod CCS): Existing/FID Exports scenario yields the same outcomes as the Net Zero 2050 (Mod CCS): Model Resolved scenario and is not shown.

Global demand for U.S. LNG depends on the global demand for natural gas. Leading models include a broad range of projections of global natural gas demand, driven by differences in model structures, levels of technological and sectoral detail, and assumptions about resources, trade, policies, and the characteristics and availability of technologies.[1] For example, the global model used for this study (the Global Change Analysis Model, or GCAM) includes representations of carbon capture and storage (CCS) technologies in power, hydrogen, and industrial sectors. Other models may differ in their representations of and assumptions about CCS and other technologies.[2] Therefore, GCAM may resolve for different levels of global gas demand in scenarios with policies that limit greenhouse gas (GHG) emissions due to the assumed availability of CCS.

To provide a more comprehensive set of projections, two scenarios of technology availability are included in this study for the *Commitments* and *Net Zero 2050* policy scenarios. The *High CCS* scenario assumes default levels of CCS availability in GCAM. The *Moderate CCS* scenario assumes moderated levels of CCS and accelerated reductions in the costs of renewable energy and storage technology, described further in Table 4, below. Modeling results indicate that global natural gas demand is lowest in a scenario that assumes global climate policies consistent with

[1] Raimi, D., Zhu Y., Newell, R.G., Prest, B.C., 2024. Global Energy Outlook 2024: Peaks or Plateaus? *Resources for the Future.* https://www.rff.org/publications/reports/global-energy-outlook-2024/
[2] Binsted, M., Lochner, E., Edmonds, J., Benitez, J., Bistline, J., Browning, M., De La Chesnaye, F., Fuhrman, J., Göke, L., Iyer, G. and Kennedy, K., 2024. Carbon management technology pathways for reaching a US Economy-Wide net-Zero emissions goal. *Energy and Climate Change*, *5*, p.100154.

limiting global warming to 1.5°C (with >50% probability) by 2100 with no or limited overshoot *(Net Zero 2050*) and moderate levels of CCS *(Moderate CCS*). Even lower levels of global gas demand may be possible under alternative assumptions, such as lower or no CCS deployment (CCS otherwise allows more natural gas use in a carbon constrained scenario), slower population and economic growth, increased adoption of energy efficiency measures, breakthroughs in other technologies, alternative industrial decarbonization options, and more rapid fuel switching in the industrial sector.

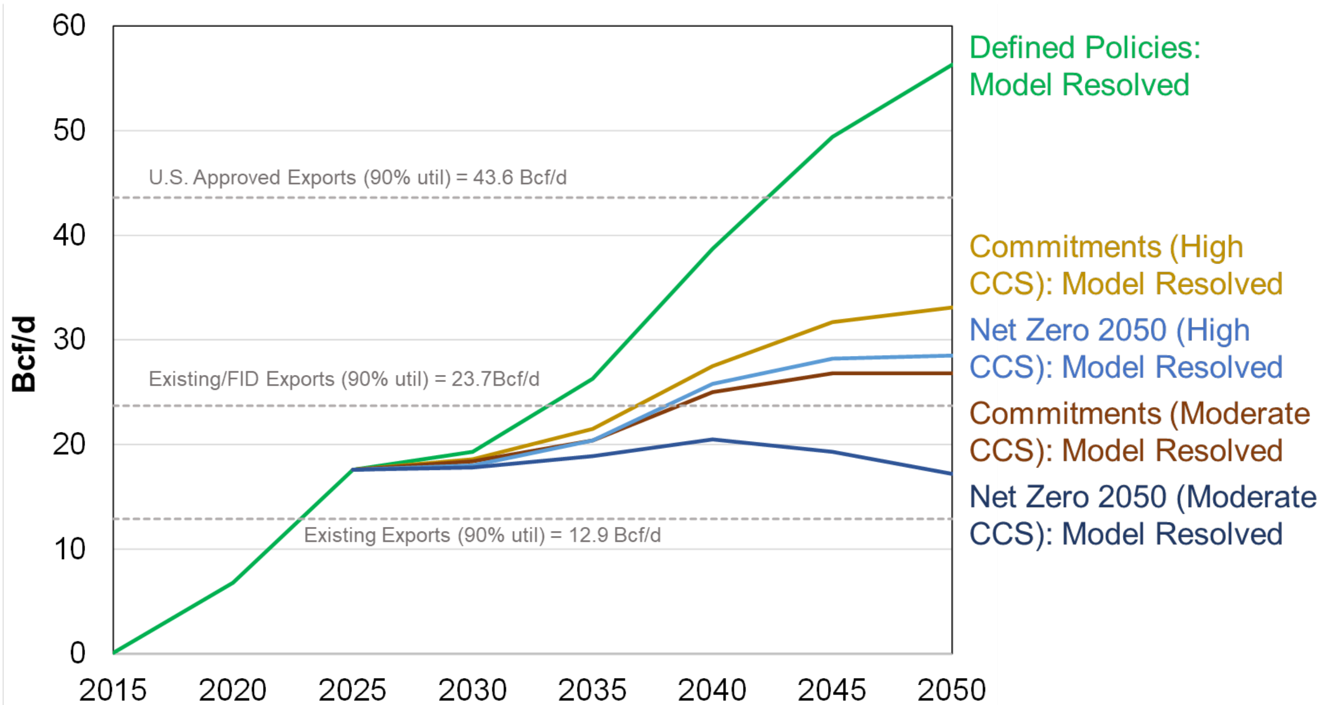

Figure ES-1. U.S. LNG exports (Billion cubic feet/day) across scenarios with Model Resolved U.S. LNG export levels.

By 2050, as shown in Figure ES-1, in all the *Model Resolved* scenarios except one (*Net Zero 2050 (Mod CCS): Model Resolved* scenario), projections of U.S. LNG exports exceed the volume of natural gas from LNG projects already in operation or under construction pursuant to a final investment decision in December 2023 (23.7 Bcf/d).[3] By 2050, U.S. LNG exports are projected to exceed authorized export levels in place as of December 2023 (90% utilization of 48.45 Bcf/d which equals 43.6 Bcf/d) in only one of the *Model Resolved* scenarios (*Defined Policies: Model Resolved*).[4] In this scenario, export levels are projected to exceed 2023 authorized export levels in 2045, reaching 43.6 Bcf/d, and increasing to 56.3 Bcf/d in 2050.[5]

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[3] Calculated as 90% of 26.2 Bcf/d which corresponds to the operating or under construction pursuant to final investment decision (FID) U.S. LNG export capacity as of December 2023. 90% is chosen as the maximum expected amount of exports from a given amount of operating capacity given maintenance and operational realities that prevent LNG export facilities from being able to export at their maximum peak consistently.

[4] Calculated as 90% of the capacity associated with projects approved for exports to non-FTA countries as of December 2023. This level includes the existing and FID level of exports.

[5] To date, approximately half of authorized non-FTA exports is associated with projects or portions of projects that are either operating or under construction pursuant to a final investment decision (FID). As of December 2023, 48.45 Bcf/d of U.S.-sourced natural gas had been approved for export as LNG to non-

Key findings from the study are below and the full analyses and environmental literature review are included as appendices.

A. Key Findings: Domestic Natural Gas Supply and Economic Impacts

- Across all scenarios, modeled U.S. domestic natural gas supply is sufficient to meet modeled global demand for U.S. LNG while continuing to meet domestic demand. This result holds across sensitivity scenarios on U.S. oil and gas supply.
- The price of natural gas at the Henry Hub in Louisiana, a main trading hub for natural gas in the U.S., increases in scenarios where the export level is *Model Resolved* (i.e., based on modeled global demand and unconstrained U.S. LNG exports) when compared with existing and FID levels of U.S. LNG exports.
    - Across the *Defined Policies* with reference U.S. supply assumptions, the 2050 Henry Hub natural gas price increases 31% (from $3.53/MMBtu to $4.62/MMBtu, $2022), as U.S. LNG exports increase in response to the modeled global demand level. The modeled price increase is equivalent to about $0.03/MMBtu for every Bcf/d of increased LNG export above existing and FID levels.
    - For comparison, Henry Hub prices in 2022 and 2023 were $6.45/MMBtu and $2.53/MMBtu, respectively.
    - This study does not include forward-looking modeling on the impacts of increasing LNG exports on natural gas price volatility. Given the unique role of the U.S. as the largest global producer, consumer, and, more recently, exporter of natural gas, there is uncertainty in how rising export levels will affect the domestic market. While there has not been a consistent relationship between domestic prices and export levels to date, that could change as a larger percentage of U.S. natural gas is exported. Current authorized export levels (over 48 Bcf/d) are equivalent to approximately 45% of current U.S. gas production.
- The impacts of increasing U.S. LNG exports on domestic natural gas prices vary by region. Within the model, LNG export facilities are assumed to be centered in the Gulf Coast region. While gas is sourced from regions around the country, the Gulf Coast and Southwest regions experience the greatest price impacts from increased LNG exports in model projections.
- Higher U.S. LNG export levels in 2050 are associated with higher U.S. residential natural gas prices.
    - For example, in the *Defined Policies* scenarios, U.S. residential natural gas prices are 4% higher in 2050 when the scenario assumes *Model Resolved* levels of exports compared to *Existing/FID Exports* levels.
    - When sensitivity scenarios assume low U.S. natural gas supply, the higher level of U.S. LNG exports under *Model Resolved* assumptions compared to *Existing/FID Exports* assumptions results in 7% higher residential gas prices in 2050. When the sensitivity scenarios assume high U.S. natural gas supply, the higher level of U.S. LNG exports results in 3% higher prices in 2050.
- Under the *Defined Policies* scenario with the reference U.S. supply assumption, the estimated annual energy expenditure impacts of the increased 2050 natural gas prices across all socioeconomic levels and census divisions include:
    - Up to a $122.54 per year average increase for natural gas plus electricity expenditures across all households, with average household expenditure impacts

FTA countries, and 26.29 Bcf/d of corresponding capacity was in operation or under construction pursuant to a final investment decision.

up to 0.50% of average annual income and 3.4% of natural gas and electricity bills.[6]

- Up to a $46.52 per year average increase for natural gas expenditures at natural gas households (households identified in NEMS as using natural gas for space heating), with an average natural gas household expenditure impact of up to 0.24% of average annual income and 6.7% of average natural gas bills.
- Up to a $118.37 per year average increase for electricity expenditures across all households, with an average household expenditure impact of up to 0.5% of average annual income and 3.5% of average electricity bills.

  - This analysis did not explore the impact of increased natural gas and electricity prices on broader consumer goods, which could have an additional impact on consumer expenditures.

- An increase in gross industrial output occurs with increased LNG exports across all oil and gas supply assumptions (by up to 1.3%, or $203 billion, in 2050), driven by increased upstream oil and gas activity to meet increased demand for LNG.
  - Industrial output from oil and gas extraction subsector makes up $147 billion, or 72%, of this increase in 2050. On a cumulative basis, gross industrial output increases $893 billion ($2022 discounted at 3%) from 2020 to 2050 with 75% of the cumulative increase as a result of output from the oil and gas extraction subsector.
- Total energy costs for the industrial sector cumulatively increase $125 billion ($2022, discounted at 3%) from 2020-2050 under reference oil and gas supply assumptions, reflecting higher natural gas prices in the sector.
  - Under the reference U.S. supply assumptions, increased LNG exports result in a 20% increase in natural gas consumption for production and processing, and a 130% increase in natural gas consumption for gas liquefaction in 2050. Natural gas consumption in other industrial subsectors decreases by 0.5% in 2050.
- NEMS includes granular detail about the energy system, such as prices, and a separate macroeconomic module that provides feedback on changes in the broader economy. One result of the model's configuration is that increases in energy production in response to LNG exports generally yield increases in GDP in the modeling framework, but secondary effects (e.g., effects resulting from changes in the price of consumer goods) may moderate this relationship.[7] As an example of this effect, in the *Defined Policies* scenario with reference U.S. supply assumptions, increasing exports from existing and FID levels to *Model Resolved* levels results in a 0.2% increase in GDP in 2050 ($80 billion, $2022), and cumulatively from 2020 to 2050, GDP increases $410 billion ($2022 discounted at 3%). Additionally, GDP increases are one of several measures of economic activity and an increase in GDP does not necessarily correlate with a positive effect on broader public and consumer welfare.

B. Key Findings: Energy Security

- The global market for LNG has been increasing for several years and LNG re-gasification and associated import infrastructure is being built out globally, but future demand for natural gas and LNG is uncertain and the demand centers are expected to shift.

[6] Combined natural gas plus electricity expenditures are lower than the combined natural gas and electricity expenditures as all values are up to the highest increases across regions and different regions have the highest natural gas and electricity expenditures, as discussed in Appendix B.
[7] See Appendix B for further discussion of how NEMS models GDP.

- DOE natural gas export authorizations do not include destination restrictions beyond a prohibition to exporting to sanctioned countries. Accordingly, U.S. LNG generally follows global market demand.
- U.S. LNG provides cost-competitive LNG to the global LNG market and is considered a stable energy supply due to the long-term nature of the off-take contracts used by U.S. LNG project developers to reach final investment decision before construction.
    - During the five years before Russia's invasion of Ukraine, from 2016 through 2021, South Korea, Japan, and China were the top three importers of U.S. LNG, collectively importing 34% of U.S. exports, while Europe imported 28%.
    - From 2022 through 2023, that mix changed, with the share delivered to Europe growing to more than 63% of total U.S. LNG exports, while exports to Asia were reduced to over 24% of the total.
- Diverse energy portfolios are critical for countries' energy security strategies. While not always the most cost-competitive source of energy, LNG imports are often part of these strategies because they are able to support baseload dispatchable power from multiple ready sources with mature technology and, in many cases, existing infrastructure. The availability of lower cost energy sources, such as coal and renewables, and countries' energy policy goals will determine the outlook for U.S. LNG's role in the global energy market and the energy transition.
- While Europe has been the primary destination for U.S. LNG from 2016 to present, global demand and the destination of U.S. LNG in the future is less certain.
    - European policies are moving to reduce the use of fossil fuels, including natural gas. Demand for natural gas and LNG in Asia is expected to increase in most scenarios.
    - China has recently become the largest global importer of LNG and has signed several contracts with operating or proposed U.S. LNG projects.
    - China is expected to have the highest LNG imports of any country across all scenarios in 2050.

C. Key Findings: Greenhouse Gas Emissions

- The ultimate global GHG consequences of U.S. LNG exports depend on market effects such as changes in energy demand and the sources used to meet that demand for electricity and other uses of natural gas. A consequential lifecycle analysis enables an examination of how the availability of U.S. LNG could affect global energy consumption, what types of energy U.S. LNG might displace, and the resulting global greenhouse gas implications.[8]
    - When comparing *Model Resolved* to *Existing/FID Exports* in the *Defined Policies* scenario, increased availability of U.S. LNG from 23.7 Bcf/d to 56.3 Bcf/d in 2050 results in an additional 0.08% in cumulative (2020-2050) global services and an increase of 711 million metric tons (MMT) carbon dioxide equivalent (CO_2e) (0.05%) in cumulative global GHG emissions, including changes in the land sink.[9]
    - Attributional studies estimate direct emissions associated with use of natural gas, LNG, or other fuels used to generate electricity. These studies do not directly

[8] A consequential LCA accounts for the direct emissions from production, delivery, and use of the U.S. exported natural gas and the indirect emissions from changes in market behavior, such as substitution of natural gas for other sources of energy or additional energy use. The consequential GHG intensity calculated in this study is therefore the total effect (direct and indirect market effects) of U.S. LNG on global GHG emissions per unit of U.S. LNG exported.
[9] Global services are defined as those products of the global economy that provide services to consumers, such as energy, commodities, fertilizers, etc.

consider market effects of the exported gas but are used to compare the potential environmental profiles of alternatives. Comparing *Model Resolved* to *Existing/FID Exports* levels in the *Defined Policies* scenario, the direct life cycle GHG emissions from production, export, and end use (assuming 100% combustion without CCS) of increased U.S. LNG exports before accounting for market effects would cumulatively (2020-2050) contribute 8,588 MMT CO_2e based on an attributional life cycle GHG profile of 76 g CO_2e/MJ. In 2050, direct life cycle GHG emissions from all U.S. LNG would be approximately 1,500 MMT CO_2e before accounting for market effects.

- As summarized in Table ES-2, the additional GHG emissions per unit of additional U.S. LNG exported, or the consequential GHG emissions intensity, varies by scenario.

Table ES-2. Cumulative (2020-2050) consequential GHG intensities of U.S. LNG exports

Comparison of Scenarios	Scenario	2050 U.S. LNG Exports (EJ) [Bcf/d][a]	Cumulative (2020-2050) change in…			Cumulative Consequential GHG Emissions Intensity (g CO_2e/MJ)
			U.S. LNG Exports (*EJ*) [% increase from *Existing/FID*]	GHG Emissions (MMT CO_2e) [% increase from *Existing/FID*][b]	Global Services (%)	
Existing/FID Exports to Model Resolved	*Defined Policies*	20.3 [56.3]	113 [50%]	711 [0.05%]	0.08%	6.3
	Commitments (High CCS)	11.9 [33.1]	31 [14%]	97 [0.01%]	0.02%	3.1
	Commitments (Mod CCS)	9.7 [26.8]	11 [5%]	67 [0.01%]	0.01%	5.9
	Net Zero (High CCS)	10.3 [28.5]	17 [8%]	21 [0.002%]	0.01%	1.2
	Net Zero (Mod CCS)[c]	6.2 [17.2]	0	NA	NA	NA

a. 2050 U.S. LNG export levels for *Model Resolved* scenarios.
b. Cumulative change in GHG emissions (2020-2050) are 1.2% higher than the GCAM results to align the upstream emission estimates with NETL estimates that are used to explore upstream and liquefaction facility contributions to the consequential results (see Appendix C for additional details).
c. *Net Zero (Mod CCS)* U.S. LNG export levels do not change between the *Existing/FID Exports* to *Model Resolved* scenarios resulting in no change in global emissions or services, the results are listed as "NA" or Not Applicable.

- Across scenarios in which U.S. LNG exports are assumed to exceed *Model Resolved* levels (up to +20 Bcf/d by 2050, corresponding to the *High Exports* assumption for U.S. LNG exports), global cumulative GHG emissions (2020-2050) are 324 MMT CO_2e to 1,452 MMT CO_2e higher than their counterparts with *Model Resolved* levels of U.S. LNG exports. With respect to cumulative consequential GHG emissions intensity, that is equivalent to a range of 3.5 g CO_2e/MJ to 12.6 CO_2e/MJ for additional U.S. LNG exports.
- The increase in global GHG emissions between the *Defined Policies: Model Resolved* and *Defined Policies: Existing/FID Exports* scenarios is estimated to result in a cumulative Social Cost of GHG (SC-GHG) impact of $84 billion using a discount rate of 2.5%, $140 billion using a discount rate of 2.0%, and $250 billion using a discount rate of 1.5% (all in 2022$). The cumulative social cost of greenhouse gas emissions (SC-GHG) of the

increase in global emissions across the study scenarios ranges from $3 billion to $170 billion (2.5%) to $13 billion to $500 billion (1.5%) in 2022$.

D. Key Findings: Environmental and Community Effects

- The production and transportation of natural gas in the U.S., including natural gas for export, has energy, labor/workforce, economic, environmental, and social justice implications, among other implications.
- Communities of color, including those with Black, Indigenous, and Hispanic populations, as well as rural and low-income communities, have historically been disproportionately exposed to the environmental risks, harms, and measurable impacts that arise from natural gas and overall fossil fuel development and production activities. These same activities also provide economic support for many communities.
- Production and Upstream Impacts
    - Increased U.S. natural gas production increases upstream environmental impacts, including impacts to water, air, and land.
    - Natural gas production and processing emits pollutants that are harmful to human health.
    - Researchers have found spatial and temporal (i.e., location and timing) correlations between seismic events precipitated by human activities and the disposal of produced water through underground injection into saltwater disposal wells (SWDs), in several states including Texas, Oklahoma, Kansas, Colorado, Arkansas, and Ohio. Various means are underway to reduce the impact, such as recycling produced water rather than disposing of it.
- Community Effects
    - Natural gas production and processing impacts upstream, midstream, and downstream communities in harmful and beneficial ways. Additional research is needed on the impact of LNG exportation on local communities. In particular, in areas with existing heavy industry, the cumulative impact of LNG exports has yet to be determined.
    - From an economic perspective, natural gas production and the development of natural gas export infrastructure tends to increase employment in regions and communities where it occurs, but some evidence indicates that jobs often go to people who either move to the area for the jobs or commute from other areas, rather than to long-term residents.
    - Oil and gas production growth brings new revenues to local governments, but can also bring additional burdens such as increased emergency services and police, additional water and wastewater infrastructure, and potential damage due to increased heavy road usage.
    - Local mineral rights holders receive royalties, though such recipients are not always local residents.
    - Quality of life impacts from natural gas development include noise, light pollution, dust, increased traffic, crime, and social disruptions due to the cyclical nature of the production industry.

I. Introduction

This report is divided into eight sections. Section I (Introduction) reviews the purpose of this study and summarizes the analyses performed. Section II (Background) provides background information on the role of U.S. liquefied natural gas (LNG) exports for global energy markets, as well as the relationship between the global natural gas market and domestic prices. Section III (Study Methodology) describes the four models used for this study. Section IV (Global Energy and GHG Assessment) outlines the results of global modeling components of this study. Section V (Domestic Energy, Economic, and GHG Assessment) summarizes the results of the domestic modeling components. Section VI (Consequential Life Cycle Analysis) reviews the use of data from the global modeling analysis to inform an updated approach to life cycle assessment (LCA) that includes the global use of U.S. natural gas. Section VII (Energy Security Analysis) provides an assessment of the global energy security considerations for U.S. LNG exports. Section VIII (Environmental and Community Impacts) summarizes key findings from a qualitative assessment of the local environmental and community impacts of U.S. LNG exports.

In addition to this summary report, four appendices are included to provide more detail on key elements of this study:

A. Global Energy and GHG Assessment of U.S. LNG Exports
B. Domestic Energy, Economic, and GHG Assessment of U.S. LNG Exports
C. Consequential Greenhouse Gas Analysis of U.S. LNG Exports
D. Addendum on Environmental and Community Effects of U.S. LNG Exports

A. Review of Public Interest Criteria

The U.S. Department of Energy (DOE) is responsible for authorizing imports and exports of natural gas, including LNG, from or to foreign countries pursuant to Section 3 of the Natural Gas Act (NGA), 15 U.S.C. 717b. Under the NGA, applications requesting authority for the import or export of natural gas, including LNG, from and to a nation with which there is in effect a free trade agreement (FTA) requiring national treatment for trade in natural gas, and/or the import of LNG from other international sources, are deemed consistent with the public interest and granted without modification or delay. For applications requesting authority to export to those countries with which the U.S. does not have such a FTA, and with which trade is not prohibited by U.S. law or policy (non-FTA countries), Section 3(a) of the NGA requires DOE to grant an authorization to export domestically produced natural gas, unless it finds that such action is not consistent with the public interest.[10]

DOE has identified a range of factors that it evaluates when reviewing an application for authorization of LNG exports to non-FTA countries. Specifically, DOE's review of non-FTA export applications focuses on:

> *1) the domestic need for the natural gas proposed to be exported, 2) whether the proposed exports pose a threat to the security of domestic natural gas supplies, 3) whether the arrangement is consistent with DOE's policy of promoting market competition, and 4) any other factors bearing on the public interest as determined by DOE, such as international and environmental impacts.*[11]

To inform its public interest determination, since 2012, the DOE's Office of Fossil Energy and Carbon Management (FECM) and its predecessor, the Office of Fossil Energy, has commissioned multiple studies on the effects of increased LNG exports on the U.S. economy and energy

[10]. 15 U.S. Code § 717b
[11] Cameron LNG, LLC, FE Docket No. 11-162-LNG, at 8 (U.S. Department of Energy May 20, 2014).

markets. The previous studies on the economic, environmental, and greenhouse gas impacts of LNG exports are listed in Table 1, below.

Table 1. Prior studies

Report Name	Authoring Organization	Short Name
Effect of Increased Natural Gas Exports on Domestic Energy Markets[12]	U.S. Energy Information Administration (EIA)	EIA 2012
Effect of Increased Natural Gas Exports on Domestic Energy Markets[13]	NERA	NERA 2012
Effect of Increased Levels of Liquefied Natural Gas Exports on U.S. Energy Market[14]	EIA	EIA 2014
Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States[15]	NETL	2014 LCA GHG Report
Addendum to Environmental Review Documents Concerning Exports of Natural Gas from the United States[16]	DOE	Addendum 2014
The Macroeconomic Impact of Increasing U.S. LNG Exports[17]	Baker Institute/ Oxford Economics	Baker 2018
Macroeconomic Outcomes of Market Determined Levels of U.S. LNG Exports[18]	NERA	NERA 2018
Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update[19]	NETL	LCA GHG Update

[12] U.S. EIA. (2012). Effects of Increased Natural Gas Exports on Domestic Energy Markets. Available at: https://energy.gov/sites/prod/files/2013/04/f0/fe_eia_lng.pdf

[13] NERA Economic Consulting. (2012). Macroeconomic Impacts of LNG Exports from the United States. Available at: https://energy.gov/sites/prod/files/2013/04/f0/nera_lng_report.pdf

[14] U.S. EIA. (2014). Effect of Increased Levels of Liquefied Natural Gas Exports on U.S. Energy Markets. Available at: https://www.eia.gov/analysis/requests/fe/pdf/lng.pdf

[15] U.S. Dep't of Energy, Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas From the United States (DOE/NETL-2014-1649) (May 29, 2014) Available at: life-cycle-greenhouse-gas-perspective-exporting-liquefied-natural-gas-united-states

[16] U.S. Dep't of Energy, Addendum to Environmental Review Documents Concerning Exports of Natural Gas From the United States, 79 Fed. Reg. 48,132 (Aug. 15, 2014). Available at: https://www.energy.gov/fecm/addendum-environmental-review-documents-concerning-exports-natural-gas-unitedstates

[17] Cooper, A., Kleiman, M., Livermore, S., & Medlock III, K. B. (2015). The Macroeconomic Impact of Increasing U.S. LNG Exports. Available at: https://energy.gov/sites/prod/files/2015/12/f27/20151113_macro_impact_of_lng_exports_0.pdf

[18] NERA Economic Consulting. (2018). Macroeconomic Outcomes of Market Determined Levels of U.S. LNG Exports. Available at: https://www.energy.gov/sites/prod/files/2018/06/f52/Macroeconomic%20LNG%20Export%20Study%202018.pdf

[19] Nat'l Energy Tech. Lab., Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update (DOE/NETL-2019/2041) (Sept. 12, 2019). Available at: https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

Similar to previous studies, this study is intended to serve as a reference for consideration in the evaluation of applications to export LNG from the U.S. under Section 3 of the NGA. FECM commissioned Pacific Northwest National Laboratory (PNNL), National Energy Technology Laboratory (NETL), OnLocation, Inc. (OnLocation), and Industrial Economics, Incorporated (IEc) to assess the impacts of increased availability of U.S. LNG exports across scenarios representing a range of economic, environmental, and policy factors. These scenarios are used to explore the impacts of increasing U.S. LNG exports on global greenhouse gas (GHG) emissions and energy consumption patterns, as well as domestic economic outcomes including energy prices and gross domestic product (GDP). These scenarios also contribute to the evaluation of life cycle GHG emissions associated with U.S. LNG exports. In addition to scenario analysis, the study includes qualitative assessments of global energy security and local environmental and community impacts. In sum, these analyses are intended to inform DOE's consideration of the public interest criteria.

Since the most recent studies on the economic impacts of U.S. LNG exports in 2018 and the life cycle GHG impacts of U.S. LNG exports in 2019, events have dramatically shifted global and U.S. natural gas markets, including:

- The Russian invasion of Ukraine in 2022 introduced a global gas supply shock, particularly in the European Union (EU), that altered global LNG markets and shipping patterns.
- Global climate policy ambition advanced, increasing demand for and deployment of clean energy resources. In the U.S., the passage of the Bipartisan Infrastructure Law (BIL)[20] in 2021 and the Inflation Reduction Act (IRA)[21] in 2022 have accelerated the deployment of clean energy technology and decarbonization.
- There has been growing national attention on the positive and negative effects of expanding natural gas production and exports, leading to a range of responses, including federal Executive Orders defining environmental justice, climate justice, racial equity, sustainability, and energy communities.
- Continued technological advancements in the production, transmission, storage, and end-use of natural gas have affected the economics of natural gas supply and demand.

This study aims to capture these recent and complex dynamics through a comprehensive update to the economic, environmental, and GHG analyses that inform DOE's public interest determination.

II. Background on Natural Gas Markets

According to the U.S. Energy Information Administration (EIA), global natural gas production reached 412 billion cubic feet per day (Bcf/d) in 2022, accounting for 25% of total global primary energy demand. Approximately 25% (100 Bcf/d) of this production came from the U.S. Russia provided 15% (60 Bcf/d), followed by Iran (25 Bcf/d, 6%), People's Republic of China (China) (22 Bcf/d, 5%), and Canada (18 Bcf/d, 4%).[22]

The U.S. was the largest consumer of global natural gas in 2022, accounting for approximately 23% (88 Bcf/d) of total global demand. Russia (46 Bcf/d, 12%) was followed by China (35 Bcf/d,

[20] Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021), https://www.congress.gov/bill/117th-congress/house-bill/3684/text.
[21] Inflation Reduction Act, Pub. L. 117-169 (Aug. 16, 2022), https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf.
[22] U.S. Energy Info. Admin., International statistics gas production, https://www.eia.gov/international/data/world/natural-gas/dry-natural-gas-production

9%), Iran (24 Bcf/d, 6%), and Canada (13 Bcf/d, 3%).[23] Of this, the global LNG export market grew from an average of 33.7 Bcf/d (12.1 EJ) in 2015 to 51.3 Bcf/d (18.5 EJ) in 2022 (52.9 Bcf/d, 19.1 EJ in 2023), representing an increase of 19.2 Bcf/d (6.9 EJ). [24]

A. U.S. LNG Export Trends

In 2016, the first lower-48 LNG export terminal commenced operations. Since then, the U.S. has become a net exporter of LNG.[25] Average annual U.S. nameplate export capacity increased from 1.0 Bcf/d in 2016 to 11.9 Bcf/d in 2023, as shown in Figure 1. In 2016, the U.S. exported 0.5 Bcf/d to 17 countries from one export project.[26]

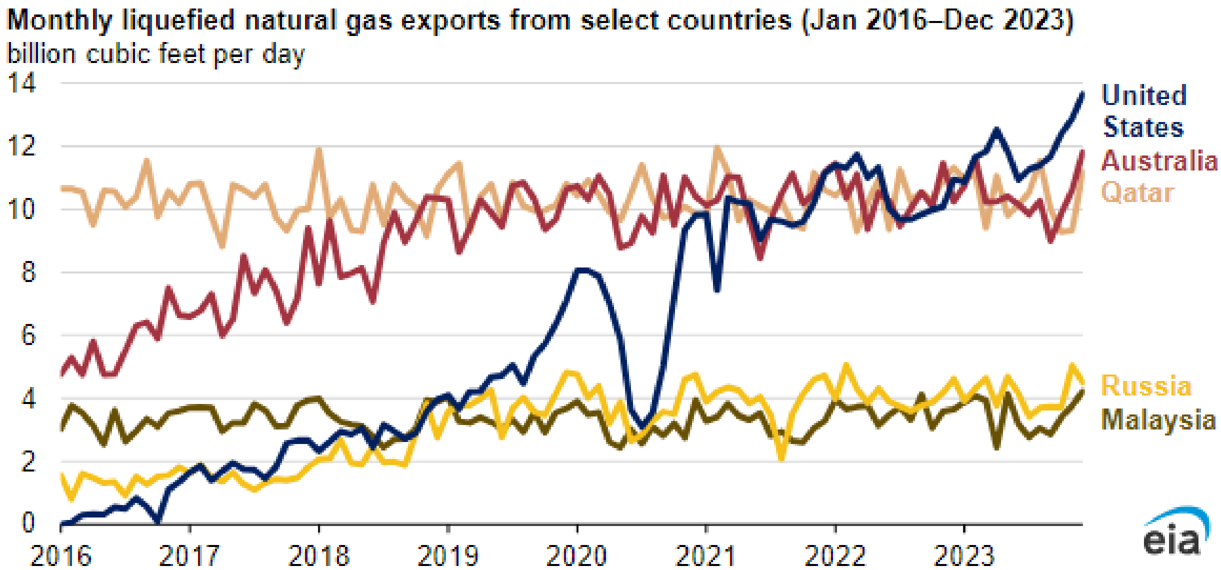

Figure 1. Top global LNG exporting countries, monthly volumes (1/2016-12/2023). Source: U.S. Energy Information Administration (2024)[27]

During the six calendar years preceding the Russian invasion of Ukraine (2016-2021), South Korea, Japan, and China were the largest importers of U.S. LNG, collectively accounting for 34% of U.S. exports. Following the Russian invasion of Ukraine in February 2022, pipeline natural exports from Russia into the EU declined dramatically. To compensate, the EU turned to LNG imports to fulfill its natural gas demand, increasing LNG imports from 9.1 Bcf/d in 2021 to 15.2 Bcf/d in 2023, as shown Figure 2. The availability of destination-flexible U.S. LNG exports helped the EU fill this supply gap. During this period, the U.S. became the largest LNG supplier to the region, and the EU became the largest importer of U.S. LNG exports (60% of U.S. LNG exports).

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[23] U.S. Energy Info. Admin., International statistics gas consumption. Available at: https://www.eia.gov/international/data/world/natural-gas/dry-natural-gas-consumption

[24] U.S. Energy Info. Admin., "Global trade in liquefied natural gas continued to grow in 2023", Today in Energy, (July 11, 2024). Available at: https://www.eia.gov/todayinenergy/detail.php?id=62464

[25] U.S. Energy Info. Admin., Natural Gas Explained: Liquified Natural Gas. Available at: https://www.eia.gov/energyexplained/natural-gas/liquefied-natural-gas.php

[26] Note: as described elsewhere in this report, for the purposes of this study, current U.S. LNG exports were assumed to be 12.9 Bcf/d, calculated as 90% of total export capacity tracked by FECM as of December 2023.

[27] U.S. Energy Info. Admin., "The United States was the world's largest liquefied natural gas exporter in 2023," Today in Energy, (April 1, 2024). Available at: https://www.eia.gov/todayinenergy/detail.php?id=61683

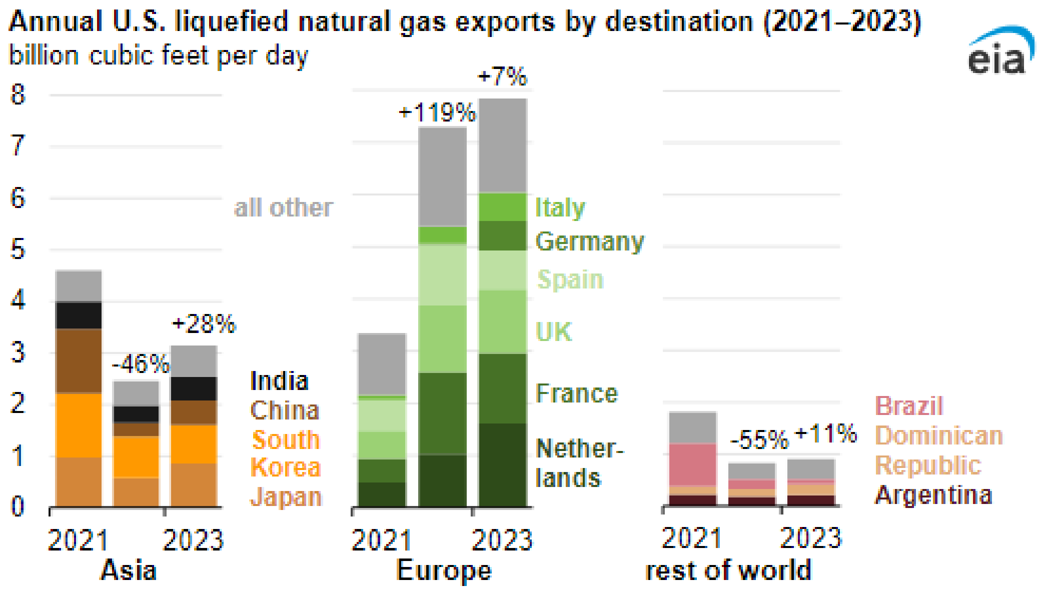

Figure 2. Annual U.S. LNG exports by destination (2021 and 2023). Source: U.S. Energy Information Administration (2024)[28]

In 2023, the U.S. became the world's largest exporter of LNG, reaching 21% of the world's LNG export market.[29] The two other largest LNG exporting countries, Australia and Qatar, each ranged from 10.1 Bcf/d to 10.5 Bcf/d annually between 2020 and 2023, according to the EIA.[30]

B. Overview of DOE non-FTA LNG Export Authorizations

As of December 2023, non-FTA export authorizations issued by DOE had a cumulative total of approximately 48.45 Bcf/d.[31] One non-FTA authorization for 2.55 Bcf/d of exports is for natural gas sourced from Alaska, with the remaining 45.9 Bcf/d of authorizations sourced from the lower-48 states. Of the 45.9 Bcf/d of authorized non-FTA exports sourced from the lower-48 states, approximately 39.8 Bcf/d of the authorized volumes are from facilities built (or proposed to be built) in the lower 48 states, and 6.3 Bcf/d of U.S.-sourced natural gas is authorized for re-export as LNG from facilities under construction or proposed to be built in Mexico and Canada (Table ES-2 below).

Of the 48.45 Bcf/d DOE had approved for non-FTA exports as of December 2023, 14.28 Bcf/d is associated with projects currently operating. An additional 12.01 Bcf/d is under construction, after having reached a final investment decision (FID). The remaining 22.16 Bcf/d is authorized for export to non-FTA countries but was not yet operating or under construction pursuant to an FID. An additional 14 non-FTA applications ranging in size from 0.057 Bcf/d to 3.96 Bcf/d and totaling 14.2 Bcf/d are currently pending at DOE.[32]

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[28] U.S. Energy Info. Admin., "The United States was the world's largest liquefied natural gas exporter in 2023," Today in Energy, (April 1, 2024). Available at: https://www.eia.gov/todayinenergy/detail.php?id=61683
[29] Ibid.
[30] Ibid.
[31] DOE's non-FTA LNG export authorizations typically correspond to the peak authorized capacity of the project that has sought the authorization.
[32] These figures correspond to non-FTA export application proceedings that are currently pending, where either (i) the environmental review under the National Environmental Protection Act (NEPA) led by other

Table 2. North American large-scale LNG export projects with non-FTA export authority from DOE (as of December 2023)

	Project	Volume (Bcf/d)			Initial Operation (or est.)	Construction Status
		Authorized	Under Construction Pursuant to a final investment decision (FID)	Operating		
1	Sabine Pass | *Cameron, LA*	4.55	0	4.55	Feb. 2016	Operating
2	Cove Point LNG | *Calvert City, MD*	0.77	0	0.77	Mar. 2018	Operating
3	Cameron | *Hackberry, LA*	3.53	0	2.12	May 2019	3 trains operating
4	Corpus Christi | *Corpus Christi, TX*	3.99	1.59	2.4	Dec. 2018	3 trains operating Stage 3 Under construction
5	Elba Island | *Chatham County, GA*	0.36	0	0.36	Sep. 2019	Operating
6	Freeport | *Quintana Island, TX*	3.10	0	2.38	Sep. 2019	3 trains operating
7	Golden Pass| *Sabine Pass, TX*	2.57	2.57	0	Late 2025 (est.)	Under construction
8	Venture Global Calcasieu Pass | *Cameron, LA*	1.70	0	1.70	Mar. 2022	Operating
9	Lake Charles | *Lake Charles, LA*	2.33	0	0	N/A	Pending FID
10	Delfin | *Gulf of Mexico*	1.80	0	0	N/A	Pending FID
11	Port Arthur | *Port Arthur, TX*	1.91	1.91	0	2027 (est.)	Under construction
12	Driftwood | *Calcasieu Parish, LA*	3.88	0	0	N/A	Pending FID
13	Gulf LNG | *Jackson County, MS*	1.53	0	0	N/A	Pending FID
14	Venture Global Plaquemines | *Plaquemines Parish, LA*	3.40	3.40	0	Late-2024 (est.)	Under construction
15	Rio Grande LNG | *Brownsville, TX*	3.61	2.10	0	2027 (est.)	Under construction
16	Texas LNG | *Brownsville, TX*	0.56	0	0	N/A	Pending FID
17	Alaska LNG | *Kenai Peninsula, AK*	2.55	0	0	N/A	Pending FID
	U.S. TOTAL	42.14	11.57	14.28		

Federal agencies is underway, or (ii) the application involves an extra-territorial proceeding where the NEPA review is led by DOE. A list of applications received by DOE is available at: https://www.energy.gov/fecm/articles/summary-lng-export-applications-lower-48-states

	Project	Volume (Bcf/d)			Initial Operation (or est.)	Construction Status
		Authorized	Under Construction Pursuant to a final investment decision (FID)	Operating		
18	Pieridae Energy (USA) Ltd. | *Nova Scotia, Canada*	0.80	0	0	N/A	Pending FID
19	Mexico Pacific Limited| *Sonora, Mexico*	1.7	0	0	N/A	Pending FID
20	Energia Costa Azul | *Ensenada, Mexico*	2.18	0.44	0	2025 (est.)	Phase 1 Under construction Phase 2 FID Pending
21	Epcilon LNG | *Sonora, Mexico*	1.08	0	0	N/A	Pending FID
22	Vista Pacifico LNG | *Sinaloa, Mexico*	0.55	0	0	N/A	Pending FID
	NORTH AMERICA TOTAL	48.45[33]	12.01	14.28		

III. Study Methodology

This study uses four models to evaluate a range of policy, technology, and U.S. LNG export scenarios:

1) The Global Change Analysis Model (GCAM) developed and maintained at PNNL's Joint Global Change Research Institute.
2) The National Energy Modeling System (NEMS) developed by EIA and modified for this study by OnLocation.
3) The Household Energy Impact Distribution Model (HEIDM) developed by IEc.
4) The natural gas system LCA model developed and maintained by NETL.

Details of each model can be found in the Appendices.

For each scenario, GCAM is first used to estimate global demand for U.S. LNG exports and global GHG emissions impacts. Projections of the global demand for U.S. LNG for key scenarios are then input into NEMS and HEIDM to evaluate domestic impacts, including changes in natural gas prices and consumption across economic sectors, changes in carbon dioxide (CO_2) emissions, and changes in energy prices experienced by American households.

Finally, projections of global demand for U.S. LNG and global GHG emissions are used in a consequential life cycle GHG analysis of U.S. LNG exports. The global analysis and the consequential life cycle GHG analysis evaluate five core scenarios that differ based on assumptions relating to policy and technology availability, as well as the treatment of U.S. LNG export levels. There are three categories of climate policy assumptions: *Defined Policies*, *Commitments*, and *Net Zero 2050*. These assumptions are described in Table 3 below.

[33] Approved amounts listed here do not include non-FTA authorizations issued to small-scale facilities, which brings the total to 48.6 Bcf/d. Additional small-scale authorizations issued specifically under DOE's Small-Scale Rule are not additive to the cumulative total.

Table 3. Policy assumptions used in this analysis

Policy Assumptions	**Descriptions**	
	United States	**Rest of World**
Defined Policies	Implements the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) as outlined in DOE's 2023 *Investing in American Energy* publication.[34] Implements additional policies including the EPA New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units (EPA 111) finalized in 2024.	Emissions policies are modeled consistent with previous published studies using GCAM by imposing regional caps on CO_2 emissions, with the caps reflecting emissions impacts of current policies.[35,36]
Commitments	In addition to the policies assumed in the *Defined Policies* scenario, the U.S. is assumed to reduce economy-wide greenhouse gas emissions by 51% in 2030 and 100% by 2050 relative to 2005.	Countries without pledges are assumed to follow an emissions pathway defined by a minimum decarbonization rate of 8% per year that is indicative of strong mitigation policies and a significant departure from historically observed decarbonization rates. The emissions pathways for the rest of the world are based on prior peer-reviewed studies.[19,20] Countries are assumed to achieve their pledges within their geographic boundaries without trading emissions.
Net Zero	Same as Commitments	The rest of world is also assumed to achieve net-zero CO_2 emissions by 2050

The *Defined Policies* scenario includes an explicit representation of recent domestic policies, including the Inflation Reduction Act and Bipartisan Infrastructure Law. The *Commitments* scenario assumes that all global regions meet stated climate commitments as made during the 26th Conference of the Parties to the United Nations Framework on Climate Change held in Glasgow, Scotland, United Kingdom in 2021. The *Net Zero 2050* scenario builds on this further, assuming that all global regions meet net-zero carbon dioxide (CO_2) emissions by 2050. The *Commitments* and *Net Zero 2050* scenarios also include implementation of EPA's Waste Emissions Charge and assumptions about high ambition in non-CO_2 emission reduction in the U.S. consistent with global commitments.

In GCAM, levels of carbon capture and storage (CCS) deployment in 2050 under assumptions about the availability of the full portfolio of technologies are higher than comparable scenarios in

[34] DOE, Investing in American Energy: Significant Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reduction, August 16, 2023. Available at: https://www.energy.gov/sites/default/files/2023-08/DOE%20OP%20Economy%20Wide%20Report_0.pdf

[35] Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J.R., Binsted, M., Cui, R., Fyson, C. and Geiges, A., 2021. Can updated climate pledges limit warming well below 2° C?. Science, 374(6568), pp.693-695.

[36] Iyer, G., Ou, Y., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J., Fuhrman, J., Waldhoff, S. and McJeon, H., 2022. Ratcheting of climate pledges needed to limit peak global warming. Nature Climate Change, 12(12), pp.1129-1135.

the literature and current levels. There is currently 0.051 $GtCO_2$/yr of operating CCS projects, an additional 0.051 $GtCO_2$/yr under construction, 0.180 $GtCO_2$/yr in advanced development, and 0.134 $GtCO_2$/yr in early-stage development, for a total of 0.416 $GtCO_2$/yr operating or in development.[37] GCAM's deployment of CCS under assumptions about the availability of the full portfolio of technologies is in large part driven by several model and scenario assumptions. First, GCAM represents an expanded set of CCS applications in the power generation, hydrogen production, refining, and industrial and manufacturing sectors.[38,39,40,41] Second, all three policy scenarios include a representation of the Inflation Reduction Act, which has provisions that incentivize CCS deployment in the U.S. In addition, the *Commitments* and *Net Zero scenarios* assume a reduction in economy-wide GHG emissions in the U.S. by 51% in 2030 and 100% by 2050 relative to 2005, that resolved for further deployment of CCS in the U.S. in those scenarios (without any limits on technology deployment). And finally, policies enacted outside of the U.S. are represented consistent with previous published studies, which resolved for further deployment of CCS outside of the U.S.[42,43]

To provide a comprehensive view on modeled demand for U.S. LNG and emissions outcomes, this study includes two categories of assumptions based on technology availability. The first (*High CCS*) assumes higher deployment of CCS technologies to meet decarbonization policy assumptions. The availability of higher levels of CCS allows the model to maintain or increase global fossil fuel demand, including global gas demand, due to the abatement of associated emissions. The second (*Moderate CCS*) limits CCS and assumes higher deployment of renewable energy to meet climate commitments.

These categories are described in Table 4.

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[37] Global CCS Institute, Global Status of CCS 2024: Collaborating for a Net-Zero Future, November 2024. https://www.globalccsinstitute.com/wp-content/uploads/2024/11/Global-Status-Report-6-November.pdf

[38] Durga, S., Speizer, S. and Edmonds, J., 2024. The role of the iron and steel sector in achieving net zero US CO2 emissions by 2050. *Energy and Climate Change*, *5*, p.100152.

[39] Muratori, M., Kheshgi, H., Mignone, B., Clarke, L., McJeon, H. and Edmonds, J., 2017. Carbon capture and storage across fuels and sectors in energy system transformation pathways. *International Journal of Greenhouse Gas Control*, *57*, pp.34-41.

[40] Binsted, M., Lochner, E., Edmonds, J., Benitez, J., Bistline, J., Browning, M., De La Chesnaye, F., Fuhrman, J., Göke, L., Iyer, G. and Kennedy, K., 2024. Carbon management technology pathways for reaching a US Economy-Wide net-Zero emissions goal. *Energy and Climate Change*, *5*, p.100154.

[41] Charles, M., Narayan, K.B., Edmonds, J. and Yu, S., 2024. The role of the pulp and paper industry in achieving net zero US CO2 emissions in 2050. *Energy and Climate Change*, *5*, p.100160.

[42] Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J.R., Binsted, M., Cui, R., Fyson, C. and Geiges, A., 2021. Can updated climate pledges limit warming well below 2° C?. Science, 374(6568), pp.693-695.

[43] Iyer, G., Ou, Y., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J., Fuhrman, J., Waldhoff, S. and McJeon, H., 2022. Ratcheting of climate pledges needed to limit peak global warming. Nature Climate Change, 12(12), pp.1129-1135.

Table 4. Technology availability assumptions used in this analysis

Technology Availability assumption	**Description**
High CCS	The *High CCS* assumption includes all default technology assumptions in GCAM. This includes “mid” scenario assumptions from the National Renewable Energy Laboratory’s (NREL’s) Annual Technology Baseline (ATB) for costs of wind, solar, and grid battery technologies, and the NREL ATB “mid” case assumptions for costs of CCS technologies in the power sector. The *High CCS* assumptions also include default assumptions about CCS and carbon management alternatives in industrial applications. Total CO_2 captured and stored from the energy system resolves to 17 to 20 Gt CO_2 in 2050. The full suite of technology assumptions in GCAM is available in the online documentation. Bioenergy is constrained to 200 exajoules (EJ) globally to limit unintended consequences of bioenergy expansion for food prices and ecosystems.[44]
Moderate CCS	The *Moderate CCS (Mod CCS)* assumption includes accelerated reductions in costs of wind, solar, and grid battery technologies consistent with the NREL ATB “low” case. It also assumes higher costs for CCS in the power sector consistent with the NREL ATB “high” case. In addition, total CO_2 captured and stored from the energy system is capped, reaching 8.7 $GtCO_2$ per year globally by 2050, consistent with average deployment of CCS levels in IPCC AR6 scenarios that limit global warming to 1.5°C (with >50% probability) by 2100 with no or limited overshoot. The *Moderate CCS* state also assumes a more stringent limit on bioenergy deployment and is assumed to be capped globally at 100 EJ.

As summarized in Table 5, within each scenario of policy and technology assumptions, three assumptions of U.S. LNG export levels are considered:

- *Existing/FID Exports*: U.S. LNG exports are held at levels equivalent to 90% of the LNG capacity that was operational or had export authorizations from DOE and reached final investment decisions as of December 2023 (23.7 Bcf/d).
- *Model Resolved Exports*: U.S. LNG exports estimated at a trajectory determined by the model.
- *High Exports*: U.S. LNG exports increase incrementally above *Model Resolved* levels starting in 2035 to reach 20 Bcf/d above *Model Resolved* levels in 2050.

The primary scenarios evaluated for the global analysis and consequential life cycle GHG analysis are outlined in Table 5.

[44] Muratori, M., Calvin, K., Wise, M., Kyle, P. and Edmonds, J., 2016. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, *11*(9), p.095004.

Table 5. Scenarios evaluated in the global and LCA analysis

Key Assumptions			Scenarios
Policy	**Technology Availability**[a]	**U.S. LNG Export Level**	
Defined Policies		*Existing/FID Exports*	*Defined Policies: Model Resolved*
		Model Resolved	*Defined Policies: Existing/FID Exports*
		High Exports	*Defined Policies: High Exports*
Commitments	*High CCS*	*Existing/FID Exports*	*Commitments (High CCS): Model Resolved*
		Model Resolved	*Commitments (High CCS): Existing/FID Exports*
		High Exports	*Commitments (High CCS): High Exports*
	Moderate CCS	*Existing/FID Exports*	*Commitments (Moderate CCS): Model Resolved*
		Model Resolved	*Commitments (Moderate CCS): Existing/FID Exports*
		High Exports	*Commitments (Moderate CCS): High Exports*
Net Zero 2050	*High CCS*	*Existing/FID Exports*	*Net Zero 2050 (High CCS): Model Resolved*
		Model Resolved	*Net Zero 2050 (High CCS): Existing/FID Exports*
		High Exports	*Net Zero 2050 (High CCS): High Exports*
	Moderate CCS	*Model Resolved*	*Net Zero 2050 (Moderate CCS): Model Resolved*
		High Exports	*Net Zero 2050 (Moderate CCS): High Exports*

[a] In the *Net Zero 2050 (Mod CCS): Model Resolved* scenario, U.S. LNG exports fall below the *Existing/FID Exports* level. As a result, a *Net Zero 2050 (Mod CCS): Existing/FID Exports* scenario yields the same outcomes as the *Model Resolved* case and is not shown.

In addition to the fourteen scenarios outlined in Table 5, the global analysis and consequential life cycle GHG analysis include six sensitivity scenarios to explore the economic competitiveness of U.S. natural gas in the global natural gas market. As described in Appendix A, the scenarios explore three assumptions related to the economic competitiveness of U.S. natural gas:

- *High U.S. Supply* assumes a flatter U.S. natural gas supply curve (i.e. lower natural gas prices with higher availability) relative to the original, making U.S. natural gas more competitive relative to other natural gas producers.
- *Low U.S. Supply* assumes a steeper U.S. natural gas supply curve (i.e. higher natural gas prices with lower availability) relative to the original, making the U.S. less competitive relative to other natural gas producers.
- *High Middle East Supply* assumes a flatter natural gas supply curve (i.e. lower natural gas prices with higher availability) compared to the original for the Middle East, which is a competing natural gas producing region, making the Middle East more competitive relative to the U.S. and other natural gas producers in the global natural gas market.

The *Model Resolved* and *Existing/FID Exports* U.S. LNG exports assumptions are combined with the above three assumptions to obtain a total of six sensitivity scenarios, all of which employ the *Defined Policies* climate policy assumption and are summarized in Appendix A.

The domestic component of this analysis evaluates the *Existing/FID Exports* and *Model Resolved* levels of U.S. LNG exports under *Defined Policies* policy assumptions (detailed in Appendix B). In addition, it layers on assumptions of domestic oil and gas supply. The scenarios evaluated for this component are listed in Table 6. The domestic analysis focuses on the *Defined Policies* scenario evaluated in the global analysis to focus on the effects of increasing U.S. LNG exports under varying assumptions of domestic oil and gas supply. Including the *Commitments* and *Net Zero 2050* global scenarios would introduce complicating factors (i.e., policy and technology assumptions) that would make it difficult to isolate the effects of increasing LNG exports from other drivers.

The *Defined Policies* scenario with reference U.S. supply assumes U.S. oil and gas resource availability and technological improvements consistent with the EIA Annual Energy Outlook 2023 (AEO 2023) *Reference* case. The *Low US Supply* scenario assumes 50% lower resource availability and 50% lower technological improvement, consistent with the EIA AEO 2023 *Low Oil and Gas Supply* side case. The *High US Supply* scenario assumes 50% higher resource availability and 50% higher technological improvement, consistent with the EIA AEO 2023 *High Oil and Gas Supply* side case.

Table 6. Scenarios evaluated in the domestic analysis (i.e., in NEMS and HEIDM)

Key Assumptions			**Scenarios**
Policy	**U.S. Oil and Gas Supply**	**U.S. LNG Export Level**	
Defined Policies	*Low US Supply*	*Existing/FID Exports*	*Defined Policies Low US Supply: Existing/FID Exports*
		Model Resolved	*Defined Policies Low US Supply: Model Resolved*
	Reference	*Existing/FID Exports*	*Defined Policies: Existing/FID Exports*
		Model Resolved	*Defined Policies: Model Resolved*
	High US Supply	*Existing/FID Exports*	*Defined Policies High US Supply: Existing/FID Exports*
		Model Resolved	*Defined Policies High US Supply: Model Resolved*

IV. GLOBAL ENERGY AND GHG ASSESSMENT

This section summarizes findings to inform DOE's consideration of the international and environmental impacts aspects of the public interest criteria, responding to the following questions:

1. What is the global demand for U.S. LNG under varying assumptions about climate policy and technology availability?
2. What are the greenhouse gas emissions impacts of additional U.S. LNG?

Both the market demand for, and emissions impacts of, U.S. LNG exports depend on combinations of energy, climate, and economic policies that influence regional market decisions. For this reason, this study does not evaluate global demand and emissions impacts based on a single reference scenario. Instead, it evaluates a range of scenarios that vary in assumptions about global climate policies and technology availability, as outlined in the Methodology section.

A. Global Demand for U.S. LNG Exports Under *Model Resolved* Scenarios

In GCAM, the two primary factors determining *Model Resolved* levels of global U.S. LNG exports are i) projections of global natural gas demand and ii) the competitiveness of U.S. LNG relative to other sources of LNG, as well as pipeline gas and domestically produced gas. Figure 3 illustrates Model Resolved levels of U.S. LNG exports.

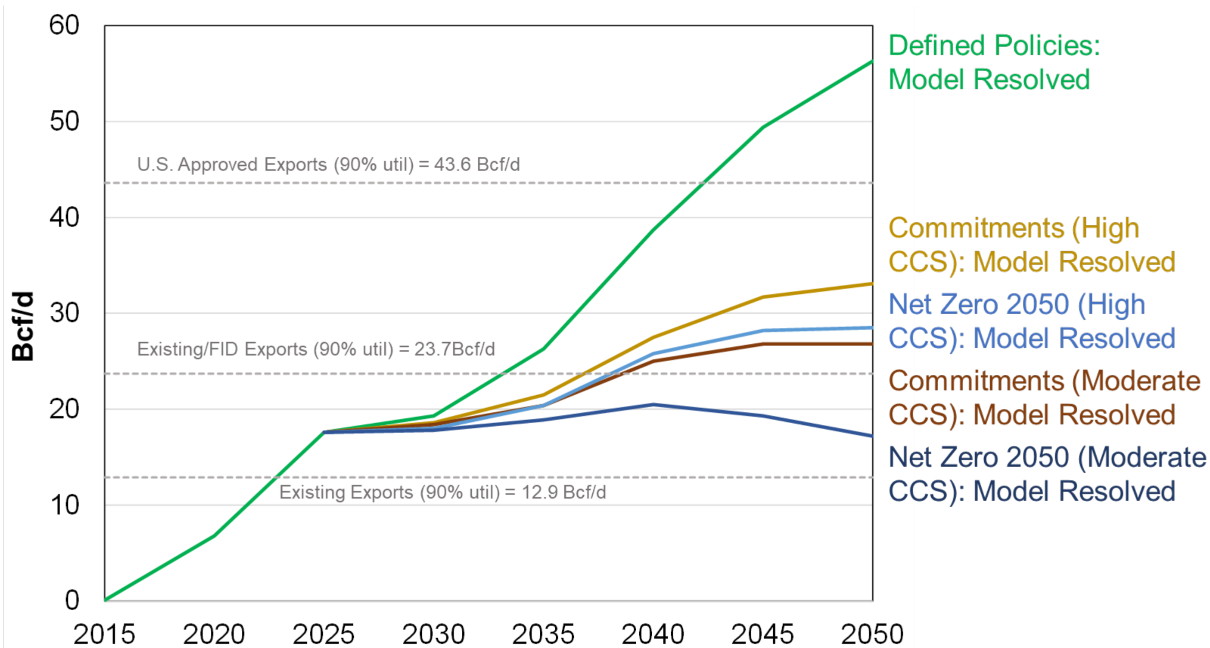

Figure 3. U.S. LNG exports (Billion cubic feet/day) across scenarios with Model Resolved U.S. LNG export levels.

Projections of U.S. LNG exports are highest in the *Defined Policies: Model Resolved* scenario, exceeding existing and FID levels in 2035 and reaching 56.3 Bcf/d in 2050. Projections of global U.S. LNG demand in the *Commitments (High CCS): Model Resolved* scenario and *Net Zero (High CCS): Model Resolved* scenario reach 33.1 Bcf/d and 28.5 Bcf/d in 2050, respectively. Projections exceed existing and FID levels in 2050 for both scenarios. The availability of higher levels of CCS in these scenarios allows the model to resolve for higher levels of global gas demand while meeting the emissions constraints. Projections of global U.S. LNG exports also increase in the *Commitments (Moderate CCS): Model Resolved* scenario, but to lower levels due to lower CCS availability, reaching 26.8 Bcf/d in 2050. In the *Net Zero (Moderate CCS): Model Resolved* scenario, global U.S. LNG exports are projected to peak in 2040 and then decline to 17.2 Bcf/d in 2050. Even at its peak, U.S. LNG exports do not exceed existing and FID levels in this scenario.

Global demand for U.S. LNG is driven by the global demand for natural gas. External analyses show a broad range in projections of global natural gas demand depending on model structures, technological and sectoral detail, and assumptions on resources, trade, policies and the characteristics and availability of technologies including CCS.[45] Results of this study suggest that in four of the five scenarios modeled, global demand for U.S. LNG does not exceed existing and FID levels of exports through 2035.

Table 7 summarizes the *Model Resolved* levels of primary energy consumption, global gas consumption, U.S. LNG exports, and shares of global LNG consumption and global gas consumption comprised by U.S. LNG across the scenarios. Additional sensitivity scenarios that explore alternative assumptions about the availability and cost of U.S. natural gas supply and the competitiveness of U.S. natural gas supply relative to other natural gas producing regions were also conducted. More details about and results from these scenarios are available in Appendix A.

Table 7. Model Resolved levels of energy consumption and U.S. LNG exports

	Global Primary Energy Consumption (EJ)		**Global Gas Consumption (EJ)**		**U.S. LNG Exports (EJ) [Bcf/d]**		**U.S. LNG Exports as Share of Global LNG Consumption**		**U.S. LNG Exports as Share of Global Gas Consumption**	
Scenario	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Defined Policies	648	806	137	163	7.0 [19.4]	20.3 [56.3]	22%	35%	5%	12%
Commitments (High CCS)	641	717	130	84	6.7 [18.6]	11.9 [33.1]	22%	26%	5%	14%
Commitments (Moderate CCS)	629	619	130	67	6.6 [18.3]	9.7 [26.8]	22%	29%	5%	14%
Net Zero (High CCS)	617	678	119	54	6.5 [18.0]	10.3 [28.5]	22%	27%	5%	19%
Net Zero (Moderate CCS)	589	581	119	35	6.4 [17.8]	6.2 [17.2]	22%	34%	5%	18%

B. Global Emissions Impacts of Increased U.S. LNG Exports

The emissions impacts of increasing U.S. LNG exports beyond existing and FID levels are evaluated in two steps:

1. In the first step, emissions in *Existing/FID Exports* scenarios are compared to emissions in *Model Resolved* scenarios. This step identifies the mechanisms that drive emissions impacts when U.S. LNG exports are increased.
2. In the second step, emissions *Model Resolved* scenarios are compared to emissions in *High Exports* scenarios. This step applies an equal increase in U.S. LNG exports so that a consistent per Bcf/d emissions impact can be derived for each policy scenario.

[45] Raimi, D., Zhu Y., Newell, R.G., Prest, B.C., 2024. Global Energy Outlook 2024: Peaks or Plateaus? *Resources for the Future.* https://www.rff.org/publications/reports/global-energy-outlook-2024/

1. Emissions Impacts of Increasing U.S. LNG Exports from *Existing/FID Exports* Levels to *Model Resolved* Levels

Table 8 below outlines the changes in cumulative GHG emissions when U.S. LNG exports increase from *Existing/FID Exports* levels to *Model Resolved* levels for each of the five core scenarios in the global analysis.

U.S. LNG exports are projected to exceed existing and FID levels (23.7 Bcf/d) under four of the five core scenarios, the exception is the *Net Zero (Moderate CCS)* scenario. Because U.S. LNG export projections do not exceed existing and FID levels in this scenario, the emissions impacts of increasing U.S. LNG exports from *Existing/FID Exports* levels to *Model Resolved* levels cannot be assessed.

Table 8. Changes in cumulative GHG emissions in core scenarios, Existing/FID Exports to Model Resolved levels

Scenario Comparison	Change in 2050 U.S. LNG Exports *Existing/FID Exports to Model Resolved levels (Bcf/d)*	Change in cumulative global GHG emissions (2020-2050) (MMT CO_2e)[a]
Defined Policies: *Model Resolved – Existing/FID Exports*	32.6	708
Commitments (High CCS): *Model Resolved – Existing/FID Exports*	9.4	97
Commitments (Moderate CCS): *Model Resolved – Existing/FID Exports*	3.1	67
Net Zero 2050 (High CCS): *Model Resolved – Existing/FID Exports*	4.8	21
Net Zero 2050 (Moderate CCS): *Model Resolved – Existing/FID Exports*[b]	0	NA

MMT CO_2e: million metric ton CO_2-equivalent, N/A: not applicable

a. GHG emissions include CO_2 emissions from fossil fuels and industry as well as land-use changes, and non-CO_2 emissions (methane, nitrous oxide, and fluorinated gases) from energy, agricultural, and land-use systems and other processes. CO_2 emissions from fossil fuels and industry are subject to uncertainties in regional emission intensities of natural gas and other fossil fuels. Emissions from land-use changes are driven in part by changes in energy production, including those driven by changes in demand (e.g., global demand for LNG). These emissions are also subject to greater uncertainties largely due to uncertainties in data. A detailed exploration of these uncertainties is beyond the scope of this study.

b. *Net Zero 2050 (Moderate CCS)* U.S. LNG export levels do not change between the *Existing/FID Exports* to *Model Resolved* scenarios resulting in no change in global emissions or services, the results are listed as “NA” or Not Applicable.

In the *Defined Policies: Model Resolved* scenario, increasing U.S. LNG exports to reach 32.6 Bcf/d above *Existing/FID Exports* levels in 2050 corresponds to a 708 million metric ton CO_2e ($MMTCO_2e$) increase in cumulative net GHG emissions from 2020 to 2050. This is equivalent to a 0.05% increase in cumulative emissions. In the *Commitments (High CCS): Model Resolved* scenario, increasing U.S. LNG exports to reach 9.4 Bcf/d above *Existing/FID Exports* levels in 2050 results in a 97 $MMTCO_2e$ (0.01%) increase in cumulative net GHG emissions (2020-2050). In the *Commitments (Moderate CCS)* scenario, increasing U.S. LNG exports by 3.1 Bcf/d from *Existing/FID Exports* levels to *Model Resolved* levels in 2050 corresponds to a 67 $MMTCO_2e$

(0.01%) increase in cumulative net GHG emissions. In the *Net Zero 2050 (High CCS): Model Resolved* scenario, increasing U.S. LNG exports by 4.8 Bcf/d from *Existing/FID Exports* levels to *Model Resolved* levels in 2050 corresponds to a 21 $MMTCO_2e$ (0.002%) increase in cumulative net GHG emissions.

Emissions impacts across scenarios can be explained by a combination of mechanisms. First, with increased availability of relatively low-cost U.S. LNG on the global market, natural gas production in the rest of the world decreases (as U.S. LNG displaces other sources of natural gas), and natural gas consumption increases. The increase in natural gas consumption results in a net increase in energy consumption along with a displacement of other fuels. Substitutions away from unabated fossil sources other than natural gas (e.g., coal, oil) to natural gas (i.e., unabated fossil-to-gas substitution) result in decreases in global GHG emissions. Meanwhile, substitutions away from renewables, nuclear, or fossil with CCS sources into natural gas (i.e., zero-/low-carbon-to-gas substitution) result in increases in global GHG emissions. Net increases in energy consumption also result in increases in global GHG emissions *Model Resolved* assumptions, relative to its *Existing/FID Exports* counterpart.

These mechanisms are illustrated in Figure 4. In the *Defined Policies: Model Resolved* scenario, U.S. LNG exports increase by 15 Bcf/d in 2040 and 32.6 Bcf/d in 2050, relative to existing and FID levels. On an energy equivalent basis, the cumulative increase in U.S. LNG exports from 2020 to 2050 is 113 EJ. The largest share of this increase in exports, 37% of the total, displaces gas production in the rest of the world (ROW). Another 25% of the increase in U.S. LNG exports relative to existing and FID levels displaces renewables in the ROW, which puts upward pressure on global GHG emissions. At the same time, 19% of this increase displaces oil and coal, which puts downward pressure on global GHG emissions. Combined with an increase in primary energy demand (illustrated as net energy increase), the net effect of increased U.S. LNG exports in the *Defined Policies: Model Resolved* is an increase in cumulative emissions of 708 $MMTCO_2e$ (0.05% of cumulative global GHG emissions).

As explored in more detail in Appendix A, in the remaining three scenarios with an increase in U.S. LNG exports relative to existing and FID levels, the cumulative increase in U.S. exports is less than a third of the *Defined Policies: Model Resolved* scenario. As result, there is less overall change relative to the existing and FID scenarios. More than half of the cumulative additional exports displace ROW sources of natural gas. The availability of CCS in the *High CCS* scenarios allows the model to resolve at higher levels of LNG exports while meeting emissions constraints due to greater emissions abatement.

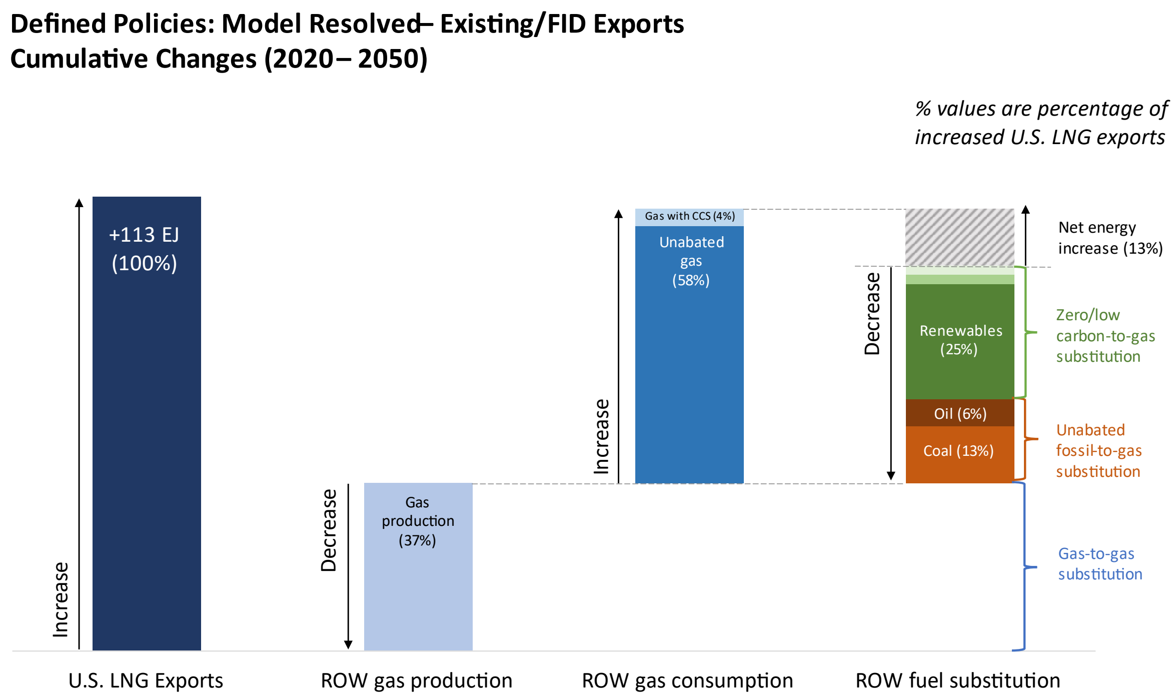

Figure 4. Cumulative changes (2020-2050) in the energy system due to increased U.S. LNG exports in the Defined Policies: Model Resolved scenario relative to the Defined Policies: Existing/FID Exports scenario.

Zero/low carbon-to-gas substitutions include displacements of renewables (dark green), nuclear (medium green), and other fossil CCS (light green). Unabated fossil-to-gas substitutions include displacements of coal (orange) and oil (brown).

2. Emissions Impacts of Increasing U.S. LNG Exports Beyond *Model Resolved* Levels

The comparison of emissions from existing and FID levels to *Model Resolved* levels across the scenarios illustrates that increased U.S. LNG exports are associated with higher global GHG emissions. In addition, the degree to which GHG emissions increase depend on the level of increase in U.S. LNG exports in the *Model Resolved* scenarios relative to their *Existing/FID Exports* counterparts. To further explore the relationship between U.S. LNG exports and global GHG emissions, additional scenarios were constructed that applied the same increase in U.S. LNG exports beyond market-resolved levels across all scenarios. Compared to the previous evaluation of emissions impacts, this evaluation provides insights on the emissions impacts of a consistent increase in U.S. LNG exports across scenarios. This also enables an analysis of increasing U.S. LNG exports in the *Net Zero 2050 (Moderate CCS): Model Resolved* scenario, which was not possible in the first step because *Model Resolved* demand for U.S. LNG exports did not exceed existing and FID levels.

Table 9 below outlines the changes in cumulative GHG emissions for each of the five core scenarios when U.S. LNG exports increase from *Model Resolved* levels to *High Export* levels. In the *High Export* scenarios, U.S. LNG exports are assumed to exceed *Model Resolved* levels starting at an additional 5 Bcf/d in 2035 and reaching an additional 20 Bcf/d in 2050.

Table 9. Changes in cumulative GHG emissions in core scenarios, Existing/FID Exports to Model Resolved levels

Scenario Comparison	**Change in 2050 U.S. LNG Exports** ***Model Resolved to High Export*** **levels (Bcf/d)**	**Change in cumulative GHG emissions (2020-2050) (MMT CO_2e)[a]**
Defined Policies: High Exports – Model Resolved	20	738
Commitments (High CCS): High Exports – Model Resolved		689
Commitments (Moderate CCS): High Exports – Model Resolved		986
Net Zero 2050 (High CCS): High Exports – Model Resolved		302
Net Zero 2050 (Moderate CCS): High Exports – Model Resolved		953

MMT CO_2e: million metric ton CO_2-equivalent

a. GHG emissions include CO_2 emissions from fossil fuels and industry as well as land-use changes, and non-CO_2 emissions (methane, nitrous oxide, and fluorinated gases) from energy, agricultural, and land-use systems and other processes. CO_2 emissions from fossil fuels and industry are subject to uncertainties in regional emission intensities of natural gas and other fossil fuels. Emissions from land-use changes are driven in part by changes in energy production, including those driven by changes in demand (e.g., global demand for LNG). These emissions are also subject to greater uncertainties largely due to uncertainties in data. A detailed exploration of these uncertainties is beyond the scope of this study.

In the *Defined Policies: High Exports* scenario, with a change in 2050 U.S. LNG exports to reach 20 Bcf/d more than market resolved levels, cumulative net GHG emissions (2020-2050) increase 738 MMTCO_2e compared to the *Defined Policies: Model Resolved* scenario.

In the *Commitments (Moderate CCS): High Exports* and *Commitments (High CCS): High Exports* scenarios, cumulative GHG emissions increase by 986 MMTCO_2e and 659 MMTCO_2e, respectively, when 20 Bcf/d of additional U.S. LNG exports by 2050 are introduced.

In the *Net Zero 2050 (High CCS): High Exports* scenario, the addition of 20 Bcf/d of U.S. LNG exports by 2050 above *Model Resolved* levels corresponds to a lower emissions impact; cumulative emissions increase by 302 MMTCO_2e. This is because, in the *Net Zero 2050 (High CCS): High Exports* scenario, additional U.S. LNG exports drive greater increases in gas with CCS, as opposed to unabated gas. The *Commitments (High CCS): High Exports* scenario also has CCS availability, but there is a less stringent emissions constraint so less CCS is deployed.

In the *Net Zero (Moderate CCS): High Exports* scenario, the additional 20 Bcf/d of U.S. LNG exports above *Model Resolved* levels results in a cumulative GHG emissions increase of 953 MMTCO_2e. This is higher than the increase in *Net Zero (High CCS): High Exports* scenario because the additional gas consumption in the *Net Zero (Moderate CCS): High Exports* scenario displaces renewables, nuclear, and biomass.

Additional details on all the global energy scenarios and findings are included in Appendix A.

V. Domestic Energy, Economic, and GHG Assessment

This section evaluates the domestic economic impacts of increasing U.S. LNG, focusing on changes to the following indicators:

- Henry Hub and delivered natural gas prices
- Gross domestic product (GDP)
- Industrial output and costs
- Domestic consumption patterns
- Price impacts by gas supply region

This analysis uses policy assumptions from the *Defined Policy* scenario and not the other policy cases. The domestic analysis focuses on the *Defined Policy* scenario to isolate the effects of increasing U.S. LNG exports (see Methodology). The domestic analysis includes scenarios that differ based on assumptions of U.S. oil and gas supply. This evaluation compares domestic economic indicators under a case in which U.S. LNG exports are held at existing and FID levels to results under another case in which U.S. LNG exports are aligned to *Model Resolved* levels from GCAM. In the *Defined Policies* scenario, *Model Resolved* U.S. LNG exports reach 56.3 Bcf/d in 2050. *Existing/FID Exports* levels are held at 23.7 Bcf/d. All scenario assumptions are outlined in the Methodology section of this report. Further details can be found in Appendix B.

A. Henry Hub and Delivered Natural Gas Prices

Table 10 summarizes changes to Henry Hub and delivered natural gas prices by economic sector in 2050, in response to increased LNG exports from existing and FID levels to *Model Resolved* levels.

Table 10. Changes in 2050 Henry Hub and delivered natural gas prices with increased U.S. LNG exports

U.S. Oil/Gas Supply Assumptions	Change in 2050 LNG Exports (Bcf/d)	Change in 2050 Henry Hub Prices ($/MMBtu)	Change in 2050 Delivered Natural Gas Prices ($/MMBtu)				
			Power	Industrial	Residential	Commercial	Transportation
Reference	32.6	1.09	0.64	0.78	0.50	0.48	0.76
High US Supply	32.6	0.94	0.46	0.64	0.36	0.35	0.51
Low US Supply	32.6	2.30	1.25	1.67	1.13	1.10	2.39

Under the *Defined Policies* scenario with reference U.S. supply assumptions, a 32.6 Bcf/d increase in U.S. LNG exports in 2050 from existing and FID levels (23.7 Bcf/d) leads to a $1.09/MMBtu (31%) increase in Henry Hub prices in 2050, from $3.53/MMBtu to $4.62/MMBtu. This equates to an increase of $0.03/MMBtu for every Bcf/d of increased U.S. LNG export above existing and FID levels. This increase corresponds to a 4% increase in residential natural gas prices. Increased LNG exports also lead to a 18% increase in power sector natural gas prices, and a 18% increase in industrial sector natural gas prices in 2050. Delivered price increases are lower than Henry Hub price increases, and they reflect average U.S. prices as opposed to prices at the Henry Hub, which is a distribution hub in Louisiana and frequent benchmark for gas contracts.

The change to Henry Hub prices in 2050 is 13% lower under assumptions of *High US Supply,* as more gas production is made available to meet incremental natural gas demand from exports. On the other hand, the change to Henry Hub prices is 113% higher under assumptions of *Low US Supply*. This is because under assumptions of low domestic supply, more of the incremental demand for LNG export is met by shifting gas from demand sectors, rather than through additional production. Neither the *High US Supply* nor the *Low US Supply* scenarios are based on real world supply curves but rather a shock to the model, consistent with the approach used by EIA in its Annual Energy Outlook to examine the sensitivity of projections to changes in assumptions regarding domestic crude oil and natural gas resources and technological progress.[46]

These findings are consistent with focused analysis of U.S. LNG EIA conducted based on AEO 2023 that state that, "higher LNG exports create a tighter domestic natural gas market (all else held equal), increasing domestic natural gas prices". In the same analysis, EIA projected that while additional U.S. LNG exports would increase Henry Hub spot prices, those increases would not be beyond recent historical levels (see Figure 5).[47] The AEO 2023 produced a range of Henry Hub spot prices (in 2022 dollars) from $2.78/MMBtu to $6.37/MMBtu in 2050. The EIA concluded that these price projections corresponded with very little variation in projected U.S. natural gas consumption, overall.[48]

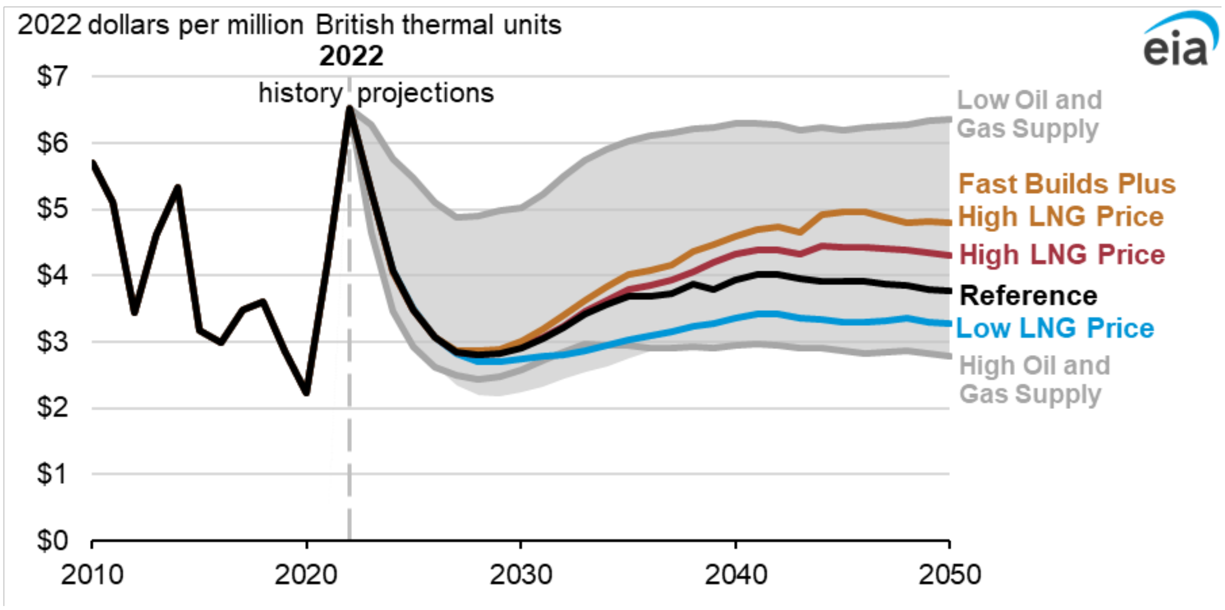

Figure 5. AEO2023 projections of U.S. natural gas spot prices at the Henry Hub. Source: U.S. Energy Information Administration (2023).[49]

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[46] EIA (March 2023). "Assumptions to the Annual Energy Outlook 2023: Oil and Gas Supply Module". https://www.eia.gov/outlooks/aeo/assumptions/pdf/OGSM_Assumptions.pdf.

[47] EIA (2023). "AEO2023, Issues in Focus: Effects of Liquefied Natural Gas Exports on the U.S. Natural Gas Market". https://www.eia.gov/outlooks/aeo/IIF_LNG/pdf/LNG_Issue_in_Focus.pdf

[48] The "Low Oil and Gas Supply" case showed the greatest deviation from the other cases ranging from around $1-2/MMBtu from the second highest price project, "Fast Builds Plus High LNG Price." Other cases included: "Reference"; "High LNG Price"; "Low LNG Price"; and "High Oil and Gas Supply."

[49] Figure 2 in the AEO2023 Issues in Focus: Effects of Liquefied Natural Gas Exports on the U.S Natural Gas Market.

B. Gross Domestic Product (GDP)

While NEMS contains rich details about the energy system, a separate Macroeconomic Activity Module (MAM) provides projections of economic drivers underpinning NEMS' energy supply, demand, and conversion modules. The MAM incorporates S&P Global's (formerly IHS Markit) model of the U.S. economy, along with EIA's extensions of industrial output, employment, and models of regional economies. The MAM iteratively receives energy prices and energy-focused elements of the model and provides feedback on changes in macro-economic drivers of the energy markets, such as growth and changes to interest rates. One result of this model configuration is that increases in LNG exports generally yield increases in GDP.[50]

Within the context of the limitations in NEMS-MAM, Table 11 shows the impact of increased U.S. LNG exports on U.S. GDP. In 2050, the difference in U.S. GDP between the *Defined Policies: Model Resolved* and *Defined Policies: Existing/FID Exports* scenarios, with reference supply, is projected to be approximately $80 billion (0.2%). This is the largest difference across all supply assumptions. By 2050, the incremental increase in U.S. GDP due to increased U.S. LNG exports under the *Defined Policies Low US Supply* and *Defined Policies High US Supply* scenarios is $24 billion (0.06%) and $11 billion (0.02%), respectively, inclusive of the limitations in NEMS-MAM articulated above.

Table 11 also shows cumulative differences in GDP over the study period (discounted at 3%) between the *Model Resolved* and the *Existing/FID Exports* scenarios under the *Defined Policies* (with reference U.S. supply), *Defined Policies High US Supply* and *Defined Policies Low US Supply* scenarios. The largest change is projected to occur in the *Defined Policies* scenario with reference U.S. supply; the cumulative difference in U.S. GDP between the *Defined Policies: Model Resolved* and *Defined Policies: Existing/FID Exports* scenarios is projected at $410 billion, inclusive of the limitations in NEMS-MAM articulated above.

Table 11. Changes in GDP with increased U.S. LNG exports

U.S. Oil/Gas Supply Assumptions	Change in 2050 LNG Exports (Bcf/d)	Change in 2050 GDP (billion 2022 USD)	Change in 2050 GDP (%)	Change in Cumulative GDP 2020-2050 (billion 2022 USD)
Reference	32.6	80	0.19	410
High US Supply	32.6	11	0.02	94
Low US Supply	32.6	24	0.06	246

C. Industrial Output and Costs

Table 12 outlines the changes to gross industrial output in 2050, and cumulatively over the study period (discounted at 3%), when U.S. LNG exports are increased to reach 32.6 Bcf/d above existing and FID levels by 2050 in NEMS.

[50] See Appendix B for further discussion of how NEMS models GDP.

Table 12. Changes in industrial output with increased U.S. LNG exports

U.S. Oil/Gas Supply Assumptions	Change in 2050 Industrial Output (billion 2022 USD)	Change in Cumulative Industrial Output (2020-2050) (billion 2022 USD)
Reference	203	893
High US Supply	123	620
Low US Supply	65	504

NEMS results show increases in gross industrial output with increased LNG exports across all U.S. supply assumptions by up to 1.3% in 2050, primarily reflecting industrial activities related to increased production, processing, transportation and export of natural gas. Under the reference U.S. supply assumption, increased LNG exports result in 1.3%, or a $203 billion increase in the value of industrial production in 2050 (with a cumulative increase of $893 billion from 2020 through 2050), over the scenario with existing and FID levels of exports. Industrial output from oil and gas extraction subsector makes up $147 billion, or 72%, of this increase in 2050 (with a cumulative increase of $672 billion from 2020 through 2050). Outputs from all other subsectors increase by $56 billion in 2050 (with a cumulative increase of $221 billion from 2020 through 2050).

Corresponding increases under assumptions of *High US Supply* and *Low US Supply* are $123 billion or 0.7% (with a cumulative increase of $620 billion from 2020 through 2050) and $65 billion or 0.4% (with a cumulative increase of $504 billion from 2020 through 2050) in response to increased LNG exports, respectively.

Across all U.S. supply assumptions, *Low US Supply* shows the smallest increase in industrial output with increased LNG exports ($65 billion, or 0.4% in 2050), due to the decreased output from the manufacturing sector in response to higher energy prices.

Total energy costs for the industrial sector increase across all supply assumptions when U.S. LNG exports increase from existing and FID levels to *Model Resolved* levels.[51] Table 13 below outlines the changes in industrial energy costs in 2050, and cumulatively over the study period (discounted at 3%) in response to increased LNG exports.

Table 13. Changes in industrial energy costs with increased U.S. LNG exports

U.S. Oil/Gas Supply Assumptions	Change in 2050 Energy Costs (billion 2022 USD)	Change in Cumulative Energy Costs (2020-2050) (billion 2022 USD)
Reference	28.2	125
High US Supply	28.6	112
Low US Supply	26.1	118

[51] Note: The industrial natural gas prices collected and published by EIA that are used as a basis for forecasted prices are reflective of the prices paid by industrial customers that purchase their natural gas from local distribution companies. These are typically smaller industrial customers. In 2023, the percentage of industrial volumes delivered that were covered by EIA's industrial price was 13.3%. (See Natural Gas Annual 2023 Table 23, Average price of natural gas delivered to consumers by state and sector, Industrial Percentage of total volume delivered, available at: https://www.eia.gov/naturalgas/annual/pdf/table_023.pdf

In the scenario with reference levels of oil and gas supply, cumulative energy costs in the industrial sector increase $125 billion from 2020 through 2050. Under assumptions of *High U.S. Supply*, cumulative energy costs increase $112 billion. Under assumptions of *Low U.S. Supply*, cumulative energy costs in the industrial sector over this period increase $118 billion. Total energy costs increase due to the increase in natural gas prices for the industrial sector and the relatively inelastic demand for natural gas. These costs also reflect the increase in electricity costs driven by increased natural gas prices for the power sector.

Cost impacts vary by industrial subsector based on elasticity of gas demand and facility locations. Industrial subsectors that have more inelastic demand for natural gas face greater energy cost impacts from increases in natural gas prices. The location of industrial facilities will also determine whether electricity inputs are more dependent on natural gas-based generation. Facilities in regions with a higher share of natural gas electricity generation are impacted more by increases in electricity costs stemming from increased natural gas prices.

D. Domestic Consumption Patterns

When U.S. LNG exports increase, this incremental demand can be met with some combination of additional gas production and reduction in gas consumption by end-use sectors. In the evaluated scenario, increasing LNG exports 32.6 Bcf/d leads to a 28% (30.2 Bcf/d) increase in gas production and no change in domestic end-use gas consumption. This indicates that, with the reference U.S. supply assumption, the U.S. can meet incremental demand with additional production. These patterns are described in Table 14 below.

Table 14. Changes in natural gas consumption by domestic sectors with increased LNG exports

U.S. Oil/Gas Supply Assumptions	**Change in 2050 Natural Gas Consumption (%)**					
	Power	**Industry**	**Residential**	**Commercial**	**Transportation[a]**	**Total**
Reference	-17.4	9.9	-0.5	-1.3	12.4	0.0
High US Supply	-7.4	7.1	-0.4	-1.0	17.0	1.5
Low US Supply	-12.9	9.0	-1.0	-2.1	11.6	2.1

a. Includes increased natural gas (pipeline fuel) transportation to LNG facilities to support increased LNG exports.

Similar to the scenario with reference U.S. supply assumptions, in both of the *Low US Supply*, and *Low US Supply* scenarios, changes in total natural gas consumption with increased LNG exports are well below 0.5 Tcf in 2050.

Although total domestic U.S. natural gas consumption does not change appreciably in response to the higher natural gas prices caused by higher LNG exports, there are observed shifts in consumption behavior on a sector-by-sector basis. With increased LNG exports, natural gas consumption increases in subsectors that are involved in production and transportation of natural gas and decreases in other subsectors in response to higher natural gas prices (see Appendix B for further detail on changes in natural gas consumption by sub-sector). For example, higher LNG exports result in higher consumption in the industrial sector and less consumption in the power sector.

Increased consumption in the industrial sector results from increased natural gas demand for gas liquefaction (required for LNG export), as well as the lease and plant fuel (consumed at natural gas production facilities) needed to support higher LNG exports. Under the reference U.S. supply assumptions, increased LNG exports result in a 20% (0.46 Tcf) increase in lease and plant fuel consumption, and a 130% (0.89 Tcf) increase in natural gas consumption for gas liquefaction in 2050. Natural gas consumption in other industrial subsectors decreases by 0.5% (0.05 Tcf) in 2050.

Increased consumption in the transportation sector results from increased natural gas (pipeline fuel) transportation to LNG facilities to support increased LNG exports.

E. Price Impacts by Gas Supply Region

The impacts of increasing U.S. LNG exports on domestic natural gas prices vary by supply region. Figure 6 below shows changes in wellhead natural gas prices in 2050 for lower 48 gas supply regions, in response to increased LNG exports. Detailed projections of these regional gas price impacts in 2025-2050 can be found in Appendix B.

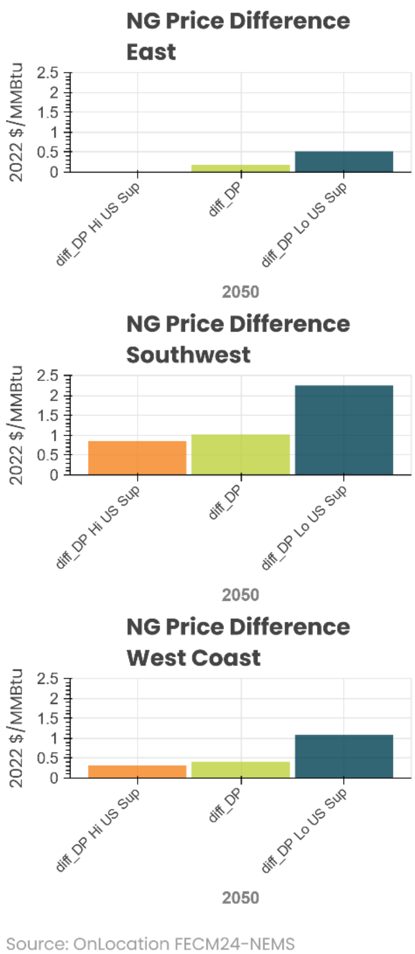


Figure 6. Differences in regional natural gas prices between Model Resolved and Existing/FID Exports scenarios in 2050 for each supply assumption

DP: Defined Policies with reference U.S. supply; DP Hi US Sup: Defined Policies High US Supply; DP Lo US Sup: Defined Policies Low US Supply (The prefix "diff_" refers to the difference of the Model Resolved scenarios from the Existing/FID Exports scenarios)

Within the model, LNG export facilities are assumed to be centered in the Gulf Coast region. As a result, incremental natural gas demand for LNG exports is met primarily with supply from the Gulf Coast and Southwest regions, and these regions experience the greatest price impacts from increased LNG exports in model projections (see Appendix B).

In the *Defined Policies* scenario with the reference U.S. supply assumption, a 32.6 Bcf/d increase in U.S. LNG exports by 2050 from existing and FID levels leads to a $1.05/MMBtu (33%) increase in natural gas prices in Gulf Coast region in 2050. For *High US Supply* and *Low US Supply*, the increased exports results in $0.92/MMBtu (44%) and $2.31/MMBtu (33%) increase in natural gas prices for Gulf Coast in 2050, respectively.

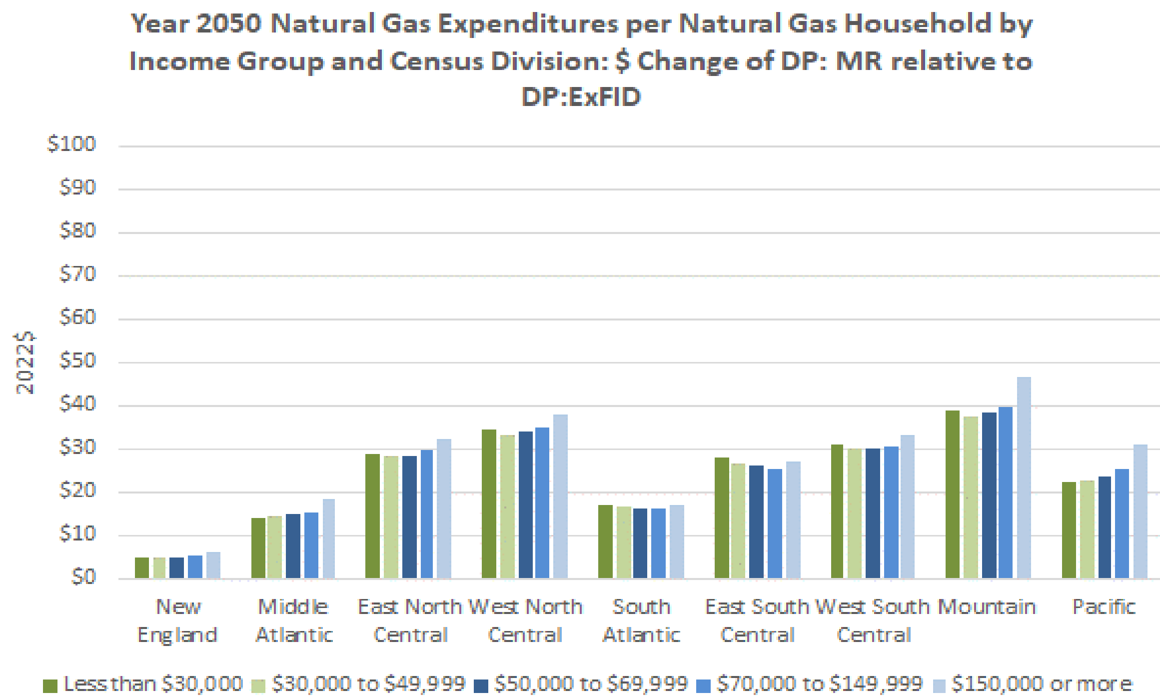
F. Distribution of Impacts

For insights into the distributional effects associated with projected changes in natural gas and electricity prices, HEIDM was used to estimate the corresponding changes in energy expenditures on a per household basis by census division and income group considering the *Defined Policies* scenarios under the reference U.S. supply and *Low US Supply* assumptions.

Figure 7 presents natural gas expenditure impacts per natural gas household (households identified in NEMS as using natural gas for space heating) by each income group and census division in 2050. Under the reference U.S. supply assumption scenario, average increased natural gas expenditures per natural gas household are up to $46.52 per year. The average natural gas household expenditure impact is up to 0.24% of average annual income (6.7% of average natural gas bills). Under the *Low US Supply* assumption, natural gas expenditure impacts per natural gas household are up to $90.10 per year. The average natural gas household expenditure impact on the *Low US Supply* assumption is up to 0.47% of household income. These impact estimates are specific to natural gas households.

Figure 8 summarizes the electricity expenditure impacts per household (all households, inclusive of households that use natural gas and those that do not use gas) by income group and census division in 2050. Under the reference U.S. supply assumption, the estimated electricity expenditure impacts per household are up to $118.37 per year. The average household expenditure impacts are up to 0.5% of average annual income (3.5% of average electricity bills). Under assumptions of *Low US Supply*, the estimated electricity expenditure impacts per household are up to $270.03 per year. The average household expenditure impact on the *Low US Supply* assumption is up to 0.9% of household income.

Combined under the reference U.S. supply assumption, the estimated natural gas plus electricity expenditures per household increase up to a $122.54 per year. This figure is lower than the combined natural gas and electricity expenditures as all values are up to the highest increases across regions and different regions have the highest natural gas and electricity expenditures. The average combined household expenditure impacts are up to 0.50% of average annual income and 3.4% of natural gas and electricity bills.



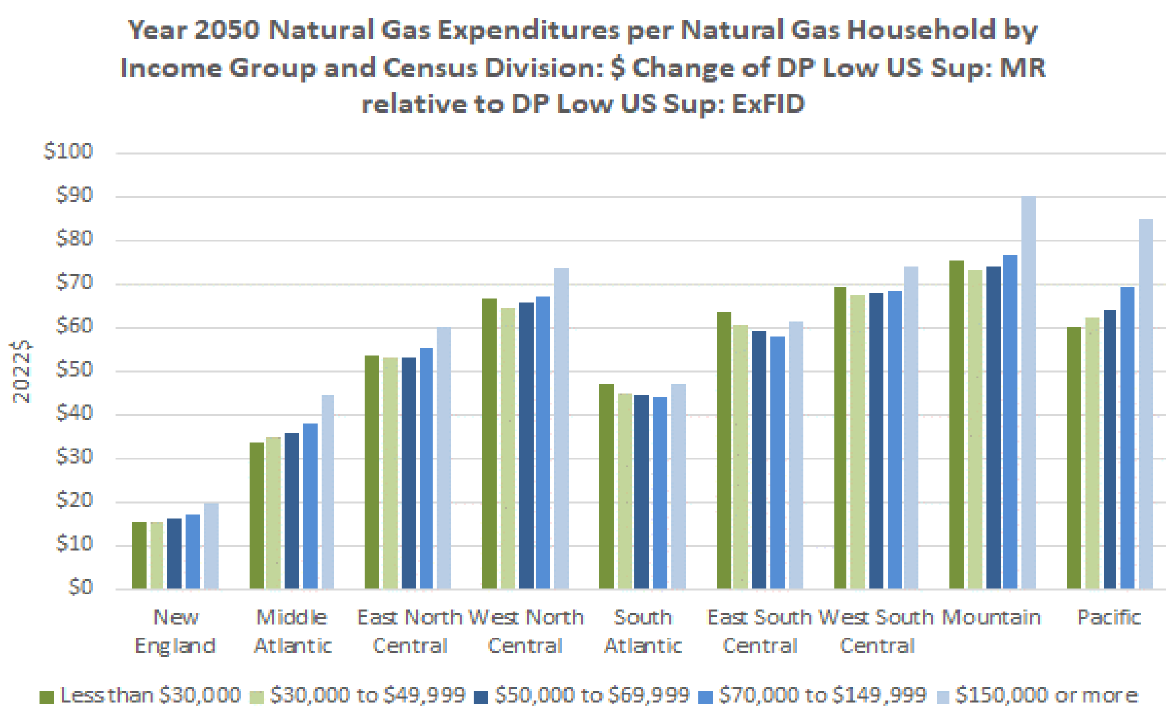


Figure 7. Natural gas expenditure impacts per natural gas household in 2050.

DP: MR stands for Defined Policies: Model Resolved; DP: ExFID stands for Defined Policies: Existing/FID Exports; DP Lo US Sup: MR stands for Defined Policies Low US Supply: Model Resolved; DP Lo US Sup: ExFID stands for Defined Policies Low US Supply: Existing/FID Exports.

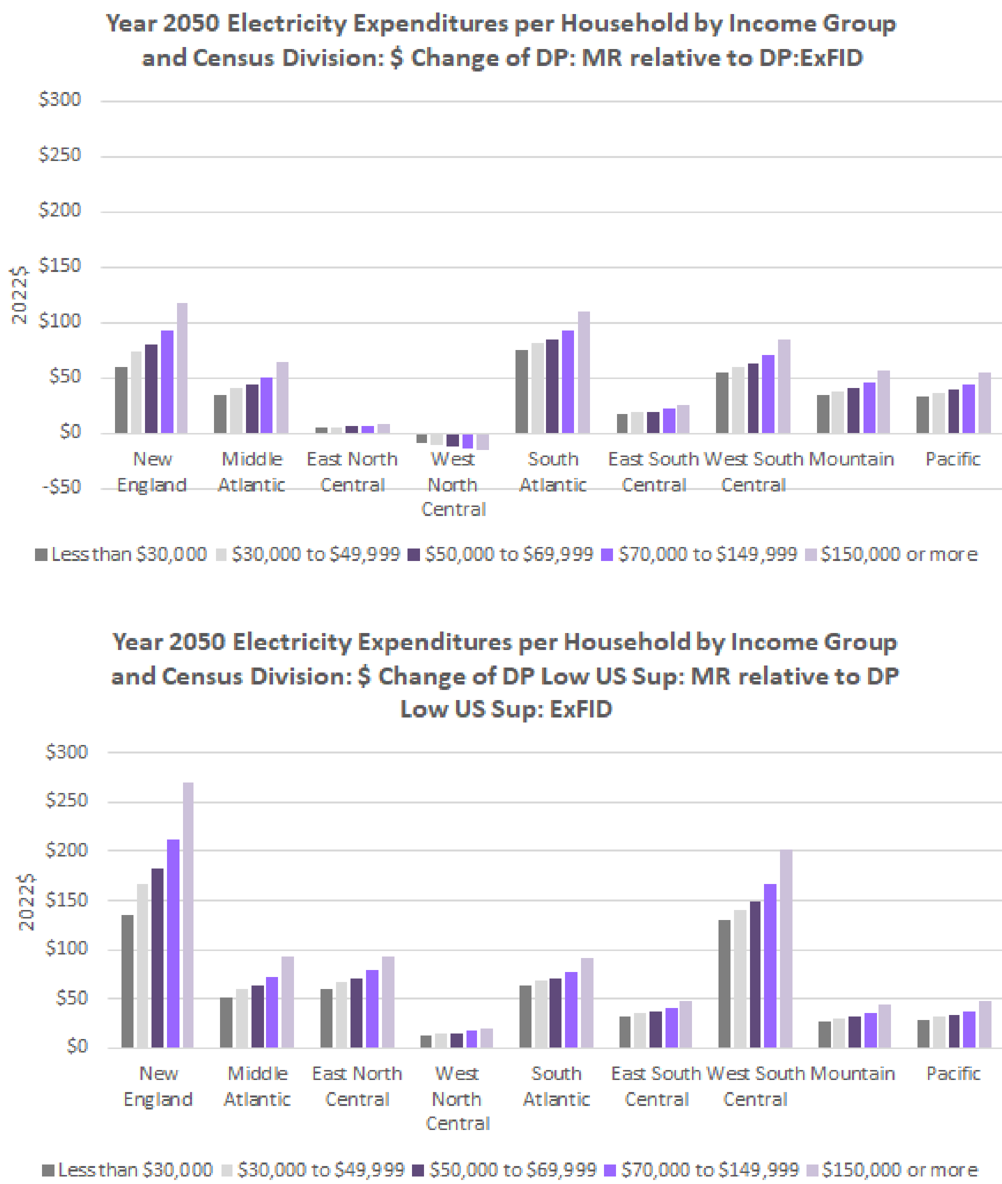


Figure 8. Electricity expenditure impacts per household in 2050.

DP: MR stands for Defined Policies: Model Resolved; DP: ExFID stands for Defined Policies: Existing/FID Exports; DP Lo US Sup: MR stands for Defined Policies Low US Supply: Model Resolved; DP Lo US Sup: ExFID stands for Defined Policies Low US Supply: Existing/FID Exports.

G. Sensitivity of U.S. Natural Gas Prices to the Global LNG Market

The rapid expansion of U.S. LNG exports has shaped the outlook for the U.S. natural gas market, raising concerns about domestic price volatility and the future stability of domestic supply. As shown in the previous section, U.S. LNG exports can impact domestic consumer prices. This section provides background on the complex relationship between U.S. natural gas price volatility and global LNG market dynamics.

The long timelines of constructing and operationalizing LNG facilities allow for U.S. natural gas producers to increase output to supply the new liquefaction facilities and, ultimately, to ensure that the feedgas flows to the export terminals are highly predictable.[52] In addition, U.S. LNG export facilities typically enter into long-term export agreements with off-takers for 75-80% of the project's nameplate capacity to support the capital investment needed to construct liquefaction facilities.[53,54] As a result, the U.S. natural gas market typically prices in additional LNG export capacity with production rising to meet the incremental demand, resulting in gradual increases in domestic natural gas prices.[55]

The long-term, take-or-pay nature of U.S. contracted LNG exports has sheltered short- and medium-term domestic natural gas prices from significant and sustained price surges.[56] With around 80% of an LNG export terminal's capacity contracted through long-term take-or-pay agreements, the level of U.S. LNG exports remains mostly constant and near maximum capacity, limiting the ability of U.S. facilities to increase output in response to a sudden increase in global demand. As a result, global supply and demand shocks have historically had little impact on domestic prices. A degree of global market exposure to U.S. natural gas price volatility in the long term is possible.[57] This study does not include forward-looking modeling on the impacts of increasing LNG exports to consumer price volatility.

When U.S. LNG supply disruptions occur, international gas and LNG prices – especially for importing regions – typically increase. This is because a reduction of destination-flexible volumes

[52] "Impact Analysis of U.S. Natural Gas Exports on Domestic Natural Gas Pricing," Prepared by Energy Ventures Analysis, March 2024

[53] DOE considers long-term to be anything beyond two years, but 15 to 25-year off-take export agreements are typical.

[54] "U.S. to See Dramatic Growth in LNG Export Capacity," BNEF, January 24, 2023; Lindsay Schneider, "Steady As She Goes, Part 2 – SPAs Keep U.S. LNG Exports Flowing Amid Global Price Volatility," RBN Energy, October 19, 2019.

[55] "Assessing the Domestic Energy Price Impact of LNG Exports" Center for Strategic & International Studies February 28, 2024 https://www.csis.org/analysis/assessing-domestic-energy-price-impact-lng-exports

[56] U.S. take-or-pay LNG contracts mitigate LNG exporters' risk to global LNG demand fluctuations. Being a net exporter of gas, the U.S. is not directly exposed the global LNG market dynamics. International Energy Agency, "Gas Market Report, Q3-2022," https://iea.blob.core.windows.net/assets/c7e74868-30fd-440c-a616-488215894356/GasMarketReport%2CQ3-2022.pdf

[57] For example, U.S. natural gas supply could be exposed to global market prices through sale price indexation of U.S. natural gas to international price benchmarks. Some U.S. natural gas producers have expressed some interest in capturing additional profits earned in the global export market, beyond Henry Hub, through increased vertically integrated exposure to international LNG prices. U.S. natural gas producer Chesapeake Energy Corp and Coterra Energy signed separate LNG Sales and Purchase Agreements where they would receive prices for small volumes indexed to the Japan-Korea Marker (JKM). Nissa Darbonne, "Chesapeake LNG Deal Moves Its Haynesville Gas Closer to Global Price" Hart Energy, March 7, 2023 (https://www.hartenergy.com/exclusives/chesapeake-lng-deal-moves-its-haynesville-gas-closer-global-price-204389); Craig Jallal, "US gas deals signal increasing transatlantic links in LNG markets," Riviera Maritime Media, October, 31, 2024 (https://www.lw.com/en/news/latham-watkins-advises-vitol-in-long-term-lng-indexed-gas-supply-agreement)

can threaten the liquidity of global LNG and gas markets. For example, U.S. Henry Hub prices were on an upward trend along with European and Asian prices, until the June 2022 outage at the Freeport LNG export facility in Freeport, Texas. At the end of June 2022, European Title Transfer Facility (TTF) and Asian LNG prices were up more than 75 percent and 50 percent respectively, while U.S. Henry Hub prices were down more than 40 percent as demand for LNG feedgas decreased.[58] Though U.S. Henry Hub prices began increasing again within weeks while Freeport LNG remained offline and did not peak until later that summer,[59] daily Henry Hub prices temporarily reacted to having more natural gas supplies available for the domestic market given the reduced demand for LNG feedgas, specifically from the temporarily shut down Freeport facility.

Case Study: U.S. Domestic Natural Gas Price Increase in 2022

At current export levels, U.S. natural gas prices are relatively low compared to other natural gas price benchmarks around the world. However, domestic prices can experience volatility. In 2022, wholesale U.S. natural gas spot prices at Henry Hub reached their highest level since 2008, averaging $6.45/MMBtu, and ranging from $3.46 to $9.85/MMBtu – overall, up 53% from 2021.[60,61] Despite this period of price volatility, U.S. gas prices remained significantly lower than other global benchmarks as the U.S. largely does not import gas from the global market.[62]

At the same time, 2022 saw higher than normal peaks of U.S. natural gas demand. Domestic consumption typically peaks in the summer when gas demand for power generation, mainly for cooling, is highest. Winter also sees a peak, albeit a smaller one, for gas heating.[63] According to the EIA, the U.S. experienced below-normal winter temperatures in the first two months of 2022, which led to reduced U.S. natural gas production due to freeze-offs, and high net withdrawals from inventories.[64] Further, reduced availability of coal resulted in above-average gas-fired power generation that winter. In September 2021, just ahead of the heating season, coal stocks for the power sector fell 37% below the five-year average due to coal supply constraints, hitting their lowest levels in 43 years.[65] As a result, domestic natural gas consumption and prices surged. During this time, the EIA also highlighted capacity constraints as driving price surges and volatility.[66] Limited pipeline takeaway capacity in the Appalachian and Waha Hub regions deflated prices in those regions compared to Henry Hub, compounding the above-normal seasonal demand peaks and periods of limited gas production.

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[58] International Energy Agency, "Gas Market Report, Q3-2022," https://iea.blob.core.windows.net/assets/c7e74868-30fd-440c-a616-488215894356/GasMarketReport%2CQ3-2022.pdf

[59] See Henry Hub prices at https://www.eia.gov/dnav/ng/hist/rngwhhdD.htm

[60] U.S. Energy Info. Admin., "Average cost of wholesale U.S. natural gas in 2022 highest since 2008," Today in Energy, January 9, 2023. https://www.eia.gov/todayinenergy/detail.php?id=55119

[61] Jamison Cocklin, "U.S. Natural Gas Price Volatility at All-Time High in 2022," Natural Gas Intel, August 16, 2022.

[62] The U.S. imports natural gas via pipeline from Canada and small amounts of LNG in pipeline constrained areas, such as New England.

[63] EIA, "U.S. natural gas consumption has both winter and summer peaks," Today in Energy, February 13, 2020. https://www.eia.gov/todayinenergy/detail.php?id=42815

[64] EIA, "Short-Term Energy Outlook," March 2022; EIA, "Record U.S. natural gas demand this winter led to largest storage withdrawal in four years," Today in Energy, June 6, 2022. https://www.eia.gov/todayinenergy/detail.php?id=52638; EIA, "The United States ended the winter with the least natural gas in storage in three years," Today in Energy, April 15, 2022. https://www.eia.gov/todayinenergy/detail.php?id=52058

[65] EIA, "In September, the United States was at its lowest coal stockpiles since 1978," Today in Energy, December 7, 2021. https://www.eia.gov/todayinenergy/detail.php?id=50558

[66] EIA, "Average cost of wholesale U.S. natural gas in 2022 highest since 2008," Today in Energy, January 9, 2023. https://www.eia.gov/todayinenergy/detail.php?id=55119

VI. Consequential Life Cycle Analysis

Past DOE and NETL life cycle studies of natural gas, including LNG, have been attributional studies that estimate emissions associated with units of natural gas, LNG, or other fuels used to generate a megawatt-hour (MWh) of baseload electricity. These studies have not, to date, fully evaluated the consequences of delivering LNG, including how domestic and foreign energy markets may be affected by increasing the supply of natural gas. In other words, they have not evaluated whether different sources of natural gas compete in the market or whether, given additional supply, natural gas power plants in other regions may take market share from other forms of electricity generation. Such market-based effects could lead to changes in GHG emissions that are the consequence of increased availability of U.S. LNG.

For comparative context, estimated attributional life cycle GHG emissions from production, export, and end use of the fuel in an Asian destination market assuming 100% combustion of U.S. LNG exports with unabated emissions at the point of end use (i.e., no CCS) are 76 g CO_2e/MJ of LNG exported.[67] This attributional GHG emission profile would represent the expected contribution to global emissions if 100% of U.S. LNG exports resulted in an equivalent increase in global services, without any market substitution. Comparing *Model Resolved* to *Existing/FID Exports* levels in the *Defined Policies* scenario, cumulative (2020-2050) attributional life cycle GHG contribute 8.6 Gt CO_2e. In 2050, direct life cycle GHG emissions from all U.S. LNG would be 1.5 Gt CO_2e before accounting for market effects.

This study updates the previous approach to include these market-based effects. The study utilizes the global GHG and U.S. LNG export volumes determined from GCAM for each scenario considered within the study to estimate the consequential life cycle GHG emissions on a per unit (MJ) of U.S LNG exported. This type of LCA accounts for the direct emissions from production, delivery, and use of the U.S. exported natural gas and the indirect emissions from changes in market behavior. The consequential GHG intensity is therefore the total effect (direct and indirect market effects) of U.S. LNG on global GHG emissions per unit of U.S. LNG exported.

A trade-off in using a consequential modeling approach is a reduction in attribution for specific source to consumption pathways, as previously modeled and used by DOE, due to aggregation of global resource supplies and services into global commodity market sectors. Therefore, this study does not present comparative results, for example of natural gas from imported LNG compared to coal for production of a MWh of electricity in an export market for U.S. LNG, or other direct source to consumption pathways.

A. Consequential LCA Results

As part of the consequential analysis, NETL reviewed GCAM model results and aligned emissions associated with upstream natural gas processes in the U.S. with the 2024 NETL Baseline Study.[68] NETL found that the intensity values of upstream natural gas in 2020, were 1.2% higher in the 2024 NETL Baseline study compared to results from GCAM. NETL used this factor to increase the upstream emissions from GCAM across the scenarios. This adjustment helps align U.S. upstream natural gas results in the study with the more granular data available from the 2024 NETL Baseline study. See Appendix C for additional details.

Using the adjusted GCAM cumulative global emissions, NETL calculated the consequential GHG intensity by comparing the emissions and export levels within each scenario to a baseline of the

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[67] Additional context for the attributional values is available in Appendix C.

[68] Khutal, H., et al. Life Cycle Analysis of Natural Gas Extraction and Power Generation: U.S. 2020 Emissions Profile. National Energy Technology Laboratory, Pittsburgh, December 2024. https://www.netl.doe.gov/energy-analysis/details?id=546d4009-c43b-43f5-bcc9-64d5e63fc8d5

related *Existing/FID Exports* scenario (e.g., *Defined Policies: Model Resolved* compared to *Defined Policies: Existing/FID Exports*).[69] The consequential GHG Intensity for *Defined Policies: Model Resolved* versus *Defined Policies: Existing/FID Exports* is defined as the total difference in annually estimated global GHG emissions over the 2020-2050 period divided by the total difference in annually estimated exported LNG over the period. Table 15 shows the cumulative change in GHG emissions, changes in U.S. LNG exported, and consequential GHG intensities of US exports for all cases (baseline scenario for each is always *Existing/FID Exports* within each policy scenario).

As summarized in Table 15, consequential GHG intensities across all global climate policies range from 1.2 to 12.6 g CO_2e/MJ.

Table 15. Cumulative (2020-2050) consequential GHG intensities of U.S. LNG exports

			Cumulative (2020-2050) change in…			**Cumulative Consequential GHG Emissions Intensity (g CO_2e/MJ)**
Comparison of Scenarios	**Scenario**	**2050 U.S. LNG Exports (Bcf/d)[a]**	**U.S. LNG Exports (*EJ*)**	**GHG Emissions (MMT CO_2e)[b]**	**Global Services (%)**	
Existing/FID Exports to Model Resolved	*Defined Policies*	56.3	113	711	0.08%	**6.3**
	Commitments (High CCS)	33.1	31	97	0.02%	**3.1**
	Commitments (Mod CCS)	26.8	11	67	0.01%	**5.9**
	Net Zero (High CCS)	28.5	17	21	0.01%	**1.2**
	Net Zero (Mod CCS)[c]	17.2	NA	NA	NA	**NA**
Existing/FID Exports to High Exports	*Defined Policies*	76.3	189	1,452	0.15%	**7.7**
	Commitments (High CCS)	53.1	107	787	0.09%	**7.3**
	Commitments (Mod CCS)	46.8	87	1,055	0.08%	**12.1**
	Net Zero (High CCS)	48.5	93	324	0.08%	**3.5**
	Net Zero (Mod CCS)	37.2	76	955	0.05%	**12.6**

a. 2050 U.S. LNG export levels for *Model Resolved* and *High Export* scenarios
b. Cumulative change in GHG emissions (2020-2050) are 1.2% higher than the GCAM results after NETL aligned results with NETL upstream emission estimates. GHG emissions include CO_2 emissions from fossil fuels and industry as well as land-use changes, and non-CO_2 emissions (methane, nitrous oxide, and fluorinated gases) from energy, agricultural, and land-use systems and other processes. CO_2 emissions from fossil fuels and industry are subject to uncertainties in regional emission intensities of natural gas and other fossil fuels. Emissions from land-use changes are driven in part by changes in energy production, including those driven by changes in demand

[69] GCAM resolves in five-year increments; the consequential GHG intensity is therefore calculated for every year (2020–2050) via linearly interpolated values of emissions and U.S. LNG exports for the non-modeled years.

(e.g., global demand for LNG). These emissions are also subject to greater uncertainties largely due to uncertainties in data. A detailed exploration of these uncertainties is beyond the scope of this study.

c. *Net Zero (Mod CCS)* U.S. LNG export levels do not change between the *Existing/FID Exports* to *Model Resolved* scenarios.

B. Adjusting the Consequential LCA to Account for Individual Project Data

The overall consequential GHG intensity values include all emissions, including those resulting from direct and indirect market effects. The values incorporate default assumptions about the emissions associated with U.S. average upstream and liquefaction emission intensities. As described in Appendix C, it is possible to replace these values with alternative estimates, including individual project estimates. The resulting consequential GHG intensity would be specific to those alternative assumptions.

For example, NETL estimates that the average liquefaction emissions for a project are 5.3 g CO_2e/MJ. If an individual project has a liquefaction process with emissions of 2.9 g CO_2e/MJ, the individual project consequential GHG intensity could be adjusted down by 2.4 g CO_2e/MJ (calculated as the difference between the average of 5.3 g CO_2e/MJ and the individual project emissions intensity of 2.9 g CO_2e/MJ). If the consequential GHG intensity is 6.3 g CO_2e/MJ (as in the first row of Table 15 above), the individual project consequential intensity would be 3.9 g CO_2e/MJ.

By contrast, if an individual project has a liquefaction system that would be higher-emitting than the default, the project-specific consequential intensity could be higher than the average.

A similar process could be followed if an individual project's upstream emissions associated with natural gas delivered to the liquefaction terminal is different than the default value of 9.2 g CO_2e/MJ.

C. Social Cost of Greenhouse Gases

The inputs to the consequential GHG intensity can also be used to monetize the impacts of the changes in GHG emissions associated with increased U.S. LNG exports using the social cost of greenhouse gas emissions (SC-GHG) estimates and methodology developed by the U.S. Environmental Protection Agency (EPA) in in the regulatory analysis of its December 2023 Final Rule, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review," (2023 SC-GHG estimates).[70]

The 2023 SC-GHG method uses three discount rates (1.5%, 2.0% and 2.5%) to provide values of the SC-GHG for a particular base year (assumed in this study as 2024) and dollar year.[71] The monetized SC-GHG values for each of the three greenhouse gases for each of the three discount rates for each year of the study period (in $2022) are summarized in Appendix C.

[70] DOE has preliminarily determined that the updated 2023 SC-GHG estimates, including the approach to discounting, represent a significant improvement in estimating the SC-GHG through incorporating the most recent advancements in the scientific literature and by addressing recommendations on prior methodologies. DOE explained the basis for its determination and made it available for public comment in a July 2024 NODA for consumer gas-fired instantaneous water heaters. 89 FR 59693, 59700. As DOE explained in the July 2024 NODA, the 2023 SC-GHG estimates represent a significant improvement because the 2023 SC-GHG estimates implement the key recommendations of the National Academies, and they incorporate the extensive scientific findings and methodological advances that have occurred since the last IWG substantive updates in 2013, 2015, and 2016.

[71] Dollar values used in the summary report are $2022, while in Appendix C uses $2020. All SC-GHG results for both dollar years are shown in Appendix C-3.

For *Defined Policies: Model Resolved* versus *Defined Policies: Existing/FID Exports*, the cumulative difference in emissions from 2020-2050 is estimated to have a cumulative SC-GHG impact of $84 billion using a discount rate of 2.5%, $140 billion using a discount rate of 2.0%, and $250 billion using a discount rate of 1.5% (all 2022$). SC-GHG estimates for the primary scenarios are provided in Table 16.

Table 16. Changes in Cumulative Social Cost of Greenhouse Gases (SC-GHG), 2022$

Comparison of Scenarios	Scenario	Cumulative (2020-2050) change in…								
		Emissions (MMT CO_2e)[a]				U.S. LNG Exports (*EJ*)	Global Services (%)	SC-GHG ($billion 2022)		
		CO_2	CH_4	N_2O	Total			2.5%	2.0%	1.5%
Existing/FID Exports to Model Resolved	*Defined Policies*	709	17	-47	711	113	0.08%	$84	$140	$250
	Commitments (High CCS)	143	-50	-4	97	31	0.02%	$13	$24	$45
	Commitments (Mod CCS)	83	-18	0	67	11	0.01%	$9	$16	$28
	Net Zero (High CCS)	49	-29	-3	21	17	0.01%	$3	$7	$13
	Net Zero (Mod CCS)[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA
Existing/FID Exports to High Exports	*Defined Policies*	1,401	79	-88	1,452	189	0.15%	$170	$290	$500
	Commitments (High CCS)	870	-95	-25	787	107	0.09%	$100	$170	$300
	Commitments (Mod CCS)	1,088	-60	0	1,055	87	0.08%	$140	$230	$400
	Net Zero (High CCS)	402	-85	-22	324	93	0.08%	$41	$71	$130
	Net Zero (Mod CCS)	1,007	-59	-11	955	76	0.05%	$120	$210	$370

a. Cumulative change in GHG emissions (2020-2050) are 1.2% higher than the GCAM results after NETL aligned results with NETL upstream emission estimates. Values shown on IPCC AR6, 100-yr basis. Total also includes F-gases (not shown in table).
b. Net Zero (Mod CCS) U.S. LNG export levels do not change between the *Existing/FID Exports* to *Model Resolved* scenarios.

Normalizing SC-GHG results per MJ of change in natural gas exported for the *Defined Policies: Model Resolved* scenario leads to estimated intensities ranging from 0.07 cents/MJ (2.5% discount rate) to 0.22 cents/MJ (1.5% discount rate). In other words, for this scenario, the social costs of the additional GHG emissions associated with increased U.S. LNG exports range from 0.07 cents/MJ (2.5% discount rate) to 0.22 cents/MJ (1.5% discount rate). SC-GHG estimates per unit of change in energy exported for all primary scenarios are provided in Table 17.

Table 17. Normalized Changes in Cumulative Social Cost of Greenhouse Gases

Comparison of Scenarios	Scenario	Change in…					
		Cumulative U.S. LNG Exports (*EJ*)	Cumulative GHG Emissions (MMT CO_2e)[a]	Cumulative Global Services (%)	SC-GHG per MJ (2022 cents/MJ)		
					2.5%	2.0%	1.5%
Existing/FID Exports to Model Resolved	*Defined Policies*	113	711	0.08%	0.07	0.12	0.22
	Commitments (High CCS)	31	97	0.02%	0.04	0.08	0.14
	Commitments (Mod CCS)	11	67	0.01%	0.08	0.14	0.26
	Net Zero (High CCS)	17	21	0.01%	0.02	0.04	0.08
	Net Zero (Mod CCS)[b]	NA	NA	NA	NA	NA	NA
Existing/FID Exports to High Exports	*Defined Policies*	189	1,452	0.15%	0.09	0.15	0.27
	Commitments (High CCS)	107	787	0.09%	0.09	0.16	0.28
	Commitments (Mod CCS)	87	1,055	0.08%	0.15	0.26	0.46
	Net Zero (High CCS)	93	324	0.08%	0.04	0.08	0.14
	Net Zero (Mod CCS)	76	955	0.05%	0.16	0.27	0.48

a. Cumulative change in GHG emissions (2020-2050) are 1.2% higher than the GCAM results after NETL aligned results with NETL upstream emission estimates.
b. Net Zero (Mod CCS) U.S. LNG export levels do not change between the *Existing/FID Exports* to *Model Resolved* scenarios.

VII. ENERGY SECURITY CONSIDERATIONS

Global LNG markets included 40 importing countries in 2020. As natural gas demand has increased in many regions of the world, more countries have become LNG importers, including Croatia in 2021; El Salvador and Germany in 2022; and the Philippines and Hong Kong (China) in 2023. The global trade of LNG grew from 13.3 Bcf/d[72] in 2000 to 48.7 Bcf/d in 2020 and 53.4 Bcf/d in 2022.[73] Some large natural gas markets, such as the EU and Japan, do not have sufficient local supply sources that can flexibly meet their needs. As a result, LNG imports have played a

[72] Converted from one million metric tons per annum (MTPA) of LNG to Bcf of natural gas using a factor of 1 MTPA = 48.03 Bcf, “Approximate conversion factors – Statistical Review of World Energy,” Energy Institute, 2023 (https://www.energyinst.org/__data/assets/pdf_file/0003/1055541/Methodology.pdf).
[73] Oxford Institute for Energy Studies (2023). "A Brave New World? LNG Contracts in the Context of Market Turbulence and an Uncertain Future". http://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/12/LNG-Contracts-in-the-Context-of-Market-Turbulence-and-an-Uncertain-Future-NG-187.pdf.

large role in meeting these regions' energy demand. However, energy policy goals and the cost to build import infrastructure and purchase LNG has led some countries to focus on the buildout of other energy sources, including renewable energy and coal.

A. The Role of Flexibility in Securing Global LNG Supply

As LNG re-gasification and associated import infrastructure is built out globally, increasing U.S. LNG exports could enhance global energy security. Most U.S. LNG contracts include a destination flexibility clause in which the buyer can deliver LNG to any destination, if it complies with DOE export authorizations and U.S. law.[74] Accordingly, U.S. LNG goes to where the global market most demands it. This flexibility of gas supply can offer increased energy security for buyers who can afford to purchase gas on the spot market, particularly in times of regional energy shortages. For example, in the wake of the Russian invasion of Ukraine, U.S. LNG exports were able to supply Europe efficiently, not only due to its geographic proximity in the Atlantic Basin, but also because of its flexible supply. It is important to note, however, that short-term supply gaps do not necessarily reflect long-term demand patterns; the EIA has noted that consumption of natural gas in Europe has consistently decreased since mid-2022 for several reasons, including government policies aimed at reducing reliance on natural gas.[75]

Off-takers of U.S. LNG have the option to re-sell the contracted cargoes for import by other countries and many contracts for U.S. LNG are held by traders who intend to resell their volumes into the global market. For the time period from first LNG exports from the lower-48 United States in February 2016 until July 2024, 49 % of U.S. LNG has been delivered to Europe, and 38% has gone to Asia.[76] During 2022 when global gas market were disrupted after Russia's invasion of Ukraine, many contracted off-takers of U.S. LNG made profits when they re-sold their contracted cargoes for consumption in the EU when delivered EU LNG prices spiked and were at a premium to Asian and other global LNG prices.[77]

Qatar, the second largest LNG exporter in 2023, currently has approximately 20% of the global LNG market. However, most of Qatari LNG is contracted on terms that are typically less flexible than U.S. contracts, with specified destinations and contract lengths.[78]

Additionally, Qatari exporters face security concerns for commercial shipping around the Arabian Peninsula's maritime chokepoints. In the Red Sea, tensions escalated since October 2023 as Yemen's Iran-backed Houthi group attacked shipping lanes and held up at least four Qatari LNG tankers en route to Europe through the Suez Canal.[79,80] In light of these attacks, LNG tankers destined for Europe have had to reroute through the Cape of Good Hope. LNG shipments from

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[74] U.S. Energy Information Administration (2024). LNG sale and purchase agreements signed in 2023 support U.S. LNG projects. https://www.eia.gov/todayinenergy/detail.php?id=61384

[75] See U.S. Energy Info. Admin., "Less natural gas consumption in Europe is keeping storage full", Today in Energy (July 23, 2024).

[76] See U.S. Natural Gas Imports and Exports Monthly, July 2024, at 45. https://www.energy.gov/sites/default/files/2024-09/Natural%20Gas%20Imports%20and%20Exports% 20Monthly%20July%202024.pdf

[77] Hernandez, America (November 15, 2022). "Why cheap US gas cost a fortune in Europe". POLITICO. https://www.politico.eu/article/cheap-us-gas-cost-fortune-europe-russia-ukraine-energy/

[78] Warren Patterson, Coco Zhang (July 18, 2024). "The US and Qatar to drive LNG supply growth," ING. https://think.ing.com/articles/article-2-the-us-and-qatar-to-drive-lng-supply-growth-hold/

[79] Maha El Dahan, Emily Chow, and Andrew Mills (January 15, 2024). "QatarEnergy halts Red Sea LNG shipping amid attacks, seeking security advice," Reuters. https://www.reuters.com/world/middle-east/lng-tankers-held-up-over-weekend-following-us-uk-strikes-houthis-data-2024-01-15/

[80] Defense Intelligence Agency (April 5, 2024). "Yemen: Houthi Attacks Placing Pressure on International Trade". https://www.dia.mil/Portals/110/Images/News/Military_Powers_Publications/YEM_Houthi-Attacks-Pressuring-International-Trade.pdf

Qatar and other exporters face the potential threat of Iran closing or blockading the Strait of Hormuz amid rising tensions with Israel. This chokepoint accounts for about one-fifth of the world's LNG flows and could effectively cut off all Qatari and other Gulf nation cargoes, which would create extreme market volatility and supply disruptions around the world.[81]

While these factors could limit Qatar's ability to offer reliable and flexible supplies to the global market, the U.S. faces parallel challenges shipping through the Suez Canal and has faced other constraints such as drought limiting vessel traffic in the Panama Canal.

B. Regional Perspectives on LNG

In 2020, LNG surpassed inter-regional pipeline trade in its share of globally traded gas. In 2023, LNG increased its share to 59%.[82] As new global LNG demand centers emerge, large natural gas producers will be compelled to find new markets for its LNG exports.

U.S. LNG has played a role in enhancing supply security for markets looking to reduce coal in their energy mix while prioritizing both renewables and gas, but LNG is unlikely to be the most cost-competitive source of energy for many countries. Countries can (and have) implemented energy strategies to give natural gas, including imported volumes, an advantage over coal to help meet national decarbonization targets and improve local air quality and environmental outcomes. This analysis explores the prospect that additional LNG volumes would also displace other sources of natural gas as well as other forms of energy such as renewables and nuclear. These displacement effects are explored across scenarios in Appendix A.

If delivered LNG prices demonstrate high volatility over a sustained period, governments with relatively lower fiscal capacity and more urgent energy needs may switch to alternatives like coal. For many regional markets, imported coal is typically more affordable and has more predictable prices compared to LNG.[83]

Shifts in structural demand in response to global LNG price volatility have emerged recently. In February 2023, Pakistan's Energy Minister said that "LNG is no longer part of the long-term plan," and announced plans to quadruple domestic coal-fired power capacity to 10 GW in the medium-term and avoid new gas-fired power plants. The minister's comments came after the country experienced severe power shortages as LNG prices surged to accommodate Europe's sudden spike in gas demand during the Russian invasion of Ukraine. Despite Pakistan's electricity demand increasing in 2022, the country's import levels fell to their lowest in five years as European importers edged out the market's price-sensitive buyers.[84]

Bangladesh similarly saw its share of natural gas in power generation fall in 2022 due to dwindling domestic reserves and lack of affordable LNG supplies. While the country recently struck a 15-

[81] Drewry (April 26, 2024). "Potential Strait of Hormuz closure threatens 21% of global LNG supply". https://www.drewry.co.uk/maritime-research-opinion-browser/maritime-research-opinions/potential-strait-of-hormuz-closure-threatens-21-of-global-lng-supply

[82] Energy Intelligence Statistical Review 2024

[83] For example, the LNG price benchmark for Japan, Korea, Taiwan (referred to as JKM) is typically higher and more volatile than the price benchmark for Newcastle Coal, a benchmark for Australian coal that is a source of supply to Asian customers. Michael Cooper (November 8, 2018). "Charting relative cost of thermal coal vs LNG in Northeast Asia reveals fresh insights," S&P Global. https://www.spglobal.com/commodityinsights/en/market-insights/blogs/coal/110818-charting-relative-cost-of-thermal-coal-vs-lng-in-northeast-asia-reveals-fresh-insights.

[84] Gibran Naiyyar Peshimam, "Exclusive: Pakistan plans to quadruple domestic coal-fired power, move away from gas," Reuters, February 13, 2023.

year LNG deal with Qatar Energy, Bangladeshi coal demand is projected to exceed LNG demand based on the higher prices and volatility of LNG.[85]

Renewables are seeing both price and policy support in their competition with natural gas and LNG. In Southeast Asia, economic expansion driven by industrial growth is increasing demand for lower cost electricity supply and energy storage. While natural gas is still expanding in the region, renewable project developers are competing with LNG suppliers, seeing strong demand signals from companies eager for lower cost clean power sources.[86] While India has economy-wide goals to increase the use of natural gas[87], both the high cost of natural gas and the intense cost competitiveness of renewables in the power sector has led to only one natural gas power plant under construction in the country as of January 2024. This is despite a surge in regasified LNG demand in India's power sector in 2023. India's gas (and LNG) demand in the power sector is expected to remain muted due to an increasing share of renewables and continued reliance on coal.[88] In Europe, LNG imports increased in 2022 to compensate for lost Russian pipeline supplies. The EU will remain dependent on LNG in the short-term for gas supply; however, legislation has been passed to phase out fossil fuels and promote renewable and low-carbon gas, including hydrogen.[89]

Countries' decarbonization policies and the availability of more cost-competitive energy sources, such as coal and renewables, will determine the outlook for U.S. LNG's role in the global energy market and the energy transition.

C. China is the World's Largest LNG Importer

According to the EIA, China is the world's third largest natural gas consumer and the world's largest LNG importer, averaging 9.5 Bcf/d in 2023.[90] The country is growing its regasification capacity more than any other country in the world, and in 2022 had 5.7 Tcf of existing regasification terminals, plus 5.5 Tcf of regasification capacity under construction with operational start dates between 2023 and 2026.[91] LNG is largely used to meet peak power generation demand in the Central and Southern coastal regions, heating in the Northern coastal region, closing the pipeline supply-demand gap in the Central coastal region, and industrial demand (as a result of coal-to-gas switching) in the Southern coastal region.

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[85] "Bangladesh Power System Gets Dirtier On Rapid Coal Use Growth" Reuters as reprinted by Energy Bangla April 5, 2024

[86] For example, see "Keppel Infrastructure, IES and Envision ink MOU to offer renewable energy solutions for ASEAN," Keppel, January 26, 2022 (https://www.keppel.com/infrastructure/news-item.aspx?aid=13578&title=keppel-infrastructure-ies-and-envision-ink-mou-to-offer-renewable-energy-solutions-for-asean); "Southeast Asia Energy Outlook 2024" International Energy Agency October 2024

[87] Press Release, "Share of Natural Gas in Total Energy Mix," Press Information Bureau, Government of India, Ministry of Petroleum & Natural Gas, December 18, 2023. https://pib.gov.in/Pressreleaseshare.aspx?PRID=1987803

[88] Zhi Xin Chong, Akshay Modi, Ashish Ranjan, "India Natural Gas Market Profile," S&P Global, January 2024

[89] See Council of the EU, "Fit for 55: Council signs off on gas and hydrogen market package," May 21,2024.

[90] See U.S. Energy Info. Admin., "Pipeline projects announced to expand Permian natural gas capacity", Today in Energy (Aug. 4, 2022)

[91] See U.S. Energy Info. Admin., China Country Analysis Brief, November 2023.

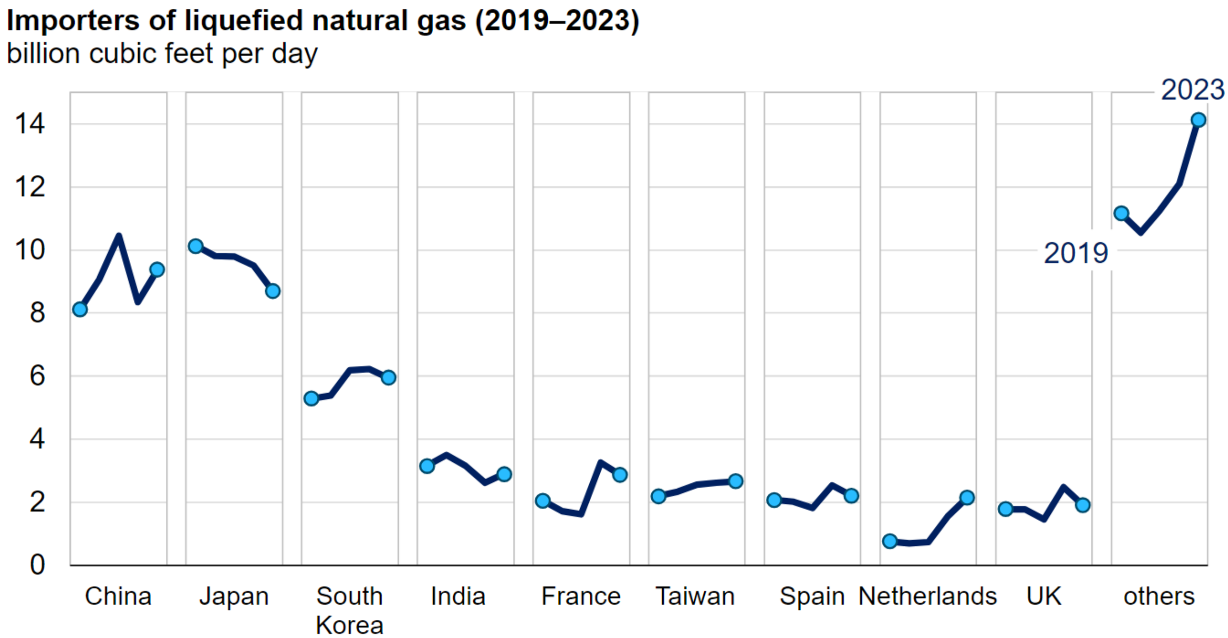

Figure 9. Global importers of LNG (2019-2023). Source: U.S. Energy Information Administration[92]

China's LNG imports shown for the years 2019 to 2023 in Figure 9, serve as a swing supply source within the country's gas market, given China's diversity of fuel supply sources. LNG comprised roughly a quarter of China's natural gas supplies in 2023.[93] Consequently, China's LNG buyers are price sensitive; they will often purchase spot LNG cargoes if a spot cargo is priced below the break-even cost of storing the volumes.

China is taking steps to integrate battery storage and its rapidly growing renewable generation capacity in order to fully utilize the cheaper low-carbon energy sources it possesses domestically and promote grid stability.[94] Based on results from the global analysis presented earlier in this report, China is projected to be the largest importer of global LNG in 2050 across most scenarios. In the *Defined Policies* scenario, China is projected to import 28.8 Bcf/d of LNG in 2050. In the *Net Zero 2050 (Moderate CCS)* scenario, which represents the lower bound for projections of global gas demand in the modeling conducted as part of this study, China is projected to import 13.4 Bcf/d of LNG in 2050.[95] The country's trajectory for renewables deployment is largely driven by pro-renewable market policy directives and declining costs of wind and solar through the long-term, compared to increasing capital and operating costs for coal and gas. Even though China has built new gas- and coal-fired power generation capacity, thermal power's share in the power capacity mix declined to 44% in 2023 from around 49% in 2020, with gas's share in power generation stable at 3% since 2015.[96]

China's contracting activity with operating and proposed LNG export projects to be sourced with U.S. gas has significantly increased over the last several years, with Chinese LNG buyers signing

[92] See U.S. Energy Info. Admin., "Global trade in liquefied natural gas continued to grow in 2023," Today in Energy, July 11, 2024.
[93] See U.S. U.S. Energy Info. Admin., "China's natural gas consumption, production, and imports all increased in 2023", Today in Energy, Aug. 14, 2024.
[94] "The next step for China's clean energy transition: industrial and commercial storage deployment". World Economic Forum, June 27, 2024.
[95] Data on LNG import projection by region and scenario can be found in Appendix A-3.
[96] Lihwei Wang, Bing Han, Changyao Peng, "China Renewable Power Market Profile," S&P Global, March 21, 2024.

sales and purchase off-take agreements for U.S.-sourced LNG with several operating, under construction, or proposed LNG projects including Calcasieu Pass, Corpus Christi Stage III, CP2, Plaquemines LNG, Rio Grande LNG, Sabine Pass, and Mexico Pacific Limited.[97] While not all of these contracts are associated with projects that have non-FTA authorizations from DOE or, if authorized, that are under construction pursuant to a final investment decision, these agreements show an increased interest from China in holding a position in U.S. LNG exports.

VIII. Environmental and Community Impacts

The production and transportation of natural gas in the U.S., including natural gas for export, has energy, labor/workforce, economic, environmental, social justice, and other implications. Communities of color, including those with Black, Indigenous, and Hispanic populations, as well as rural and low-income communities have historically been disproportionately exposed to the environmental risks, harms, and measurable impacts that arise from fossil fuel development and production activities, while often simultaneously relying on such activities to sustain their livelihoods and economies.[98]

Understanding the many environmental and societal effects of natural gas production and export and how they intersect with various federal, state, or local regulations is part of DOE's consideration of the public interest in reviewing applications to export natural gas, including LNG, to non-FTA countries.

Appendix D, *Addendum on Environmental and Community Effects of U.S. LNG Exports, serves as an update to the Addendum to Environmental Review Documents Concerning Exports of Natural Gas from the United States* (2014 Addendum), which explored many of these effects, but was prepared and published prior to 2016, when exports of LNG from the lower-48 states first started.[99] Appendix D contains a summary of publicly available peer-reviewed research across the physical and social sciences on the effects of natural gas production, transportation and exports on the environment and on local communities, supplemented in some instances by publicly available NGO and industry materials and news articles.

Consistent with the 2014 Addendum, the environmental and community impacts discussed in Appendix D are those from GHG and other air pollutants, water withdrawal and management, induced seismicity, land use and development, and the effects on communities. This update also considers two topics that were not addressed in the 2014 Addendum: effects on communities from activities associated with natural gas production and transportation, and effects on U.S. communities from natural gas exports from LNG facilities. As part of this report, FECM, with support from NETL and other DOE offices, reviewed the literature to identify and discuss many of these key implications for communities including labor, economic, environmental and social considerations.

Key findings from this review are summarized by topic area below.

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[97] See Long-term contract and registration information at https://www.energy.gov/fecm/articles/long-term-contract-information-and-registrations

[98] National Academies of Sciences, Engineering, and Medicine (NASEM). (2023). Pathways to an Equitable and Just Energy Transition: Principles, Best Practices, and Inclusive Stakeholder Engagement: Proceedings of a Workshop. Washington, DC: The National Academies Press. https://doi.org/10.17226/26935

[99] The first export of U.S. LNG from the lower-48 states was in February 2016. See U.S. Energy Information Administration (EIA), "Growth in domestic natural gas production leads to development of LNG export terminals," 4 March 2016 https://www.eia.gov/todayinenergy/detail.php?id=25232

A. GHG and Air Pollutants

Emissions of GHGs and other air pollutants can vary significantly across regions and supply chains, depending on the composition of the natural gas, the type of equipment used to process and transport it, and the number and size of emissions sources. Detection and quantification of methane emissions are key areas of focus for understanding the climate impacts of natural gas production, transport, and use. Higher methane emissions in the natural gas supply chain increase the life cycle climate impacts of natural gas. When the 2014 Addendum was published, DOE had not undertaken analyses of the GHG impacts of LNG exports. The subsequent studies, including the consequential GHG intensity analysis conducted as part of this study provide more detailed information on GHG impacts.

Natural gas development has impacts on local air quality due to emissions from activities such as vehicle emissions associated with well pad development and pipeline construction, well drilling and fracking, the venting or flaring of gas during well development, and related fugitive emissions. There are also impacts due to activities at the completed wells to clean and compress the produced natural gas and along the pipelines that deliver the gas to market. Depending on the pollutant, people at greater risk for experiencing air pollution-related health effects may include older adults, children and those with heart and respiratory diseases.

B. Water Withdrawals and Management

Water is used extensively in natural gas production through the hydraulic fracturing process. The amount of water used to hydraulically fracture a well varies depending on the region, the geology, the depth, thickness and extent of the shale formation, the technology used, the length of the horizontal well, operator decisions, availability of nearby water supplies, and regulatory requirements. Operators generally use some combination of fresh or brackish water from surface and groundwater sources, and/or produced water and recycled water that has already been used for fracking. While water consumption for hydraulic fracturing has been described as relatively minor compared with other industrial water uses in different regions and over different time periods, large withdrawals of water from local surface and groundwater sources can be significant locally.[100,101] Water withdrawals can impact local watersheds, though recycling process water is common. Increasing demand for water for hydraulic fracturing has incentivized operators to seek supplemental sources of water and alternatives to local freshwater supplies. Producers are increasingly prioritizing the use of brackish surface or groundwater, treated produced water, and municipal wastewater effluent.[102] For example, in 2023, about 50 percent of the water used for hydraulic fracturing in the Permian Basin was recycled produced water.[103]

Outside of water withdrawal effects, there are three major water contamination concerns around natural gas development: 1) the upward migration of fluids (injected hydraulic fracturing fluids, stray hydrocarbons) into groundwater aquifers; 2) surface spills of oil and gas production fluids, including produced water; and 3) the discharge of inadequately treated produced water to surface

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[100] Kondash, A.J., Albright, E., and Vengosh, A. (2017). Quantity of flowback and produced waters from unconventional oil and gas exploration. Science of the Total Environment, 574: 314–321. [Online]. Available from: https://www.sciencedirect.com/science/article/abs/pii/S004896971631988X

[101] Kondash, A.J., Lauer, N.E., and Vengosh, A. (2018). The intensification of the water footprint of hydraulic fracturing, Science Advances, 4(8). [Online]. Available from: https://www.science.org/doi/10.1126/sciadv.aar5982

[102] GWPC. (2023a). Produced Water Report: Regulations and Practices Update. [Online]. Available from: https://www.gwpc.org/wp-content/uploads/2023/06/2023-Produced-Water-Report-Update-FINAL-REPORT.pdf

[103] Norton, R. (2024). Presentation by Robert Norton of Deep Blue at the Produced Water Society Conference, 7 February 2024.

water sources. Migration of fracturing fluid from the deep subsurface into shallow groundwater is very rare. To date, it has only been documented in a few locations, such as in Pavilion, Wyoming, where the hydraulic fracturing process was mismanaged.[104] Gas migration along wellbores with integrity issues from the producing formation upwards into groundwater aquifers is a greater concern than fracturing fluid contamination, but still somewhat rare. Wastewater spills appear to pose more of a risk than subsurface migration pathways from oil and gas development. Most leaks and spills are accidental. Intentional illegal dumping of produced water and other wastes also occurs. Dumping of produced water may cause significant changes in soil chemistry and changes in microbial community structure, likely due to the high salinity of the produced water.

C. Induced Seismicity

The term “induced seismicity” refers to seismic events precipitated by human activities. Two practices that have been studied in relation to induced seismicity are underground injection and hydraulic fracturing. Underground injection is the practice of pumping produced water and wastewater deep underground into highly permeable, porous subsurface rock formations where it can be permanently stored, and it is one of the most commonly used methods of managing produced water. Researchers have found extensive spatial and temporal correlations between induced seismicity and the disposal of produced water through underground injection into saltwater disposal wells (SWDs) in the U.S. Midwest including Texas, Oklahoma, Kansas, Colorado, Arkansas, and Ohio. Researchers have focused on produced water injection as the source of most induced seismicity in oil and gas producing areas in the U.S. While some research has also identified spatial and temporal correlations between hydraulic fracturing and seismic activity, in the U.S., seismicity caused by produced water injection is much more frequent. Good management practices (which cannot be developed without transparency and data sharing) can substantially reduce, but will likely not fully eliminate, seismic hazards.[105,106] Effective management requires careful site selection and characterization, sensitive seismic monitoring to detect problematic seismicity before it negatively impacts operations or surrounding communities, and risk-based mitigation planning.[107,108]

D. Land-Use Changes

Land use changes result from well drilling and other production activities; gathering and transportation pipelines, compressor stations and processing plants; water and waste disposal facilities; and impacts on railroads and highways due to natural gas development. A review of existing literature finds evidence that oil and gas production and transportation activities contribute

[104] DiGiulio, D. C., and Jackson, R. B. (2016). Impact to Underground Sources of Drinking Water and Domestic Wells from Production Well Stimulation and Completion Practices in the Pavilion, Wyoming, Field. Environmental Science and Technology, 50, 4524-4536. [Online]. Available from: https://doi.org/10.1021/acs.est.5b04970

[105] Rathnaweera, T. D., Wu, W., Yinlin, J., Gamage, R.P. (2020). Understanding injection-induced seismicity in enhanced geothermal systems: from the coupled thermo-hydro-mechanical-chemical process to anthropogenic earthquake prediction. Earth-Science Reviews. [Online]. Available from: https://research.monash.edu/en/publications/understanding-injection-induced-seismicity-in-enhanced-geothermal

[106] White, J. and Foxall, W. (2016). Assessing induced seismicity risk at CO_2 storage projects: Recent progress and remaining challenges. International Journal of Greenhouse Gas Control. [Online]. Available from: https://doi.org/10.1016/j.ijggc.2016.03.021

[107] Ibid.

[108] Templeton, D., Schoenball, M., Layland-Bachmann, C., Foxall, W., et al. (2021). Recommended Practices for Managing Induced Seismicity Risk Associated with Geologic Carbon Storage. Lawrence Livermore National Laboratory (LLNL). [Online]. Available from: https://www.osti.gov/servlets/purl/1841840

to habitat loss and degradation for plants and animals.[109] In particular, the development and siting of drilling sites for natural gas production can temporarily disrupt the habitat of both plant and animal species through the clearing and reconfiguration of the land area occupied by well pads, pipelines, and roads.

However, horizontal drilling allows operators to drill more wells from a single pad. Research shows that, for instance, in West Virginia, unconventional oil and gas wells drilled between 2009 and 2012 caused land disturbances five times greater at well sites than conventional oil and gas wells; however, unconventional wells produced 28 times more energy per hectare of land disturbed.[110]

Other impacts include increased noise, light, and human activity associated with natural gas production and transportation, which can have consequences for wildlife populations. Options for mitigating habitat fragmentation and other detrimental effects to wildlife include requiring buffers or setbacks, fewer but larger well pads to reduce well density, placement of infrastructure on degraded land, and controls on emissions, noise, and light. Many operators already utilize such practices.

E. Effects on Communities

Multiple studies have found that natural gas production, transportation and export facilities tend to be sited in areas that are disproportionately home to communities of color and low-income communities. Gas production and processing emits air pollutants harmful to human health including methane, volatile organic compounds (VOCs), particulate matter (PM), nitrogen oxides and hazardous air pollutants (HAPs).[111] Proximity to oil and gas production is associated with increased mortality in local communities.[112],[113] Research is limited on the health effects of populations living in proximity to transportation facilities such as pipelines and compressor stations.

From an economic perspective, natural gas production tends to increase employment and wages in regions and communities where it occurs, and oil and gas production activities overall can have a multiplier effect where one direct job leads to additional jobs. However, there is some evidence that production-related jobs often go to people who either move to the area for the jobs or commute from other areas rather than to long-term residents. Growth in oil and gas production generates new revenues to local governments, but it also brings additional burdens, such as increased emergency services and police, water and wastewater infrastructure, and heavy road usage and associated damages. Furthermore, local mineral rights holders will receive royalties through leasing their land for development, though many such recipients are often not local residents. Finally, property prices may rise with increased production, though properties near production facilities or natural gas pipelines may decline. Quality of life impacts include noise,

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[109] Deziel, N. C., Clark, C.J., Casey, J.A. et al. (2022). Assessing Exposure to Unconventional Oil and Gas Development: Strengths, Challenges, and Implications for Epidemiologic Research. Curr Envir Health Rpt 9, 436–450 (2022). https://doi.org/10.1007/s40572-022-00358-4

[110] Grushecky, S. T., Zinkhan, F. C., Strager, M. P., and Carr, T. (2022). Energy production and well site disturbance from conventional and unconventional natural gas development in West Virginia. Energy, Ecology and Environment. [Online]. Available from: https://doi.org/10.1007/s40974-022-00246-5

[111] EPA. (2023). Basic Information about Oil and Natural Gas Pollution Standards. EPA. [Online]. Available from: https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-operations/basic-information-about-oil-and-natural

[112] Li, L., Dominici, F., Blomberg, A.J. et al. (2022). Exposure to unconventional oil and gas development and all-cause mortality in Medicare beneficiaries. Nat Energy 7, 177–185 (2022).

[113] Apergis, N. and Ghulam Mustafa, S. (2021). An analysis of the impact of unconventional oil and gas activities on public health: New evidence across Oklahoma counties, Energy Economics, Volume 97, 2021, 105223, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2021.105223

light pollution, increased traffic, and social disruptions due to the cyclical nature of the production industry.

Significantly less research is available on the impact of LNG facilities themselves on local communities. The operation of LNG export facilities releases pollutants that are harmful to human health, mostly from venting or flaring to burn away excess natural gas. Existing and proposed U.S. LNG export facilities are concentrated on the Gulf Coast, particularly in Texas and Louisiana. Some areas, such as Port Arthur, Cameron Parish and Calcasieu Parish, and Corpus Christi already have extensive petroleum industry activity. The concentration of industries in these areas has left a legacy of pollution and public health impacts that many residents and local community groups weigh when considering the potential impact of existing and proposed LNG export facilities, even though their emissions profiles are different.

Development of LNG facilities also impacts local employment. LNG export facility operators and construction contractors typically employ thousands of workers during facility construction, but the facilities have a much smaller staff of employees when operational. Both the construction and operational phases of LNG export terminals provide for high-wage employment. At the same time, some local community members assert that the high-wage positions tend to go to workers from out of the area. In addition, other local industries, such as shrimping and fishing, have already been struggling with the effects of climate change, hurricanes, and particularly with low-cost imported shrimp, and some people in those industries have raised concerns that LNG export facilities add further disruptions and challenges.[114,115]

[114]Chavez, R. (2023). Louisiana shrimpers are in trouble. Here’s why. PBS News, 2 June 2023. https://www.pbs.org/newshour/economy/louisiana-shrimpers-are-worried-imports-will-sink-them-for-good

[115] Villareal, L. (2023). 'A gulf and national issue' | Southeast Texas shrimpers struggling to survive due to influx of imported shrimp. 12 News Now, 4 September 2023. https://www.12newsnow.com/article/news/local/shrimpers-struggling-imported-shrimp/502-5e2452b3-cce6-4d8a-8c2e-ab0c9a7e7813