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SPECIAL REPORT

Competition on Emissions: Coal Vs LNG

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In January 2024, U.S. President Joe Biden issued a moratorium on the expansion of liquefied natural gas (LNG) exports, citing the need for a comprehensive assessment of the environmental, economic, and geopolitical impacts. A recent study by Professor Robert Howarth, which was among other sources to justify President Biden's moratorium, compared life cycle greenhouse gas (GHG) emissions of LNG exported from the United States to coal. According to Howarth's findings, LNG has a larger GHG footprint than coal and his study recommended that additional resources should not be allocated to further LNG projects. Is LNG a cleaner energy source than coal? What is the basis for Howarth's assertions that coal has less of a GHG footprint than LNG? Are there feasible technological innovations that can make LNG and coal less polluting?

SPECIAL REPORT

This research paper is a Special Report published by the Al-Attiyah Foundation. Each Special Report focuses on a prevalent current affairs topic that has ramifications for the energy industry and wider community. The papers are distributed in hard copy to members, partners, and universities, as well as made available online to all Foundation members.

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- This report provides a comprehensive analysis of the greenhouse gas (GHG) emissions associated with liquefied natural gas (LNG) and coal, evaluating their respective environmental impacts through detailed life-cycle assessments. The study debates the methodologies and findings of key research, including Professor Robert Howarth's 2023 analysis, which suggests LNG's GHG footprint may surpass coal under certain conditions. The document contrasts this view with studies by other experts, such as Dr Leslie Abrahams, and data from the National Energy Technology Laboratory (NETL).
- While LNG is widely considered cleaner than coal due to lower combustion emissions, the analysis underscores the critical importance of upstream methane leakage rates in determining its overall environmental performance. Empirical evidence indicates methane leaks from U.S. natural gas systems are higher than some official estimates, emphasising the need for updated data and technological advancements to reduce emissions. Available benchmarking exercises by various authors reveal that LNG outperforms coal in most scenarios, especially for power generation under a 100-year GWP framework. However, specific assumptions—such as a 20-year GWP or high methane leakage rates and production of heat rather than power—can sporadically tip the balance in favor of coal.
- This paper will explore the viability of technological innovations that reduce methane emissions in the LNG supply chain.
- Overall, the paper finds that LNG represents a superior alternative to coal, particularly when robust methane management practices are implemented.

In January 2024, U.S. President Biden issued a moratorium on the expansion of LNG exports, citing the need for a comprehensive assessment of the environmental, economic, and geopolitical impacts. This decision has sparked debates, as it came at a time when global energy demand is surging due to population growth and increased urbanisation. A recent study by Professor Robert Howarth[1], which was cited among other sources to justify President Biden's moratorium[2], assessed the life-cycle GHG emissions of LNG exported from the U.S. compared to coal[3].

According to Howarth's findings, LNG has a larger GHG footprint than coal. Consequently, his study recommended that additional resources should not be allocated to further LNG projects.

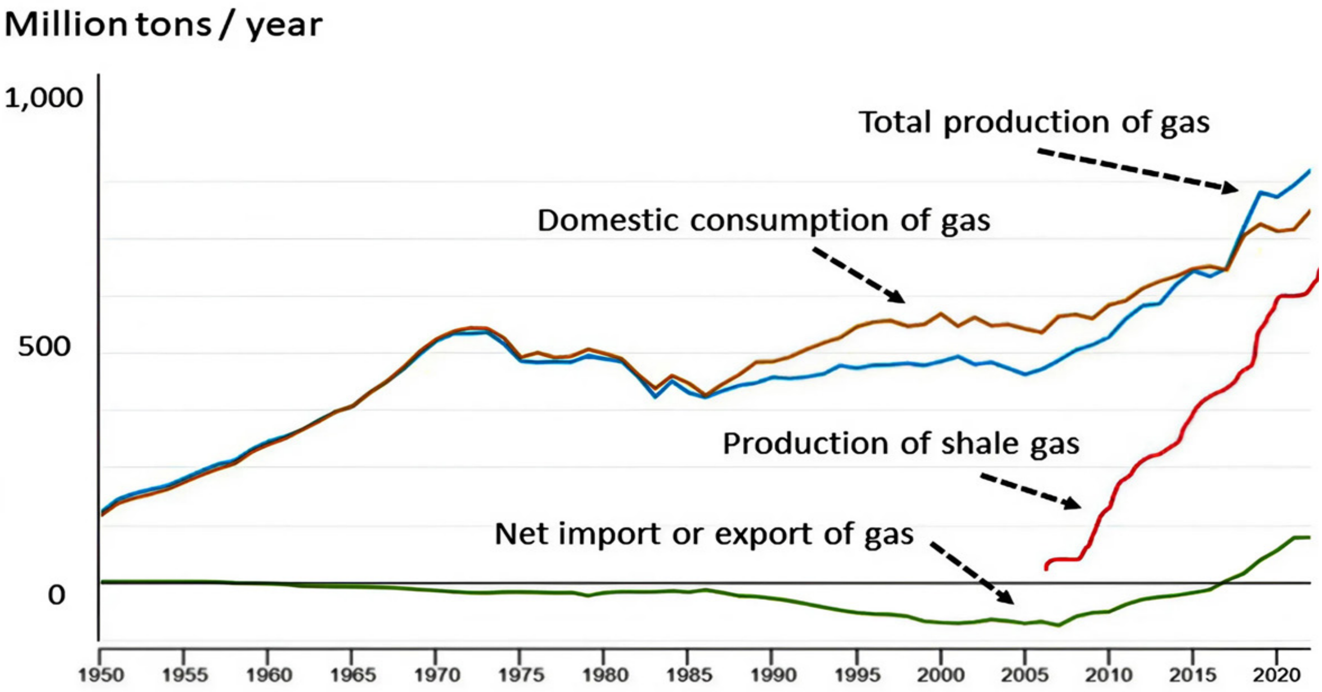
In the following pages, we aim to analyse the arguments and counterarguments regarding LNG and coal, ultimately providing a fact-based set of recommendations.

1.1 The Role of the United States

The U.S. became a net exporter of LNG in 2016, capitalising on abundant shale gas reserves.

Graph 1 -Trends in natural gas production in the U.S. from 1950 to 2022, showing total production of gas (conventional plus shale), production just of shale gas, domestic consumption, and the net import or export of gas. Almost all of the increase in natural gas production since 2005 has been shale gas. The U.S. was a net importer of natural gas from 1985 to 2015 but has been a net exporter since 2016.

Graph 1 -Trends in Natural Gas Production in the United States from 1950 to 2022

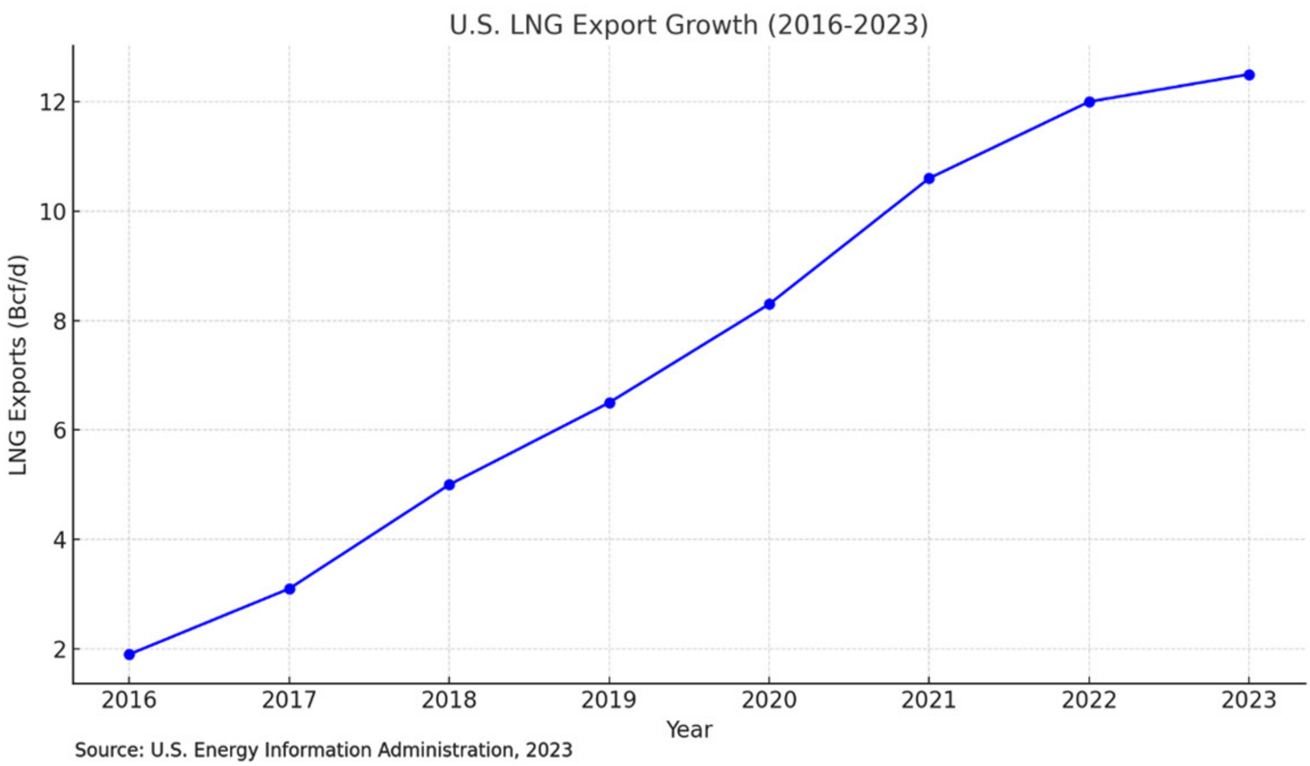


Source: The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States by Robert W. Howarth

By 2023, LNG exports from the U.S. had grown exponentially, with data from the U.S. Energy Information Administration (EIA) showing a rise from about 1.9 billion cubic feet per day (Bcf/d) in 2016 to over 12 Bcf/d by late 2023. The country emerged as a critical supplier, particularly to Europe, which sought alternatives to Russian natural gas in light of geopolitical tensions.

The moratorium, however, reflects concerns about the broader implications of expanding LNG exports. A key consideration is the environmental impact. While natural gas is often described as a "transition fuel" due to its lower carbon dioxide emissions compared to coal and oil, its extraction and transportation can involuntarily release significant amounts of methane, a potent greenhouse gas. Biden's directive prioritises studies that will evaluate these emissions, ensuring that U.S. energy policies align with climate goals outlined in the Paris Agreement.

Graph 2 - U.S. LNG Export Growth (2016-2023)

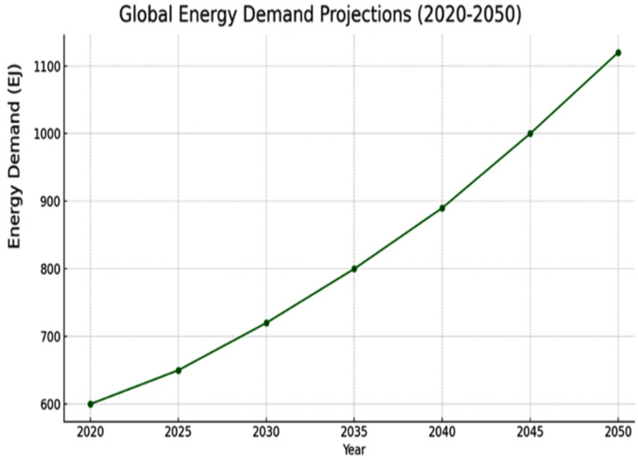


1.2 The Need for Energy in a Densely Populated World

The global context underscores the complexity of this decision. The United Nations projects that the world population will reach 9.7 billion by 2050, driving energy demand.

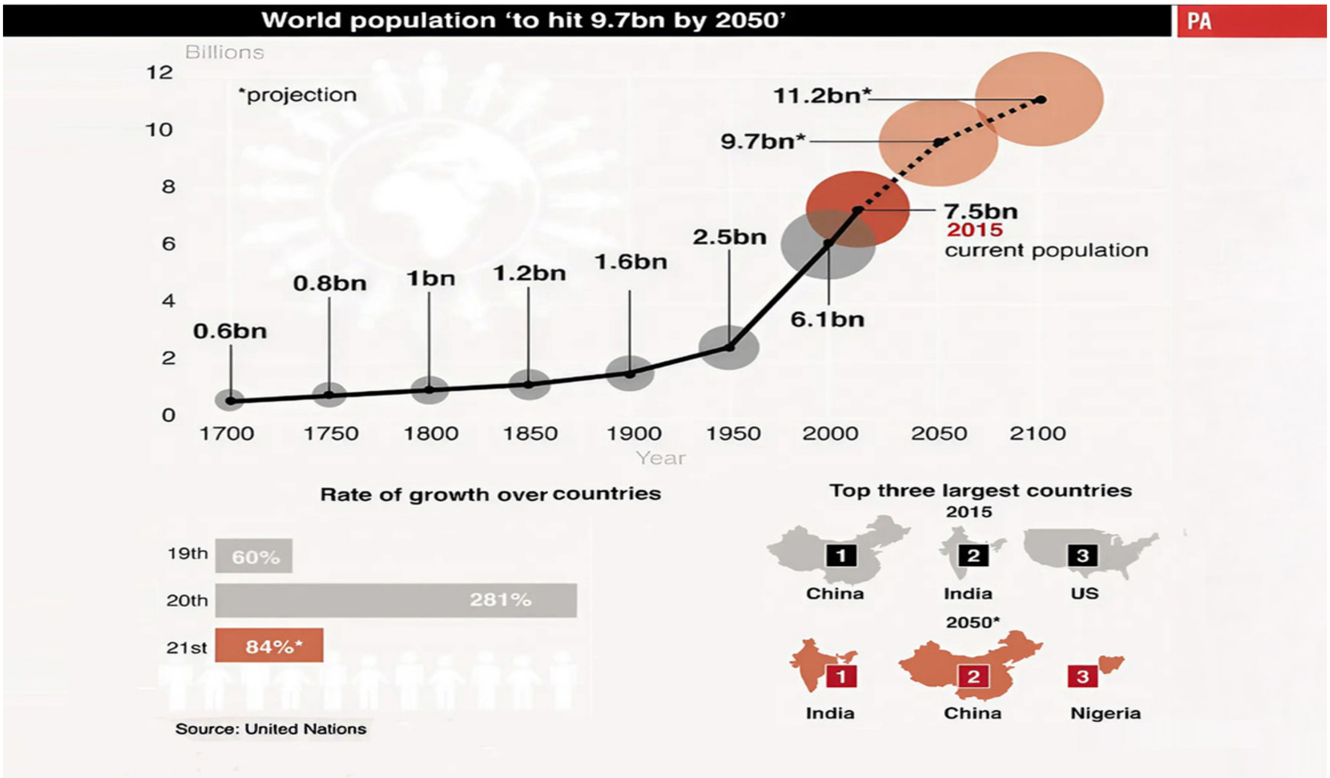
According to the International Energy Agency (IEA), global energy consumption is expected to increase by approximately 50% between 2020 and 2050.

Graph 4 – Evolution of Global Energy Demand by 2050



Source: International Energy Agency, World Energy Outlook 2023

Graph 3 – Global Population Projection by 2050



1.3 NG's Role in the Energy Mix

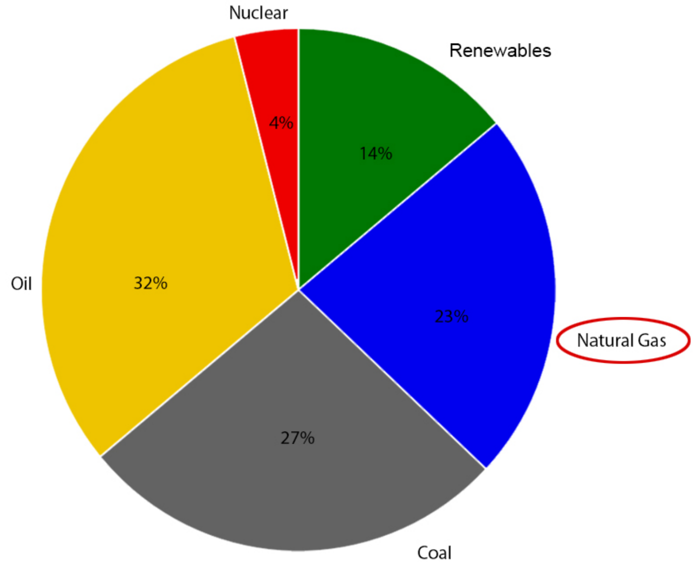
Currently natural gas (NG) plays a growing role in the global energy mix, accounting for about 23% of global energy consumption in 2023. However, balancing this demand with sustainability remains a challenge.

The moratorium issued by President Joe Biden also encourages investment in renewable energy and energy efficiency technologies. Such technologies seek to reduce methane leaks and improve the energy efficiency of the current upstream and midstream practices in the LNG life cycle.

While critics argue it potentially risks "a step back" on the constant reduction of Co_2 emissions in the power sectors[4] and see it as a contributor factor for inflation[5] in both exporting and importing countries, proponents contend it signals a commitment to national long-term energy security and environmental responsibility.

Prior to the President's moratorium, the prevailing consensus in the U.S. and Europe was that liquefied natural gas (LNG) represented a "cleaner" energy source for power production at global level. This perception was one of the significant factors driving the rapid growth of LNG exports. Support for this view comes from academia, the political establishment, and the general public[6].

Graph 5 – The Contribution of NG to the World Energy Mix



Source: BP Statistical Review of World Energy 2023

2.1 Life-Cycle Emissions: LNG

Howarth contests that although carbon-dioxide emissions are greater from burning coal than from burning re-gasified natural gas, LNG emissions can more than offset this difference over the entire life cycle (upstream, liquefaction, transport and regassification) of this product against coal.

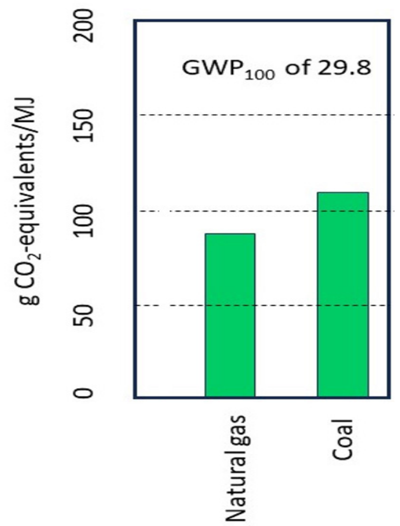
Natural gas is widely considered to be an environmentally cleaner fuel than coal because it does not produce detrimental by-products such as sulfur, mercury, ash and particulates and because it provides twice the energy per unit of weight with half the carbon footprint during combustion.[7] This statement is agreed and supported by Howarth's own calculations as shown in the online supplemental materials of his paper (graph 6 below)[8].

However, in Howarth's paper over the evaluation of shale gas drilling he suggests that shale gas has a larger GHG footprint than coal. His study is based exclusively on the export from the US and on the usage of highly energy intensive upstream processes (hydraulic fracturing and high-precision directional drilling).

The pillars of the study are the GHG footprints of the following phases of the life cycle of LNG calculated in accordance with the 20-year Global Warming Potential (GWP)[9]:

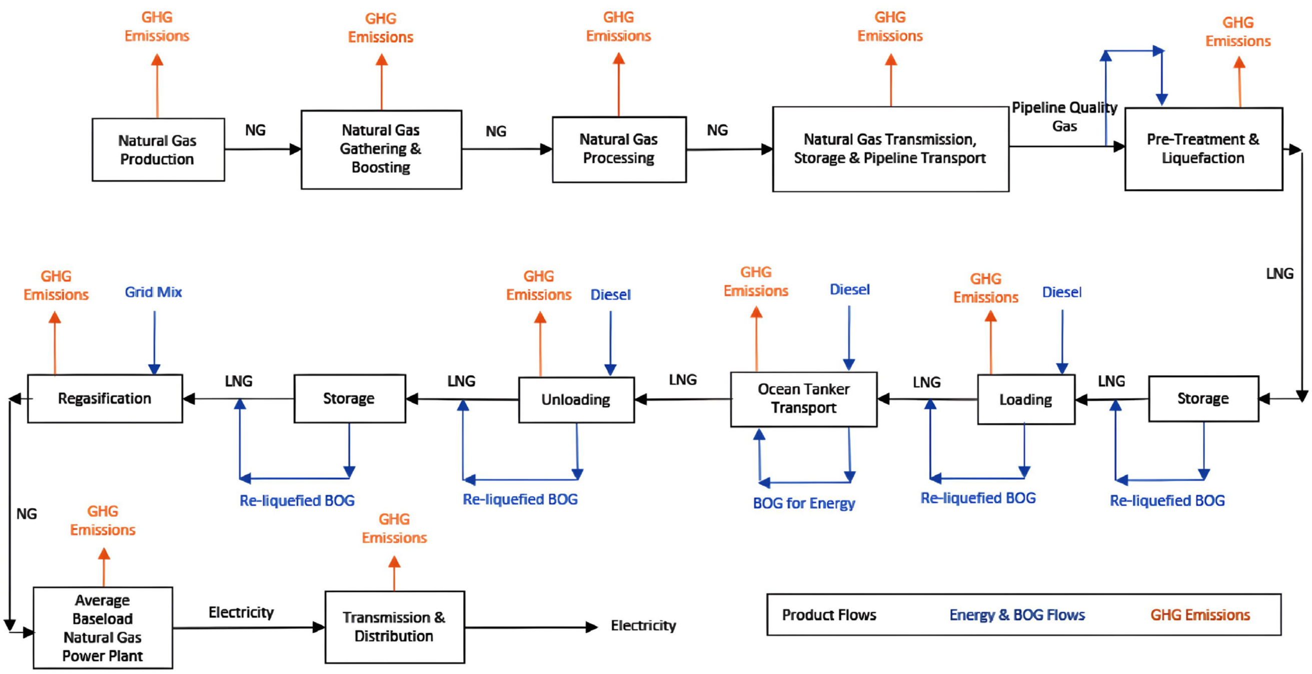
- Upstream and midstream emissions
- Liquefaction emissions
- Emission from tankers
- Final transmission and distribution emissions
- Combustion by final consumer

Graph 6 - LNG Vs Coal: Methane Emissions are Converted to Carbon Dioxide Equivalents Using GWP



This analysis, also named "cradle-to-grave,"[10] begins with extraction of natural gas or coal and ends with electricity delivered to the final consumer and is aimed to incorporate all stages of the GHG emissions in the life of the analysed source of energy. During each step of the LNG process there are exchanges of energy with the surrounding environment such as involuntary leakages of methane or usage of diesel to feed compressors, engines, tankers and pumps. Additionally, as the LNG supply chain runs at an average of minus 160 degrees Celsius[11] throughout the entire process there are emissions generated under the form of Boil off Gas (BOG)[12]. In modern two and four stroke propelled tankers BOG is partially recovered to feed the engines and, if not completely combusted, it is expelled in the atmosphere through the exhaust. Howarth's argues that due to these additional emissions the overall GHG balance turns in favor of coal. A visual representation of the entire life cycle of LNG and its energy interactions with the environment is shown below.

Figure 1 - Flow Diagram of the Life Cycle of LNG and the Energy Exchanges with the Surrounding Environment



Source: Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 update. Selina Roman-White, Srijana Rai, James Littlefield, Gregory Cooney, Timothy J. Skone, P.E., DOE/NETL-2019/2041

2.2 Life-Cycle Emissions: Coal

Similarly, in the lifecycle of coal, there are several exchanges of energy with the surrounding environment in the form of Co_2 (burned diesel) and emissions of methane from the coal mines or CMM (Coal Mine Methane)[13].

CMM can be released the following types of mines:

- Active underground mines
- Abandoned/closed mines
- Surface mines

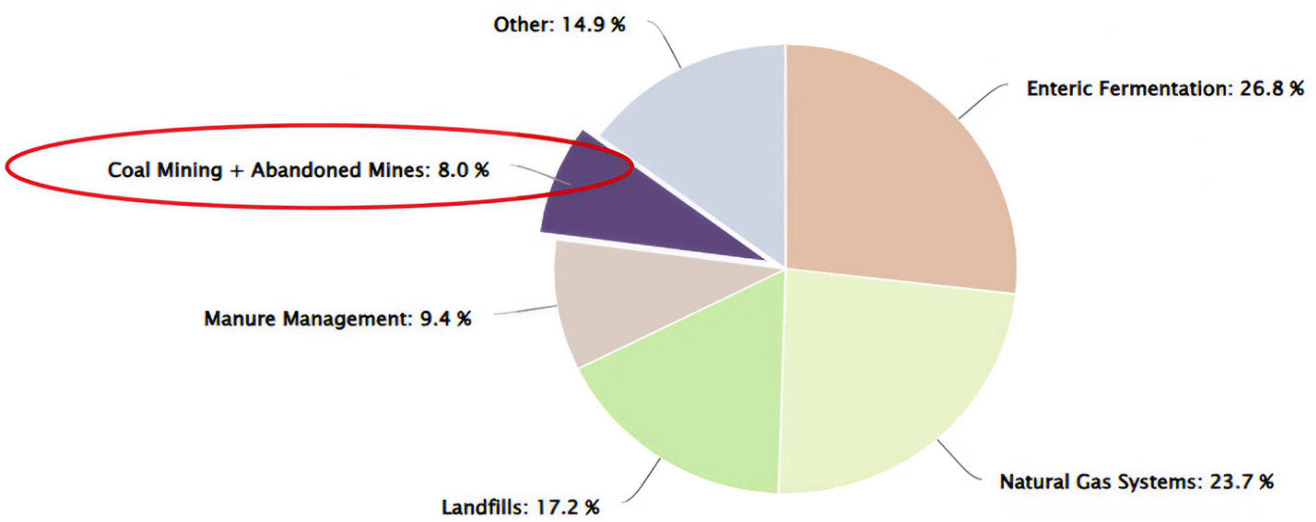
CMM poses a safety risk due to its explosiveness when mixed with air and represents an important source of GHG associated with the coal industry. Methane emissions from coal mining and abandoned coal mines accounted for about 8% of total U.S. methane emissions in 2019. It was the fifth-largest methane-emitting sector, based on the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019[14]. Currently, EPA's Coalbed Methane Outreach Program (CMOP), a voluntary program with the goal of reducing methane emissions from coal mining activities is aware of 19 active and 57 abandoned[15] closed coal mines in the U.S. that host methane mitigation projects. Active coal mines may host multiple projects because they generally release larger volumes of methane. Abandoned coal mines typically release smaller volumes and usually contribute to one single project.

CMM emissions represent a wasted potential source of energy (when not captured) and a safety hazard. In the U.S., when CMM is captured is most often sold to natural gas pipeline systems. Other uses include:

- Power generation
- Heat generation
- Flaring[16]

Howarth's research does not provide any explicit and detailed references to CMM and its direct impact in terms of GHG footprint[17].

Graph 7 – Methane Contribution by Sector in the US, 2019

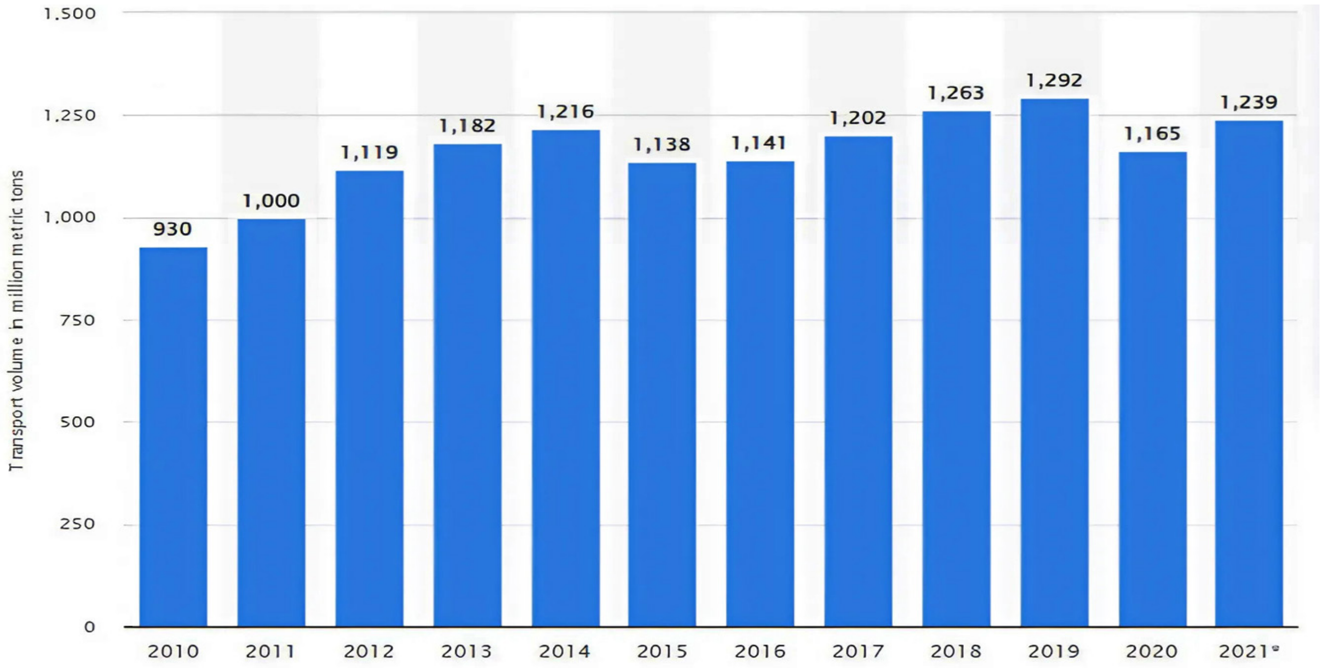


The unclear role of CMM and its impact in terms of GHG footprint in the comparison between LNG and coal in their entire life cycle, in our opinion undermines the results of this part of Howarth's analysis.

Additionally, coal is transported at ambient temperature, making its supply chain less energy-intensive. However, despite being less relevant to overall emissions than LNG, greenhouse gas emissions from transoceanic coal transport by tanker were entirely overlooked in Howarth's analysis.

In fact, according to the International Energy Agency (IEA)[18], global coal production, consumption, and seaborne volumes reached record levels in 2023. While coal usage is declining in the West, it remains robust in Asia and continues to grow on a global scale. Consequently, dry bulk shipping supply chains for coal have not contracted[19]; rather, they have expanded worldwide.

Graph 8 – Transport Volume of Coal in Global Seaborne Trade from 2010[20]



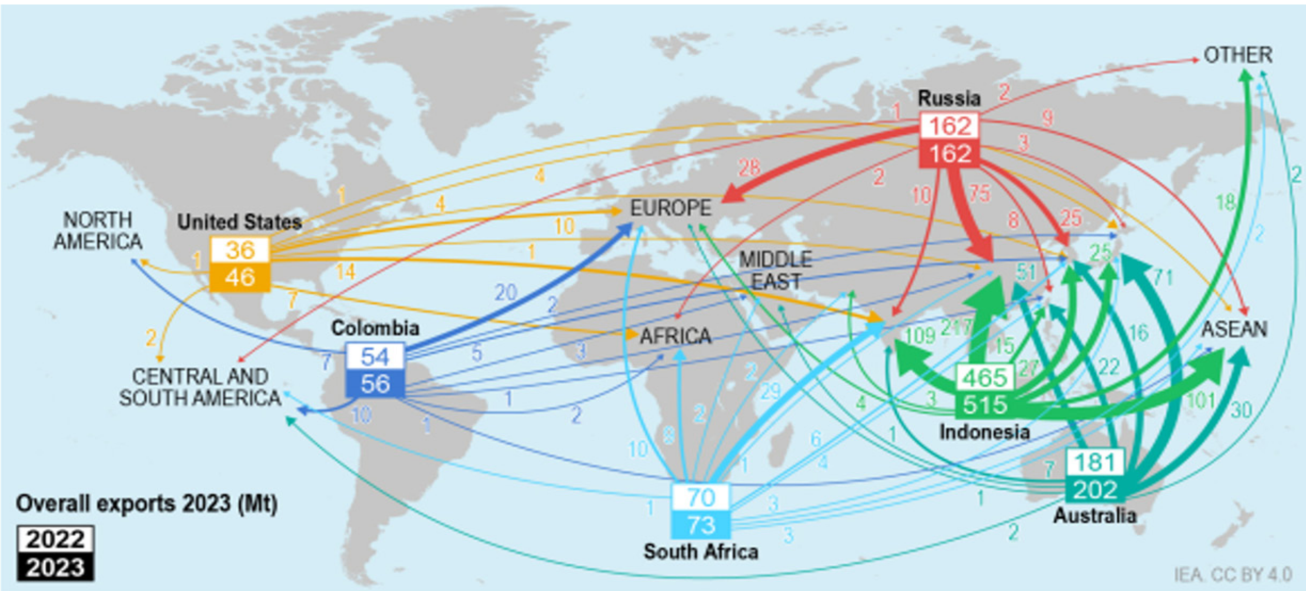
This growth is driven, in part, by increased exports from nations such as the U.S.[21], Indonesia, Australia, South Africa, Colombia and Russia, which transport their mining output via long-haul voyages to Asia and worldwide. The following graph visually describes this process highlighting the main supply and delivery points and the relative volume.

Similarly to LNG, the average emissions from shipping coal vary over distance:

- Australia to China (~5,000 km): ~17.7 kg CO_2 per ton of coal
- Australia to Europe (~20,000 km): ~70.8 kg CO_2 per ton
- South Africa to India (~8,000 km): ~28.3 kg CO_2 per ton

For comparison, burning one ton of coal with a carbon content of 78% (this may vary depending on coal type) releases around 2,863 kg CO_2 so maritime transport emissions add at least 0.6–2.5%[23].

Figure 2 – Main Trade Flows in the Thermal Coal Market, 2023 (Mt)[22]



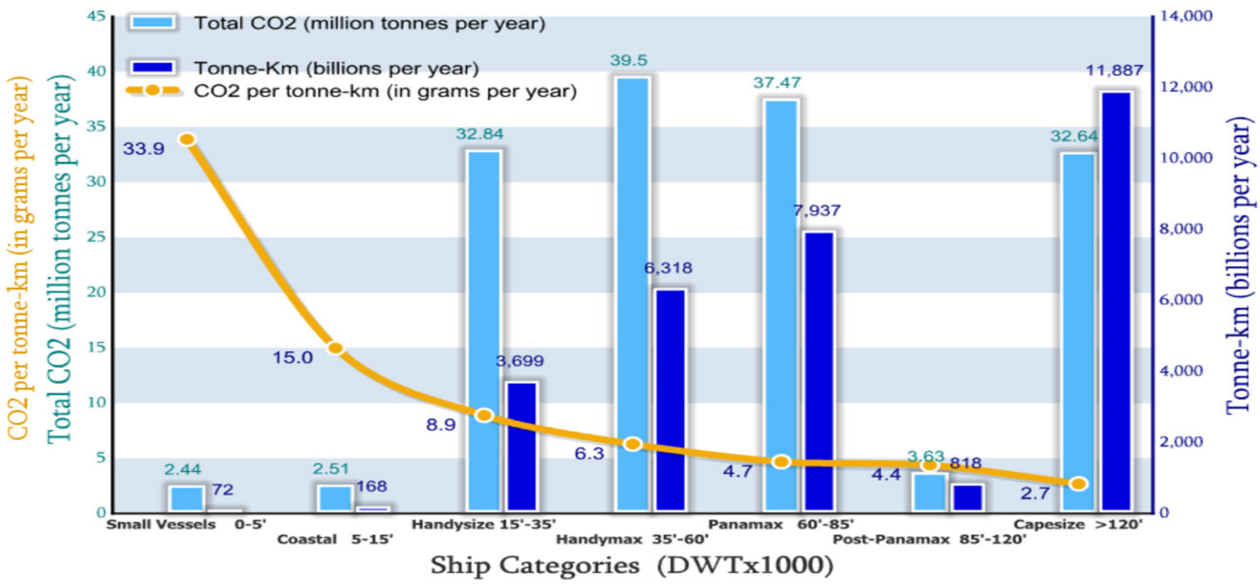
Note: Map values are based on available export data and do not necessarily match import numbers due to reporting times.

The above calculation is based on average values. The punctual emission rate for different types of dry bulk carriers is shown in the following graph.

In this context, seaborne trade accounted for over 90%[26] of all traded coal in 2023, although land-based trade also experienced growth during the year.

A 2020 study[27] - conducted by Dr John Sherwood (Clemson University) and colleagues -analyses datasets from the Energy Information Administration, Environmental Protection Agency, and the U.S. Geological Survey to provide a comprehensive assessment of CO_2-equivalent emissions generated by coal rail transportation over the previous decade.

Graph 9 – Dry Bulk Carriers[25]



The study compares the scale of transportation emissions to the operational emissions of coal feed power plants. Findings indicate that rail transportation distances in the U.S. range from 0 km to over 3,500 km. Furthermore, transportation emissions can account for up to 35% of a power plant's operational emissions—a figure significantly higher than previously estimated in the literature, underscoring the importance of including also these emissions in a balanced and comprehensive comparison with LNG.

For a fair study, all modes of transportation within LNG and coal supply chains must be analysed. It is imperative that research considers the substantial emissions generated by transatlantic coal shipments, domestic rail transport and transportation by truck and barge in different geographies (although the latter's impact remains relatively minor).

Figure 3 – 2014 Power Plant-Destined Coal Rail Shipments Along the U.S. Rail Network[28]

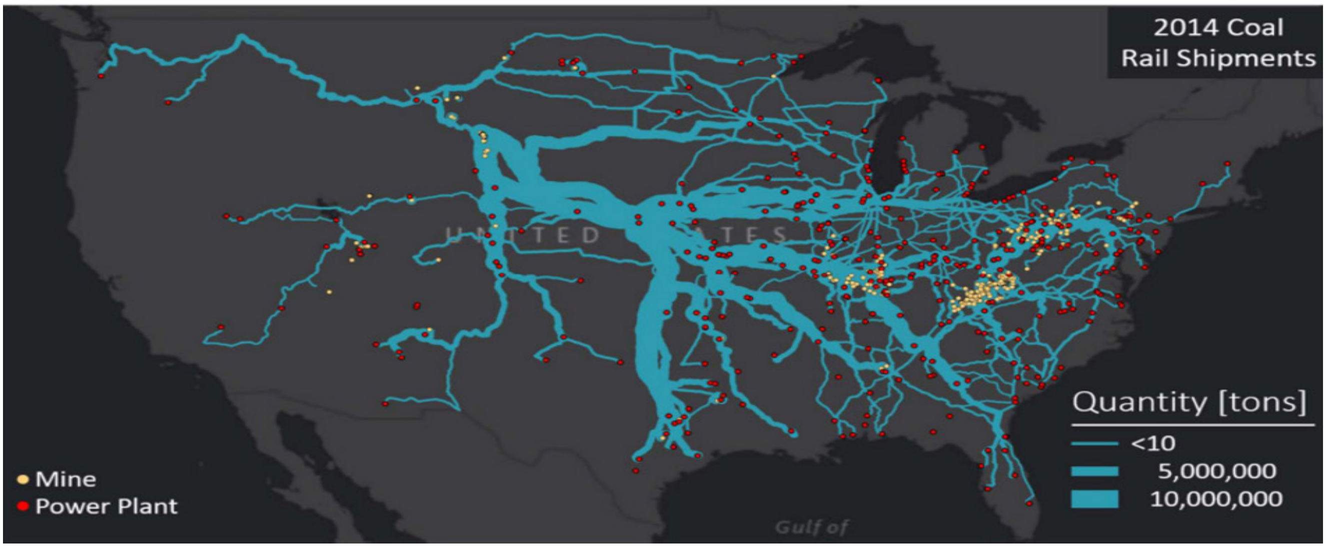
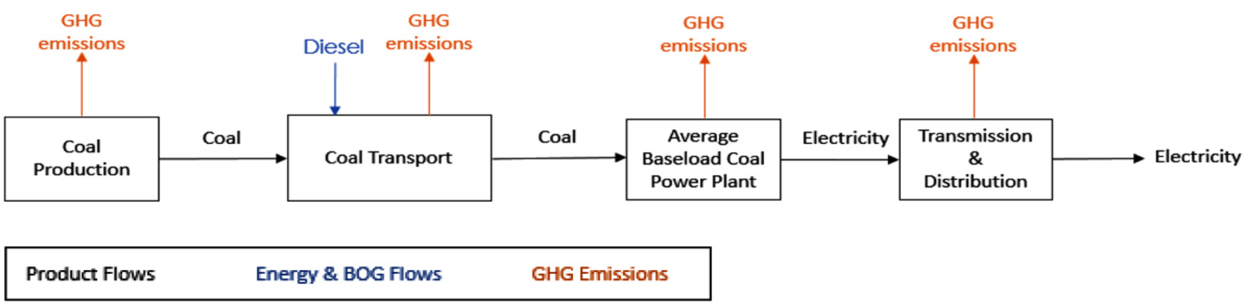


Figure 4 - Flow Diagram of the Life Cycle of Coal and the Energy Exchanges With the Surrounding Environment[29]



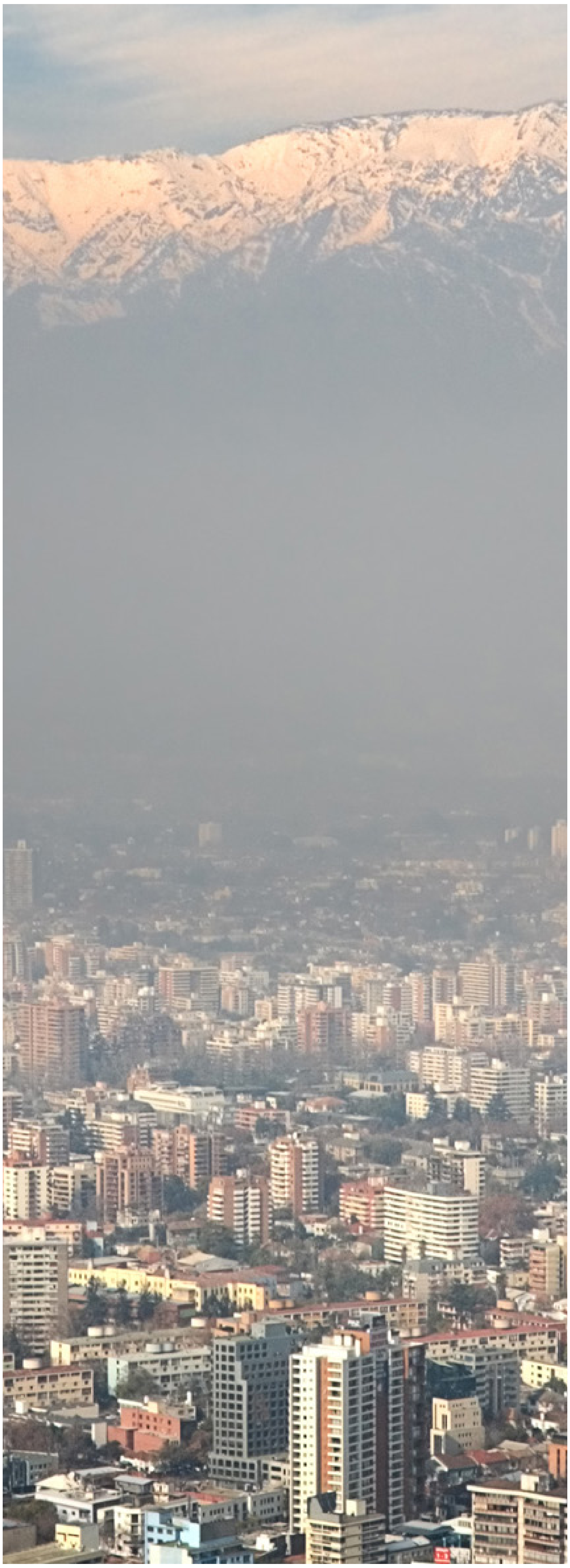
2.3 Controversial Assumptions in Howarth's Paper

Focusing on the LNG side, estimating boil-off gas (BOG) and fugitive emissions throughout production flows—and translating these into measurable GHG emissions—sparked debate surrounding Howarth's paper.

2.3.1 GWP-20 Vs GWP-100

Howarth caused controversy by using the GWP-20-year methodology. The GWP-20-year methodology measures the heat-trapping impact of GHG over a 20-year period relative to CO_2. This approach emphasises short-term climate effects and is particularly sensitive to short-lived GHGs, such as methane (CH4), which have high immediate warming effects, but decay more quickly. It can be argued that a GWP-100, that assesses the warming impact of GHG over a 100-year period, would yield more accurate and fairer data. A GWP-100 is the most commonly used (hence comparable with other papers and official statistics from other countries[30]) metric and provides a long-term perspective on climate impacts, effectively BLUEaveraging out the contributions of both short-lived (CH4) and long-lived GHGs (CO_2). This means that if you average the impact of GHG emissions over 20 years instead of 100, it boosts the relative influence of methane, and hence the downsides to LNG.

In terms of methodology, our observation here does not suggest alternative approaches such as 50 or 75-year GWP that would be, in any case, arbitrary[31]. On the other hand, we want to emphasise Howarth's short-term approach as future reference for the emphasis that this has on methane GHG footprint potential while drawing his conclusions[32].



2.3.2 Methane Leakage Rate

Howarth's paper drew public criticism for several key assumptions. We've already covered the choice to use the 20-year GWP and its impact on the analysis. The remaining three main points of contention are outlined in this sections.

First, the data on methane leakage from well completions and pipelines during the upstream and midstream phases. Howarth argued these stages contribute the most to overall methane emissions. While many researchers agree in principle, critics challenged the scale, methodology, and accuracy of the data underpinning his conclusions.

In his study of methane emissions from natural gas, Howarth used data derived from a recent analysis of upstream and midstream emissions in the U.S. The analysis combines a data set of observations taken by aircraft flyovers with empirically derived simulations[33]. For his study, he averaged the emission factor on the production of eight different campaigns in the Permian Basin. This figure slightly differs from the inputs used by Abrahams[34] and is higher compared to studies by Gan et al.[35], Lawrence M.Cathles III and others[36] and NETL[37] that used the default methane estimates in the GREET model[38], which are derived from inventory estimates from the US Environmental Protection Agency (EPA)[39].

There are two observations here to be highlighted. Firstly, the leakage percentage in the upstream LNG operations is a very sensitive factor that may affect the comparability of the results of the different analysed models. The leakage rate used by Howarth is in line with the triangular distribution (minimum of 2%, maximum of 4% and most likely value of 3%) cited by Abrahams et al.

Notwithstanding this, the impact that upstream methane leakages have in the two respective models drive quite a substantial difference when translated into total upstream GHG emissions by the authors (47% by Howarth and 33% by Abrahams) under their different assumptions. This, in our opinion, should be the real debate. The upstream and midstream leakage rate used by Professor Howarth is fine per se and it is consistent with modern technology (aircraft flyovers). However, what is questionable is how this raw data is translated into GHG emissions. Secondly, the general poor reliability and high variability of the available data[40]. As extensively explained by Abrahams, Michael Levi (a Special Assistant to the President for Energy and Economic Policy in the Obama White House) and others, the availability of leakage data is fragmented

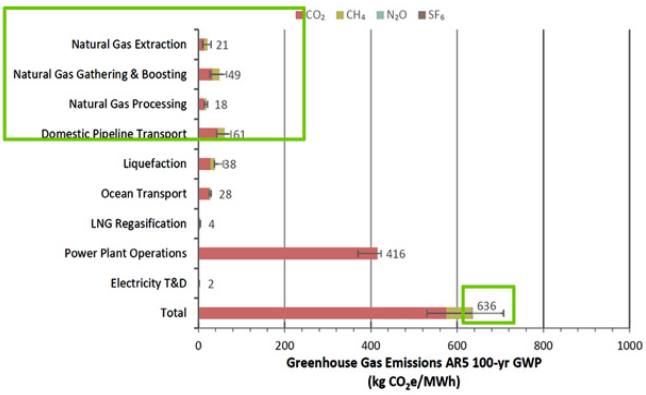
and presents some issues in terms of consistency and reliability with astonishing variations per region and project (refer to the different campaigns cited in the previous foot notes). This presents an issue in all papers aimed at benchmarking LNG Vs coal. As we will see in the conclusions of this paper, the overall footprint of LNG is heavily influenced by the leakage in the upstream and midstream phases and hence all sensitivities aimed to a comparison of LNG Vs coal are mainly influenced by the "punctual" leakage value of the specific project under scrutiny. The benchmarking exercise to compare a specific gas production field, whose production will become LNG Vs the alternative use of coal, could not prescind a scrupulous assessment of methane leakage in the upstream phase.

Graph 10 – Comparison of the GHG Emissions Generated During Upstream and Midstream Phases as Calculated by Howarth vs Other Sources.

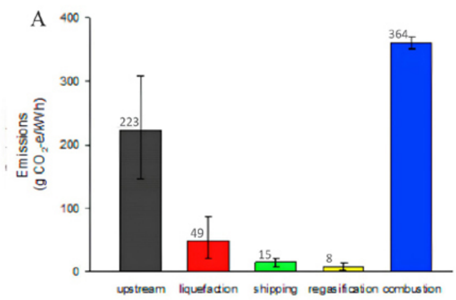
Note that the comparability is in % due to the different timescale 20 Vs 100 GWP years and unit of measure MJ-heat Vs MWh-power: int

	Total combined g CO_2-equivalent/MJ
Average for LNG	
Upstream and midstream emissions	75.6
Liquefaction	14.2
Emissions from tanker	9.3
Final transmission and distribution	5.4
Combustion by final consumer	55.0
Total	**160**

According to Howarth's view in a **20-year GWP scenario the GHG** footprint for upstream and midstream sums up to 47 % of the emissions of the entire process over MJ (Heat) generated



According to National Energy Technology Laboratory (S. Roman-White, and others) view in a **100-year GWP** scenario the GHG footprint for upstream and midstream sums up to 23 % of the emissions of the entire process over MWh generated (Power).



According to Abrahams and others view in a **100-year GWP** scenario the GHG footprint for upstream and midstream sums up to 33 % of the emissions of the entire process over MWh generated (Power).

2.3.3 Heat Vs Power Comparisons

Second, Howarth's gas-to-coal comparisons are on a per energy (heat) unit basis. That means that he compares the emissions involved in producing a gigajoule[41] of coal with the amount involved in producing a gigajoule of gas.

This involves comparing the emissions associated with two different energy sources, LNG and coal, for generating the same amount of thermal heat. However, this comparison is not practically applicable as the coal displaced by LNG is almost exclusively used for electricity generation. Therefore, a comparison based solely on heat output is misleading. Since coal is primarily used for power generation, LNG that replaces coal will similarly be used to generate electricity. For those specific uses in which LNG is not a substitute of coal, coal will continue to be used. The appropriate comparison of gas to coal is thus in terms of electricity generation. Modern gas power generation technology is a lot more efficient than modern coal generation, so a gigajoule of gas produces a lot more electricity than a gigajoule of coal.

Accordingly, the comparison should be made in kWh (MJe) and, as suggested by Lawerence M. Cathles III in his commentary on a previous article by Howarth, should be based on 60%[42] efficiency for natural gas combined cycle power plants generation of electricity and 30% efficiency for coal generation of electricity in average plants.

2.3.4 Role of Technology

Howarth underestimates current and future technological developments that reduce the leaks in the upstream phase of the LNG life cycle. Leak preventing technology is constantly evolving and overall losses of methane in the range of 2.8% of the whole production in the sole upstream phase seem inflated when projected in the medium and long-term (consider that this represents roughly 47% of the total combined g Co_2-equivalent/MJ according to Howarth in his 2023 paper).

This percentage should decrease in the future. As previously mentioned, the present leakage data presents several collection and validation issues and should be assessed on specific assets due to the high variability it presents[43]. Nevertheless, there is room for improvement due to the available and under-development technology as shown by some international players[44].

Note the remarkable results achieved in Norway45. (See below graph. Methane intensity is defined as the total methane emissions from up- and midstream oil and gas activities, expressed as a percentage of the total amount of marketed gas).

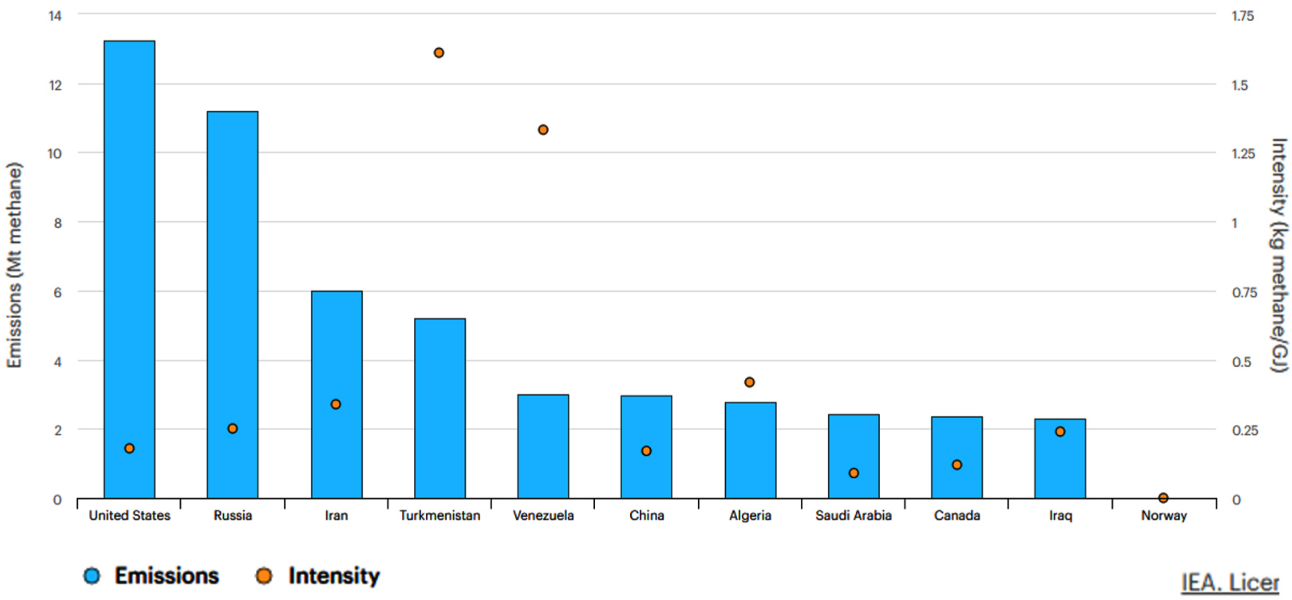
Methane that escapes into the atmosphere represents a loss from a monetary point of view and a serious risk in terms of safety that no investor wants to run. Furthermore, advanced in green well completion techniques[46], better pipeline care, remote/ digitalised detectors and new construction materials might be enforced through industry standards and institutional barriers and enforced by law.

As LNG continues to scale up and the efforts to reduce fugitive methane continue, there are plenty of actions from a technical and legislative standpoint that can be taken.

Despite the surge in production, the diminishing trend of methane leakages and fugitive emissions thanks to the technological innovations and efforts by the energy industry main players is confirmed by the Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 -2022 by EPA.

In the U.S., natural gas systems emitted 173.1 MMT CO_2 Eq. (6,183 kt CH4) of CH4 in 2022, a 21 percent decrease compared to 1990 emissions[47], and 1 percent decrease compared to 2021 emissions. The 1990 to 2022 emissions trend is not consistent across segments. Overall, the 1990 to 2022 decrease in CH4 emissions is due primarily to the decrease in emissions from the following segments: distribution (70 percent decrease), transmission and storage (38 percent decrease), processing (37 percent decrease), and exploration (97 percent decrease).

Graph 11 – Methane Emissions from Oil and Gas Production and Methane Intensity for Selected Producers, 2023



Over the same period, the production segment saw increased CH4 emissions of 38 percent (with onshore production emissions increasing 16 percent, offshore production emissions decreasing 86 percent, gathering and boosting emissions increasing 108 percent), and and post-mater emissions increasing by 65%.

For coal the future scenario is different, with most important technological advance likely to be Carbon Capture and Storage (CCS). Despite its promise and while CCS technologies are operational and commercially available, their widespread adoption is still developing. Ongoing efforts are focused on reducing costs, expanding infrastructure, and addressing regulatory and social challenges to facilitate broader implementation.

As of January 2025, CCS technologies are still in their deployment and early stages. Globally, there are 42 operational commercial CCS and Carbon Capture, Utilization, and Storage (CCUS) projects, collectively capturing approximately 49 million metric tons of CO_2 annually. This accounts for about 0.13% of the world's annual energy and industry-related CO_2 emissions[48]. While these projects demonstrate the feasibility of CCS, three main challenges remain in terms of high costs, infrastructure and location constraints and regulation and social acceptance[49]. It should be noted that CCS projects might apply to both LNG and coal emitting sources, hence the impact of this new technology should be beneficial globally but if applied evenly will not alter the comparison between LNG and coal for the purposes of an independent and factual analysis.

Table 1 – CH4 Emissions from Natural Gas Systems in the U.S. (MMT CO2 Eq)

Segment	**1990**	**2005**	**2018**	**2019**	**2020**	**2021**	**2022**
Exploration	6.7	19.6	2.6	2.1	0.2	0.1	0.2
Production	65.2	93.4	104.9	103.6	96.7	92.2	89.7
Onshore Production	*39.9*	*64.4*	*60.5*	*58.0*	*53.1*	*48.3*	*46.2*
Gathering and Boosting	*20.5*	*27.0*	*43.6*	*44.8*	*42.7*	*43.3*	*42.8*
Offshore Production	*4.8*	*2.0*	*0.9*	*0.8*	*0.9*	*0.6*	*0.6*
Processing	23.9	13.0	13.5	14.2	13.8	14.2	15.1
Transmission and Storage	64.0	46.0	41.2	40.5	41.1	39.8	39.6
Distribution	50.9	28.5	15.6	15.5	15.5	15.3	15.2
Post-Meter	8.1	9.6	12.5	12.8	13.0	13.0	13.4
Total	**218.8**	**210.1**	**190.3**	**188.7**	**180.3**	**174.6**	**173.1**

Note: Totals may not sum due to independent rounding.

Segment	**1990**	**2005**	**2018**	**2019**	**2020**	**2021**	**2022**
Exploration	238	700	93	75	7	4	6
Production	2,328	3,335	3,748	3,701	3,453	3,293	3,202
Onshore Production	*1,424*	*2,299*	*2,162*	*2,073*	*1,895*	*1,726*	*1,650*
Gathering and Boosting	*733*	*963*	*1,556*	*1,601*	*1,527*	*1,545*	*1,528*
Offshore Production	*170*	*73*	*31*	*28*	*32*	*22*	*23*
Processing	853	463	483	507	495	507	541
Transmission and Storage	2,285	1,645	1,470	1,448	1,468	1,421	1,413
Distribution	1,819	1,018	556	554	553	547	544
Post-Meter	290	344	445	457	463	464	477
Total	**7,813**	**7,505**	**6,795**	**6,741**	**6,439**	**6,235**	**6,183**

Note: Totals may not sum due to independent rounding.

Table 2 – Coal Production (KT)

Year	1990	2005	2018	2019	2020	2021	2022
Underground							
Number of Mines	1,683	586	236	226	196	174	185
Production	384,244	334,399	249,804	242,557	177,380	200,122	201,525
Surface							
Number of Mines	1,656	789	430	432	350	332	354
Production	546,808	691,447	435,521	397,750	307,944	323,142	336,990
Total							
Number of Mines	**3,339**	**1,398**	**666**	**658**	**546**	**506**	**539**
Production	**931,052**	**1,025,846**	**685,325**	**640,307**	**485,324**	**523,264**	**538,515**

Table 3 – CH4 Emissions from Coal Mining (KT)

Activity	1990	2005	2018	2019	2020	2021	2022
Underground (UG) Mining	**2,968**	**1,669**	**1,557**	**1,375**	**1,257**	**1,176**	**1,124**
Liberated	3,237	2,388	2,382	2,022	1,917	1,868	1,989
Recovered & Used	(269)	(720)	(825)	(646)	(660)	(692)	(865)
Surface Mining	**430**	**475**	**280**	**255**	**194**	**205**	**215**
Post-Mining (UG)	**368**	**306**	**212**	**206**	**155**	**170**	**173**
Post-Mining (Surface)	**93**	**103**	**61**	**55**	**42**	**44**	**47**
Total	**3,860**	**2,552**	**2,110**	**1,892**	**1,648**	**1,595**	**1,558**

Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Finally, while the number of coal mines in U.S. and consequently the total production both dropped in the last 35 years by 84% and 42% respectively, the related methane emissions reduced by 60%[50].

Additional emissions were also reported for abandoned coal mines as shown in the table below [51].

Table 4 – CH4 Emissions from Abandoned Coal Mines (KT)

Activity	1990	2005	2018	2019	2020	2021	2022
Abandoned Underground Mines	288	334	355	341	335	330	324
Recovered & Used	NO	(70)	(107)	(104)	(103)	(106)	(100)
Total	**288**	**264**	**247**	**237**	**232**	**224**	**225**

NO (Not Occurring)
Note: Parentheses indicate negative values. Totals may not sum due to independent rounding.

2.4 Analytical Comparison of Howarth's Paper Vs the Views of Other Authors

Following the four main controversies outlined so far, other analytical items should be highlighted in Howarth's paper and in comparison with other studies.

The table below shows Howarth's results for LNG.

1) The data shows that taking into account the total emissions for combustion by the final consumer LNG is less polluting than coal in GHG terms (55 Vs 99, last column on the right circled in red). This is in line with other research papers.

2) The sole direct Co_2 emissions of the entire life cycle of LNG are lower than coal (83.1 Vs 102.4, first column on the left circled in light blue)

3) As previously mentioned, taking into consideration the entire life cycle of both products, in Howarth's study the overall emissions by LNG are greater than the one of coal (160 Vs 119.7 last column on the right circled in yellow). The above results are influenced by the following factors:

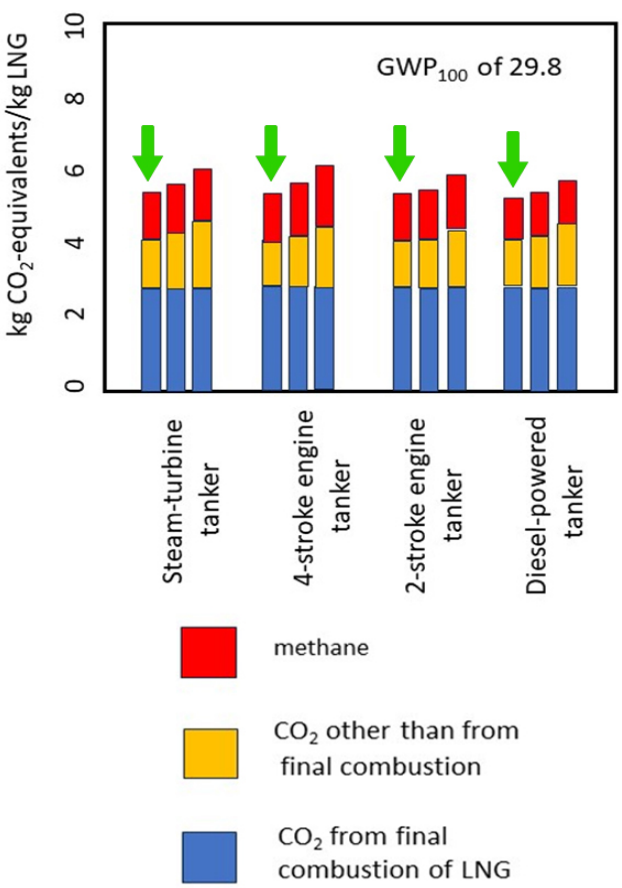
A) There is one piece of the equation that is partially missing. The emissions of LNG include the transport phase (on average 38 days by tanker), while for coal it is assumed "produced domestically near the final site of consumption", according to Howarth. As seen in section 2.2, this is partially true for markets like Poland, China or India, but does not apply for the coal industry worldwide. In Japan and South Korea, for example, coal is imported mainly from Australia and other oversea countries via transatlantic cargos and the related emission have been omitted. Additionally, the conspicuous[52] GHG footprint generated by CMM, as described above, is potentially missing from Howarth's study [53]. In practical terms this means that we are not comparing the full life cycle of the two alternative combustibles in a complete and exhaustive manner.

Table 5 – Emissions for LNG and Coal Used Domestically in Howarth's Model

	Carbon dioxide g CO_2/MJ	Methane g CH_4/MJ	Methane g CO_2-equivalent/MJ	Total combined g CO_2-equivalent/MJ
Average for LNG				
Upstream and midstream emissions	15.5	0.73	60.1	75.6
Liquefaction	7.7	0.078	6.5	14.2
Emissions from tanker	4.9	0.053	4.4	9.3
Final transmission and distribution	0	0.066	5.4	5.4
Combustion by final consumer	55.0	0	0	55.0
Total	**83.1**	**0.93**	**76.5**	**160**
Coal used domestically				
Upstream and transport emissions	3.4	0.21	17.3	20.7
Combustion by final consumer	99.0	0	0	99.0
Total	**102.4**	**0.21**	**17.3**	**119.7**

In contrast, Howarth's analysis considers only the emissions from the production and logistics phases of LNG, without explicitly accounting for CMM or transatlantic and rail logistics for coal. This approach is acceptable as long as the author clarifies his assumptions, which should be acknowledged and highlighted in the benchmarking exercise. For instance, as discussed in a later section, limiting the scope to a "European scenario"—where LNG is exported from Texas on a 21.4-day roundtrip (under the 100-year GWP criterion, as highlighted by the green arrows in the graph below)—Howarth's results indicate that the GHG emissions from coal and LNG are nearly identical, even when considering the previously noted assumptions.

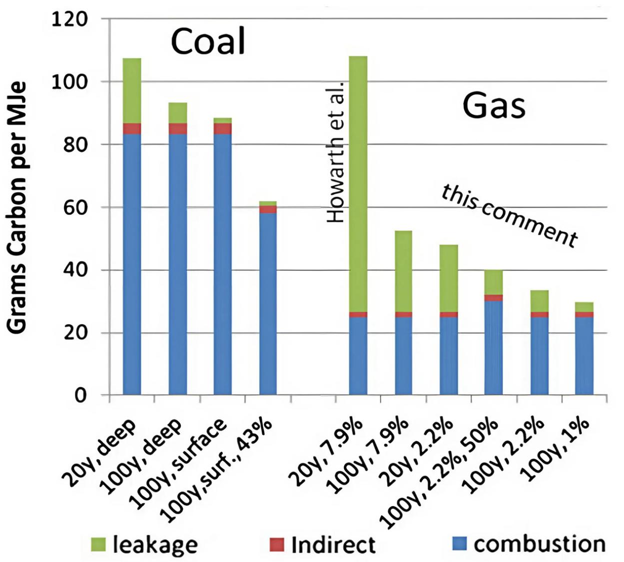
Graph 12 – LNG Export Emissions



Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by final consumer, comparing four scenarios where the LNG is transported by different types of tankers. For each type of tanker, scenarios are shown for shortest voyage times (21,4 days roundtrip, bars to the left), average voyage times (38 days roundtrip, center bars), and longest voyage times (70 days roundtrip, bars to the right)[54]. Emissions of methane, the carbon dioxide emitted from the final combustion, and other carbon dioxide emissions are shown separately. Methane emissions are converted to carbon dioxide equivalents using GWP100.

To demonstrate a differing perspective on LNG and coal, see the table below. The table details the results of the review conducted by Lawrence M. Cathles III et al, that visually compare the results by Howarth (as expressed in a 2011 paper, then re-emphasised in his 2024 article) in a scenario without transatlantic transport associated emissions for both products (in essence a domestic comparison of methane Vs coal).

Graph 13 – GHG Footprint to produce Electricity Without the GHG Emissions from Transatlantic Transport



Under this set of assumptions, both fuels are combusted to produce electricity and their GHG footprint is expressed as the grams of GHG-equivalent CO_2 carbon per megajoule of electricity generated both in a 20- and 100-year GWP scale. The conversion efficiency to electricity of coal and gas are assumed to be 30% and 60% respectively in all columns except the fourth and eighth columns, which compare a very efficient coal plant (43%) to a less efficient gas plant (50%). Other bars describe the percentage of methane leakage through-out the boundaries of a very wide spectrum (1, 2.2 and 7.9%) and whether the burned coal comes from deep or shallow mines.

As stated, no allowance is made for the transport or transmission for either fuel, (which is what Howarth implies solely for coal in his 2024 paper) which effectively assumes electricity generation at the well/mine head. In this "pound for pound" comparison, the logistic phase is excluded for both combustibles and the CMM values are properly accounted for different types of coal mines. The results are clearly in favour of natural gas. Even adding back 14.6%[55] or 11% [56] or 10.9% [57] of the total calculated emissions as estimated contributions for liquefaction, oceanic transport and LNG regasification (essentially the emissions necessary to transform natural gas into (LNG), the final result does not change substantially.

B) New tankers that have a lower impact in terms of Co_2 (higher fuel efficiency) are assumed to have greater methane slippages through their exhaust. The real slippages rate for tankers must be investigated further as pointed out by Howarth. Data is somehow scarce and heavily dependent on constant evolving technology (type of engine, insulation materials and efficiency of BOG recovery units).

C) The sole combustion phase according to Howarth represents 82,7% of the total GHG emissions for coal and 34.4% for LNG (figures circled in red divided by the figure circled in Table 5 above) clearly placing a lot of emphasis on the upstream methane emission component in the LNG production process. This data impressively differs from the CLNG (Center for Liquefied Natural Gas) fact sheet[58]. They reported between 79% and 77% for coal (existing and new, more efficient plants) and 67%-74% for LNG (emissions high and low case). The difference clearly implies an over or underestimate of the other phases of the life cycle for the LNG.

The below graph from Abrahams' study also shows different percentages. According to her study, the combustion phase accounts for 55.2 % of the overall emissions for the entire life cycle of LNG for a 100-year GWP. In a similar calculation over a 20-year GWP, the percentage for LNG drops to 40% (above the 34.4% from Howarth). Additionally, as previously highlighted this entire comparison cannot prescind from the observation regarding the adoption of "heat" metrics by Howarth instead of the "power" metric used by other authors. This means that even in a 20-year GWP scenario by Abrahams the overall GHG emissions from coal and LNG are mainly influenced by the final combustion figures and hence LNG is still "cleaner" than coal. In a 100-year GWP scenario the total GHG footprint for LNG (first figure circled in red below) represents a mere 54.58% of the same parameter for coal (second figure circled in red below) despite the upstream GHG emissions for LNG (first figure circled in green below) represent 190.59% of the same parameter for coal (second figure circled in green below). The delta in favour of LNG in terms of total GHG footprint cannot be compensated by the relatively minor emissions by coal in the upstream phase.

Graph 14 – Lifecycle Emissions in Abrahams' Model

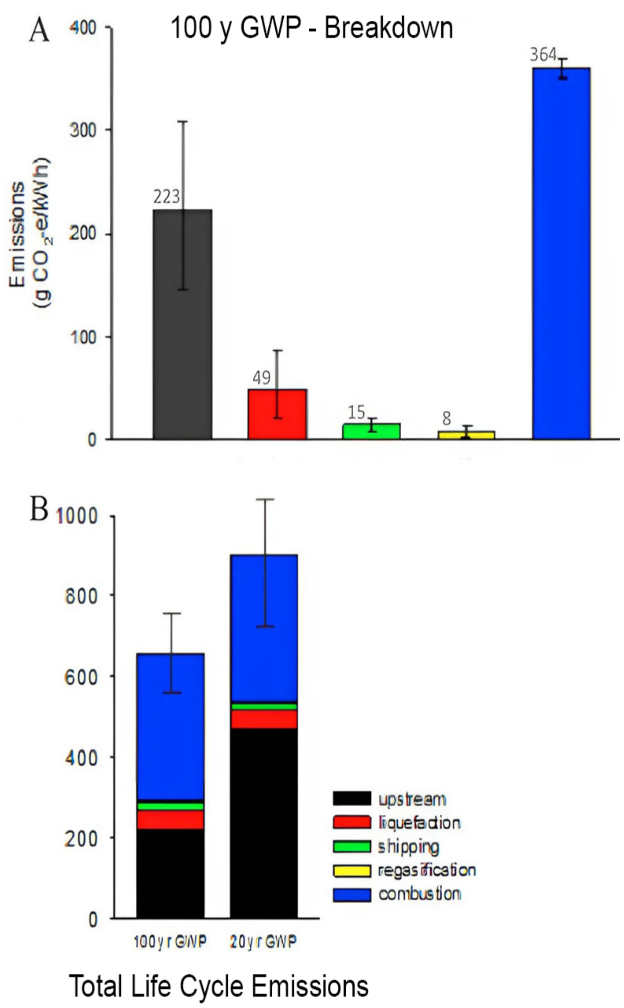


Figure 5 - LNG Exports by Abrahams' Under 100-yr GWP Assumption

100-yr GWP	g CO2-e/kWh
LNG EXPORTS	
upstream	223
liquefaction	49
shipping	15
regasification	8
combustion	364
total	655
COAL:	
upstream	117
combustion	1085
total	1,200

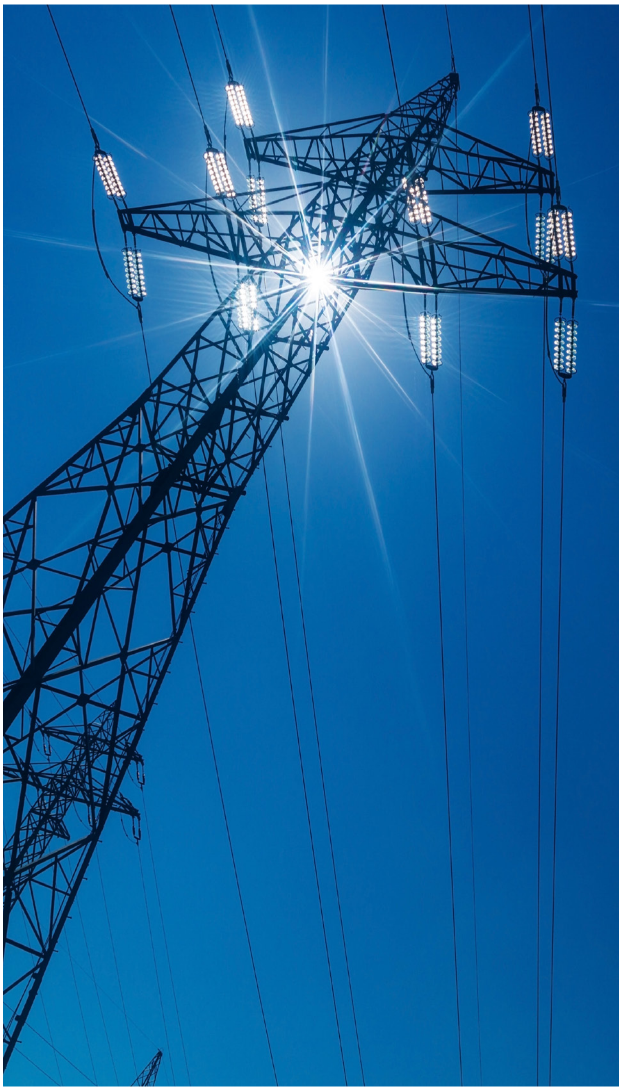
The same conclusions that are highlighted by Abrahams e al. in their paper under a 100-year GWP scenario are also confirmed adopting the 20-year GWP view (figures below) [59].

Figure 6 - LNG Exports by Abrahams' Under 20-yr GWP Assumptions

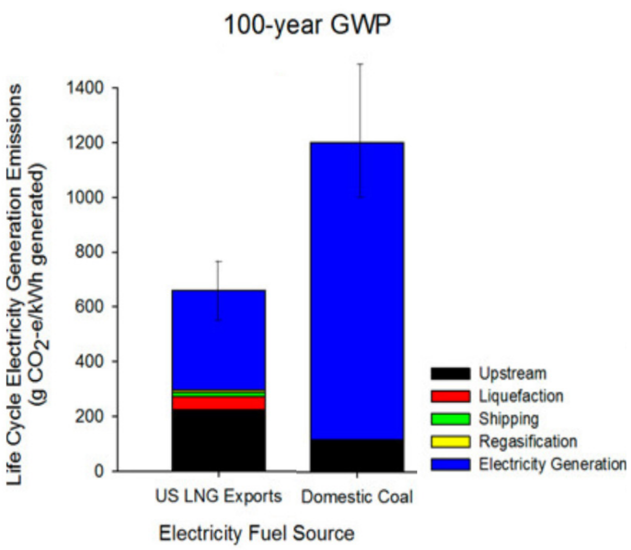
20-yr GWP	g CO2-e/kWh
LNG EXPORTS	
upstream	469
liquefaction	49
shipping	15
regasification	8
combustion	364
total	900
COAL:	
upstream	248
combustion	1,085
total	1,332

The first figure circled in blue is lower than the second figure circled in blue, even though the first figure circled in green is larger than the second figure circled in green.

4) Abrahams' overall conclusion also differs from Howarth's study. According to Abrahams, the benefit of displacing coal inter alia depends on the GWP metric chosen and is definitively sensitive to the upstream fugitive emissions rate. This is further emphasised by the fact a 100-year GWP mean life cycle emissions from exported U.S. LNG results in about 45% fewer emissions than coal used to generate electricity[60] as shown in Graph 15.

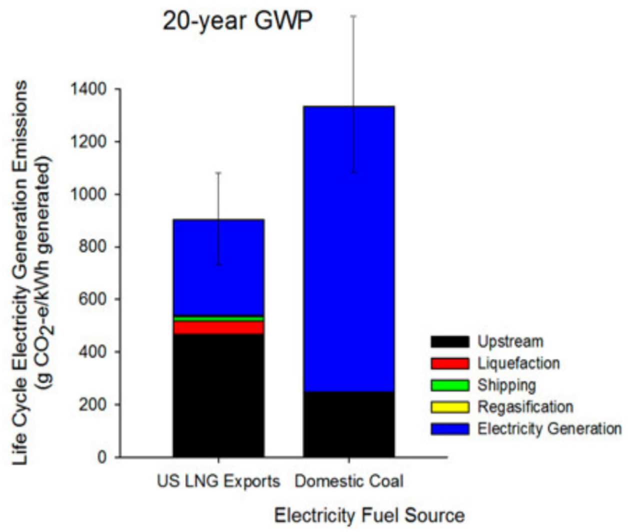


Graph 15 – Lifecycle Electricity Generation Emissions Under a 20 Year GWP Assumption by Abrahams



Even in a 20-year GWP scenario, according to Abrahams, exporting LNG from the US would reduce emissions from electricity production from coal by 32%[61].

Graph 16 – Lifecycle Electricity Generation Emissions Under a 20 Year GWP Assumption by Abrahams



5) According to Abrahams the comparison between coal and LNG partially changes if we alter the final usage of the combustion, shifting from power generation to industrial heating. Currently, the main final usage of both LNG and coal is the production of power rather than the production of heat so we suggest sticking to the most applicable case. Despite this, Abrahams' research does not reach unexpected conclusions due to the different efficiency factors of turbo-gas turbine (aimed at electricity production) and burner (aimed at industrial heat production).

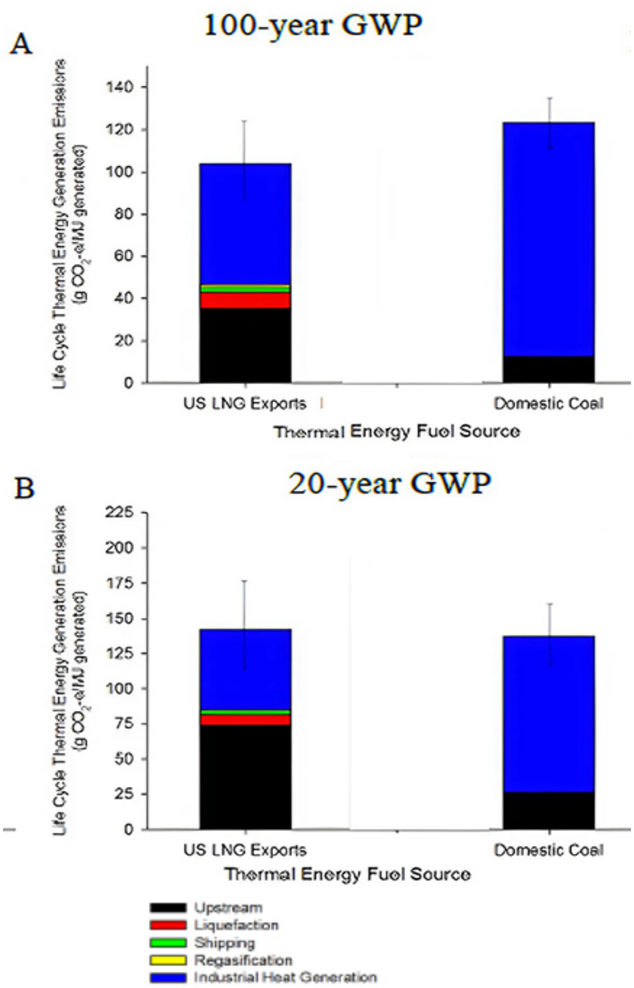
Even under these specific circumstances (combustion to generate industrial heating), LNG remains the first choice although coal becomes slightly more competitive.

Under a 100-year GWP, mean GHG emissions from U.S. LNG exports would be 13% lower than coal even producing industrial heat (in line with the power generation scenario). However, when using a 20-year GWP, mean GHG emissions from U.S. exports would be 4% higher than coal (see Graph 17)[62].

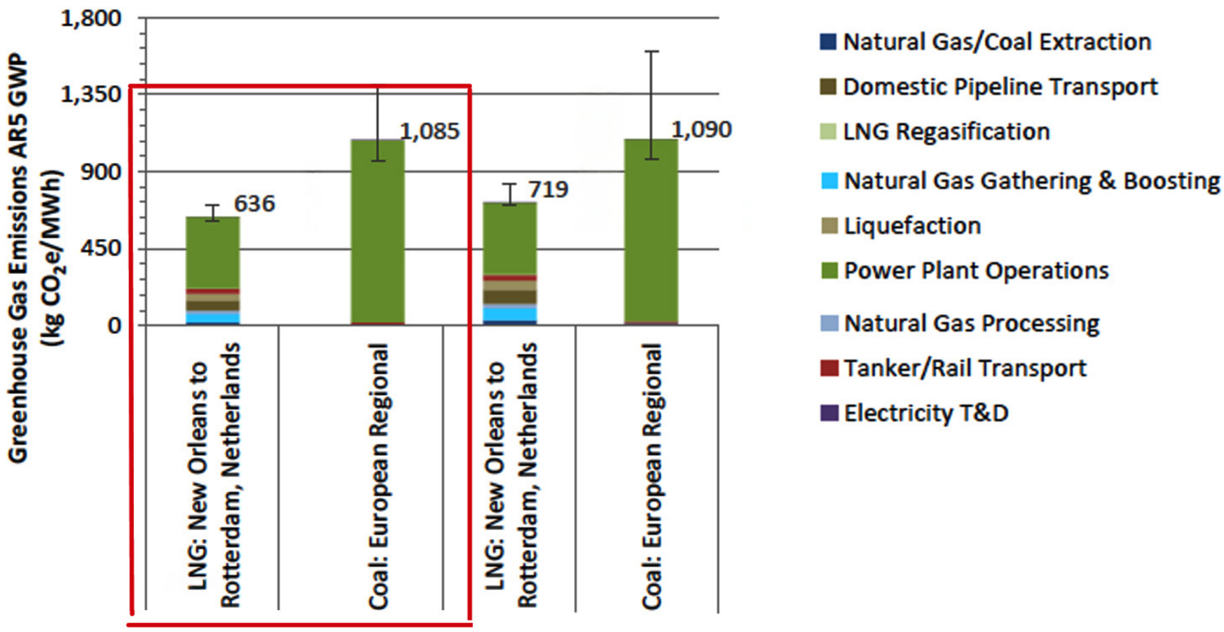
The above results from Abrahams confirm the different cases and scenarios analysed so far and the most diffused view[63] that LNG overall has a lower GHG footprint compared to coal in almost all scenarios. There are several sensitivities that open up different scenarios and results. The analysis from Howarth and Abrahams coincides in just one specific case (20-year GWP, heat production, absent or limited CMM and no local transport emissions for coal) and according to Abrahams coal prevails for a mere 4%. Abrahams writes: "This is illustrative of the complexity of quantifying net impact of LNG exports; there are numerous first-order consequential pathways influenced by the emergence of a U.S. natural gas export".

6) The overall results from Abrahams are also in line with a detailed study by Selina Roman-White et al[64] for NETL. LNG is always the best choice when used to displace coal in power production both in the case of 100 GWP (circled in red in Graph 18) and 20 year assumptions. In the NETL study there are several geographical scenarios. For clarity and conciseness, we show below solely the LNG exports from USA to Europe Vs domestic coal in Europe. These results confirm that the majority of GHG emissions come from combustion at the power plant; however, the contributions from the upstream acquisition of the two fuels are very different. For the "European" scenario, 34% of the life cycle emissions for LNG are from the supply chain prior to the power plant, compared to 2 percent for coal on a 100-year basis. On a 20-year basis, the upstream share (precombustion) for LNG scenario increases to 42% vs a stable 2 % for coal, due to the high GWP associated with methane. Comparing the overall figures, this means that exporting LNG to Europe from the USA reduces the GHG footprint by 41.4% in a 100-year scenario[65] and by 34% in a 20-year scenario.

Graph 17 – Lifecycle Thermal Energy Generation Emissions by Dr Abrahams



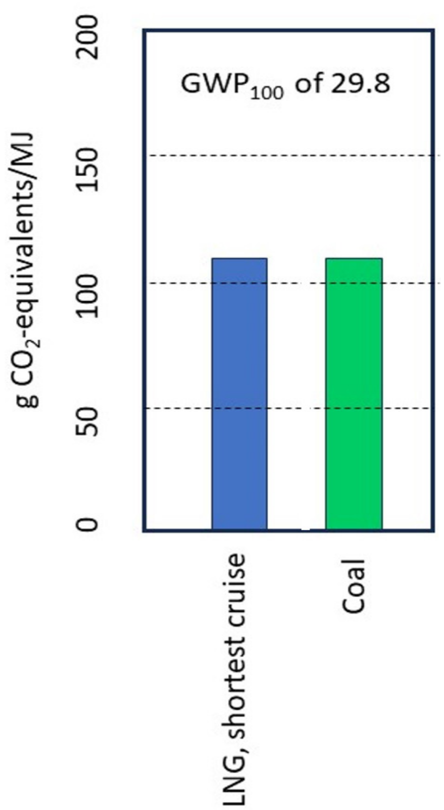
Graph 18 – Lifecycle GHG Emissions for Natural Gas and Coal Power in Europe by NETL



7) Howarth's results are not unexpected when all parameters are adjusted to create the least favorable scenario for LNG—using a 20-year GWP, assuming final combustion for heat rather than power, minimising or excluding CMM, omitting coal transport emissions, and applying an above-average percentage of upstream GHG emissions.

The assumptions adopted by the author influence the final result of the model. This is confirmed in the sensitivities section in Howarth's paper. Even changing solely two different assumptions, 100-year GWP and short voyages by tanker (these correspond to the regular commercial route from Texas to the UK, 9070 km each way[66]) ceteris paribus the emissions for LNG and coal are equal[67](Graph 19).

Graph 19 – 100-year GWP and Short Voyages by Tanker Emissions



In the analytical trajectory undertaken thus far, we have presented Howarth's perspectives regarding the "Cradle-to-Grave" process for LNG and coal, emphasising his assertion that coal may have a lower GHG emissions profile compared to LNG under certain specific assumptions. We subsequently reviewed the primary methodological critiques of his findings, which include his use of the 20-year global warming potential (GWP) metric, the underestimation of technological advancements to reduce methane leakage, and his preference for heat units over power units in his calculations. In section 2.4, we further detailed numerical evidence derived from the works of other researchers, consistently concluding that LNG has a significantly better GHG footprint than coal when the full life cycle of both fuels is comprehensively analysed with the aim of power production.

We also underscored the critical importance of the upstream methane emission factor, as it constitutes a substantial portion of the total emissions from LNG's pre-combustion supply chain[68]. Accurate measurement of this factor is essential for robust evaluations. Moreover, we highlighted how technological advancements have enabled significant progress in this area, both through improved measurement methods (e.g., aircraft flyovers) and the physical reduction of emissions via enhanced insulation materials, modern procedures, and advanced leak detection technologies.

Given the rationale underpinning our previous analysis, it is now appropriate to proceed with a benchmarking exercise to compare how NETL and Abrahams address this issue. The objective of this exercise is to establish a reference point for future decision-making on specific projects and to promote efforts aimed at achieving zero methane emissions as quickly as possible.

3.1 NETL Methane Emission Rates

The table below presents the upstream and cradle-to-delivery methane emission rates for LNG exported from the U.S. to Europe, as analysed by NETL in their study. It also highlights the breakeven upstream emission rates, which are derived by comparing the projected greenhouse gas (GHG) emissions of natural gas with those of coal. As expected, the breakeven rates based on the 20-year global warming potential (GWP) are lower than those based on the 100-year GWP, reflecting methane's significantly higher GWP over a 20-year timeframe compared to a 100-year period.

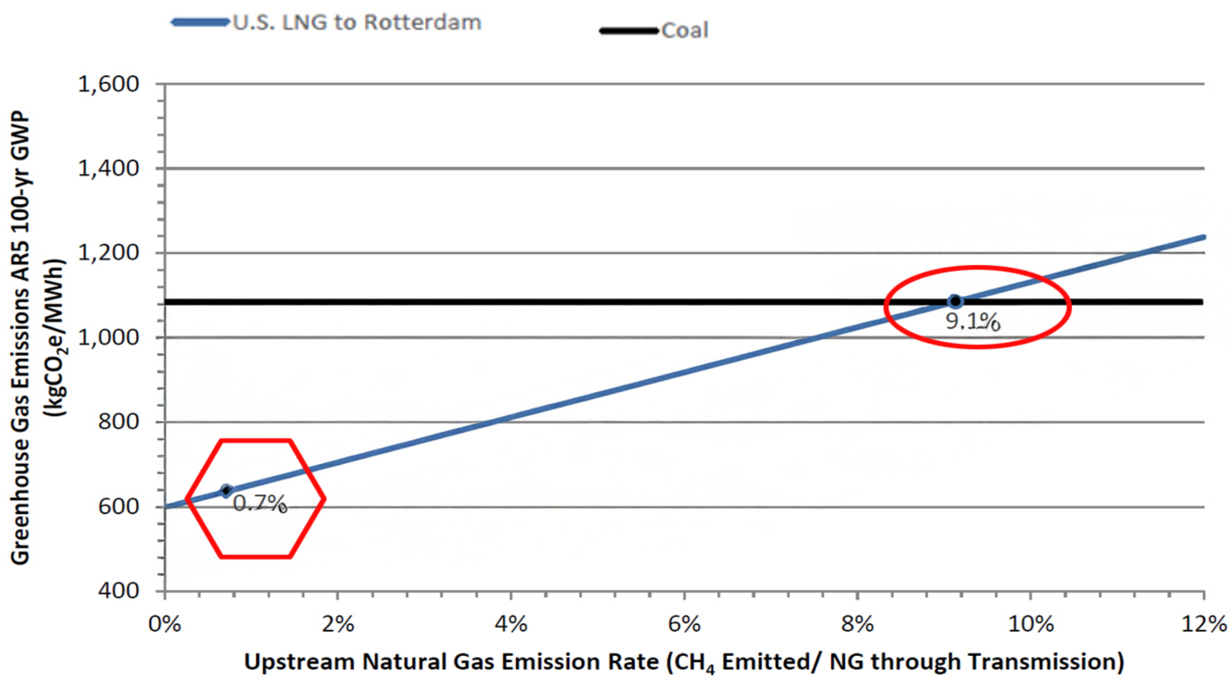
The subsequent two graphs illustrate the life cycle GHG emissions for U.S. LNG as a function of the upstream emission rate. The first graph uses the 100-year GWP, while the second employs the 20-year GWP. Both graphs include a reference line indicating emissions from a coal-based power generation scenario. Diamond-shaped markers represent the actual upstream emission rates, whereas oval-shaped markers denote the breakeven emission rates at which cradle-to-delivery GHG emissions for natural gas are equivalent to those of the coal reference case.

For U.S. LNG exported to Europe (Rotterdam), the breakeven upstream emission rate is estimated at 9.1% based on the 100-year GWP metric. Even under the 20-year GWP scenario, the upstream emission rate for U.S. LNG (0.7%) remains significantly lower than the breakeven rate for export to Europe, which is calculated at 3.6%.

Table 6 – Upstream and Cradle-to-Delivery Methane Emission Rates for LNG Exported from the United States to Europe According to NETL[69]

Scenario	Upstream Emission Rate	Cradle-through-delivery Emission Rate	Breakeven Upstream Emission Rate	
			100-yr GWP	20-yr GWP
U.S. LNG to Rotterdam	0.7%	1.1%	9.1%	3.6%

Graph(s) 20/21 – Coal and Natural Gas Breakeven for U.S. LNG by NETL



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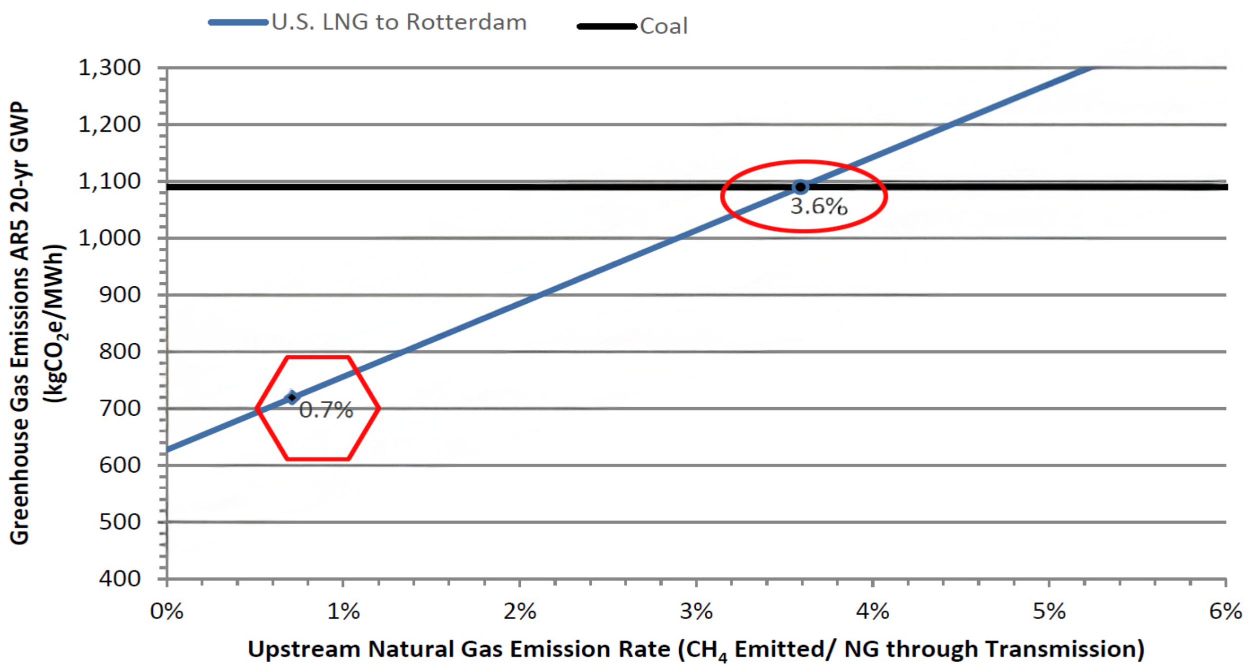
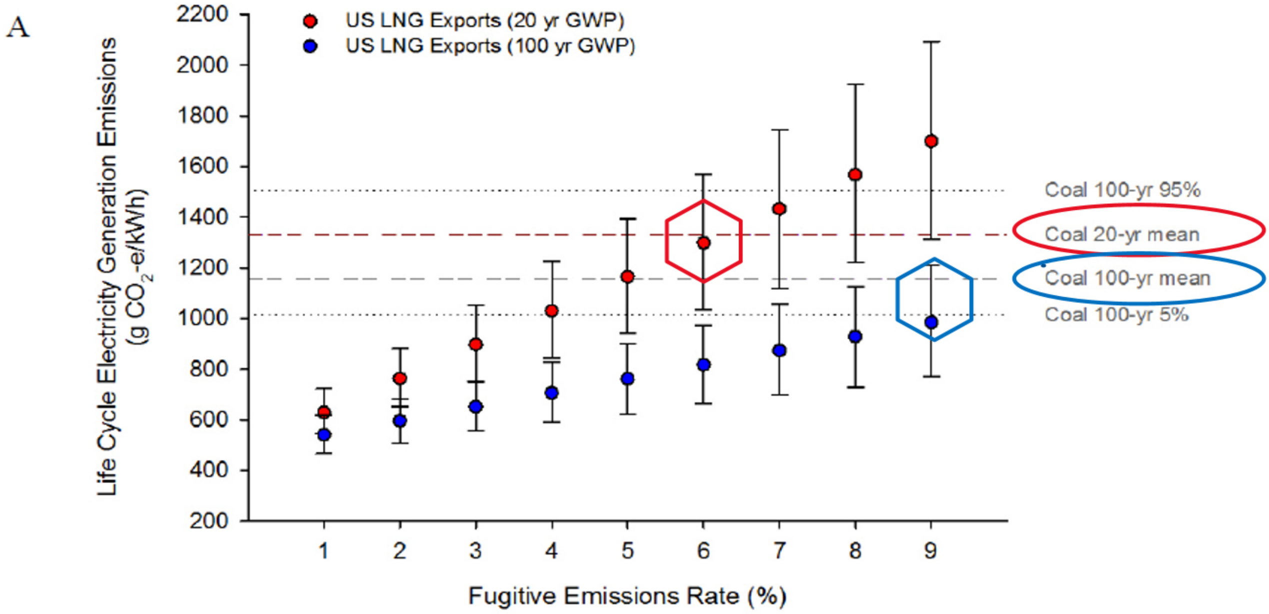


3.2 Abrahams' Methane Emission Rates

The sensitivity of the results in Abrahams' study to the assumption of fugitive methane emissions rates was examined in the online supporting information section of her paper. These tests confirmed that her model is highly sensitive to variations in methane emission rates, consistent with the numerical findings highlighted in sections 2.3.2 and 2.4 of this paper.

Furthermore, Abrahams conducted a benchmarking analysis comparing methane fugitive emission rates with coal under power production scenarios based on both 20-year and 100-year global warming potential (GWP). The results of this analysis are shown in Graph 22 below. For the 100-year GWP, natural gas results in lower emissions than coal up to a methane leakage rate of approximately 9% (figures circled in blue). However, for the 20-year GWP, the breakeven point occurs at a fugitive emissions rate of approximately 6% (figures circled in red).

Graph 22 – Coal and Natural Gas Breakeven for U.S. LNG by Abrahams



3.3 Key Insights and Considerations

According to these comparative studies, two key insights emerge. First, there is a significant opportunity to close the gap in technological advancements to reduce methane leakage rates to near zero. Achieving this would result in substantial reductions in polluting emissions, benefiting the environment while saving producers millions of dollars. Second, the comparison between LNG and coal, particularly for electricity production under the 100-year global warming potential (GWP) framework, strongly favours LNG, making it a "no contest" in terms of greenhouse gas (GHG) emissions. However, before drawing definitive conclusions, it is essential to critically examine the benchmarking exercises conducted by NETL and Abrahams.

The NETL study derives its calculations from methane leakage factors based on raw data from various sources.

As previously mentioned, in commentary on other authors' studies, the methane upstream leakage factor serves as a critical input in similar models. This factor directly influences the cradle-to-delivery methane leakage rate, the overall GHG footprint, and the resulting emissions trajectory within a model. Consequently, any underestimation or overestimation of the upstream leakage factor can lead to skewed results.

In the NETL study, the upstream methane leakage rate is set at 0.7%, with an overall leakage rate of 1.1%, based on datasets from the Environmental Protection Agency (EPA[70]) and prior NETL[71] studies. However, empirical evidence suggests that the actual leakage rate "on the ground" is significantly higher. For example, a study led by researchers from the Environmental Defense Fund (EDF) and reported by the Stanford School of Sustainability[72] estimates that the current leakage rate from the U.S. oil and gas system is 2.3%, compared to the EPA's inventory estimate of 1.4%. Although these percentage differences may appear minor, the volume of leaked gas is substantial—enough to power 10 million homes—and represents a financial loss of approximately $2 billion.

This concern about methane leakage rates is not new. When analysing Howarth's paper in Section 2.3.2, one of the critical issues identified was the accuracy of methane leakage rates in ensuring comparability across full life cycle LNG studies. In our view, the methane leakage rate used in the NETL study should be updated to reflect the most current data, and the benchmarking exercise should be repeated with these updated figures.

Despite these data issues, we concur with the general conclusion that LNG is a preferable option to coal from a GHG footprint perspective. Notably, the findings of NETL are corroborated by Abrahams' model, which, under similar assumptions (power generation and 100-year GWP), also demonstrated a lower overall GHG footprint for LNG compared to coal. It is worth emphasising that Abrahams' results were achieved even with a higher initial methane fugitive rate (3%).

Howarth's 2023 work has garnered significant attention, as it was cited as one of the influences behind President Biden's decision to declare a moratorium on the expansion of LNG exports from the U.S. in January 2024.

The core argument in Howarth's articles is that while LNG—the cryogenic form of natural gas, often marketed as a "transition fuel"—is generally seen as cleaner than coal in terms of combustion emissions, its full life cycle GHG footprint may challenge that perception. Howarth identifies critical stages in LNG's lifecycle, including extraction, liquefaction, transportation, and regasification, as energy-intensive processes prone to methane leakage. Methane, a potent GHG with a short-term warming impact far exceeding that of CO_2, plays a pivotal role in his argument.

Despite the complexity of the analysis and the numerous interconnected variables that influence the outcomes, our research—based on prior work by Abrahams, Michael Levi, Michael Barnard, institutions such as the National Energy Technology Laboratory (NETL) and the Center for Liquefied Natural Gas (CLNG), and an extensive review of other sources—concludes that, in almost all scenarios analysed, LNG proves to be a cleaner option than coal. While there are rare instances where the results appear even or slightly favor coal, these are limited to highly specific and less concrete assumptions, such as a 20-year Global Warming Potential (GWP) instead of a 100-year GWP and less realistic simplifications in efficiency and emissions modeling.

Thus, we do not advocate burning coal over LNG, as suggested by Howarth. However, we agree with his assertion that reducing unnecessary methane leaks should be a priority to mitigate the emissions associated with LNG's supply chain.

4.1 General Findings: LNG Vs Coal

1. LNG vs. Coal Emissions: LNG is not as harmful as coal, when methane leaks are kept under control, combustion occurs in low-slippage engines, and it is used in combined cycle gas turbines operated at higher capacity factors. Technical advancements adopted in Northern Europe, for example, should be replicated in global facilities.

2. Lower Pollution: LNG emits significantly lower levels of greenhouse gases and pollutants compared to coal. It is widely regarded as an environmentally cleaner fuel due to the absence of harmful by-products like sulfur, mercury, ash, and particulates, and it provides twice the energy per unit of weight with half the carbon footprint during combustion. Replacing coal plants with natural gas plants has demonstrably saved lives.

3. Upstream and Midstream Emissions: The primary focus of most studies is upstream and midstream emissions (i.e., pre-combustion leakages). There is a broad consensus that these emissions should be minimised or eliminated. However, the translation of methane precombustion emissions into percentages of overall GHG emissions remains a contentious point, with varying results across studies. Finally, there are extreme variances in raw data depending mainly on data collection techniques, better material and procedure and geography.

4. Technological Innovation: Technological advances in the LNG industry, such as improved well completion techniques, better pipeline monitoring, and enhanced tanker efficiency, have significantly reduced methane leaks. While CCS offers potential for coal, its adoption is still limited by high costs and logistical challenges. These trends suggest that while LNG's GHG footprint will likely improve with innovation, coal's mitigation measures may encounter systemic and economic barriers.
   As confirmed by the benchmarking exercise and the example of countries in Northern Europe, there is room for substantial improvement on the LNG side.

5. Use of GWP Metrics: We recommend using the 100-year GWP metric as the basis for analysis or at least presenting results under both the 100-year and 20-year GWP frameworks, primary for comparability purposes. While this increases complexity, it ensures a more robust evaluation of results across studies. We re-emphasise that whatever decision in this matter is arbitrary but should not be driven by pre-assessed goals or bias.

6. Unit of Measure in Comparisons: Comparing LNG and coal using thermal units rather than power units can distort benchmarking efforts. As our research indicates, LNG primarily displaces coal in power generation, making power units the appropriate metric. LNG is an alternative and substitutive product for coal mainly for power generation, less so for other industrial uses.

7. Context-Specific Evaluations: The debate between coal and LNG is not binary but must be contextualised. Each project should be assessed individually, accounting for unique variables. For instance, the U.S. LNG system differs significantly from that of Northern Europe, where the entire lifecycle is engineered to minimise methane leakage. Comparisons between best-in-class and suboptimal facilities could yield markedly different conclusions.

8. Final Reflections: Our comparative assessment of coal and LNG highlights the importance of context-specific evaluations, methodological rigor, and proactive policy and technological interventions. While LNG generally offers a lower GHG footprint than coal, this advantage hinges on effective methane management across all lifecycle stages. The future of energy production lies in leveraging these insights to accelerate the transition to cleaner, less-leaking energy systems.

01- Robert W. Howarth, Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY 14853 USA.

02- https://www.bloomberg.com/news/features/2024-02-29/biden-lng-approval-pause-influenced-by-cornell-methane-scientist?leadSource=uverify%20wall

03- Howarth RW. The greenhouse gas footprint of liquefied natural gas
(LNG) exported from the United States. Energy Sci Eng. 2024;1-17. doi:10.1002/ese3.1934.

04- Natural gas accounted for more than 60% of the CO2 reductions from the power sector from 2005-2021 per EIA data. https://www.eia.gov/environment/emissions/carbon/

05- Criticisms Of LNG Export Emissions Study Don't Withstand Scrutiny Criticisms Of LNG Export Emissions Study Don't Withstand Scrutiny - CleanTechnica

06- https://twitter.com/coefficientpoll/status/1750602918053503216?s=20

07- Lawrence M. Cathles III & Larry Brown & Milton Taam & Andrew Hunter. A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea.

08- Howarth RW. The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States. Energy Sci Eng. 2024;1-17. doi:10.1002/ese3.1934 On-line only supplemental materials Figure B

09- GWP is a metric used to compare the impact of different greenhouse gases (GHGs) on global warming. It quantifies the cumulative radiative forcing (heat-trapping effect) of a gas over a specific time horizon, relative to the same mass of carbon dioxide (Co2), which is assigned a GWP of 1

10- Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 update. Selina Roman-White, Srijana Rai, James Littlefield, Gregory Cooney, Timothy J. Skone, P.E., DOE/NETL-2019/2041

11- https://www.nationalgas.com/sites/default/files/documents/28039-LNG%20Technical%20Information.pdf
When natural gas is cooled to a temperature of approximately - 160°C, at atmospheric pressure, it condenses to a liquid called liquefied natural gas (LNG). 600 cubic meters of natural gas condense to approximately ONE cubic meter of LNG

12- The insulation alone, as efficient as it is, will not prevent the ingression of heat. LNG is stored as a "boiling cryogen," that is, it is a very cold liquid at its boiling point for the pressure at which it is being stored. LNG will stay at near constant temperature if kept at constant pressure. This phenomenon is called "autorefrigeration". As long as the LNG vapor (boil off) is allowed to leave the tank, the temperature will remain constant. If the vapor is not drawn off, then the pressure and temperature inside the vessel will rise.

13- https://www.epa.gov/cmop/about-coal-mine-methane

14- https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019

15- Coalbed Methane Outreach Program (CMOP) | US EPA

16- In some instances where end uses are not economic or available, the destruction of methane through flaring may be the most appropriate option for reducing GHG emissions and mitigating CMM-related mine hazards. https://www.epa.gov/cmop/benefits-capturing-and-using-coal-mine-methane

17- The solely quantitative reference mentioned for methane direct emissions referred to coal is CH4 = 0.21g CH4/MJ. We were not able to reconcile the presented figures with the type of coal mine chosen by Howarth. For reference on the methodology to be used to calculate emission factors for coal mines please look at: Estimating methane emissions from coal mines at Estimating methane emissions from coal mines - Global

Energy Monitor

18- Trade – Coal 2024 – Analysis - IEA

19- There's more coal being shipped by sea than ever before

20- https://www.statista.com/statistics/264017/global-seaborne-trade-of-coal-since-1985/

21- 5 Transport of Coal and Coal Products | Coal: Research and Development to Support National Energy Policy | The National Academies Press

22- https://iea.blob.core.windows.net/assets/a1ee7b75-d555-49b6-b580-17d64ccc8365/Coal2024.pdf?utm

23- 1. CO_2 Emissions from Maritime Transport
To estimate the CO_2 emissions from shipping coal, we use the following formula:
CO_2 Emissions (kg) = Distance (km) × Cargo Weight (tons) × Emission Factor (kg CO_2/ton-km)
Emission Factor:
• Bulk Carriers: Approximately 3.54 grams of CO_2 per ton-kilometer. This data is derived from https://www.statista.com/statistics/1233482/carbon-footprint-of-cargo-ships-by-type-uk/?utm_source {Average carbon footprint of cargo ships in the United Kingdom (UK) in 2024, by type (in grams of CO_2e per metric ton of goods shipped per kilometer)}
Example Calculations:
• Australia to China (~5,000 km):
5,000 km × 1 ton × 0.00354 kg CO_2/ton-km=17.7 kg CO_2 per ton of coal
• Australia to Europe (~20,000 km):
20,000 km × 1 ton × 0.00354 kg CO_2/ton-km=70.8 kg CO_2 per ton of coal
• South Africa to India (~8,000 km):
8,000 km × 1 ton × 0.00354 kg CO_2/ton-km=28.3 kg CO_2 per ton of coal
2. CO_2 Emissions from Coal Combustion
The CO_2 emissions from burning coal can be estimated using its carbon content and the combustion process. The general formula is:
CO_2 Emissions (kg) = Coal Weight (kg) × Carbon Content Fraction × Molecular Weight of CO_2/ Molecular Weight of Carbon
Where:
• Molecular Weight of CO_2: 44
• Molecular Weight of Carbon: 12
• Ratio (CO_2/C): 44/12 ≈ 3.67
Example Calculation:
For 1 ton (1,000 kg) of coal with a carbon content of 78% (which varies depending on coal type):
1,000 kg × 0.78 × 3.67 ≈ 2,863 kg CO_2
This aligns with data from the U.S. Environmental Protection Agency, which states that burning a pound of coal emits approximately 2.07 pounds of CO_2, translating to about 4,554 pounds (2,065 kg) of CO_2 per ton of coal. https://www.epa.gov/energy/frequent-questions-epas-greenhouse-gas-equivalencies-calculator?utm_source
3. Conclusion:
These calculations indicate that the CO_2 emissions from transporting coal can add approximately 0.6% to 2.5% to the total emissions from its combustion, depending on the transport distance.

24- https://business.purdue.edu/faculty/hummelsd/papers/YJEEM-1749_FINAL082312.pdf?utm and https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/?utm

25- http://martrans.org/documents/2008/sft/final%20report%20v10.2.pdf SHIP EMISSIONS STUDY. National Technical University of Athens Laboratory for Maritime Transport. prepared for Hellenic Chamber of Shipping

26- Trade – Coal 2024 – Analysis - IEA

27- Rolling coal: The greenhouse gas emissions of coal rail transport for electricity generation Rolling coal: The greenhouse gas emissions of coal rail transport for electricity generation - ScienceDirect

28- The width of each line represents the quantity shipped along that rail segment. The map shows that a significant portion of U.S. coal travels out of a few Wyoming mines and reaches Texas, the Midwest, and the eastern United States. Looking at individual routes, many eastern mines do not ship far west (e.g. past Wyoming.) Rolling coal: The greenhouse gas emissions of coal rail transport for electricity generation

29- Life Cycle Greenhouse Gas Perspective on

Exporting Liquefied Natural Gas from the United States: 2019 update. Selina Roman-White, Srijana Rai, James Littlefield, Gregory Cooney, Timothy J. Skone, P.E., DOE/NETL-2019/2041

30- Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York by Robert W. Howarth. [Full article: Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York]

31- Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York by Robert W. Howarth. [Full article: Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York]

32- Other Authors presented results using both 20- and 100-year GWP approach. For reference inter alia: Leslie S. Abrahams, Constantine Samaras, W. Michael Griffin, H. Scott Matthews, Selina Roman-White, Srijana Rai, James Littlefield, Gregory Cooney, Timothy J. Skone

33- Sherwin, E.D., Rutherford, J.S., Zhang, Z. et al. US oil and gas system emissions from nearly one million aerial site measurements. Nature 627, 328–334 (2024). https://doi.org/10.1038/s41586-024-07117-5

34- Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses
Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews.
“There is significant debate in the literature over the fugitive emissions rate for the upstream natural gas life cycle stages. As such, in this analysis the fugitive emissions rate is presented in three ways: (1) a “most likely” range commonly cited in literature.27−32 This uncertainty is represented as a triangular distribution with a minimum of 2%, maximum of 4% and most likely value of 3%, (2) a sensitivity analysis showing the effects of fugitive emissions rates across a range encompassing most values discussed in the literature. Additional details can be found in the Supporting Information at http://pubs.acs.org/ and below.
Upstream GHG Emissions
The Monte Carlo simulation inputs for the production stage of the LNG life cycle (Table S.2) were adapted from Weber 20121. The units are g CO2-equiv/MJ unless otherwise noted.

	min	most likely	max
Well pad construction	0.05	0.13	0.3
Well drilling	0.1	0.2	0.4
Fracturing water management	0.04	0.23	0.5
Fracturing chemicals	0.04	0.07	0.1
Conv well completion	0.01	0.12	0.41
Unconv well completion: total vent/flare (mt CH4)	13.5	177	385
Well completion: flare rate (fraction)	0.15	0.41	1
Well completion: EUR (Bcf)	0.5	2	5.3
Flaring	0	0.43	1.3
Unconv Lease/Plant energy	2	3.3	4.1
Conv. Lease plant energy	2	3.3	4.3
CO_2 vent	0.2	0.7	2.8
Compression fuel	0.2	0.38	0.6
Leak percent[2]	2	3	4

Parameter	Type	Unit	Value (min, avg, max)		
Energy input	Assumed parameter	MJ		1	
percent methane by volume	Triangular (min, avg, max)	%	0.83	0.93	0.95
Fugitive Emissions	Calculated (5th, avg, 95th)	g CO2-e/MJ	11.9	20.7	30.72
unconventional emissions	Calculated (5th, avg, 95th)	g CO2-e/MJ	18	27	37
conventional emissions	Calculated (5th, avg, 95th)	g CO2-e/MJ	19	28.5	39.5
% of gas mix from shale	Assumed parameter	%		0.4	
Total Upstream Emissions	Calculated (5th, avg, 95th)	g CO2-e/MJ	18.5	27.9	28.4

	Harmonized Life Cycle Emissions[3]		**harmonized upstream***	**leakage rate**	**Results from this study's model ($g\ CO_2$-e/MJ)**		
study	Shale	Conventional	($g\ CO_2$-e/MJ)	%	mean	5%	95%
Howarth[4]	746	647	46.3	2.8	20.3	18.8	22
Howarth[4]	567	473	21.3	6.2	36.6	34.5	38.5
Jiang[5]**/Venkatesh**[6]	497	439	14.5	2.2	17.5	16	19
Skone[7]	438	439	11.1	3.9	25.6	23.8	27.4
Hultman[8]	438	438	11.1	2.8	20.3	18.8	22
Burnham[9]	517	557	25.6	2	16.5	15.1	18
Stephenson[10]	434	420	9.3	0.66	10	8.7	11.6
Heath[11]**/ O'Donoughue**[12]	459	450	13.3	1.3	13	11.8	14.8
Laurenzi[13]	470	450	13.9	1.4	13.6	12.2	15.2
This study	-	-	-	triang(2,3,4)	21.3	17.6	24.8

* Adapted from Heath et al. (2014)

35- Gan Y, El-Houjeiri HM, Badahdah A, et al. Carbon footprint of global natural gas supplies to China. Nat Commun. 2020;11: 824. https://www.nature.com/articles/s41467-020-14606-4

36- A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth,
R. Santoro, and Anthony Ingraffea by Lawrence M. Cathles III & Larry Brown & Milton Taam & Andrew Hunter

37- NETL. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

38- https://en.wikipedia.org/wiki/GREET_Model

39- https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation

40- Total estimated leaked emissions range from just less than one percent to as much as 9.6% of total volume, with an average of 3% across the surveyed regions. The federal government estimates that methane emissions from oil and gas facilities nationwide average roughly 1% of gas production. Sherwin noted that in the surveyed regions of Pennsylvania and Colorado, the team's estimates were on par with or lower than estimates from the U.S. Environmental Protection Agency. Methane emissions from major U.S. oil and gas operations higher than government predictions | Stanford Report

41- A gigajoule (GJ) is a unit of energy in the International System of Units (SI). It is defined as: 1 gigajoule = 1 billion joules (10^9 joules). A joule (J) is the amount of energy transferred when applying a force of one newton over a distance of one meter. A gigajoule represents a much larger amount of energy, suitable for describing industrial or large-scale energy usage. The conversion of Joules (J) into kilowatt-hours (kWh) is a fixed mathematical relationship. However, the amount of usable energy derived from it depends on the efficiency of the machine or process.

42- https://www.woodwayenergy.com/natural-gas-efficiency-in-power-generation/#:~:text=Natural%20gas%20outperforms%20other%20fossil%20fuels%20significantly%20in,coal%20plant%20has%20a%20thermal%20efficiency%20around%2033%25.

43- Methane emissions from U.S. oil and gas operations cost the nation $10 billion per year. Stanford Report. https://news.stanford.edu/stories/2024/03/methane-emissions-major-u-s-oil-gas-operations-higher-government-predictions?utm_sourc

44- Key findings – Global Methane Tracker 2024 – Analysis - IEA

45- Reducing methane emissions - Equinor

46- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Main Text

47- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Main Text page 97

48- https://economictimes.indiatimes.com/small-biz/sustainability/why-carbon-capture-is-no-easy-solution-to-climate-change/articleshow/105432427.cms?

49- High Costs: CCS costs range from $15 to $120 per metric ton of captured CO_2, depending on the emissions source. Direct Air Capture (DAC) projects are even more expensive, between $600 and $1,000 per metric ton, due to the energy-intensive process of capturing CO_2 directly from the atmosphere.
Infrastructure and Location Constraints: The effectiveness of CCS depends on suitable geological formations for CO_2 storage, which are not uniformly available worldwide. This limitation can necessitate extensive pipeline networks or shipping fleets to transport captured CO_2 to appropriate storage sites, posing logistical and environmental challenges.
Regulatory and Social Acceptance: The establishment of supportive policies and obtaining public consent are crucial for the successful implementation of CCS projects. For instance, Japan enacted the Act on Carbon Dioxide Storage Businesses in May 2024 to create a conducive environment for CCS commercialization.
https://economictimes.indiatimes.com/small-biz/sustainability/why-carbon-capture-is-no-easy-solution-to-climate-change/articleshow/105432427.cms?
https://www.enecho.meti.go.jp/en/category/special/article/detail_201.html?utm

50- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Main Text

51- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Main Text

52- https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf

53- Refer to footnote 17 above

54- Howarth online supplemental materials. The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States - Howarth - 2024 - Energy Science & Engineering - Wiley Online Library

55- Please refer to graph10 results for Howarth

56- Please refer to graph10 results for National Energy Technology Laboratory

57- Please refer to graph 10 results for Abrahams et al.

58- FACT SHEET: COMPARING U.S. LNG AND COAL GREENHOUSE GAS EMISSIONS (CLNG, Centre for Liquefied Natural Gas)

59- Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews. Supporting information at: ACS Publications | Chemistry Journals, Scientific Articles & More

60- Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses
Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews.

61- Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses
Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews. Supporting information at: ACS Publications | Chemistry Journals, Scientific Articles & More

62- Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses
Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews. Supporting information at: ACS Publications | Chemistry Journals, Scientific Articles & More

63- Lawrence M. Cathles III & Larry Brown & Milton Taam & Andrew Hunter. A commentary on “The greenhouse-gas footprint of natural gas in shale formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea.

Council on foreign relations. Some Thoughts on the Howarth Shale Gas Paper by Michael Levi. https://www.cfr.org/blog/some-thoughts-howarth-shale-gas-paper

FACT SHEET: COMPARING U.S. LNG AND COAL GREENHOUSE GAS EMISSIONS (CLNG, Centre for Liquefied Natural Gas)

NETL. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

64- NETL. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

65- Refer to Graph 18.

66- Howarth RW. The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States. Energy Sci Eng. 2024;1-17. doi:10.1002/ese3.1934

67- Howarth RW. The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States. Energy Sci Eng. 2024;1-17. doi:10.1002/ese3.1934 On-line only supplemental materials Figure B

68- Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses
Leslie S. Abrahams,*,†,‡ Constantine Samaras,‡ W. Michael Griffin,† and H. Scott Matthews. Supporting information at: ACS Publications | Chemistry Journals, Scientific Articles & More

69- NETL. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.
Upstream emission rate: Comprises cradle-through-transmission methane emissions for natural gas delivered to a liquefaction terminal (precombustion leakage). The numerator for this emission rate is methane emissions from production through pipeline transmission. The denominator for this emission rate is natural gas that exits a transmission pipeline.
Cradle-through-delivery emission rate: Com-

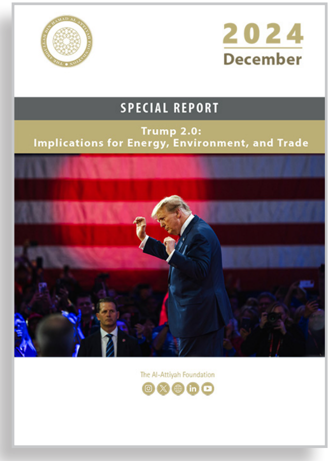
prises cradle-through-delivery methane emissions for natural gas delivered to a natural gas-fired power plant. For the LNG this includes upstream emissions plus the emissions from the LNG segment of the supply chain. The numerator for this emission rate is methane emissions from production through regasification. The denominator for this emission rate is natural gas that exits a regasification facility.

70- "The Greenhouse Gas Reporting Program (GHGRP) and the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI) are two data sources that account for most vented and fugitive emissions (EPA, 2016; EPA, 2018). DI Desktop is also used to stratify annual production activity at a basin level (DrillingInfo, 2018). A complete list of parameters and their corresponding uncertainty is provided in NETL's LCA of Natural Gas Extraction and Power Generation (NETL, 2019)". NETL. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

71- Emission rates are highly variable across the entire supply chain. The national average CH4 emission rate is 1.24%, with a 95% confidence interval ranging from 0.84% to 1.76%. Energy Analysis Details Page Life Cycle Analysis of Natural Gas Extraction and Power Generation DOE/NETL-2019/2039.

72- U.S. oil and gas methane emissions are 60 percent higher than EPA reports | Stanford Doerr School of Sustainability U.S. oil and gas methane emissions are 60 percent higher than EPA reports. By Stacy MacDiarmid, Environmental Defense Fund

Have you missed a previous issue? All past issues of The Al-Attiyah Foundation's Research Series, both Energy and Sustainability Development, can be found on the Foundation's website at www.abhafoundation.org/publications



December– 2024

Trump 2.0: Implications for Energy, Environment, and Trade

The return of Donald Trump to the White House promises major changes in the United States' energy and environmental policies and in broader areas that affect energy, including trade and international politics. However, Trump has sent mixed signals about the kinds of policy change he might pursue, and the individuals advanced for roles in his administration sometimes have incompatible positions.

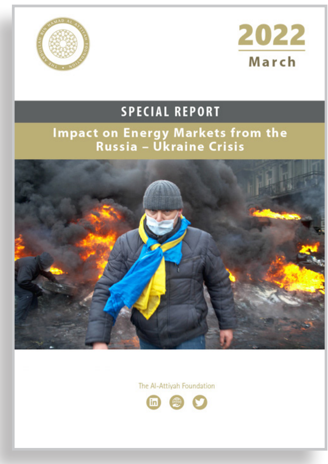
(QRCO.DE)

July – 2021

Are Electric Vehicles Really Green? The Truth About EVs

Electric vehicles (EVs) are touted as one of the pillars of a net-zero carbon future, along with renewable energy. Unlike internal combustion engines (ICE) that usually run on diesel or petrol (gasoline), they produce zero greenhouse gas emissions or other air pollutants from combustion at the point of use and continue gaining in "cleanliness" each year due to improvements in manufacturing processes and the "greening" of the electricity generation mix.

(QRCO.DE)



March – 2022

Impact on Energy Markets from the Russia – Ukraine Crisis

Russia is a critical global energy exporter:it accounts for 25 percent of world gas exports, nearly all to Europe, 18 percent of coal sales, and 11 percent of oil exports, as well as being an important supplier of metals, fertilisers and food. The Russian invasion of Ukraine has brought global energy supply chains to the forefront once again.

(QRCO.DE)

Our partners collaborate with The Al-Attiyah Foundation on various projects and research within the themes of energy and sustainable development.

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