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The Climate Implications of U.S. Liquefied Natural Gas, or LNG, Exports

By Gwynne Taraska and Darryl Banks

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Introduction and summary

As the expansion of shale gas production has positioned the United States to become a potential net exporter of natural gas, the overall effect that increased exports would have on the climate has been in dispute.

Many aspects of an increased natural gas exports scenario would affect emissions. On the one hand, natural gas could partially displace the use of coal overseas in the generation of electricity. This would put downward pressure on emissions, as natural gas plants on average emit approximately 50 percent less carbon dioxide, or CO_2, than coal plants.[1]

On the other hand, methane, which is a potent, short-lived greenhouse gas with many times the warming potential of CO_2, escapes into the atmosphere from leaks and intentional venting throughout the natural gas supply chain. Although cost-effective technologies exist that minimize the escape of methane, there is evidence that current levels of methane emissions can be high. Recent studies of air samples collected over natural gas production sites in the western United States reveal leakage rates of 4 percent at the Denver-Julesburg Basin and 6.2 percent to 11.7 percent at the Uinta Basin.[2]

Other aspects of the natural gas trade further complicate the climate effect of exports. For example, the physical process of transporting natural gas carries a sizable emissions penalty. Natural gas destined for overseas ports is liquefied, shipped, and later re-gasified. Each stage of the exports process results in greenhouse gas emissions.[3] A recent analysis from the National Energy Technology Laboratory estimates that liquefaction, shipping, and re-gasification account for approximately 17 percent of total emissions associated with liquefied natural gas, or LNG, exports when the destination is Europe, and 21 percent of total emissions when the destination is Asia.[4]

It is possible for an increased LNG exports scenario to result in an overall benefit for the climate, but the necessary conditions are formidable. In the near term, fuel switching could drive a net decrease in global emissions, but only if methane emissions are strictly controlled. Taking a longer view, it is important to consider whether exports to a particular region would slow a transition to a low-carbon economy. Heavy investments in natural gas infrastructure could lock in the use of fossil fuels. LNG exports to a particular region could therefore be defensible from a climate perspective only if the following conditions are met:

- Methane emissions are strictly controlled domestically and overseas
- The exported LNG displaces coal or prevents new use of coal
- The exported LNG does not displace low-carbon power sources or impede growth in the use of low-carbon power sources

These conditions set a high bar, although not an impossible one. Not only must the potential near-term benefit of LNG exports be realized—by displacing coal and controlling methane emissions—but it must be ensured that the exports do not serve to prolong the world's dependence on fossil fuel.

This report explains the aspects of an increased exports scenario that affect emissions and the conditions that are necessary for LNG exports to be defensible from an emissions standpoint. In addition, given that many applications to export LNG have already been approved by the Department of Energy and it is likely that further approvals are forthcoming—see the next section for background information—this report makes several recommendations for mitigating emissions in the context of the impending LNG trade and for moving some distance toward meeting the conditions necessary to see a net emissions benefit. In particular, it recommends that the Environmental Protection Agency, or EPA, set enforceable, stringent limits on methane emissions and that the Bureau of Land Management, or BLM, address methane leakage in the context of its proposed rules on venting and flaring. It also recommends using any LNG exports to create dedicated revenues to support clean energy and energy efficiency.

Background

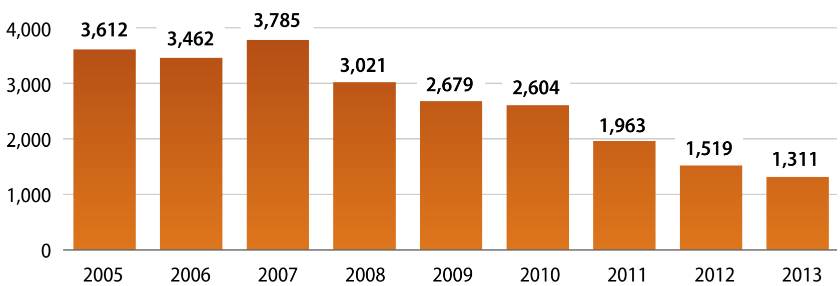
New directions in the U.S. natural gas trade

The recent expansion in shale gas production in the United States has changed the natural gas trade. U.S. natural gas production reached a record of 70.18 billion cubic feet per day in 2013 and is expected to increase by 4 percent in 2014.[5] As the supply of natural gas in the United States has grown, net imports of natural gas have been on a downward trend. In 2013, net imports decreased by 14 percent, reaching their lowest point since 1989.[6] The United States is still a net importer of natural gas; it is expected to be a net exporter before 2020.[7]

FIGURE 1

U.S. natural gas net imports, 2005-2013

Billion cubic feet, or Bcf



U.S. Energy Information Administration, "U.S. Natural Gas Imports & Exports 2013," available at http://www.eia.gov/naturalgas/importsexports/annual/ (last accessed July 2014).

A substantial increase in export volumes could have a number of effects, including effects on geopolitics, the U.S. economy, the U.S. manufacturing sector, the environment, and the climate. A debate therefore has been unfolding about whether a substantial increase in exports should be blocked or encouraged. A previous CAP report, titled "U.S. Liquefied Natural Gas Export: A Primer on the Process and the Debate," covers this ground; this paper focuses exclusively on the climate effects of increased exports.[8]

Regulatory conditions for export

There are two regulatory requirements for proposed LNG export facilities. The first is approval by the Federal Energy Regulatory Commission, or FERC. As required by the Natural Gas Act, FERC must approve the construction and siting of onshore or near-shore LNG export terminals.[9] As required by the National Environmental Policy Act, or NEPA, FERC assesses the environmental effects of LNG projects under its jurisdiction. An environmental impact statement must be prepared for projects that will have a significant effect on the environment.

The second regulatory requirement is approval by the U.S. Department of Energy, or DOE. Under the Natural Gas Act, DOE is required to immediately approve applications to export LNG to countries with which the United States has a free-trade agreement, or FTA. For applications to export LNG to non-FTA countries, DOE grants authorization unless it finds that the project is at odds with the public interest. Some of the largest markets for LNG are currently non-FTA regions, such as Japan and Europe.[10]

In June 2014, the House passed a bill that would require DOE to decide applications within 30 days of the conclusion of the NEPA process. The bill would also require the applicant to publicly disclose the destination countries. It has been sent to the Senate.[11]

Current state of applications to export LNG to non-FTA countries

Since granting long-term authorization in May 2011 for the Sabine Pass terminal (Louisiana) to export LNG to non-FTA countries, DOE has approved applications from Freeport LNG (Texas), Lake Charles Exports (Louisiana), Dominion Cove Point (Maryland), Jordan Cove Energy Project (Oregon), Cameron LNG (Louisiana), and, most recently, Oregon LNG on July 31, 2014.[12] More than 20 additional applications to export LNG to non-FTA countries are under review.[13]

Sabine Pass, Cameron LNG, and Freeport LNG have also received approval from FERC. The Sabine Pass project is under construction and is expected to begin exports in late 2015.[14] The Freeport and Cameron projects are expected to begin construction later this year with commercial operations beginning in 2018 and 2019.[15]

Aspects of an increased exports scenario that would affect emissions

The question of whether exporting substantial volumes of LNG would result in a net benefit for the climate is complicated by the fact that many aspects of an increased exports scenario—such as increased domestic production, emissions from the exports process, fuel switching, and methane leakage—would affect greenhouse gas emissions.

Increased domestic production and associated greenhouse gas emissions

An increase in LNG exports would cause an increase in the domestic production of natural gas. A 2012 study by the U.S. Energy Information Administration, or EIA, estimated that 60 percent to 70 percent of exports would be supplied by increased natural gas production.[16]

As the production of natural gas causes both CO_2 and methane emissions, an increase in LNG exports would cause an increase in domestic greenhouse gas emissions. There have been a number of studies of the footprint of natural gas before it reaches the power plant. For example, an analysis by the National Energy Technology Laboratory, or NETL, estimates that "upstream" greenhouse gas emissions—from the extraction and processing of natural gas and the transmission of natural gas through U.S. pipelines—are 9.1 grams of CO_2-equivalent per megajoule, or g CO_2e/MJ, for natural gas from the Marcellus Shale in the eastern United States.[17] An analysis by Christopher L. Weber and Christopher Clavin, which examines six studies of the upstream footprint of natural gas, finds a mean of 14.6 CO_2e/MJ for shale gas.[18]

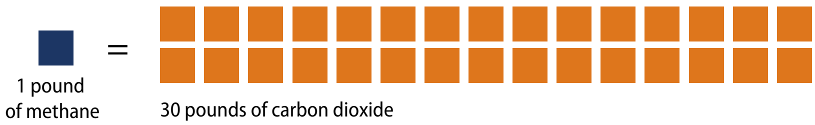
The exact upstream footprint of natural gas is debated; a main point of contention is the rate of methane leakage, which is discussed separately below. However, many studies of upstream emissions will need to adjust their numbers upward in light of the latest science. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change finds that methane traps 85 times as much heat as CO_2 over a 20-year time frame and 30 times as much heat over a 100-year time frame.[19]

Many of the studies above rely on the now-outdated figure that methane traps 25 times as much heat over a 100-year time frame. It is also important to note that studies typically use the longer time frame and therefore do not reflect the short-term potency of methane. Using the shorter time frame, the NETL figure for the upstream footprint of gas from the Marcellus Shale jumps from 9.1 g CO_2e/MJ to 20.5 g CO_2e/MJ.[20]

FIGURE 2

Global warming potential of methane

Methane causes approximately 30 times as much warming over a 100-year time frame as an equivalent mass of carbon dioxide



Intergovernmental Panel on Climate Change, "Fifth Assessment Report" (2014), available at http://www.ipcc.ch/index.htm#.U0QQ7GbD-70.

Upstream greenhouse gas emissions are therefore a main consideration when evaluating the climate effect of LNG exports. To put the figures in perspective: upstream emissions were equivalent to roughly a quarter of the emissions from natural gas power plant operations in NETL's recent analysis of export scenarios using the 100-year time frame for the global warming potential of methane. They were equivalent to more than half of the emissions from natural gas power plant operations using the 20-year time frame.[21]

It may be relevant to U.S. policymakers that the emissions from natural gas production would obviously be incurred domestically, whereas the bulk of the emissions reductions caused by exports—from fuel switching, for example—would be incurred overseas. From a global perspective, however, upstream emissions associated with increased production are only one of the factors relevant to the question of whether LNG exports would have a positive or negative effect on the climate.

Before moving on to these other factors, it is worth noting—although the environmental and health effects of increased production are formally outside the scope of this paper—that the majority of increased production would come from shale formations. Extracting natural gas from shale is accomplished through hydraulic fracturing, or fracking, which carries a raft of well-known risks, including surface water and groundwater pollution, air pollution, earthquakes, and habitat destruction.[22]

Greenhouse gas emissions from the exports process

Natural gas destined for overseas is first liquefied, then shipped, and finally re-gasified. Each step of the process carries an emissions penalty. According to NETL's recent analysis, liquefaction, shipping, and re-gasification account for approximately 17 percent of total greenhouse gas emissions—from extraction through power distribution—in the scenario of LNG exports to Europe, and 21 percent of total greenhouse gas emissions in the scenario of LNG exports to Asia.[23]

FIGURE 3

Percentage of total greenhouse gas emissions from LNG per life-cycle stage

European scenario

National Energy Technology Laboratory, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States" (2014), available at http://energy.gov/sites/prod/files/2014/05/f16/Life%20Cycle%20GHG%20Perspective%20Report.pdf.

The exports process also carries an energy penalty. NETL finds that 8 percent of natural gas that reaches a liquefaction facility would be used to power the liquefaction process.[24] An EIA analysis assumes a 10 percent loss due to gas used to power the liquefaction process.[25]

Fuel switching and changes in electricity demand overseas

LNG is expected to displace some amount of coal in power generation overseas.[26] This is a reasonable assumption: LNG buyers, including China, India, Japan, Germany, and Korea, currently use a substantial amount of coal for power generation.[27] In fact, these countries are in the global top 10 in terms of electricity generation by coal.[28] For example, in Japan, coal is the second-largest source of electricity, behind gas and ahead of oil and nuclear.[29] Coal is the largest source in Germany, Korea, and China.[30]

As greenhouse gas emissions from the combustion of coal are more than twice the emissions from the combustion of natural gas, coal-to-gas switching puts more downward pressure on greenhouse gas emissions than any of the other effects of LNG exports.[31] This, however, must be weighed against factors that put upward pressure on emissions, such as increased production and methane leakage, as well as the fact that LNG could cut into not just the use of coal in power generation but also the use of clean energy sources.

Furthermore, LNG exports are also expected to reduce prices for natural gas overseas, which in turn is expected to increase demand for electricity overseas and therefore put some upward pressure on greenhouse gas emissions.

Fuel switching and changes in electricity demand in the United States

While the price of natural gas overseas is expected to decline with an influx of LNG exports, the price of natural gas in the United States is widely expected to increase.[32] This is expected to contribute to an increase in the price of electricity resulting in a decrease in demand for electricity, which would put some downward pressure on emissions.

In contrast, an increase in the price of natural gas is also expected to reduce the use of natural gas in electricity generation. According to a previous EIA analysis, 65 percent of the reduction in natural gas-fired generation is offset by an increase in coal-fired generation, which would put upward pressure on emissions.[33] The EPA's proposed plan to reduce emissions from power plants, however, may prevent a shift toward coal.

EIA is currently updating its analysis, and DOE is commissioning a new study on the economic effects of LNG exports, which will clarify the effect of exports on the domestic fuel mix and energy demand.[34]

Emissions from methane leakage

Methane escapes into the atmosphere throughout the life cycle of natural gas. These emissions could significantly cut into the climate benefits of replacing coal with natural gas in the electric-power sector if the rate of methane emissions is high.

The rate of methane emissions from natural gas systems is contentious and differs from study to study. NETL estimates that 1.1 percent of produced gas escapes into the atmosphere from extraction through delivery to domestic large-scale consumers.[35] The EPA's estimate of methane leakage is 1.5 percent of gross production, but several notable new analyses, including a study by Scot Miller and others and another by A.R. Brandt and others, find that official inventories of methane emissions need to be revised significantly upward.[36] A study from Andrew Burnham and others finds the leakage rate for unconventional natural gas to be 2.01 percent, and a study from Weber and Clavin finds the rate to be 2.42 percent.[37] Recent studies that have collected air samples over natural gas production sites in the western United States have found rates that are even higher, such as 4 percent over the Denver-Julesburg Basin and 6.2 percent to 11.7 percent over the Uinta Basin.[38]

These studies show that although methane emissions can be kept low with adequate equipment and monitoring—see, for example, a study by David T. Allen and others that finds a leakage rate of 0.42 percent at well-maintained production sites—the reality can be quite different.[39] Methane emissions—from the domestic production site to the gate of the overseas power plant—are therefore a primary factor in the determination of the climate effect of LNG exports.

The potential overall effect of LNG exports on near-term emissions

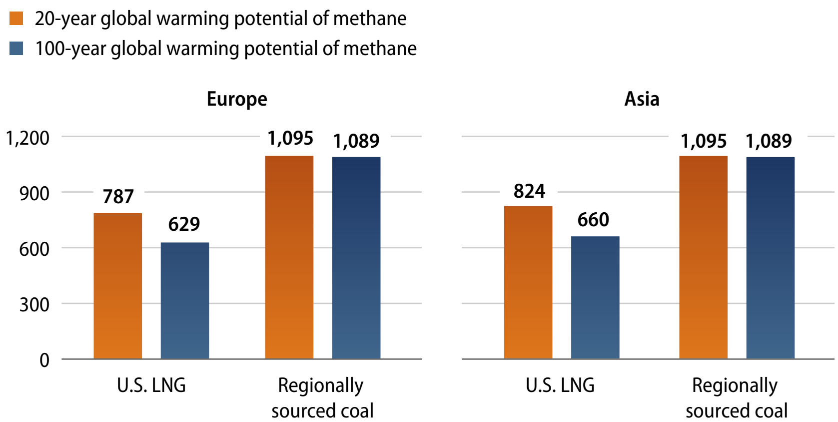
Given that some aspects of an increased LNG exports scenario would put upward pressure on emissions and some would put downward pressure on emissions, there has been disagreement about the overall effect on the climate.[40]

NETL recently released an analysis of the overall effect that LNG exports could have on global emissions, which used the newest information about the global warming potential of methane. It held that exporting U.S. LNG for power generation would result in a decrease in greenhouse gas emissions compared to scenarios where regionally sourced coal is used for power generation. According to NETL, the decrease would be 28 percent in the case of exports to Europe and 25 percent in the case of exports to Asia, using the 20-year global warming potential of methane. It would be 42 percent and 39 percent, respectively, using the 100-year time frame, which masks the short-term potency of methane.[41]

FIGURE 4

Greenhouse gas emissions: U.S. LNG versus regionally sourced coal

kg CO_2e/MWh



Source: National Energy Technology Laboratory, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States" (2014), available at http://energy.gov/sites/prod/files/2014/05/f16/Life%20Cycle%20GHG%20Perspective%20Report.pdf.

It is worth noting that the analysis does not take into account EPA's New Source Performance Standards, which, according to NETL, would reduce emissions from the U.S. LNG scenarios by 3.4 percent.[42]

However, a striking finding of the analysis is that there is some overlap between the uncertainty ranges of the U.S. LNG scenario and the regional coal scenario in Asia when the greenhouse gas results use the 20-year global warming potential of methane. NETL maintains that the overlap is based, in part, "on an assumption of high methane leakage (1.6%)."[43] But it is clear from recent studies that 1.6 percent does not constitute an assumption of high leakage. The "breakeven leakage"—that is to say, the point at which emissions from the LNG scenario equal emissions from the regional coal scenario—is 1.9 percent for Europe and 1.4 percent for Asia on the 20-year time frame. Given recent studies, it is likely that these break-even points would be exceeded under current conditions.

In addition, the NETL study does not take into account pipeline transport in the importing country. Instead, it assumes that the power plant is near the re-gasification facility. Taking pipeline transport into account could increase methane estimates in the LNG scenarios and further offset any advantage of U.S. LNG over regional coal.

TABLE 1

Breakeven methane leakage rates for U.S. LNG

	LNG to Europe	LNG to Asia
20-year time frame	1.9%	1.4%
100-year time frame	5.8%	4.6%

Source: National Energy Technology Laboratory, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States" (2014), available at http://energy.gov/sites/prod/files/2014/05/f16/Life%20Cycle%20GHG%20Perspective%20Report.pdf.

The NETL analysis makes it clear that LNG exports have the potential to decrease near-term emissions if they substitute for coal, but a more realistic estimate of current leakage rates makes it clear that exports could do more harm than good in the absence of adequate measures to control methane. The outlook could be even bleaker if LNG displaces not only coal but also low-carbon power sources.

It should be noted that the NETL study—and this paper—concerns only power generation; a study is also needed for exported LNG destined for other sectors, such as the industrial and residential sectors.

The conditions under which LNG exports could benefit the climate

Even if LNG exports result in a modest near-term decrease in emissions, they could do long-term damage to the climate if they cause heavy investments in natural gas terminals and power plants that serve to prolong the use of fossil fuels in the world's energy systems. As discussed in a previous CAP report, titled "U.S. Natural Gas Must Peak by 2030," natural gas has emissions benefits compared to coal, but it is not a solution for global warming.[44]

In order for LNG exports to a particular region to maintain some climate benefit over the long term, it is therefore necessary not only for methane emissions to be controlled and for the LNG to be used to displace coal rather than displacing low-carbon energy or local natural gas. It is also imperative that investments in natural gas infrastructure do not hamper a transition to a low-carbon economy.

It may be difficult—although not impossible—for these conditions to be met. Follow-up work will be needed to determine whether likely LNG importers meet them.

Recommendations

A certain level of LNG exports is inevitable given applications already approved by U.S. regulatory bodies. It is also possible that nonclimate considerations such as economic and geopolitical considerations will politically dominate concerns about locking in the use of fossil fuels. This underlines the importance of identifying and then implementing measures to control methane along with measures to leverage LNG exports to financially support clean energy.

- **The EPA should set enforceable, stringent limits on methane emissions through the Clean Air Act.** President Barack Obama recently released his Strategy to Reduce Methane Emissions, in which he directs the EPA to assess sources of methane leakage from oil and gas systems. The EPA has completed a set of white papers and is currently considering whether to drive methane reductions through regulations.

- **The BLM should also establish standards to reduce methane leakage.** The Bureau of Land Management is in the process of developing a proposed rule to curb methane emissions from the venting and flaring of gas from oil and gas development on federal lands. They should also address methane leakage in the context of this rulemaking.

- **The United States should consider ways of pricing LNG to capture the externalities of fossil fuels and help drive emissions reductions.** A previous CAP report suggested that fees—including a possible export fee—should be assessed on natural gas.[45] Policymakers should explore the options for utilizing the natural gas expansion in the United States to create dedicated revenues to support clean energy and energy efficiency.[46]

In addition, the Department of Energy, when evaluating export applications in the future, should take into account the long-term climate effect of further exports. It also may want to consider whether the applicant's planned contracts are with companies that participate in methane reduction programs, such as the Climate and Clean Air Coalition's Oil and Gas Methane Partnership.

Conclusion

Much has been made of the climate benefit of displacing coal with natural gas and of the associated methane emissions, which work to offset that benefit. But while the strict control of methane worldwide and the displacement of coal in the generation of electricity are necessary conditions for LNG exports to be defensible from a climate perspective, they are insufficient. It would be shortsighted to settle for methane reductions at the cost of locking in avoidable levels of CO_2 emissions from the combustion of natural gas. Natural gas may be cleaner than coal, but it still produces significant levels of carbon emissions upon combustion. From a climate perspective, LNG exports to a particular region are therefore defensible only if they result in a near-term emissions benefit and, in addition, do not serve to prolong the world's dependence on fossil fuels and the associated carbon pollution.

About the authors

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3 Natural gas is liquefied before transport by tanker because the volume of natural gas in its liquid state is only 1/600 of its volume as a gas.

4 Timothy J. Skone and others, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States" (Washington: National Energy Technology Laboratory, 2014).

5 Total marketed production. U.S. Energy Information Administration, "Short-Term Energy Outlook 2014: Table 5a: U.S. Natural Gas Supply, Consumption, and Inventories," available at http://www.eia.gov/forecasts/steo/tables/?tableNumber=15 (last accessed July 2014).

6 U.S. Energy Information Administration, "U.S. Natural Gas Imports & Exports 2013," available at http://www.eia.gov/naturalgas/importsexports/annual/ (last accessed July 2014).

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9 Offshore facilities are under the jurisdiction of the Maritime Administration, or MARAD. The vast majority of applications to export LNG to countries with which the United States does not have a free-trade agreement are for facilities under the jurisdiction of FERC.

10 It should be noted that Japan is one of the countries involved in the Trans-Pacific Partnership, which is a trade agreement currently under negotiation among 11 countries including the United States and Canada.

11 *Domestic Prosperity and Global Freedom Act,* H. Rept. 6, 113 Cong. 2 Sess. (Government Printing Office, 2014).

12 U.S. Department of Energy, "Energy Department Conditionally Authorizes Oregon LNG to Export Liquefied Natural Gas," Press release, July 31, 2014, available at http://energy.gov/articles/energy-department-conditionally-authorizes-oregon-lng-export-liquefied-natural-gas.

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16 The remaining amount of exports—30 percent to 40 percent—would be diverted from existing production that would have been consumed in the United States in the absence of dampened demand caused by higher natural gas prices. A minor fraction of exports would be supplied by imports from Canada. U.S. Energy Information Administration, "Effect of Increased Natural Gas Exports on Domestic Energy Markets: As Requested by the Office of Fossil Energy" (2012), available at http://energy.gov/sites/prod/files/2013/04/f0/fe_eia_lng.pdf.

17 Anthony Zammerilli and others, "Environmental Impacts of Unconventional Natural Gas Development and Production" (Washington: National Energy Technology Laboratory, 2014).

18 The uncertainty range in Weber and Clavin for shale is 11.0 g CO_2e/MJLHV to 21.0 g CO_2e/MJLHV. The six studies examined are from NETL, Stephenson, Burnham, Hultman, Howarth, and Jiang. Christopher L. Weber and Christopher Clavin, "Life Cycle Carbon Footprint of Shale Gas: Review of Evidence and Implications," *Environmental Science and Technology* 46 (2012): 5688–5695. The focus is on the figures for shale rather than conventional gas, as the majority of new production would come from shale sources. However, upstream emissions from conventional and shale sources have been found to be comparable. See, for example, Weber and Clavin.

19 Intergovernmental Panel on Climate Change, "Fifth Assessment Report" (2014).

20 Timothy J. Skone and others, "Life Cycle Analysis of Natural Gas Extraction and Power Generation" (Washington: National Energy Technology Laboratory, 2014).

21 Skone and others, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States." The IPCC AR5 figures for the global warming potential of methane were used.

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23 Using the current IPCC AR5 global warming potential of methane over a 100-year time frame. Skone and others, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States."

24 Zammerilli and others, "Environmental Impacts of Unconventional Natural Gas Development and Production."

25 U.S. Energy Information Administration, "Effect of Increased Natural Gas Exports on Domestic Energy Markets."

26 Michael Levi, "A Strategy for U.S. Natural Gas Exports" (Washington: The Hamilton Project, 2012).

27 International Energy Agency, "Statistics by Region, 2011," available at http://www.iea.org/statistics/statisticssearch/ (last accessed July 2014).

28 International Energy Agency, "Key World Energy Statistics" (2013).

29 International Energy Agency, "Statistics by Region."

30 Ibid.

31 See Skone and others, "Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States." In this analysis, combustion in the scenario of regionally sourced coal produces more than twice the emissions as combustion in the LNG scenario.

32 In an analysis by EIA, the price increases in its export scenarios peak between 14 percent and 36 percent above the reference case, and consumers pay up to 3 percent more for electricity. U.S. Energy Information Administration, "Effect of Increased Natural Gas Exports on Domestic Energy Markets." In an analysis by Kemal Sarica and Wallace Tyner, the price increases in its export scenarios peak between 16 percent and 47 percent above the reference case. Kemal Sarica and Wallace E. Tyner, "Economic and Environmental Impacts of Increased U.S. Exports of Natural Gas" (West Lafayette, IN: Purdue University, 2013).

33 U.S. Energy Information Administration, "Effect of Increased Natural Gas Exports on Domestic Energy Markets."

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36 Scot Miller and others, "Anthropogenic Emissions of Methane in the United States," *PNAS* (2013); A. R. Brandt and others, "Methane Leaks from North American Natural Gas Systems," *Science* 343 (2014): 733-735.

37 Andrew Burnham and others, "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum," *Environmental Science and Technology* 46 (2012): 619–627; Weber and Clavin, "Life Cycle Carbon Footprint of Shale Gas: Review of Evidence and Implications." These and other leakage rates are given in James Bradbury and others, "Clearing the Air: Reducing Upstream Greenhouse Gas Emissions from U.S. Natural Gas Systems" (Washington: World Resources Institute, 2013).

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40 For the net-detriment argument, see, for example, Joe Romm, "Energy Department Bombshell: LNG Has No Climate Benefit for Decades, if Ever," Climate Progress, June 4, 2014, available at http://thinkprogress.org/climate/2014/06/04/3443211/energy-department-lng-no-climate-benefits/. See also James Bradbury, "Testimony of James Bradbury," Testimony before the U.S. House of Representatives Energy and Commerce Subcommittee on Energy and Power," "U.S. Energy Abundance: Exports and the Changing Global Energy Landscape," May 7, 2013. For the net-benefit argument focused on fuel switching, which is commonly found in the natural gas industry, see, for example, Center for Liquefied Natural Gas, "About LNG: Environment," available at http://www.lngfacts.org/about-lng/environment/ (last accessed July 2014).

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