Problems with Greenhouse Gas Life Cycle Analyses of U.S. LNG Exports and Locally-Produced Coal

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Plain Language Summary

By law, exports of natural gas must be in the public interest. On 26 January 2024 the DOE announced it was updating its public interest analysis, and pausing permitting of facilities allowed to export liquefied natural gas (LNG) while this update is underway. An important element of the public interest analysis is an assessment of the contribution of LNG to global climate change. A 2019 National Energy Technology Laboratory (NETL) life cycle analysis found that use of U.S. LNG results in lower overall greenhouse gas (GHG) emissions than locally produced coal or Russian pipeline gas. The NETL study has been called into question by Robert W. Howarth (Cornell) who found that life cycle GHG emissions from U.S. LNG equals or exceeds that of locally sourced coal. Howarth's study has been publicized in the mainstream media, including the New Yorker magazine. Bloomberg reported that it attracted attention in the White House, contributing to the January 2024 decision to pause DOE permitting of new LNG projects. In an examination of the technical details of both reports, I found that NETL selected methods and data that favored gas, while Howarth selected methods and data that favored coal. Both groups used the Global Warming Potential / carbon dioxide equivalent assessment method which climate scientists have found to be misleading.

	NETL	Howarth
Current Methane Emissions From Gas Supply Chains	1.2%: Favoring Gas	4.6%: Favoring Coal
Future Methane Emission Reductions	Not an Option in 2019	Not Considered: Favoring Coal
GWP/CO_2-e Method	Defective & Misleading	
Methane GWP	36: Favoring Gas	82.5: Favoring Coal
Energy Denominator In GHG Intensity	MJ(e): Favoring Gas	MJ(t): Favoring Coal
Overall Effect	Promotes Gas	Promotes Coal

Conclusion: I believe the choices of methods and data reflect the best judgements of the respective authors and were not driven by a desire to come to any predetermined conclusion. However, these results strongly argue for better analytical methods, as described in my report.

Abstract

Exports of liquefied natural gas (LNG) from the United States are growing rapidly, and the United States government must balance a multiplicity of interests in deciding to what extent the growth of LNG exports should be further encouraged. Its decisions must be consistent with the Natural Gas Act, which mandates that exports of natural gas be in the public interest. In the current administration, reduction of greenhouse gas emissions is an important component of the public interest determination. It has generally been regarded that the replacement of coal with natural gas, reducing the volume of power plant carbon dioxide emissions, satisfies this component of the public interest determination. However, a recent life cycle analysis has cast doubt on this conclusion. Here we compare two life cycle analyses that come to different conclusions as to the wisdom of coal-to-gas conversion of electric power industries. We identify the technical factors underlying the various results. Among other problems, both studies use a widely accepted but defective and misleading methodology. Recommendations for improvements are provided.

Introduction

We know we must reduce our use of fossil fuels, and we know the transition from fossil fuels to zero carbon sources of energy will take time. One of our chief challenges will be to minimize the damage associated with fossil fuel use during this transition. Of the fossil fuels, natural gas is the most benign with respect to both conventional air pollution and climate change forcing. It is particularly attractive as a replacement for coal.

Commerce in natural gas in the twentieth century was largely limited to supply and demand centers that could be connected by pipeline. In the twenty-first century the expansion of sea-borne traffic in liquefied natural gas (LNG) cargoes has made gas an intercontinentally traded commodity. In 2022 a total of just over 4000 billion cubic meters (bcm) of natural gas were produced and consumed, of which 720 bcm crossed international frontiers in pipelines and 540 bcm were traded across oceans as LNG [Energy Institute, 2023]. It is difficult to estimate to what extent natural gas production and trade will be sustained during the energy transition. A great deal depends on the extent to which imported natural gas displaces coal in consumption centers such as China and India.

Commercial developers of U.S. LNG export facilities are placing large bets that these markets will continue growing. From 2016 to 2023, 104 million metric tons per annum (Mtpa) (144 bcm per year) of peak nameplate liquefaction capacity have been placed in commercial operation in the United States. Another 85 Mtpa (117 bcm per year) are under construction, scheduled to come on line between late 2024 and 2028. A further 122 Mtpa (169 bcm per year) of capacity have received all necessary approvals but have not yet cleared final investment decision (FID) [EIA, 2023]. Moreover, 187 Mtpa (258 bcm per year) are awaiting final approval by the U.S. Department of Energy (DOE) [DOE, 2023]; it is unlikely all of the yet-to-be permitted projects will prove commercially viable. The economic impact of these projects, particularly in the U.S. Gulf Coast states of Texas and Louisiana, has been immense. In 2018 (pre-Covid), in the Lower 48 United States, liquefaction plant capital expenditures averaged USD 660 per ton per annum (tpa) of export capacity [Steuer, 2019]. Therefore a typical 10 Mtpa liquefaction plant is a multibillion dollar asset.

The United States government must balance a multiplicity of interests in deciding to what extent the growth of LNG exports should be further encouraged. Its decisions must be consistent with the Natural Gas Act, which mandates that exports of natural gas be in the public interest (15 USC 717b(a)) [DOE, 2024a]. On 26 January 2024 the DOE announced it was updating its public interest analysis, and pausing permitting of facilities allowed to export LNG to non-Free Trade Agreement (non-FTA) countries while this update is underway [DOE, 2024b]. The twenty countries with which the United States has comprehensive free trade agreements are generally not important importers of LNG [U.S. Trade Representative, 2024], hence the importance of permits to export to non-FTA countries.

An important element of the public interest analysis is an assessment of the contribution of LNG to global climate change. As stated in Executive Order 14008, issued in the first week of the Biden Administration: “It is the policy of my Administration to organize and deploy the full capacity of its agencies to combat the climate crisis [and] to implement a Government-wide approach that reduces climate pollution in every sector of the economy” [White House, 2021]. In the DOE this mandate has been addressed using a National Energy Technology Laboratory (NETL) life cycle analysis of greenhouse gas (GHG) emissions, in which U.S.-exported LNG, used in electric power generation, is compared to locally produced coal and to pipeline-supplied Russian gas in both Europe and Asia [NETL, 2019]. According to the NETL study, use of U.S. LNG results in lower overall GHG emissions than local coal or Russian pipeline gas thus providing environmental support for DOE approval of LNG exports to non-FTA countries.

The NETL study has been called into question, most recently by a study authored by Robert W. Howarth that found that for fossil fuels burned in European and Asian electric power plants, life cycle GHG emissions from U.S. LNG equals or exceeds that of locally sourced coal [Howarth, 2024]. This study has been publicized in the mainstream media [McKibben, 2023]. It is reported to have attracted attention in the White House and to have been at least a contributor to the January 2024 decision to pause DOE permitting of new LNG projects while updating the environmental aspects of the public interest analysis [Bloomberg, 2024]. Representative results of the NETL and Howarth studies are shown in Figure 1.

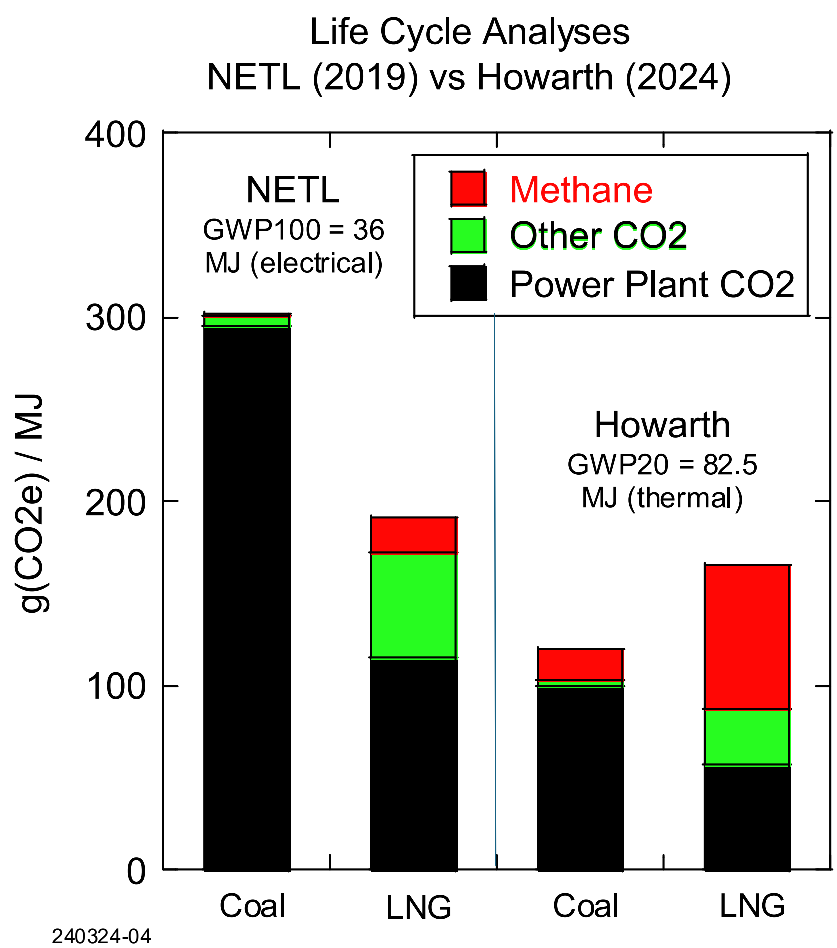

Figure 1. Comparison of representative results of the life cycle analyses comparing greenhouse gas emissions of domestic Chinese coal to U.S. LNG fueling electric power plants in Shanghai. Left: National Energy Technology Laboratory [NETL, 2019]. Right: Howarth [Howarth, 2024]. Input parameters are explained in connection with Table 2 below.

We take the position that, although they come to opposite conclusions, NETL and Howarth studies share inconsistencies and flaws, and therefore neither study is reliable.

1. Both analyses are hobbled by uncertainties in the input parameters, particularly in connection with methane emissions.

2. To take into account both carbon dioxide and methane in their GHG quantifications, both approaches utilize the Global Warming Potential / carbon dioxide equivalent (GWP/CO_2-e) methodology. This method uses global warming potentials to put methane and carbon dioxide on a common scale for the purpose of estimating their impacts on climate. Climate scientists have long recognized this methodology is unphysical, unintuitive, arbitrary,

unable to consider the time dependence of emission sources, and in some cases qualitatively misleading.

3. NETL and Howarth calculate different emissions intensities. The emission intensity selected by NETL tends to make gas look like a lower GHG-emitting fuel while that selected by Howarth tends to preference coal.

4. Recent important changes in European Union (EU-27) methane legislation and U.S. methane regulations are ignored. While this is understandable in the case of the 2019 NETL study, it is not pardonable in the 2024 work of Howarth.

5. While the recent rush of interest in methane emissions is justified, the effects of carbon dioxide emissions in supply chains have not been given the attention they deserve.

These flaws are explored systematically in the balance of this paper, and recommendations for improvement are provided.

Uncertainties in Input Parameters

Methane – LNG Supply Chains

The most important problem of the life cycle analyses is the poor quality of the methane emission data upon which they depend. This is not the fault of the authors, but a widely acknowledged consequence of the general state of knowledge in climate science. Even in the United States, where a tremendous amount of work has been done over the last ten years, there remain glaring discrepancies between official reports of methane emissions and careful and extensive measurements of them [Alvarez, 2018] [Duren, 2019] [Sherwin, 2024]. Data gaps and uncertainties are immeasurably worse in nations such as the Russian Federation [Kleinberg, 2023a].

In view of these uncertainties, there is ample scope for a diversity of honest estimates of methane emissions. Using very careful bottom-up inventories based on U.S. Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program data, NETL estimates U.S. LNG supply chain methane emissions from wellhead through delivery at Shanghai to be 1.2% [NETL, 2019, Exhibit 6-8]. Howarth selects a higher but not unreasonable estimate for upstream emissions and focuses more closely on losses from liquefaction and shipping of LNG, finding a methane emission intensity of 46.0 grams of methane per kilogram of LNG delivered by the most efficient tankers, or 4.6% [Howarth, 2024, Supplemental Table B]. This is a large difference, which affects the conclusions of the works.

Fortunately, this situation is improving with time. Aerial surveys, especially in nations that allow unrestricted overflights of oilfield infrastructure such as Canada and the United States, are becoming more comprehensive [Sherwin, 2024]. Satellite surveys, which are unrestricted and cover the entire world, are improving in sensitivity and spatial and temporal resolution from year to year [Jacob, 2022] [Watine-Guiu, 2023].

Methane – Coal Supply Chains

Recent satellite-based estimates attribute 21.0 Tg = 21.0 million tons methane emissions per year to the Chinese coal sector [Scarpelli, 2022, Figure 2], which produced 3.8 billion tons of coal in 2019 [CEIC, 2024]. The thermal content of Chinese coal averages 20.93 GJ/t (lower heating value) [NRC, 2000, page 92], indicating a national average methane emission intensity of 0.26 g(CH_4)/MJ (LHV), in good agreement with Howarth's estimate of 0.21 g(CH_4)/MJ (LHV). NETL's estimate is negligible in comparison.

Carbon Dioxide

Electric power plant CO_2 emissions are handbook values.

Emissions of carbon dioxide from coal supply chains are estimated to be 1.7 and 3.4 g(CO_2)/MJ(t) by NETL and Howarth respectively. However, Chinese resource engineering literature cites coal production emission intensity of 34.14 g(CO_2)/MJ(t) [Yang, 2022]; this not negligible compared to power plant emissions of 99 g(CO_2)/MJ(t), strengthening NETL's conclusions and weakening Howarth's.

Emissions of carbon dioxide from LNG supply chains are also important but the difference in estimates between the works is not large enough to affect the conclusions of the analyses.

Global Warming Potential Methodology

A second major problem of the analyses is the use of Global Warming Potential (GWP) methodology to drive CO_2-equivalent (CO_2-e) calculations [IPCC, 2007] [IPCC, 2013]. In the GWP/CO_2-e model, quantities of various greenhouse gases are added together to produce a composite emission effect. Because greenhouse gases differ in their radiative efficiency, it is not possible to simply add the masses of released gases to assess the climate effect of a combination of emissions. Therefore GWPs have been devised to allow the effects of various gases to be added together. Carbon dioxide is assigned GWP = 1. If carbon dioxide and methane are the only gases considered, m(CO_2) and m(CH_4) are the masses of carbon dioxide and methane emitted, and GWP is the Global Warming Potential of methane, the CO_2-equivalent mass is

$$CO_2\text{-e} = m(CO_2) + m(CH_4)\cdot GWP \qquad (1)$$

A significant complication of using GWP is that greenhouse gases have various lifetimes in the atmosphere. Carbon dioxide lingers for centuries while methane remains in the atmosphere for only a few decades. Therefore GWP depends on a user-selected time horizon [IPCC, 2007]. The longer the time horizon, the smaller the value of GWP. The numerical values depend on details of atmospheric chemistry, which are subject to refinement. In its 2019 report, NETL used IPCC AR5 values [IPCC, 2013]; in 2024 Howarth used IPCC AR6 values [IPCC, 2021], as shown in Table 1.

Both reports present at least some results using both GWP-20 and GWP-100 inputs. However, NETL refers to GWP-100 as the "default timeframe", consistent with the U.S. government standard [EPA, 2024]. Howarth presents an extended argument that GWP-20 is the "preferred approach", and his principal results use that input.

	GWP-20	GWP-100
NETL (2019)	87	36 "Default"
Howarth (2024)	82.5 "preferred approach"	29.8

Table 1. Global Warming Potentials for methane. GWP-20 is for the twenty year time horizon, GWP-100 is for the one hundred year time horizon.

In fact, the entire GWP/CO_2-e methodology is defective and misused in both reports. As pointed out elsewhere [Kleinberg, 2020]:

> Despite its widespread acceptance, we find GWP to be poorly grounded in physics, arbitrarily designed, difficult to understand intuitively, overly naïve as a policy driver, and in some cases potentially misleading. The same doubts have been expressed by the convening lead author of the relevant chapter in the First Assessment Report of the Intergovernmental Panel on Climate Change, in which GWP was introduced [Shine, 1990; Shine, 2009; Collins, 2020], and have been echoed by others over the years [O'Neill, 2000; Myhre, 2013a, page 711 and references therein]. Economists have also recognized shortcomings of GWP, which has been rejected as a method to relate the social cost of methane to the social cost of carbon dioxide [IWG, 2016].

The problems of Global Warming Potential and related back-of-the-envelope metrics can be avoided by calculating the time variations of contributions to global mean surface temperature for policy options under consideration. A simple example is shown in Figure 2. The system modeled is a 1000 TW-h per year electrical power industry, roughly the size of the electric power industry of India. In each case, the industry starts at t=0 and runs for fifty years before being retired. The modeling utilizes the closed form analytical equations vetted and fully described in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Myhre, 2013b], executed for simple examples elsewhere [Kleinberg, 2020].

- The black line shows the change of global mean surface temperature for an entirely coal-fired industry, during and after its fifty year duration. Due to the long atmospheric lifetime of carbon dioxide, temperature increases almost linearly during the duration of coal burning, reflective of the almost linear increase in the resulting atmospheric concentration of carbon dioxide. Following the closure of the coal plants, the temperature declines slowly as carbon dioxide is slowly removed from the atmosphere, mostly by dissolution in seawater.

- The red line shows the change of global mean surface temperature for an entirely gas-fired industry, during and after its lifetime. In this case, it is assumed there are no emissions of methane to the atmosphere and the resulting temperature trajectory is due entirely to the carbon dioxide resulting from combustion of gas in the power plants. The shape of the temperature trajectory is the same as for the coal-fired case, but scaled by a factor of 0.4. This scaling accounts for both (1) the reduced quantity of carbon dioxide per unit of thermal energy output for combustion of natural gas relative to coal, and (2) the superior thermal efficiency of U.S. fleet average gas-fired electric power plants versus U.S. fleet average coal-fired power plants.

- Other colored lines show the temperature effects of gas-fired plants with supply chain methane leaks. Temperatures in excess of the "No Leaks" case are due to methane emissions added to the "No Leaks" carbon dioxide baseline. Temperature increases during plant operation are sublinear because methane, which has a 1/e atmospheric lifetime of twelve years, is removed from the atmosphere by natural causes while it is being added by the power industry. Once the power plants are retired, methane and its effect on global mean surface temperature disappear in a few decades.

The deficiencies of the GWP/CO_2-e method are clearly demonstrated by comparing Figures 1 and 2. The GWP method gives no indication of the lasting nature of carbon dioxide emissions compared to the relatively brief influence of methane. Moreover, there is no provision in the GWP/CO_2-e methodology to account for the limited lifetime of infrastructure.

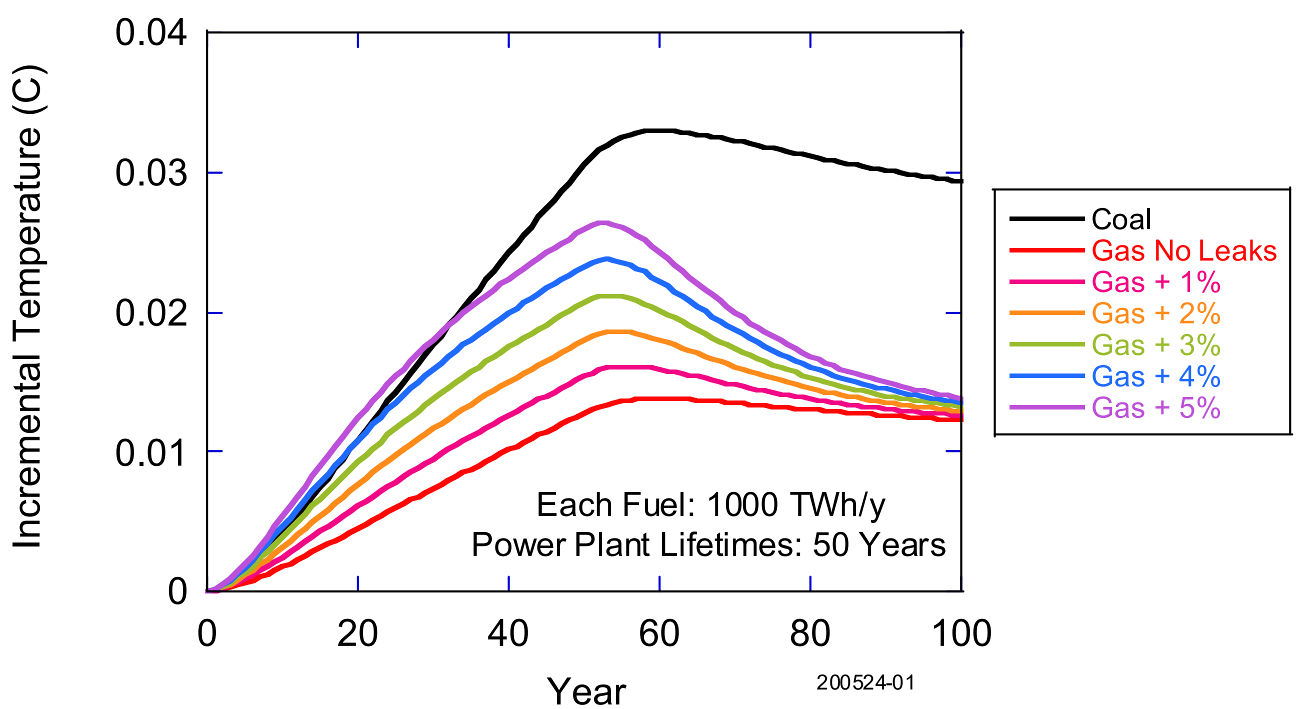

Figure 2. Change of global mean surface temperature (vertical axis) versus time after the commencement of a 1000 TWh per year electric power industry. The industry is shut down after fifty years. Black line: fuel is coal, with no methane emissions. Red line: fuel is natural gas with no methane emissions. Other colors: fuel is natural gas with methane emissions during industry lifetime as per legend.

Two Different Emissions Intensities

Another reason why NETL and Howarth arrive at different conclusions regarding the advisability of replacing coal with LNG is they calculate different measures of GHG intensity, which I label I(thermal) and I(electrical).

The numerator of either GHG intensity is the sum of masses of greenhouse gases lost from the supply chain, $M_{GHG\text{-}SC}$ and produced by combustion in the power plant, $M_{GHG\text{-}PP}$, in grams of carbon dioxide equivalent (g(CO_2-e)), divided by the final mass of fuel consumed at the power plant, M_{PP} [Howarth, 2024, Supplemental Table B]. While $M_{GHG\text{-}SC}$ are difficult to estimate, $M_{GHG\text{-}PP}$ (all of which is CO_2) depends only on the fuel used. Pipeline grade natural gas is generally assigned intensities of 2.75 kg(CO_2)/kg(gas) and 50 kg(CO_2)/GJ(gas); corresponding values for coal depend on the rank of the fuel [Engineering Toolbox, 2024].

The denominator of the thermal GHG intensity, I(thermal), is the thermal energy input to the power plant, MJ(t), in megajoules of thermal energy, divided by the final mass of fuel consumed at the power plant, M_{PP}. Like the CO_2 intensity, this is a property of the fuel and does not depend on the characteristics of the power plant.

The denominator of the electrical GHG intensity, I(electrical), is the electrical energy output from the power plant, MJ(e), in megajoules of electrical energy, divided by the final mass of fuel consumed at the power plant, M_{PP}. MJ(e)/M_{PP} depends on both the fuel and the details of electrical power generation.

$$\mathrm{I(thermal)} = \frac{(M_{GHG-SC} + M_{GHG-PP})/M_{PP}}{\mathrm{MJ(t)}/M_{PP}} = \frac{(M_{GHG-SC} + M_{GHG-PP})}{\mathrm{MJ(t)}} \qquad (2)$$

$$\mathrm{I(electrical)} = \frac{(M_{GHG-SC} + M_{GHG-PP})/M_{PP}}{\mathrm{MJ(e)}/M_{PP}} = \frac{(M_{GHG-SC} + M_{GHG-PP})}{\mathrm{MJ(e)}} \qquad (3)$$

The plant-specific output electrical energy MJ(e) is related to input thermal energy MJ(t) by the thermal efficiency of the plant, MJ(e)/MJ(t).

$$\frac{\mathrm{I(thermal)}}{\mathrm{I(electrical)}} = \frac{\mathrm{MJ(e)}}{\mathrm{MJ(t)}} = \text{thermal efficiency of power plant} \qquad (4)$$

I(thermal), with the larger denominator, is smaller than I(electrical), with its smaller denominator. I(thermal) is sensitive to fuel type but not to the properties of the power plant. I(electrical) is sensitive to both fuel type and the properties of the plant. Thermal efficiency, like output electrical energy per mass of fuel, is specific to both the fuel and the process of electrical generation. In a Congressional Research Service compilation, coal-fired electrical power plant efficiency ranges from 0.338 to 0.421 with a U.S. fleet average of 0.338. Gas fired electrical power plant efficiency ranges from 0.300 to 0.502 with a U.S. fleet average of 0.445 [CRS, 2015].

Howarth uses I(thermal) while NETL uses I(electrical). In the NETL report, the dimensions of the denominator are megawatt-hours of electrical energy, MWh(e), where 1 MWh(e) = 3600 MJ(e).

Because the thermal efficiency of coal-fired power generation is less than the thermal efficiency of gas-fired power generation, using I(electrical) (NETL) amplifies the GHG intensity of fuel going to coal-fired plants relative to fuel going to gas-fired plants. Power plant thermal efficiency does not enter into the calculation of I(thermal) (Howarth) so there is no extra amplification of GHG intensity associated with coal plants.

Table 2 presents various ways of calculating greenhouse gas intensities. I(thermal) = g(CO_2)/MJ(t) or g(CO_2-e)/MJ(t); I(electrical) = g(CO_2)/MJ(e) or g(CO_2-e)/MJ(e). Representative results used by NETL and Howarth respectively are shaded yellow and plotted in Figure 1. If Howarth had used electrical GHG intensities (unshaded boxes), there would have been substantially less difference between coal and gas than he observed using thermal GHG intensities (boxes shaded yellow). If NETL had used thermal GHG intensities (unshaded boxes), there would have been substantially less difference between coal and gas than they observed using electrical GHG intensities (boxes shaded yellow). Thus, if the methods used in the two reports for calculating GHG intensity were exchanged, the conclusions of both reports would be weakened.

I take no position on which GHG intensity formula should be used; that would depend on the question being asked.

		China Coal		U.S. LNG	
		NETL GWP=36	Howarth GWP=82.5	NETL GWP=36 CH_4=1.2%	Howarth GWP=82.5 CH_4=4.6%
Supply Chain CH_4	g(CH_4)/MJ(t)	0.009	0.21	0.23	0.95
	g(CH_4)/MJ(e)	0.03	0.62	0.52	2.13
	g(CO_2-e)/MJ(t)	0.33	17.3	8.3	78.1
	g(CO_2-e)/MJ(e)	1.0	51.2	18.6	175.5
Supply Chain CO_2	g(CO_2)/MJ(t)	2	3	25	31
	g(CO_2)/MJ(e)	5	10	57	70
Power Plant CO_2	g(CO_2)/MJ(t)	100	99	51	57
	g(CO_2)/MJ(e)	295	293	116	127

Table 2. The greenhouse gas intensities, I(thermal) and I(electrical), in grams of greenhouse gas emitted per megajoule of energy, derived from NETL and Howarth estimates of GHG emissions for electric power plants burning domestic Chinese coal or U.S. LNG shipped from Louisiana to Shanghai by the most efficient tanker. Data used by NETL or Howarth are shaded yellow and plotted in Figure 1. Gray shaded boxes are methane data without GWP multipliers.

Legislation and Regulation Developments

While Howarth's paper was being written, a flood of greenhouse gas legislation and regulation was pouring out of Europe and the United States. The Council of the European Union and the European Parliament are on the verge of final passage of legislation that has the goal of reducing embodied methane in the fossil fuels Europe imports from the rest of the world in this decade [EU, 2023] [Kleinberg, 2023b]. As a result of mutual embargoes and sabotage that have halted almost all pipeline gas imports from the Russian Federation since mid-2022, Europe is now paradoxically in a stronger position than ever to impose its environmental rules on the rest of the world [Boersma, 2023].

In the United States, the Inflation Reduction Act of 2022 (Public Law 117-169, Section 60113) instituted incentives to reduce methane emissions in the oil and gas industry, as well as establishing the Waste Emission Charge ("methane fee") to punish emitters. It appears Congress anticipates that methane emissions can be reduced by perhaps 90% from current emissions levels.

In the Howarth modeling, methane emissions account for a large part of greenhouse gas emissions attributed to LNG exports. If government actions prove effective, life cycle modeling that does not account for future reductions may soon be outdated – an unfortunate circumstance for permitting of infrastructure designed to operate for many decades.

Importance of Supply Chain Carbon Dioxide Emissions

Both NETL and Howarth analyses usefully highlight the importance of carbon dioxide emissions in the LNG supply chain. Embodied methane emissions in internationally traded natural gas appear to be slated for reduction due to government action on both sides of the Atlantic. Physics-based climate modeling shows that the concentration of methane in the atmosphere is reversible on decadal time scales, see Figure 2. Neither is true of carbon dioxide. Therefore, the current interest in methane reduction, laudable as that is, should not be allowed to overshadow the more serious problems of CO_2.

Summary of Differences Between NETL and Howarth Studies

Factors that tend to promote the use of gas include:

- minimizing estimates of methane emissions from gas supply chains
- minimizing the GWP multiplier for methane
- using the output electrical energy in the denominator of GHG intensity
- considering likely future methane emission decreases
- considering future global mean surface temperatures

Factors that tend to promote the use of coal include:

- maximizing estimates of methane emission from gas supply chains
- maximizing the GWP multiplier for methane
- using the input thermal energy in the denominator of GHG intensity
- not considering likely future methane emission decreases
- not considering future global mean surface temperatures

Table 3 is a summary of the choices made in the comparative life cycle analyses of LNG and coal by NETL and Howarth. The choices made by NETL tend to promote the use of U.S. LNG while the choices made by Howarth tend to promote the use of Chinese domestic coal in preference to imported U.S. gas. I believe the choices of methods, parameters, and input data assumptions reflect the best judgement of the respective authors and were not driven by a desire to come to any predetermined conclusion. However, these results strongly argue for better analytical methods, and the incorporation of better data when they are available.

	NETL	Howarth
Current Methane Emissions From Gas Supply Chains	1.2%: Favoring Gas	4.6%: Favoring Coal
Future Methane Emission Reductions	Not an Option in 2019	Not Considered: Favoring Coal
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Energy Denominator In GHG Intensity	MJ(e): Favoring Gas	MJ(t): Favoring Coal
Overall Effect	Promotes Gas	Promotes Coal

Table 3. Summary of the effects of methods, parameters, and input data assumptions on the conclusions of life cycle analyses comparing liquefied natural gas and coal.

Recommendations for Future Life Cycle Analyses

The biggest discrepancy between NETL and Howarth analyses originates with the uncertainty in methane emission data. There is little individual authors can do to ameliorate this, beyond taking care to use good quality data. Fortunately the international climate science community is working hard to improve this situation.

The choice of emission intensity measures, I(thermal) vs I(electrical), is neither hidden in the NETL and Howarth reports, nor is it highlighted. Authors need to make clear to readers how these methods differ, and their implications when comparing competing policy prescriptions.

Foreseeable effects of legislation and regulation should be included in life cycle assessments, along with caveats that actual consequences of government actions are not always predictable.

While the current focus on methane is laudable, analysts should keep in mind that carbon dioxide is a greater long term threat to climate stability.

The problems of Global Warming Potential and carbon dioxide-equivalent methodology are well known in the climate science community. Elimination of this unphysical and misleading method is long past due. Research reports and life cycle analyses invoking Global Warming Potential or carbon dioxide-equivalents should no longer be accepted for publication.

General circulation models and similar methods are complex but carefully curated and should be more widely used. While even reduced complexity models, such as the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) [Meinshausen, 2011] [MAGICC, 2017] are complicated, they are accessible to non-specialists willing to invest time and effort to ascend the learning curve.

Conflicts of Interest

The author declares no conflicts of interest.

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