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FURTHER DEVELOPMENT OF THE LIFE CYCLE GHG ASSESSMENT (LCA) FRAMEWORK

Literature review on well-to-tank emissions from liquefied natural gas (LNG) imports to the EU

Submitted by CSC

SUMMARY

Executive summary:	This document shares the findings of an extensive literature review on the well-to-tank (WtW) GHG intensity of liquified natural gas (LNG) imports to the European Union. The review aggregates data from 130 references from eight LNG-exporting nations, covering 92.6% of EU imports in 2023. The study concludes that the overall WtT GHG intensity of LNG in Europe is 22.39 gCO_2e/MJ.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 15
Related document:	Resolution MEPC.391(81)

Introduction

1 Liquefied natural gas (LNG) is gaining traction as an alternative marine fuel with 1,120 LNG-powered vessels in operation and a further 951 vessels in the order books.* However, the full life cycle emissions depend on several factors: the well-to-tank (WtT) emissions occurring during the production and extraction, processing, boosting and gathering, transport, storage, unloading and bunkering of LNG, combined to the tank-to-wake (TtW) emissions related to the fuel combustion and methane slip.

2 This document summarizes the findings of an extensive literature review conducted by Energy and Environmental Research Associates (EERA) regional and national variations

* Clarksons World Fleet Register. Includes all LNG-powered merchant vessels above 5,000 GT.

in WtT emissions from the LNG production and supply chain of eight countries. It intends to inform the work of the LCA Guidelines from a data-gathering and methodological perspective as well as shed light on the GHG intensity associated with the use of LNG. The study can be found in the annex to this document.

Methods and sources

3 EERA performed a detailed and systematic review of peer-reviewed, grey, and white literature on eight countries, selected due to their roles as major suppliers of LNG to Europe in 2022. These are Algeria, Nigeria, Norway, Qatar, the Russian Federation, Trinidad and Tobago, the United Kingdom and the United States.

4 GHG emission factors were collected, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and in some cases, nitrogen oxides (NO_x: NO and NO_2). Where applicable, carbon dioxide equivalent (CO_2e) units were collected as well. Papers were differentiated between natural gas (NG) and liquefied natural gas (LNG) production. Table 1 shows the count of documents, estimated emission values by reference type, and LNG vs. NG values for each country.

Table 1: Count of references, emission estimates, and references made to LNG and NG, by country

Country	Nr of references	Nr. of emission values							
		Total	Peer reviewed	Governmental	Gray	Industry	NGO	LNG	NG
Algeria	13	51	28	6	1	1	15	46	5
Nigeria	9	36	13	--	–	1	22	36	–
Norway	18	69	9	5	4	1	50	52	17
Qatar	22	80	19	6	3	1	51	79	1
Russia	15	90	25	9	5	1	50	32	58
T&T	8	29	--	–	2	9	18	29	–
UK	9	14	9	--	3	1	1	8	6
USA	32	405	72	75	12	3	243	300	105
Global	4	25	--	4	15	--	6	25	--

5 The studies' values varied depending on which processes were included in the calculation, the level of detail considered, and the defined boundaries. Upstream processes can have different GHG emissions profiles due to equipment use, modes of transport, distances travelled, and other contextual factors.

6 Data were provided in various GWP20 or GWP100 potentials, individually identified for each reference. Throughout the review, the focus lay on GWPs consistent with the IPCC AR5 and AR6 reports. Where possible, data was additionally normalized based on the most up-to-date GWPs of the IPCC AR6's values. In line with the 2024 LCA Guidelines (resolution MEPC.391(81)), this document reports on the GWP100 values as identified in the IPCC AR5, while providing GWP20 values for comparison, emphasizing the large short-term impact of methane.

7 The data gathered relied on different metrics to indicate the GHG intensity of LNG production and supply chain. The study standardized those into CO_2e/MJ for ease of comprehension and comparison purposes.

Results

8 Assuming AR5 GWP values, this study found that the highest WtT CO_2e emissions from LNG ranged between 27.96 gCO_2e/MJ to 27.25 gCO_2e/MJ, while the lowest values ranged from 14.68 gCO_2e/MJ to 12.57 gCO_2e/MJ. Table 2 and figure 1 show the country-level AR5 WtT values, including their range across different sources.

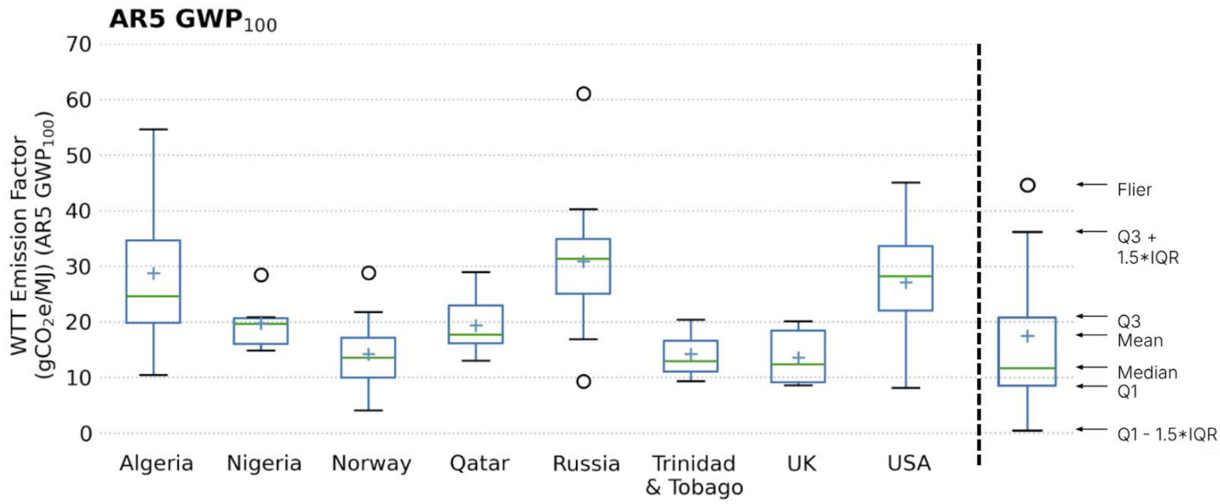

Figure 1: Boxplot of country-level well-to-tank carbon intensity (gCO_2e/MJ, AR5, GWP100), as represented in surveyed literature by percentile

Table 2: Highest, lowest, and average country-level well-to-tank carbon intensity (gCO_2e/MJ, AR5, GWP100), as represented in surveyed literature

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Country	Mean	Lowest	Highest
Algeria	27.41	10.44	54.58
Nigeria	19.65	14.42	28.48
Norway	12.75	1.61	28.22
Qatar	18.06	10.90	28.92
Russia	27.96	6.41	61.00
Trinidad & Tobago	14.86	9.14	20.39
UK	14.05	8.57	20.04
USA	27.25	8.10	49.66

9 The study further provides GWP20 values for comparison. While not as frequently referenced, substantially higher values compared to GWP100 show the major impact that methane has on short-term warming. As only nine references provided estimates on AR5 GWP20 parameters, table 3 shows country-level AR6 WtT estimates for GWP20. For countries where mean, lowest and highest values are equal, only one reference was available.

Table 3: Highest, lowest, and average country-level well-to-tank carbon intensity (gCO_2e/MJ, AR6, GWP_{20}), as represented in surveyed literature

Country	Mean	Lowest	Highest
Algeria	28.72	28.72	28.72
Nigeria	--	--	--
Norway	20.02	1.72	44.73
Qatar	19.42	14.61	24.40
Russia	23.54	8.37	36.67
Trinidad & Tobago	24.36	16.78	31.93
UK	18.60	18.60	18.60
USA	52.68	25.81	115.00

10 The study concluded that the weighted average WtT GHG intensity of LNG was 24.40 gCO_2e/MJ (AR5 GWP100) – or 34.87 gCO_2e/MJ (AR6 GWP20) for comparison. The countries assessed in this study represented 92.6% of the EU's total LNG imports by mass in 2023. The study assumed that the remaining 7.4% accounting for the rest of LNG imports – distributed across 18 countries – were representative of the countries assessed (table 4).

Table 4: EU LNG Gross Import Volumes by Import Origin

Year	Import Origin	Quantity (MT)	% Total	% Study
2023	United States	38,353,500	42.0%	45.3%
	Russian Federation	12,414,100	13.6%	14.7%
	Qatar	11,841,900	13.0%	14.0%
	Algeria	8,987,010	9.8%	10.6%
	Nigeria	5,868,530	6.4%	6.9%
	Norway	3,744,420	4.1%	4.4%
	Trinidad and Tobago	1,814,930	2.0%	2.1%
	United Kingdom	1,553,960	1.7%	1.8%
	World	**91,363,800**	**100.0%**	**NA**

11 The GHG intensity of the WtT shows that depending on how and where the LNG is sourced from and transported, it could have a significant impact on its WtW GHG intensity. Even if a bunker ship was equipped with a two-stroke high-pressure engine (assumed to have the lowest methane slip or 0.20% of the fuel). In some cases, the WtW GHG intensity of LNG on a ship would be close to the WtW intensity of heavy fuel oil, especially if LNG originated from Russia, Algeria or the United States. Figure 2 shows the impact of different WtT GHG intensities across countries and compares the WtW intensities to that of heavy fuel oil based on the WtW values from annex II to the Fuel EU Maritime Regulation.

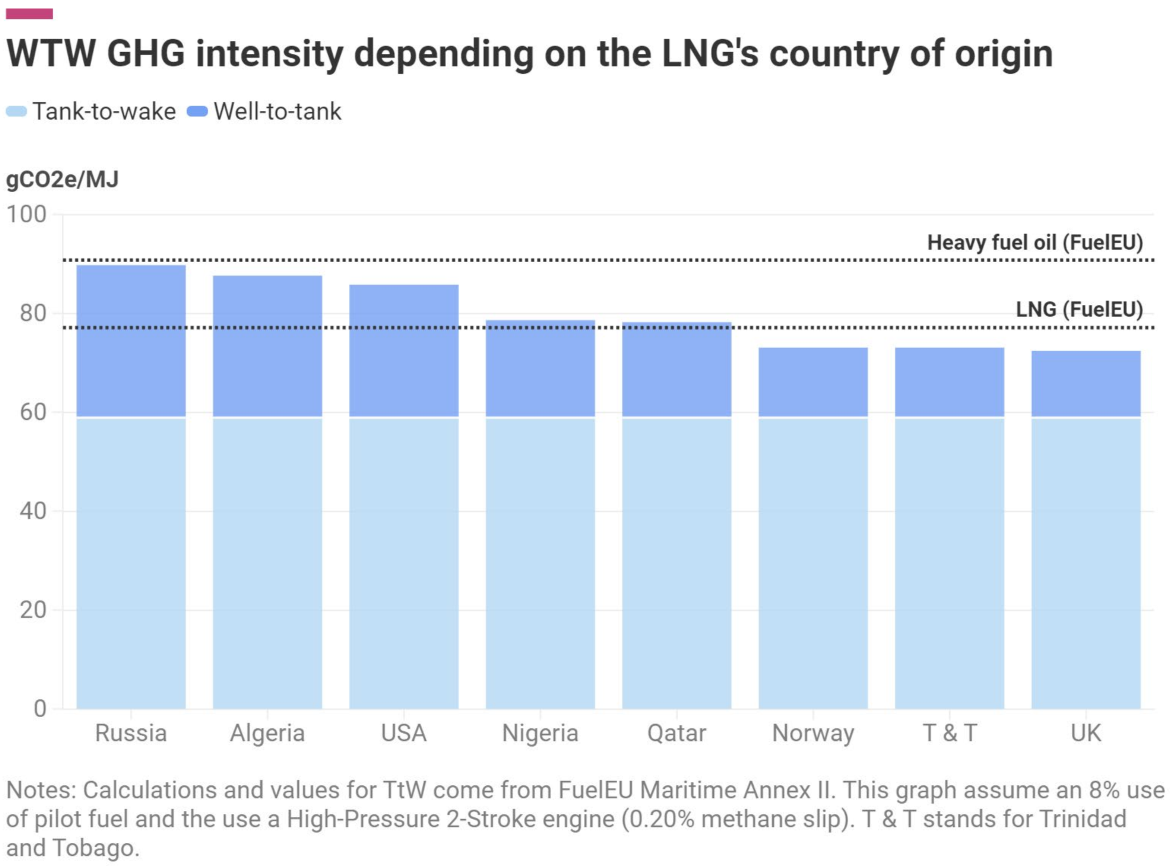

Figure 2: Well-to-tank and tank-to-wake GHG intensities of LNG by import origin

Conclusion

12 This document reports the key findings of a literature review on country-specific WtT emissions from LNG exports to the EU in 2023 with the weighted average GHG intensity estimated at 24.40 gCO_2e/MJ as per AR5 values. The identified range of GHG intensity values varied significantly between countries ranging from 12.57 gCO_2e/MJ to 27.96 gCO_2e/MJ.

13 While varying across countries, the main causes for high GHG emissions were gas flaring rates, methane leaks, and transport via tanker.

14 The most GHG-intensive LNG exporting countries were found to be some of the main and fastest growing suppliers, suggesting LNG's GHG intensity to remain consistent, or even to grow as more ships decide to switch to LNG as a marine fuel.

Action requested of the Working Group

15 The Working Group is invited to note the information provided in this document, in particular when revising the 2024 IMO LCA Guidelines, and take action as appropriate.

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ANNEX

Energy & Environmental Research Associates

Well-to-Tank Carbon Intensity of European LNG Imports

August 26, 2024

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Executive Summary

Liquefied natural gas (LNG) supply chains contribute to greenhouse gas (GHG) emissions, in addition to LNG combustion emissions. Fugitive emissions include methane (CH_4) leaks and losses from all stages from natural gas extraction to liquefaction and beyond. Process emissions include emissions associated with energy inputs to the system, such as carbon dioxide (CO_2) emissions from producing the energy required for compression or liquefaction. Life cycle analyses consider the emissions of greenhouse gasses for the entire supply chain, including combustion. This analysis focuses on emissions of GHGs from the stages from natural gas production and extraction to liquefaction and transport, the so-called well-to-tank (WtT) emissions.

This work describes the methodology and results from a comprehensive review and aggregation of the peer-reviewed, government, industry, and other relevant literature sources to describe the reported GHG emissions calculations for the LNG supply chains for countries supplying the European Union (EU) and broader European region. This analysis focuses on identifying literature estimating the WtT GHG emissions from eight countries that supply LNG and natural gas (NG) to the EU: Algeria, Nigeria, Norway, Qatar, Russia, Trinidad and Tobago (T&T), the United Kingdom (UK), and the United States of America (U.S.A.).

This review identified nearly 800 emission factors from the literature, along with specific values that account separately for the contribution of CO_2, CH_4, and nitrous oxide (N_2O). The literature identified 607 emission factors specific to LNG and 192 to NG supply chains, covering the range of upstream and midstream stages including extraction, production, storage, transportation, and liquefaction.

Results are presented in terms of carbon dioxide equivalents (CO_2e), normalizing methane and nitrous oxide based on their Global warming potential (GWP). GWP is a metric that assesses the cumulative impact of GHGs in addition to CO_2 (methane and nitrous oxide in the case of this study) relative to the heat-trapping effect of CO_2, over a specific timescale, either 20- and 100-years. Conversion to CO_2e requires knowing the specific contributions of each GHG. Whenever possible, literature estimates were weighted for both 20- and 100-year timescales using the GWP values from the Fourth, Fifth, and Sixth IPCC Assessment Reports (AR4, AR5, AR6). This enables comparison with sources using different GWP frameworks and to assess how changes in GWP weightings impact the reported climate warming of LNG. If a study did not provide a breakdown of individual gas emissions, values could not be converted to other GWP frameworks or timescales.

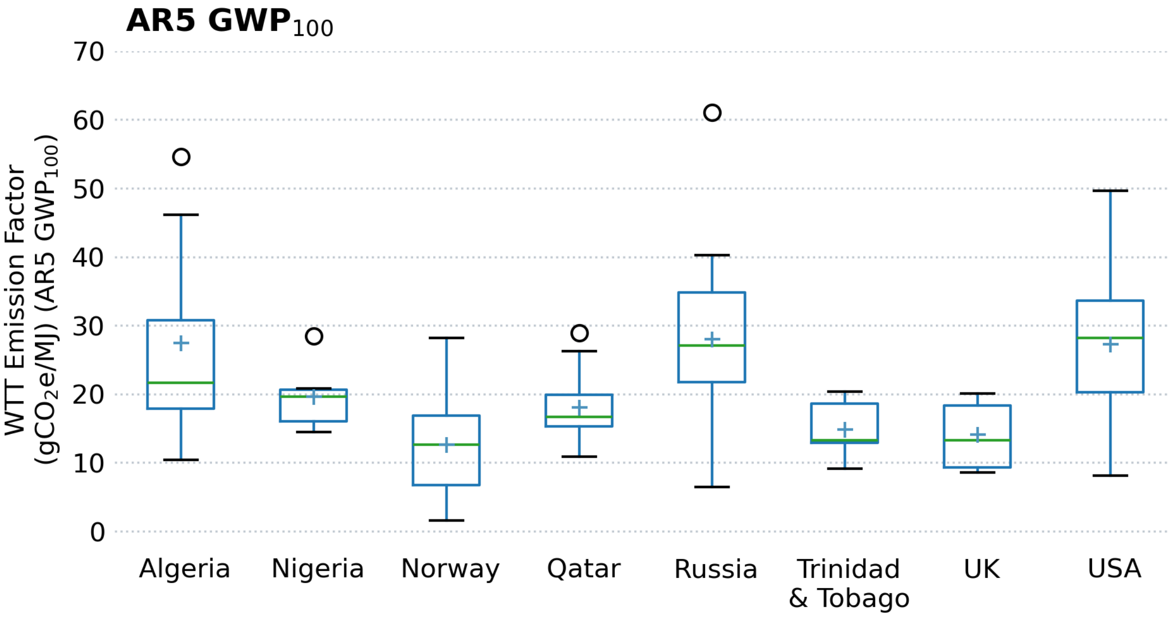
There were 200 emission factors for country-level WtT carbon intensity reported in the literature. This is in addition to over 500 values for the individual contributions of CO_2, CH_4, and N_2O. This extensive dataset provided the foundation for our analysis before we undertook the work of converting values for different GWP metrics and assessment reports. Our analysis yielded over 1,700 values for CO_2, CH_4, and N_2O emissions across AR4, AR5, and AR6, and for combined and individual WtT stage emissions.

The WtT carbon intensities (gCO_2e/MJ, AR5, GWP_{100}) from the LNG supply chain for exports from the studied countries are presented in ES Figure 1, depicting the variability in country-specific emissions and the spread of values reported for each nation. Algeria had the highest standard deviation, meaning its emission rates vary most significantly from the average. Russia had the largest interquartile range, meaning that its emissions values were more spread out compared to other countries. This suggests that there is greater inconsistency in reported emissions within these countries.

Key findings and conclusions of this review are summarized in Box 1. They emphasize the importance of standardizing GHG reporting practices to enhance accuracy and comparability across studies. It also shows the need for more research in countries like Trinidad and Tobago and Nigeria, where data is limited, and in nations where underreporting may occur due to insufficient regulatory oversight or monitoring capabilities.

Executive Summary - Figure 1

Well-to-Tank carbon intensity (gCO_2e/MJ, AR5, GWP_{100})



Box 1

Key Findings and Conclusions

- The U.S.A., Algeria, Russia, and Nigeria exhibited the highest WtT emissions (AR5 GWP_{100}), aligning with their positions as top contributors to global flaring volumes.
- Standardizing CO_2e reporting, particularly by detailing contributions of individual GHGs in calculations, will strengthen the accuracy of carbon intensity assessments and ensure values stay relevant and up-to-date as scientific understanding evolves.
- Russia has adjusted its national emission reporting methods to present lower estimates, drawing criticism from UNFCCC reviewers. While official reports may underreport emissions, other studies supplement estimates with satellite data and other gap filling methods.
- T&T and Nigeria had relatively few references, likely due to low prioritization driven by political and economic factors, lack of mandated reporting, and insufficient reporting networks.
- Countries with less regulatory oversight, inadequate monitoring equipment, aging infrastructure, or other causes for equipment negligence and repair may have emissions that are underreported or inaccurately estimated.
- WtT processes that most significantly influence carbon intensity of LNG and show substantial variation across export countries are flaring/venting, liquefaction, and transportation.
- Venting, flaring, and fugitive emissions were not reported as distinct process stages in the literature. While grouping these emissions under broader WtT stages should not lead to underreporting, their omission could. A follow-up study is recommended to determine the weight of these emissions on carbon intensities across countries and to assess how many studies incorporate measurements from satellites or other methodologies to accurately measure and validate these emissions.

Introduction

EERA performed a detailed and systematic review of the peer-reviewed, gray, and white literature to identify greenhouse gas emission factors for the LNG value chain from WtT relevant to the following countries:

Algeria	Russia
Nigeria	Trinidad and Tobago (T&T)
Norway	United Kingdom (UK)
Qatar	United States of America (U.S.A.)

This literature review focused on identifying regional variations in WtT emissions from the LNG supply chain. GHG emission factors were collected, including CO_2, CH_4, and N_2O. Where applicable, we gathered CO_2e units, which express the cumulative impact of these emissions in terms of the GWP of CO_2. CO_2e is widely used in climate policy, emissions reporting, and life cycle carbon calculations to compare the warming impact of different GHGs on a common scale. The context and assumptions underlying GWP values are significant and must be accounted for (See Methodology: Global Warming Potential).

Literature search was conducted using Google Scholar and other standard research databases. WtT emissions searches included sources upstream of on board storage tanks include emissions from natural gas production and extraction, processing, boosting and gathering, transport (by mode), storage, unloading and bunkering. WtT encompasses the summation of greenhouse gas emissions across these stages. However, the absence of standardization becomes apparent in the gathered literature, where no uniform methodology prevails for upstream emissions. Studies vary in which processes are included in the calculation, the level of detail considered, and the defined boundaries. This reflects the reality that upstream processes are inherently unique and methods can mirror the differences in equipment, modes of transport, distances traveled, and other contextual factors. Where applicable, we noted which processes each study considered within the scope of WtT emissions (i.e. conventional and unconventional).

Box 2

Conventional and unconventional natural gas production

> Conventional natural gas production refers to the extraction of natural gas from traditional reservoirs in subsurface porous rock formations, obtained via drilling wells into these formations. These reservoirs are considered to be relatively easy to extract from and rely primarily on pressure within the reservoir to bring the gas to the surface. Natural gas may also be extracted using unconventional methods from reservoirs that do not have the same porous characteristics, including shale gas, tight gas, coal bed methane, etc. Unconventional reservoirs require additional techniques, such as hydraulic fracturing ("fracking") to extract the gas.
>
> Unconventional gas production has become less uncommon, in contrast to what its name implies. In recent years, unconventional production, particularly shale gas, has surged due to technological advances. The global share of unconventional gas in total global production has grown rapidly from 4% in 2000 to 35% in 2023. Furthermore, this share is projected to continue growing, due to declining exploration success for conventional projects over the last decade, indicating a decrease in the conventional gas supply.[1] Shale gas does not have higher emission intensities than conventional gas, on average. However, it can pose greater localized environmental risks.[2,3]

Papers were differentiated between NG and LNG production, based on the inclusion or exclusion of the liquefaction process upstream. Moreover, we checked for the utilization of renewable energies, carbon capture technologies, or other emission-abatement methods within its assessment of upstream processes, if discussed in their methodology. This was not common for the studies collected, but it is worth noting that an increasing number of nations are exploring alternative pathways to mitigate emissions along the supply chain due to domestic and international climate goals.

To date we have identified 55 literature resources, which together provide nearly 800 CO_2e emissions values for the various process-level emissions from countries studied. We identified 200 literature estimates for the combined WtT life cycle and over 500 emissions for the individual contributions of CO_2, CH_4, and N_2O. This extensive dataset provided a robust foundation for our analysis, before we undertook the additional work of converting these values for different GWP metrics and assessment reports. We have also compiled top-down observed estimates (See Resources by Country: Top-Down Observation Data), These top-down values are particularly useful for evaluating emissions in countries in North Africa, the Middle East, and Russia, where available data sources in the literature were sparse. These sources involve rigorous collection techniques, third-party validation, and expert interpretation. The methodologies and data validation processes of the top-down observation sources are discussed in detail in the later section, Top-Down Observation Data.

We extracted detailed information for each resource identified, including

- Title, Year, Authors, Citation, DOI
- Country, Sub-Region
- Resource Type (e.g. peer-reviewed, gray[4], etc.)
- Methods
- GWP used
- WtT EFs (CO_2e, CO_2, CH_4, N_2O) and units

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[1] https://www.rystadenergy.com/news/new-natural-gas-production-needed-middle-east

[2] https://www.systemiq.earth/wp-content/uploads/2023/05/Unconventional-White-Paper_Final.pdf

[3] See EERA analysis on the 'Health and Equity Impacts of LNG' / https://oceanconservancy.org/wp-content/uploads/2024/04/Final-LNG-as-a-Marine-Fuel-in-the-United-States.pdf

[4] Gray literature encompasses publications created outside of traditional peer-reviewed or validated channels. We prioritize reputable gray literature sources that draw upon data from validations sources for reliability.

Papers were reviewed for relevance, and greenhouse gas estimates associated with natural gas activity were compiled in a spreadsheet format, to feed into the aggregation and analysis for reporting emission factors. Resources used are summarized in the following section. Citations are provided in the References section.

Resources by Country

The countries in this study were selected as major exporters to Europe. In 2022, the EU and the UK relied significantly on LNG imports, with the U.S.A. in a dominant position at 55%, followed by Qatar at 14%, and Russia at 10%. Nigeria and Algeria also contributed substantially, at 6% and 4% respectively, while other nations collectively accounted for 14% of the imports, including notable contributors like the UK and Trinidad and Tobago.[5] In 2023, the EU27[6] imported approximately 167 billion cubic meters of LNG, with the U.S.A. maintaining its leading position at 46%, followed by Qatar (12.1%), Russia (11.7%), Algeria (9.5%), Nigeria (5.6%), and Norway (4.8%).[7] Additional resources such as the International Group of LNG Importers,[8] the European Commission,[9] and the Institute for Energy, Economics, and Financial Analysis[10] can be referenced for key details about Europe's LNG market and imports.

We compiled data by country, identifying as many resources as possible. The count of references per country are shown in Table 1, and the count of estimated values per country are shown in Table 2. In addition to broad estimates of emissions within national boundaries, some studies focused on specific geographic areas (e.g. individual basins or operations) or covered states or sub-regions within the country of scope (e.g. Texas or the Gulf of Mexico in the U.S.A.). Other studies had broader estimates of the larger regions or continents inclusive of the country of scope (e.g. the Middle East or Europe). Some studies calculated the average emissions of total global LNG/NG imports into the EU or UK; we have categorized these values under "global", which encompasses emissions including but not limited to countries within this project scope.

Table 1
Count of references per country

Country	n References
Algeria	13
Nigeria	9
Norway	18
Qatar	22
Russia	15
T&T	8
UK	9
U.S.A.	32
Global	4

Several factors can contribute to difficulty finding estimates and the accessibility of data, including but not limited to, the level of industry transparency and/or mandated reporting mechanisms; research prioritization influenced by political or economic stability; the reach of the industries in attracting or deterring attention and investment; and the presence of networks, research institutions, government agencies, etc. dedicated to collecting and reporting emissions data.

[5] https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_MMR_2023_Gas_market_trends_price_drivers.pdf
[6] The 27 European Union countries after the UK left the EU
[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=554503
[8] https://giignl.org/giignl-releases-2023-annual-report/#
[9] https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/liquefied-natural-gas_en
[10] https://ieefa.org/european-lng-tracker#section3

Regulations and research have been written with focus on the tank-to-wake, combustion or downstream, emissions and efficiencies. Life cycle assessment is not a novel field. The International Organization for Standardization (ISO) has set guidelines and elaborated methodologies for life cycle assessments since 1997.

The U.S.A. and Qatar are among the largest global exporters of natural gas and receive heightened research attention accordingly. Across the literature, focus on the full life cycle analysis of energy development, encompassing all stages of a product's extraction to end-use, is a relatively limited subset of analysis, where until recently the focus has been on combustion emissions.

As more stakeholders recognize the significance of these regional differences in upstream emissions, with its impact on the total life cycle, alongside growing confidence in assessment methodologies, the topic is gaining more research attention. For example, the 2023 International Maritime Organization (IMO) Strategy updated its levels of ambition and indicative checkpoints to take into account the well-to-wake GHG emissions of marine fuels, thereby becoming inclusive of the well-to-tank, upstream emissions.[11]

The earliest study for upstream WtT emissions, within the countries' scope, was in 2009, whereas the most recent study was published in 2024. The average and median year of all identified emission estimates were 2019 and 2020, respectively. This aligns with the growing importance of LCA methodologies in recent years.

Table 2 shows a breakdown of the emission estimates in total and by reference type among the literature sources identified. Search preference was given to peer-reviewed resources, though in some countries the availability of sources was limited. As anticipated, Algeria, Nigeria, and Trinidad & Tobago had the most limited data availability. The U.S.A. has the highest number of relevant emission estimates, driven by data availability for all 50 states or regional basins in some resources.

The UK has minimal sources because it does not produce LNG domestically. Its exports to the EU are reloads of LNG imported from other countries. Many emission estimates tracked LNG exports from other project countries to Europe through the UK or the Netherlands.

Papers were categorized based on the inclusion or exclusion of liquefaction in the upstream stages. When liquefied, natural gas is held at cryogenic temperatures requiring additional infrastructure and energy inputs. This differentiation impacts not only an energy-intensive step of production, but also influences the modes of storage and transportation, which all contribute to the total emissions profile. Typically, natural gas is transported over shorter distances through pipelines whereas LNG is transported overseas by tanker over longer distances. As a result, LNG would be anticipated to have higher upstream emission factors than natural gas to include the cumulative differences in its upstream stages.

Table 2
Count of emission estimates by country by reference type

Country	Peer Reviewed	Government	Gray	Industry	NGO	Total
Algeria	28	6	1	1	15	51
Nigeria	13	--	--	1	22	36

[11] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2014.pdf

Norway	9	5	4	1	50	69
Qatar	19	6	3	1	51	80
Russia	25	9	5	1	50	90
T&T	--	--	2	9	18	29
UK	9	--	3	1	1	14
U.S.A.	72	75	12	3	243	405
Global	--	4	15	--	6	25

As shown in Table 3, there were more emissions estimates for LNG than for NG per country, except Russia. This is largely due to its extensive pipeline network for transporting natural gas throughout Europe, while its LNG infrastructure remains less developed. Russia has only recently been expanding its LNG capabilities, targeting 100 million tonnes of LNG capacity by 2030.[12] As a result, there are fewer studies and emission estimates on LNG due to the long-standing focus on pipeline transport.

Table 3
Count of emission estimates per country based on NG or LNG sources

Country	**LNG**	**NG**
Algeria	46	5
Nigeria	36	--
Norway	52	17
Qatar	79	1
Russia	32	58
T&T	29	--
UK	8	6
U.S.A.	300	105
Global	25	--
Total	607	192

With the most references and emission estimates, the United States includes over a hundred studies focused on emissions for natural gas and 300 for LNG. This is likely due to a larger pool of geographic-specific estimates, for which studies focused on quantifying the site- or operation-specific emissions might not extend their analysis to its subsequent transportation and/or export.

Data were provided in a variety of GWP, where 20- (GWP_{20}) or 100-year (GWP_{100}) potentials identified the time frame of the estimates. We identified and recorded the actual GWP value used by the studies. GWP is commonly sourced from the Intergovernmental Panel on Climate Change (IPCC) scientific assessment reports, based on the latest research and contributions from the worldwide scientific community. GWP values aligned with IPCC Assessment Reports (i.e. AR4, AR5, AR6) are found in the literature, including some variation around these values.

Data were also originally provided in a variety of units outlined below. For the necessary aggregations and analysis we standardized these values in terms of energy units, converting them to grams of carbon dioxide equivalent emitted per megajoule, gCO_2e/MJ.

g CO_2e/kg	kg CO_2e/m^3
g CO_2e/kWh	kg CO_2e/mt LNG
g CO_2e/L	kg CO_2e/mt NG
g CO_2e/MJ	lbs CO_2e/MWh

[12] https://oilprice.com/Energy/Natural-Gas/Russias-LNG-Expansion-Plans-Hit-the-Wall.html

g CO_2e/MWh
g CO_2e/t LNG-km
kg CO_2e/$1.0x10^7$ MJ
kg CO_2e/boe
kg CO_2e/kWh
kg CO_2e/L
MMT CO_2e/yr
mt CO_2e/mt LNG
mt CO_2e/yr
t CO_2e/t LNG
t/1000t

Top-Down Observation Data

Top-down estimates from Kayrros, IEA, IMEO datasets, utilizing satellite and ground-based observations, will complement the literature and supplement where literature is scarce, especially in regions like North Africa, the Middle East, and Russia.

Among the mentioned top-down sources, both Kayrros and IMEO are datasets derived from high-resolution satellite imagery. Each dataset has undergone peer review for its methodology. Kayrros collects its own data directly from the Sentinel-5P/TROPOMI and undergoes third-party validation. Whereas, IMEO utilizes a global satellite network, including collaboration with Kayrros, to detect and measure emission sources. The IMEO team's specialized expertise validates the data for false positives, interprets it, and generates methane emissions estimates.
IEA employs rigorous methodologies for collecting and analyzing data across its reports and databases, including the Methane Tracker Database. For the Methane Tracker, it utilizes country-specific data, incorporating factors such as regulatory oversight and effectiveness to generate emission intensities. This includes metrics like government effectiveness, regulatory quality and the rule of law given by the Worldwide Governance Indicators compiled by the World Bank (2023). The IEA database also integrates methane data from Kayrros.

Kayrros Methane Watch[13] data are derived from monitoring of methane emissions, including large emissions from episodic emission events. These data feed into estimates for the International Methane Emissions Observatory and International Energy Agency. In addition to their "Super Emitter View," Kayrros data include country-level estimates in terms of methane emitted per barrel of oil equivalent (kg-CH_4/bboe) from oil and gas infrastructure in 2022.

Kayrros data are compiled from a range of satellite imagery and sensors, including raw imagery and processed files from European Space Agency Sentinel satellites and the NASA/JPL EMIT sensors. The data are independently verified and have been used in multiple peer-reviewed studies. Country level emission rates per unit production are generated based on satellite observations coupled with country-specific production reports.

Kayrros data should theoretically assess all the nations in the scope of this project, however the satellite imagery can only detect large emitting sources and provides limited insights. Basin-level inversions, a method used by Kayrros, attempts to estimate methane emissions over a broader production region and assess multiple sources within a given basin. While not source-specific, this can provide validation data points for the entire natural gas and LNG supply chain which are particularly useful in instances where there is a paucity of available data.

IEA's Methane Tracker estimates methane emissions from global oil and gas operations by creating emission intensities specific to each country and production type. These intensities are then applied to production and consumption data on a country-by-country basis. Utilizing the U.S.A. baseline emission factors, there is data estimated for Algeria, Nigeria, Norway, Qatar, the UK, Trinidad & Tobago, and Russia.

Their approach scales U.S.A. emission intensities, due to the credibility and range of its data, to provide the emission intensities of other countries based on country-specific information, including age of infrastructure, types of operator within each country (namely international oil companies, independent companies or national oil companies), average flaring

[13] https://methanewatch.kayrros.org/

intensity (flaring volumes divided by oil production volumes), the strength of regulation and oversight, and methane-specific policy efforts. It also includes satellite data from Kayrros and various data sources from the World Bank.

IMEO incorporates point-source satellite data from a range of sources, including Kayrros, but also independent data from the European Space Agency Sentinel Satellites, Italian Space Agency, Germany's EnMAP, NASA EMIT aboard the International Space Station (ISS), NOAA GOES, and NASA/United States Geological Survey (USGS) Landsat 8 and Landsat 9.[14] One of IMEO's strengths is that it compiles and provides data from "all methane-detecting satellites with publicly available data." From the perspective of this study, IMEO data[15] cover the globe, but focus on plumes and point sources, and so may best be thought of as supplemental resources to the country-level estimates from IEA and Kayrros.

Methodology

This study provides an aggregation of carbon intensity values associated with the LNG value chain from well-to-tank. The primary sources for these data are life cycle reports and emission inventory studies, which report emission rates for various GHG species. The methods applied here convert all values to gCO_2e/MJ, to allow for direct comparison of the greenhouse gas emissions on an energy-weighted basis. We do not employ additional weighting to process-level emissions to aggregate those up to WtT reporting, and instead rely on prior reporting of WtT emission rates.

Global Warming Potential

Emission factor sources are based on a range of different GWPs. GWP measures how much energy a particular GHG traps in the atmosphere compared to CO_2 over a specific time period. GWPs are generally reported on 20-year and 100-year time scales, and the potency of GHGs can vary significantly depending on the time scale used. GWP values can vary across sources, as these values are subject to revision as scientific understanding and data evolve. Variations in GWP values are often the result of the baseline year of data collection, in which older studies would utilize older reports and values.

Methane is a relatively short-lived species, with a lifetime around 11.8 ± 1.8 years, per the Sixth IPCC Assessment Report (AR6). Nitrous oxide is another commonly reported GHG with a lifetime around 109 years. Together with CO_2, GWP-weighted emissions of CH_4 and N_2O are combined to calculate the CO_2e emissions associated with a source category.

The formula for calculating CO_2e is:

$$CO_2e_i = mass_{CO_2} \times GWP_{CO_2,i} + mass_{CH_4} \times GWP_{CH_4,i} + mass_{N_2O} \times GWP_{N_2O,i}$$

Where i is the time period used for the analysis, typically either 20 or 100-years. It is common to denote the GWP time frame used in the CO_2e value, e.g. as CO_2e_{GWP100}. The IPCC has updated GWP estimates with each assessment report, with the estimates shown in Table 4.

Table 4

Global Warming Potentials from the Fourth, Fifth, and Sixth Assessment Reports

		CO_2		CH_4		N_2O	
		GWP_{20}	GWP_{100}	GWP_{20}	GWP_{100}	GWP_{20}	GWP_{100}
AR4		1	1	72.0	25.0	289	298
AR5[16]	No CC fb	1	1	84.0	28.0	264	265
	W. CC fb	1	1	86.0	34.0	268	298
AR6	Fossil	1	1	82.5	29.8	273	273

[14] https://methanedata.unep.org/faq

[15] Available at https://methanedata.unep.org/export

[16] AR5 values for fossil methane are higher by 1 and 2 for the 20 and 100 year metrics, respectively.

Non-fossil	1	1	79.7	27.0	273	273

We have identified over 500 estimates, based on a range of GWPs from different AR values and time frames. For comparison and consistency we have normalized the estimated values based on the reported GWP to be consistent with the IPCC AR6 20- and 100-year GWP values, as possible. All the sources identified are for LNG derived from fossil sources, therefore we use the fossil values for AR6 in the table above.

Normalizing the literature estimates is performed using a straightforward scaling factor based on the following equation.

$$Estimate_{AR6,i} = Estimate_{Base,i} \times \frac{GWP_{AR6,i}}{GWP_{Base,i}}$$

That is, the estimate is converted to AR6-equivalent GWP values by multiplying the base emission estimate, from the source, by a conversion factor defined as the ratio of the AR6 GWP to the source base for equivalent species and time frames, i. Across all countries and processes 91 emission estimates provided sufficient data to convert the values between AR4, AR5, and AR6 values.

Unit Conversions

The source data provide emission estimates in a wide array of units. Quantities are expressed as rates, mass (weight), volume, and energy content. For the purposes of considering all emissions on an energy equivalent basis, we convert the source estimates in their base units to energy units, specifically grams of CO_2e per megajoule (gCO_2e/MJ).

We have developed a table of conversion factors that we use to adjust the source data. Sources using energy-based emission factors provided in barrels of oil equivalent (BOE), British Thermal units (BTU), tonnes of oil equivalent (TOE), and kilowatt hours (kWh) can be converted using linear scaling factors. Linear scaling factors can also be used for mass- and volume-based emission data (e.g. MJ/kg of LNG, MJ/m^3, etc.) and combinations such as standard cubic meters oil equivalent (S.m^3oe) of gas.

The conversion process involves two main steps: first, transforming the energy content to a common unit of energy, and then adjusting for the specific unit of measurement. For a detailed breakdown of these conversions and the specific factors used, refer to Table 5, which presents the various energy and unit conversions applied in our analysis.

Table 5

Conversion factors used to standardize source data emission estimates

Unit	Conversion
1 BOE	5,400 MJ
1 BTU	0.001055 MJ
1 kg LNG	49.4 MJ
1 kWh	3.6 MJ
1 L LNG	22.5 MJ
1 m^3 NG	38.622 MJ
1 sm^3oe	40 MJ
1 TOE	41,868 MJ

Unit	Conversion
1 Gg	1,000,000,000 g
1 kg	1,000 g
1 lb	0.453592 kg
1 m^3 NG	781.82 gCH_4
MMBtu	Million BTU
MMT	Million metric tonnes
1 MT	1,000 kg
1 MWh	1,000 kWh

By way of illustration consider the following example for the extraction phase of the supply chain from one of our data sources:

Base estimate: 211 gCO_2e / kWh reported in AR6 GWP_{20} (CH_4 GWP = 82.5)

First, convert kWh to MJ. From Table 5 we see that

$$1 \text{ kWh} = 3.6 \text{ MJ}$$

So the estimated emissions per megajoule is

$$211 \text{ gCO}_2\text{e} / 3.6 \text{ MJ, or } \underline{58.6 \text{ gCO}_2\text{e/MJ}}$$

Using the values from Table 4, converting the AR6 GWP_{20} value to GWP_{100} is then given by

$$GWP_{100} = \underline{58.6 \times \frac{29.8}{82.5}} = 21.17 \text{ gCO}_2\text{e/MJ}$$

So the two final values would be, e.g. 21.17 gCO_2e/MJ (AR6 GWP_{100})
58.6 gCO_2e/MJ (AR6 GWP_{20})

LNG Production Chain

Many of the data sources identified are provided in terms of total WtT emissions. In those instances, we will report and include WtT estimates in the totals presented. In cases where the data allow, we have broken down the LNG production and supply chain into the following components or source categories.

Upstream	Extraction
	Production[17]
	Gathering and boosting
Midstream	Processing
	Compression
	Storage
	Transport (pipeline, truck, rail, tanker)
	Liquefaction

[17] In some studies "production" also broadly included other upstream stages like well-drilling, recovery, production, processing, etc. together and reported estimates as a singular value.

Upstream	Extraction
	Venting

Note that not all source categories apply to all production and supply chains, and supply chain elements can sometimes occur in different order. We have used commonly used categories to group the reporting into "Upstream" and "Midstream" stages. "Downstream" stages include the distribution of gas to end users from the city gate, and beyond the meter emissions (e.g. from natural gas appliances). Downstream stages do not apply to this study.

We report country and regional emission factors for all source categories for which data are available. While emissions from specific processes are also reported, these estimates cannot be simply "rolled up" or aggregated to calculate the sum total WtT emission rates, as they would need to be properly weighted by the energy moving through each process. This study is a compilation of literature values, and does not apply relative weights to various methane emission pathways, instead relying on aggregating prior life-cycle literature for the whole WtT value chain to compute those aggregations for country-level data in terms of total Well-to-Tank emissions (gCO_2e/MJ).

With the data sources identified and the emissions data converted into gCO_2e/MJ units and adjusted on a 20- and 100-year GWP basis, we developed country- and regional-level emission factors from the available data, as well as a unified, mass/energy weighted emission factor for WtT emissions from imports into the European Union.

Carbon Intensity of LNG Imports

National-level estimates of the WtT carbon intensity of NG and LNG imports to the EU were calculated for the countries identified in the Introduction. Estimates are presented in gCO_2e/MJ, accounting for the total emissions for CO_2, CH_4, and N_2O (where available), and weighted for both the 20- and 100-year GWP timescale.

The goal was to present results utilizing the most recent AR6 GWP values, however literature that presented CO_2e values without breaking down the contributions of individual GHGs cannot be simply rescaled to other AR values. As GWP assigns specific weights to each GHG species, without knowing the individual contributions of CH_4 or N_2O, we cannot accurately apply and adjust the estimate to reflect alternate AR estimates.

Upon inspection of the data, we found that including N_2O in calculations, where available, increased the median estimate by just 0.05%. The data were highly skewed to the right, and the mean increase when including N_2O was 3.76%, though this was driven by comparatively few values that were very high. Out of 105 values where we were able to test the contribution of N_2O on the CO_2e estimate, the increase seen when including N_2O was 0.58% at the 90th percentile. Therefore, we conclude that for the processes studied the influence of N_2O on CO_2e estimates is generally limited. Where N_2O emission factors are available we use them to compute the CO_2e estimate, otherwise we compute the CO_2e estimate using only CO_2 and CH_4.

Natural gas specific values help inform upstream and midstream emissions before the liquefaction stage. Moreover, for countries closer to the EU, such as Norway and Russia, natural gas can often be transported strictly as a gas via pipelines, which depending on its end-use may not undergo the energy-intensive liquefaction stage. To benchmark the intensity of pipeline transport, when distance indicators were provided, we calculated a secondary intensity value in gCO_2e/MJ-km.

Subsequent country-specific sections include additional detail on the gCO_2e/MJ for the different process-level emissions. Here we discuss analysis of WtT values from the literature.[18] Conversions require studies to provide detailed GHG breakdowns or data that allows for conversion from other units (e.g., g CH_4) by providing the necessary contribution details.

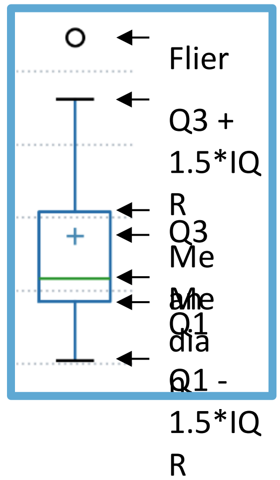
Box 2 describes the anatomy of a boxplot, used to display the distribution of emission factors across the different countries

[18] Note that computing the arithmetic sum of WtT values along the supply chain (e.g. gCO_2e/MJ from production and extraction + gCO_2e/MJ from processing etc…) may yield incongruous results compared to WtT estimates in the literature, particularly where estimates of process emissions are sparse.

by displaying the median, quartiles, and potential outliers. They can highlight the variations in literature values, offering insights into the consistency and range of reported values.

Box 2

Anatomy of a boxplot



AR6

In this section, we use AR6 GWP values (Table 4) to convert literature reported emission factors into AR6 gCO_2e. Only studies that either reported gCO_2e values weighted for AR6 or offered enough information for accurate conversion were included in the AR6 assessment. In total, we identified 40 literature values that were either provided in AR6 gCO_2e values, or could be converted based on the pollutant species provided. These results are shown in Table 6 and Figure 1.

We performed Shapiro-Wilk tests for normalcy of the data. Test results indicate that the majority of country estimates follow an approximately normal distribution with the data showing high test statistics (>0.75),[19] indicating that the assumption that the data follow a normal distribution generally cannot be rejected. Therefore using the mean values provides a reasonable measure of the central tendency of the data. In all cases we provide summary statistics, including median estimates.

Boxplots showing the distribution of the data are shown in Figure 1. The U.S.A has the highest mean WtT emissions rate at 27.40 gCO_2e/MJ, followed by Algeria at 19.02 gCO_2e/MJ and Russia at 18.75 gCO_2e/MJ. The range in values is not consistent across countries. The U.S.A has the highest standard deviation, indicating that its emissions rates are more spread out around the mean and greater variation in the data. Russia has the largest interquartile range, meaning that the range between the first quartile and the third quartile of its emissions data is more spread out compared to other countries.

The AR6 GWP_{20} emission factors are detailed in Table 7 and Figure 2 below. We converted the AR6 data to provide weightings for both GWP_{100} and GWP_{20} wherever detailed GHG data allowed for such conversions. However, the majority of the AR6 literature defaulted to GWP_{100}, with significantly fewer studies reporting in GWP_{20}. Consequently, there is limited availability of GWP_{20} data, reflecting its less frequent use and making comprehensive near-term impact assessments more challenging.

We identified 26 estimates that were either originally calculated or able to be converted to AR6 GWP_{20} (Table 7). Some countries (e.g. Nigeria and the UK) only had a single estimate available, and Algeria and Trinidad & Tobago only had a couple of estimates. For countries with more than a single value the highest mean value is for the U.S.A. (52.68 gCO_2e/MJ, AR6,

[19] The Shapiro-Wilk test for normality tests the null hypothesis under the assumption that the data follow a normal distribution. If the test statistic is high, i.e. close to 1, and $p > 0.05$ then we cannot reject the null hypothesis. Note that results are significant for both the U.S.A. (test statistic = 0.816, and p = 0.011) and Trinidad and Tobago (test statistic = 0.752, and p = 0.004)

GWP_{20}), followed by the Trinidad and Tobago (24.36 gCO_2e/MJ, AR6, GWP_{20}), and Russia (23.54 gCO_2e/MJ, AR6, GWP_{20}). These estimates are shown graphically in Figure 2.

Table 6

Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR6**, GWP_{100})

country	count	mean	std	min	25%	50%	75%	max
Algeria	3	19.02	2.41	16.90	17.71	18.52	20.08	21.64
Nigeria	1	14.81	-	14.81	14.81	14.81	14.81	14.81
Norway	9	12.45	8.77	1.61	6.71	9.17	16.60	28.82
Qatar	4	13.88	2.35	11.03	12.48	14.10	15.51	16.28
Russia	6	18.75	9.75	6.47	10.99	20.21	24.85	31.31
Trinidad & Tobago	3	12.02	2.39	9.26	11.33	13.40	13.40	13.41
UK	1	18.32	-	18.32	18.32	18.32	18.32	18.32
U.S.A.	13	27.40	11.60	12.89	21.50	24.59	28.56	51.81

Figure 1

Well-to-Tank carbon intensity (gCO_2e/MJ, **AR6**, GWP_{100})

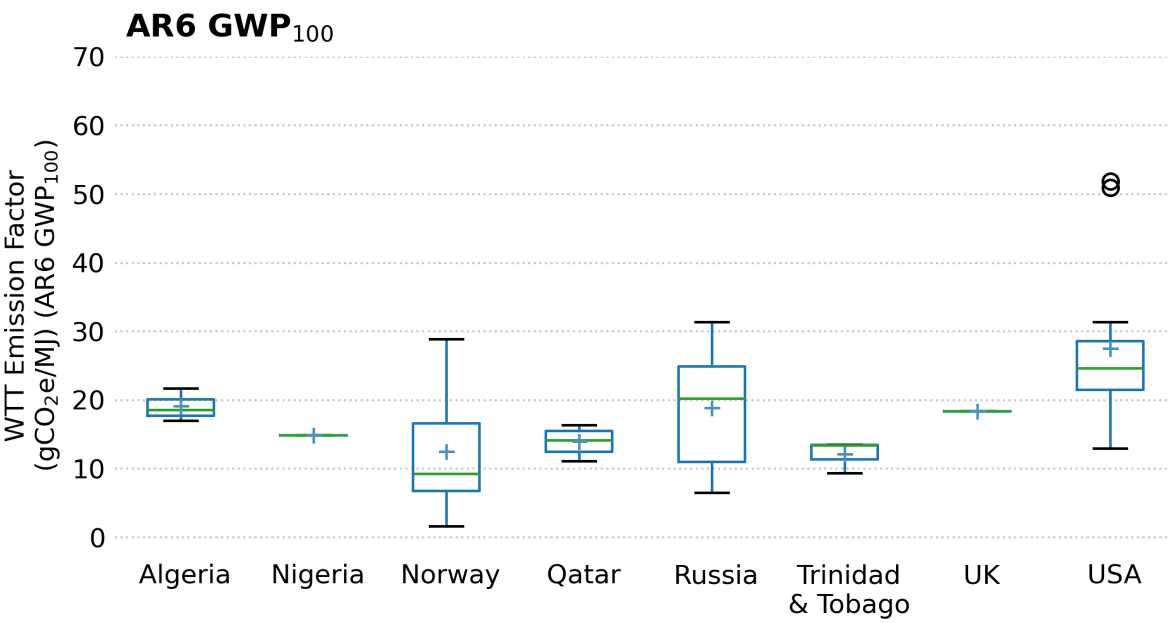
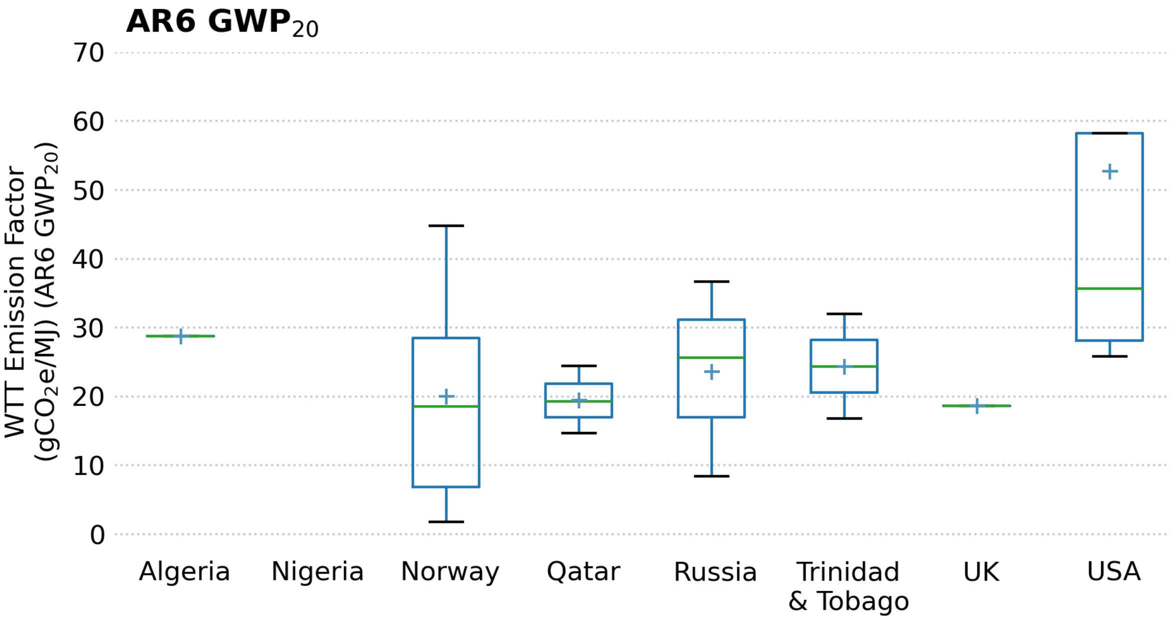


Table 7

Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR6**, GWP_{20})

country	count	mean	std	min	25%	50%	75%	max
Algeria	1	28.72	-	28.72	28.72	28.72	28.72	28.72
Nigeria	0	-	-	-	-	-	-	-
Norway	8	20.02	15.70	1.72	6.82	18.50	28.50	44.73
Qatar	3	19.42	4.90	14.61	16.94	19.26	21.83	24.40
Russia	3	23.54	14.26	8.37	16.98	25.59	31.13	36.67
Trinidad & Tobago	2	24.36	10.71	16.78	20.57	24.36	28.14	31.93
UK	1	18.60	-	18.60	18.60	18.60	18.60	18.60
U.S.A.	8	52.68	38.45	25.81	28.11	35.67	58.19	115.00

Figure 2
Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR6**, GWP_{20})



AR5

We identified 102 values that reported LNG WtT emission estimates in AR5 GWP_{100}.[20] These, as well as values that we were able to convert (n=22), are shown in Table 8 and Figure 3. With 47 of the 124 emission factors, the U.S.A. represented over a third of the total values. Norway contributed 17 values, Russia provided 16, and Qatar added another 15, and then the remaining countries had fewer than 10 values each. For the values reported or converted to AR5 Russia had the highest emissions, while Norway had the lowest.

As for the AR6 estimates, Russia, Algeria, and the U.S.A. are the highest emitting countries on a WtT basis, though the values are slightly different. The mean estimates for the U.S.A. (27.40 gCO_2e/MJ (AR6) vs. 27.25 gCO_2e/MJ (AR5)) differ by 0.5%, while Algeria (19.02 gCO_2e/MJ (AR6) vs. 27.41 gCO_2e/MJ (AR5)) differs by 31%.The AR6 GWP_{100} estimate for Russia is ~33%% lower compared to the AR5 estimate (18.75 gCO_2e/MJ (AR6) vs. 27.96 gCO_2e/MJ (AR5)).

Our review of the available literature returned a limited number of studies where the WtT value was estimated using the AR5 GWP_{20} parameters. In total, we found and re-calculated 34 estimates for AR5, which are presented in Table 9. Given the sparse data set, statistical inference from this limited pool is not feasible. Consequently, we only provide results in tabular form for AR5 GWP_{20}.

Of the limited AR5 GWP_{20} values, the U.S.A. and Norway accounted for over half of the total, with 20 out of 34 emission factors. These countries had the most studies reported in AR4 and that could be converted using other GWP weightings. The limited data from other countries might lead to skewed results due to its less comprehensive nature and the influence of outdated information.

Table 8
Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR5**, GWP_{100})

country	count	mean	std	min	25%	50%	75%	max
Algeria	9	27.41	14.41	10.44	17.85	21.62	30.74	54.58
Nigeria	6	19.65	5.09	14.42	16.00	19.65	20.60	28.48

[20] These are values strictly reported in AR5 and do not include conversions of estimates based on other assessment reports

Norway	17	12.57	6.93	1.61	6.71	12.59	16.89	28.22
Qatar	15	18.06	5.04	10.90	15.31	16.69	19.92	28.92
Russia	16	27.96	13.13	6.41	21.70	27.05	34.78	61.00
Trinidad & Tobago	5	14.86	4.58	9.14	12.85	13.29	18.63	20.39
UK	9	14.05	4.75	8.57	9.30	13.26	18.35	20.04
U.S.A.	47	27.25	9.99	8.10	20.23	28.18	33.60	49.66

Figure 3
Well-to-Tank carbon intensity (gCO_2e/MJ, **AR5**, GWP_{100})

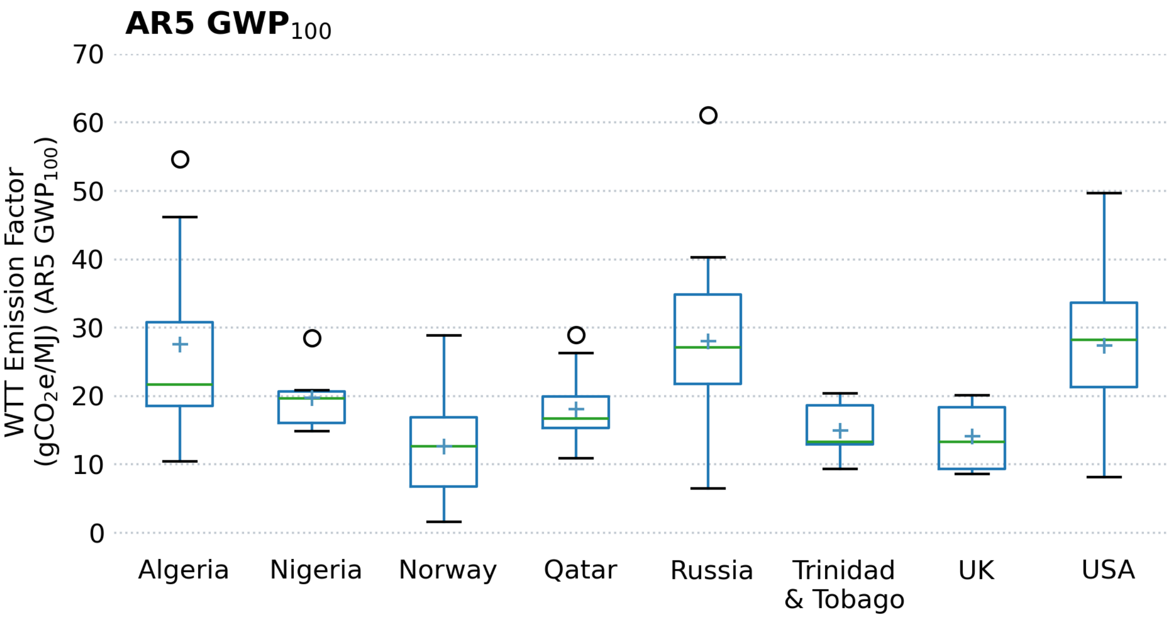


Table 9
Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR5**, GWP_{20})

country	count	mean	std	min	25%	50%	75%	max
Algeria	2	36.76	10.95	29.02	32.89	36.76	40.63	44.50
Nigeria	1	34.90	-	34.90	34.90	34.90	34.90	34.90
Norway	8	20.21	15.88	1.72	6.83	18.68	28.82	45.08
Qatar	4	21.45	5.53	14.71	18.21	22.00	25.24	27.10
Russia	4	52.07	57.83	8.42	21.48	31.43	62.02	137.00
Trinidad & Tobago	2	24.59	10.90	16.88	20.74	24.59	28.44	32.30
UK	1	18.61	-	18.61	18.61	18.61	18.61	18.61
U.S.A.	12	48.20	36.36	14.00	27.21	36.20	51.01	116.39

AR4

For AR4, we identified and re-calculated 57 estimates for GWP_{100} (Table 10) and 26 estimates for GWP_{20} (Table 11). Due to the small number of studies, with four or more countries having only three or fewer values for AR4, we also present these results in tabular form only. The U.S.A. and Norway had the most extensive representation in the AR4 datasets, due to the greater number of studies that were capable of conversion under other GWP weightings. The limited data for other countries could lead to skewed results due to less comprehensive data, and the chance that outdated information could disproportionately affect the results.

Of the limited AR4 GWP_{100} data, the U.S.A. and Norway literature represented over half of the total values. The highest average emission factor in this dataset was the U.S.A. at 23.29 gCO_2e/MJ, followed by Algeria at 18.44gCO_2e/MJ, and then Russia at 15.81 gCO_2e/MJ (Table 10). As with the AR6 calculations, these nations remain the top emitters in the literature.

Among the more limited AR4 GWP_{20} data, the U.S.A. and Norway continued to have the most extensive representation, with 8 values each, accounting for 16 of the 26 emission factors or over half of the dataset. The U.S.A. has the highest mean emission factor at 47.79 gCO_2e/MJ, followed by Algeria at 26.58 gCO_2e/MJ, and then Trinidad & Tobago at 22.74 gCO_2e/MJ, which surpassed Russia's value of 22.02 gCO_2e/MJ (Table 11).

Table 10

Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR4**, GWP_{100})

country	count	mean	std	min	25%	50%	75%	max
Algeria	3	18.44	2.72	16.74	16.87	17.00	19.29	21.58
Nigeria	1	13.77	-	13.77	13.77	13.77	13.77	13.77
Norway	15	10.36	8.72	1.60	4.39	6.70	14.82	28.83
Qatar	6	12.76	3.43	7.00	11.19	13.78	15.39	15.79
Russia	9	15.81	9.68	2.50	8.18	16.19	23.10	31.06
Trinidad & Tobago	3	13.31	4.48	8.94	11.02	13.10	15.50	17.90
UK	2	9.90	11.88	1.50	5.70	9.90	14.10	18.30
U.S.A.	18	23.29	9.54	12.18	18.19	20.21	25.24	46.09

Table 11

Country-level Well-to-Tank carbon intensity (gCO_2e/MJ, **AR4**, GWP_{20})

country	count	mean	std	min	25%	50%	75%	max
Algeria	1	26.58	-	26.58	26.58	26.58	26.58	26.58
Nigeria	0	-	-	-	-	-	-	-
Norway	8	18.65	14.33	1.69	6.8	17.26	26.19	41.74
Qatar	3	18.39	4.45	13.9	16.18	18.47	20.63	22.79
Russia	3	22.02	13.2	7.99	15.93	23.88	29.03	34.19
Trinidad & Tobago	2	22.74	9.38	16.11	19.42	22.74	26.06	29.37
UK	1	18.54	-	18.54	18.54	18.54	18.54	18.54
U.S.A.	8	47.79	33.58	24.67	26.31	32.6	52.87	102.09

Weighted Average Well-to-Tank Carbon Intensity

Data from the World Bank World Integrated Trade Solution (WITS)[21] for imports of "Natural Gas, Liquefied" (HS6 271111) show that around 42% of all LNG delivered to the European Union in 2023 came from the United States (45.3% of imports from the countries in this study). The countries in this study represent 92.6% of total LNG imports by mass to the EU in 2023. The remaining ~7.4% of LNG imports to the EU originating from the rest of the world are distributed over 18 other countries.

Considering these import volumes we are able to compute a weighted average WtT carbon intensity, in gCO_2e/MJ, for countries in this study. We apply the study weights to the WtT values under the assumption that the values obtained for the study countries are representative of the remaining 7.4% of imports from countries outside the study area.

[21] World Bank, WITS, European Union LNG Imports. HS6 271111. https://wits.worldbank.org/trade/comtrade/en/country/EUN/year/2023/tradeflow/Imports/partner/ALL/product/271111

Table 12
EU LNG Gross Import Volumes by Import Origin

Year	Import Origin	Quantity (MT)	% Total	% Study
2023	United States	38,353,500	42.0%	45.3%
	Russian Federation	12,414,100	13.6%	14.7%
	Qatar	11,841,900	13.0%	14.0%
	Algeria	8,987,010	9.8%	10.6%
	Nigeria	5,868,530	6.4%	6.9%
	Norway	3,744,420	4.1%	4.4%
	Trinidad and Tobago	1,814,930	2.0%	2.1%
	United Kingdom	1,553,960	1.7%	1.8%
	World	**91,363,800**	**100.0%**	**NA**

To compute the weighted emissions, we apply the formula for calculating the arithmetic mean using the study import weight percentages directly, as follows

$$Weighted\ Mean\ WtT\ CO_2e = \sum_{i \in N} p_i WTT_i$$

Where N is the set of countries in the study, p is the percent of total LNG imports by mass from country i, and WtT is the WtT carbon intensity for country i.

The weighted mean WtT carbon intensity for the AR6, AR5, and AR4 GWP_{100} estimates are:

AR6 GWP_{100}: 21.31 gCO_2e/MJ
AR5 GWP_{100}: 24.40 gCO_2e/MJ
AR4 GWP_{100}: 18.51 gCO_2e/MJ

The AR5 weighted mean value is 14.5% higher than the weighted mean AR6 value considering all countries in the study and their respective contributions to EU LNG imports. Note that while we include the AR6 and AR4 values in these aggregations, the sample sizes for each country are small, compared to the number of AR5 estimates, and results should be treated accordingly.

The weighted mean WtT carbon intensity for the AR6 and AR5 GWP_{20} estimates are:

AR6 GWP_{20}: 34.87 gCO_2e/MJ
AR5 GWP_{20}: 40.59 gCO_2e/MJ
AR4 GWP_{20}: 31.96 gCO_2e/MJ

Note that sample sizes for the GWP_{20} values are considerably smaller than for GWP_{100} (AR6 n = 26, AR5 n = 34, AR4 n = 26) with some countries having none or only a single GWP_{20} estimate.
These results are presented for a set of three AR values. Differences in the results are not necessarily indicative of temporal changes in the literature estimates, and instead reflect the best available literature and conversions we were able to estimate for each AR estimate. Independent differences in the sample sizes, and specific studies for each AR are likely the driving influence behind the observed differences.

Country-Specific Estimates

This section provides process-level estimates of emissions, in gCO_2e/MJ for the LNG production and supply chain by country. The goal was to convert emissions data to AR6 GWP100 for consistency. However, due to limited studies providing detailed CO_2e values or convertible units for AR6, most available emission factors were reported under AR5. Thus, AR5 became the most viable framework for comparing emissions across countries in our analysis.

The country-specific discussions compare both AR6 and AR6 WtT emissions data to provide a comprehensive overview of the literature. However, our detailed examination of the specific upstream and midstream processes are focused on AR5 data. This is because AR5 has a larger number of studies and emission factors that break down these stages and provide detailed insights. In the following discussions, all figures and tables related to these finer process details are based on AR5 data. For AR4 and AR6 upstream and midstream process values readers can refer to tables in the appendix for both GWP timescales.

Note that the "Production++" emission factor includes a set of similar but different methodologies in the literature. Some studies provide a detailed breakdown of upstream emissions, separating extraction, production, processing, and other stages. In contrast, other studies combine these stages into a singular upstream production value. This variation in how emissions are reported can skew the overall "Production++" emission factor. When interpreting results for Production++ the reader should consider that it may include additional processes in that part of the production chain.

Algeria

The Nations of the European Union have sought to reduce their dependence on Russian energy. As a result, Algeria has become the European continent's second largest pipeline gas supplier, behind Norway, in addition to its LNG imports.[22] In 2023, Algeria was the fourth largest source of LNG imports to the EU (Table 12), with the largest volumes received by Turkey, France, and Italy.[23] Though Algeria has significant exports to the EU by pipeline, this report focuses on emission factors observed in the literature for the LNG value chain. Out of 51 total emission factors we found for Algeria, 46 were for LNG, and 5 were for natural gas (Table 3).

Algeria has three major intercontinental pipelines capable of exporting natural gas to Europe: The Enrico Mattei pipeline to Italy, the subsea Medgaz pipeline to Spain, and the Maghreb-Europe pipeline to Spain. The latter of these pipelines flows through Morocco. A long-standing territorial dispute between Algeria and Morocco over Western Sahara, has led to border closures and trade disruptions, including Algeria's decision to stop exporting gas through the Maghreb pipeline in 2022. In 2024, Spain reopened and reversed the flow of this pipeline to supply Morocco with re-exports of natural gas, monitoring to ensure no gas is sourced from Algerian imports.[24]

Algeria has fewer studies (n=13; Table 1) compared to the other top emitting countries under this report, the United States and Russia. Evaluated by AR6 GWP_{100}, Algeria has the second highest mean WtT emissions rate at 19.02 gCO_2e/MJ (n=3; Table 6). The limited sample can be attributed to Algeria's relatively recent emergence as a significant supplier for Europe, resulting in fewer comprehensive studies on its emissions and practices. Algeria had three times more emission factors in the AR5 GWP_{100} dataset, resulting in a substantial increase in the mean WtT emissions rate at 27.41 gCO_2e/MJ (n=9; Table 8) but remaining the second highest emitter.

Algeria's energy-intensive liquefaction stage has an estimated rate of 6.52 gCO_2e/MJ. Although it's high WtT emissions are likely attributed to leakage and flaring rates during the production stages, with mean emissions of Production++ found to be 9.00 gCO_2e/MJ (Table 13), as the nation has the fourth fourth-largest gas flaring country in the world, as well as infrastructure with high methane leakage.[25] According to data from Kayrros, an ongoing leak at the Algerian Hassi R'Mel basin emitted ~939,000 tons of methane in 2021, roughly equivalent to the annual emissions from 17 million American cars.[26]

Table 13

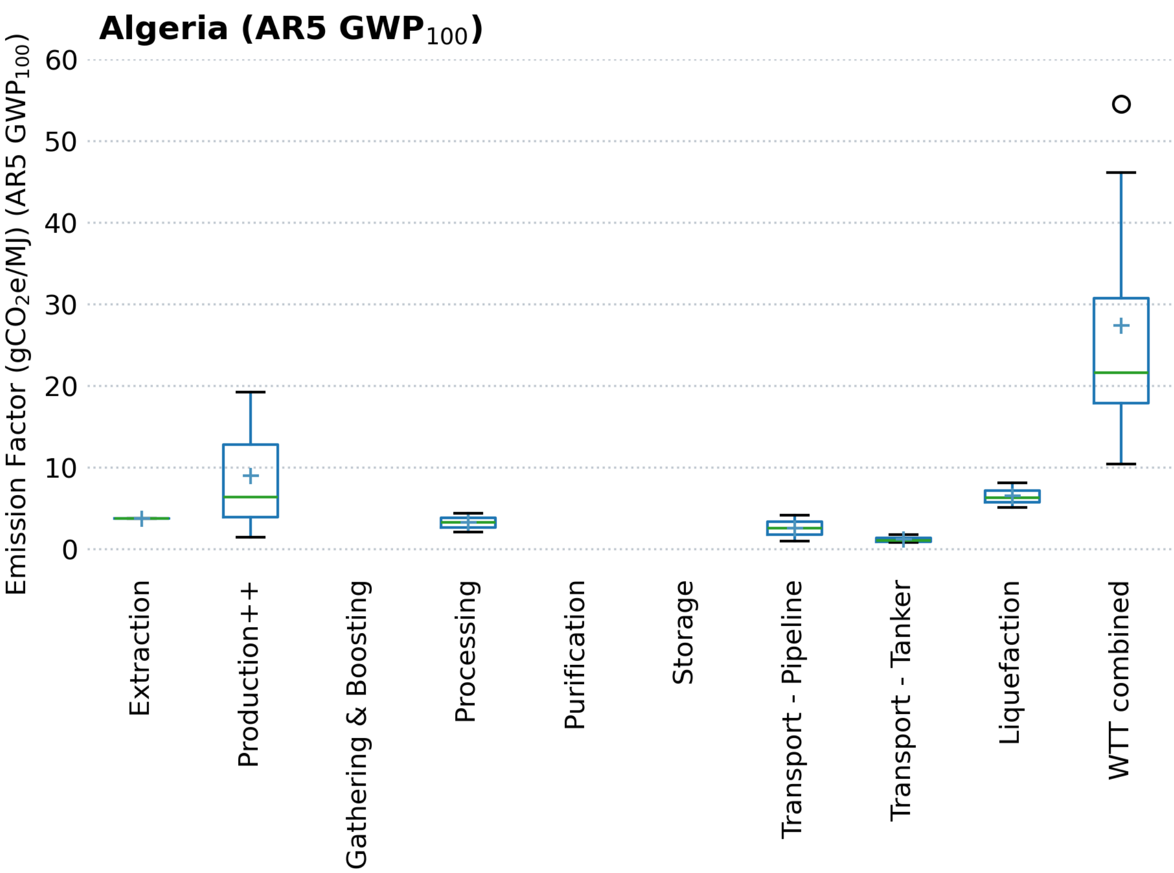
[22] https://apnews.com/article/algeria-gas-06149e3252a4a827d2cbc08a07a022e6
[23] https://ieefa.org/european-lng-tracker
[24] https://www.moroccoworldnews.com/2024/06/363377/morocco-emerges-as-major-buyer-of-gas-from-spain-two-years-after-reopening-pipeline
[25] https://www.elibrary.imf.org/view/journals/002/2024/089/article-A001-en.xml
[26] https://unearthed.greenpeace.org/2022/05/30/methane-satellite-algeria-gas-eu/

Emission Factors Across LNG Supply Chain in Algeria (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Algeria	Extraction	1	3.78	--	3.78	3.78	3.78	3.78	3.78
Algeria	Production++	3	9.00	9.17	1.45	3.90	6.36	12.78	19.20
Algeria	Processing	2	3.24	1.63	2.09	2.67	3.24	3.82	4.40
Algeria	Transport - Pipeline	2	2.56	2.21	1.00	1.78	2.56	3.34	4.12
Algeria	Transport - Tanker	3	1.20	0.51	0.80	0.92	1.04	1.40	1.77
Algeria	Liquefaction	3	6.52	1.50	5.14	5.72	6.30	7.20	8.11
Algeria	WTT combined	9	27.41	14.41	10.44	17.85	21.62	30.74	54.58

Figure 4

Emission Factors Across LNG Supply Chain in Algeria (AR5, GWP_{100}, gCO_2e/MJ)



Nigeria

Nigeria is growing as an exporter of natural gas and LNG to the European Union to replace Russian supplies. Nigeria, which holds Africa's largest natural gas reserves[27], has become the EU's fifth largest LNG supplier (Table 12). In 2023, the largest volumes of LNG to the EU were imported to Spain, Portugal, and France.[28] Unlike Algeria, Nigeria lacks an intercontinental pipeline network for exporting gas to Europe or elsewhere without liquefaction. Out of 36 total emission factors for Nigeria, all were for LNG, with no values for natural gas (Table 3). Nigeria had only nine references for these values (n=9; Table 1).

The EU expressed plans to increase LNG imports from Nigeria, through at least 2027, as it continues to decrease its dependency on Russian gas.[29] Nigeria has struggled to meet European gas demand, while North African countries, especially Algeria have capitalized more effectively.[30] To meet demand, Nigeria began making significant investments to expand LNG production and export infrastructure. However, as climate targets strengthen and the transition to low-carbon energies accelerate after 2030, these LNG assets could become stranded.[31]

Nigeria, Algeria and Niger formed a collaborative venture to build the Trans-Saharan pipeline, aiming to transport natural gas from Nigeria, through Niger, to Algeria, where it would link with existing intercontinental pipelines. However, a military coup in Niger triggered economic sanctions and a potential exit from the Economic Community of West African States (ECOWAS), halting the project. Nigeria is exploring alternative routes, including Morocco.[32]

Nigeria's WtT emissions were the fifth highest under the AR6 GWP_{100} assessment at 14.81 gCO_2e/MJ, behind the U.S.A., Algeria, Russia, and the UK. However, Nigeria had only a single emissions factor in the AR6 GWP_{100} dataset (n=1; Table 6). In contrast, Nigeria's WtT emissions factor was the fourth highest at 19.65 gCO_2e/MJ, surpassing the UK when assessing the AR5 GWP_{100} values (n=6; Table 8).

Compared to Algeria, Nigeria had higher mean emissions reported during its production stages of 11.20 gCO_2e/MJ (Table 14). Nigeria has substantial emissions from infrastructure leaks, and from venting and flaring. Despite significant strides in reducing its flaring volumes in recent years, Nigeria remains in the top nine countries responsible for over 75% global flaring volumes – along with Algeria, the U.S.A., and Russia.[33]

27 https://www.lngindustry.com/special-reports/08122023/africa-the-making-of-a-major-exporter/
28 https://ieefa.org/european-lng-tracker
29 https://businessworld.africa/eu-plans-higher-lng-exports-from-nigeria-between-2023-and-2027/
30 https://www.moroccoworldnews.com/2024/02/360666/nigeria-looks-to-reroute-gas-supply-to-europe-through-morocco-after-niger-crisis
31 https://www.iisd.org/articles/press-release/nigeria-lng-risks-asset-stranding-eu-gas-demand-forecast-fall
32 https://www.moroccoworldnews.com/2024/02/360666/nigeria-looks-to-reroute-gas-supply-to-europe-through-morocco-after-niger-crisis
33 https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report

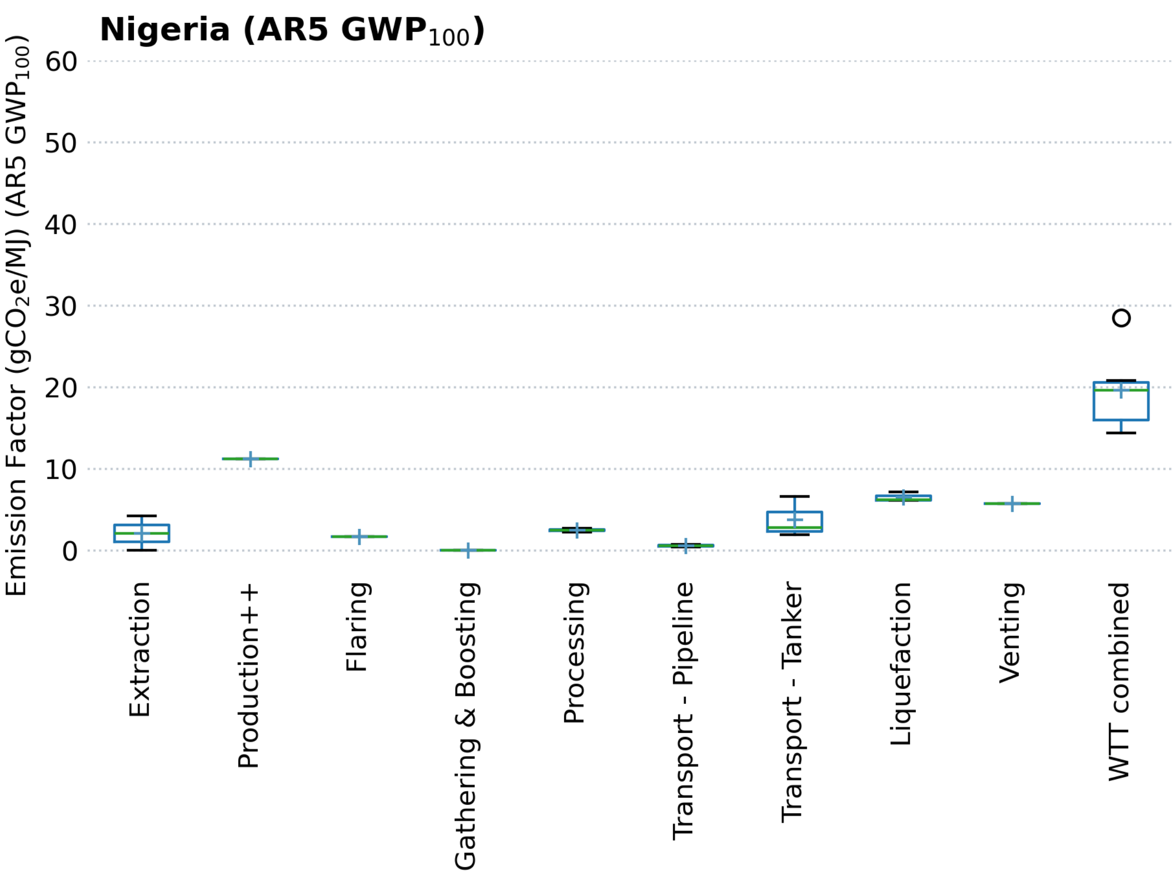
Table 14

Emission Factors Across LNG Supply Chain in Nigeria (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Nigeria	Extraction	2	2.12	2.95	0.03	1.07	2.12	3.16	4.20
Nigeria	Production++	1	11.20	--	11.20	11.20	11.20	11.20	11.20
Nigeria	Flaring	1	1.68	--	1.68	1.68	1.68	1.68	1.68
Nigeria	Processing	2	2.48	0.33	2.25	2.37	2.48	2.60	2.71
Nigeria	Transport - Pipeline	2	0.57	0.25	0.40	0.49	0.57	0.66	0.75
Nigeria	Transport - Tanker	3	3.75	2.49	1.90	2.34	2.77	4.68	6.59
Nigeria	Liquefaction	3	6.51	0.60	6.13	6.17	6.21	6.70	7.20
Nigeria	Venting	1	5.70	--	5.70	5.70	5.70	5.70	5.70
Nigeria	WTT combined	6	19.65	5.09	14.42	16.00	19.65	20.60	28.48

Figure 5

Emission Factors Across LNG Supply Chain in Nigeria (AR5, GWP_{100}, gCO_2e/MJ)



Norway

In 2023, Norway was the fourth largest natural gas exporter in the world, with 95% supplied by pipelines and 5% supplied by LNG tankers.[34] As Europe moves away from Russian gas, Norway has become the leading gas supplier within the EU.[35] Gas is transported across Europe via pipelines to seven receiving terminals. These are located in the UK[36] and Germany (each with two terminals), and in Belgium, Denmark, and France (each with one). Norway was the sixth largest LNG supplier to the EU (Table 12), with the largest volumes received by Lithuania, France, and the Netherlands.[37]

There are five export terminals in Norway, but only Hammerfest (also known as Melkøya) is a large-scale facility, with a capacity of 4.2 million tons per year. In comparison, the other four terminals have a combined capacity of just 0.48 million tons per year.[38] Despite a larger network for pipeline gas exports, and carriers that could transport gas worldwide, almost all LNG exports are received from European nations.[39] Out of 69 literature values found for Norway, 52 were for LNG and 17 were for natural gas (Table 3).

Under the AR6 GWP_{100} framework, Norway had the second lowest WtT emissions of 12.45 gCO_2e/MJ for its supplies to the EU (n=9; Table 6).[40] Although there is a slight increase when evaluating the AR5 GWP_{100} values, at 12.57 gCO_2e/MJ, under this assessment Norway had the lowest WtT emissions (n= 17; Table 8). Despite high production volumes, Norway maintained the lowest flaring intensity of global hydrocarbon producers between 2012 and 2022,[41] although its production stage emissions were not the lowest in this assessment. Norway's transport of LNG by tanker had the highest process-specific value, contributing an average 5.07 gCO_2e/MJ. Increased efficiency measures onboard its carriers could potentially have the greatest impact in reducing WtT emissions.

WtT emissions of Norway's LNG supplies are targeted to decrease by 2030 to align with climate initiatives[42] and efforts under the Global Methane Initiative, the Global Methane Pledge, and the Climate and Clean Air Coalition. More than 90% of Norway's electricity is generated from renewable energy sources, however, Hammerfest is powered by gas and not the national grid. Plans to convert its infrastructure to utilize the national power grid by 2030 has the potential to reduce approximately 850,000 tons of CO_2 per year.[43]

Table 15

Emission Factors Across LNG Supply Chain in Norway (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Norway	Extraction	1	4.30	--	4.30	4.30	4.30	4.30	4.30
Norway	Production++	2	3.38	0.59	2.97	3.18	3.38	3.59	3.80
Norway	Processing	1	5.03	--	5.03	5.03	5.03	5.03	5.03
Norway	Transport - Pipeline	1	1.10	--	1.10	1.10	1.10	1.10	1.10
Norway	Transport - Tanker	2	5.07	3.07	2.90	3.98	5.07	6.16	7.24
Norway	Liquefaction	1	4.05	--	4.05	4.05	4.05	4.05	4.05
Norway	WTT combined	17	12.57	6.93	1.61	6.71	12.59	16.89	28.22

34 https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/

35 https://www.bloomberg.com/news/features/2024-05-13/equinor-how-norway-s-gas-giant-quietly-took-over-europe

36 The UK is a non-EU nation, whereas the other four nations are EU member states.

37 https://ieefa.org/european-lng-tracker

38 https://cleanarctic.org/wp-content/uploads/2024/04/LNG-and-Shipping-in-the-Arctic-Final.pdf

39 https://www.reuters.com/business/energy/how-does-norway-export-its-natural-gas-2023-10-12/

40 This finding is supported by an analysis from Wood Mackenzie, which found that Norway has the lowest average upstream emissions intensity for the oil & gas industry among major European supply sources / https://go.woodmac.com/l/131501/2024-08-05/32s5nv/131501/1722852275dwdIHbIk/Norway_Emissions_Assessment_Wood_Mackenzie_August_2024vF.pdf

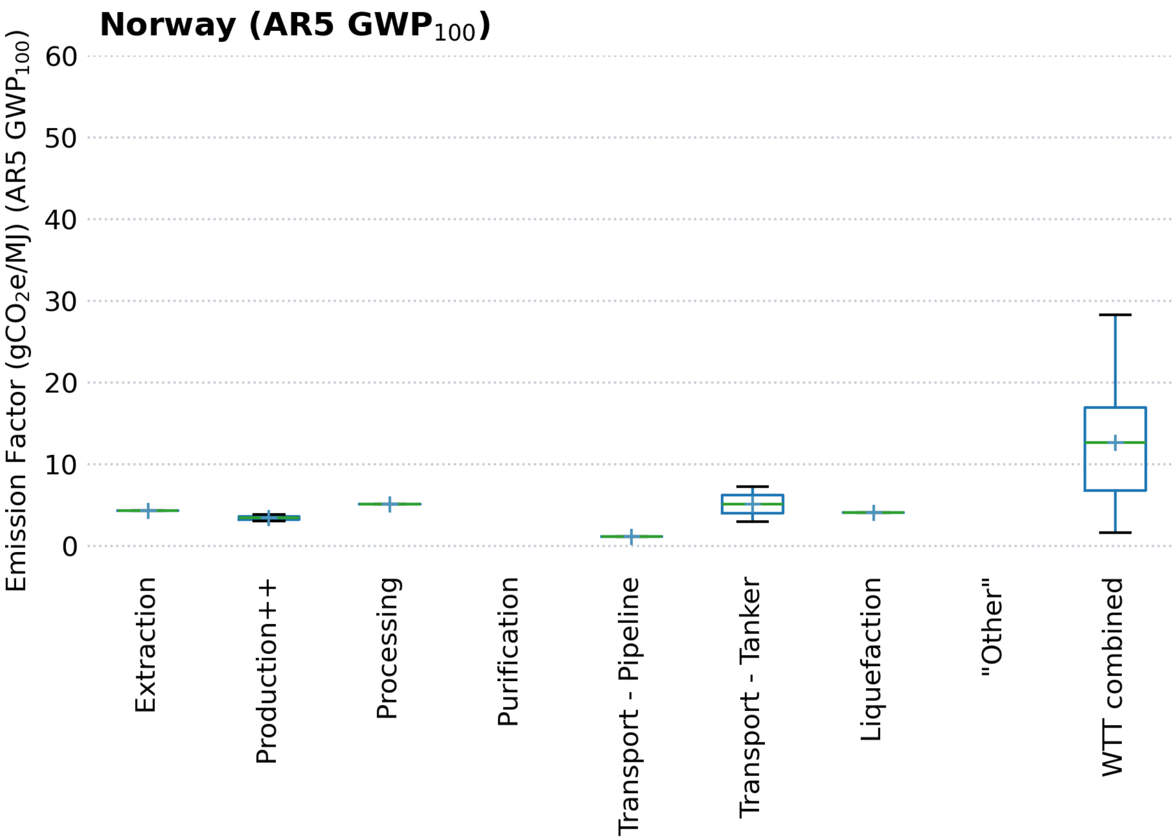
41 https://flaringventingregulations.worldbank.org/norway

42 It is important to note that while these measures are steps toward reducing emissions, they do not guarantee that Norway's LNG will have lower emissions than other alternative energies

43 https://www.reuters.com/business/energy/norway-approves-lng-plant-electrification-cut-co2-emissions-2023-08-08/

Figure 6

Emission Factors Across LNG Supply Chain in Norway (AR5, GWP_{100}, gCO_2e/MJ)



Qatar

Qatar is the second largest supplier of LNG to the European continent,[44] and the third largest specifically to the EU (Table 12), with volumes increasing as EU buyers compensate for the loss of supply from Russia. The largest EU importers of LNG from Qatar are Italy, Belgium, and Poland.[45] Several EU member states, including Italy, France, and the Netherlands have signed agreements committing to have Qatar supply LNG from 2026 out to 2053.[46] From 2026, Qatar will become the primary supplier of LNG to the Port of Rotterdam, highlighting its role in the maritime bunker fuel industry.[47]

The Dolphin pipeline is Qatar's only international export pipeline. It extends to Taweelah in the United Arab Emirates (UAE) and then connects to additional pipelines distributing gas throughout the UAE and export to Oman. Asia is Qatar's largest export destination, and the nation has been strengthening its relations with the European market, both necessitating LNG carriers. Qatar plans to greatly expand its LNG production and export infrastructure by 2030, aiming for an increase of nearly 85% over current volumes.[48] This includes commitments to build over 100 LNG vessels, including 18 large-scale LNG carriers (capacity > 260,000 m^3).[49,50] Out of 80 emission factors identified for Qatar, 79 were for LNG and just 1 was for natural gas (Table 3).

Qatar has faced criticism for underreporting or failing to report national emissions. Although the U.N. Framework Convention on Climate Change (UNFCCC) requires countries to provide regular and detailed updates on their GHG emissions, Qatar's last formal submission only included emissions up to 2007.[51]

Whether as a high volume supplier to key bunkering ports, or through operating its own ship-to-ship bunker vessels, Qatar's WtT emissions will significantly contribute to the overall life cycle emissions of LNG as a marine fuel. Averaging 13.88 gCO_2e/MJ, Qatar had the sixth highest emission factor identified in AR6 GWP_{100} (n=4; Table 6). Under the AR5 dataset, the mean WtT emissions for Qatar increased to 18.06 gCO_2e/MJ, making it the fifth highest value (n=15; Table 8). The emission factors across its WtT supply chain were largest at liquefaction, 6.78 gCO_2e/MJ, and transport by tanker stages, 4.80 gCO_2e/MJ (Table 16). Given the high emissions from transport and large distance between the EU, carrier transport efficiency measures could considerably reduce the carbon intensity of Qatar's LNG. Despite being one of the world's largest LNG exporters, Qatar ranked 23rd in terms of flaring volumes in 2023.[52]

Table 16

Emission Factors Across LNG Supply Chain in Qatar (AR5, GWP_{100}, gCO_2e/MJ)

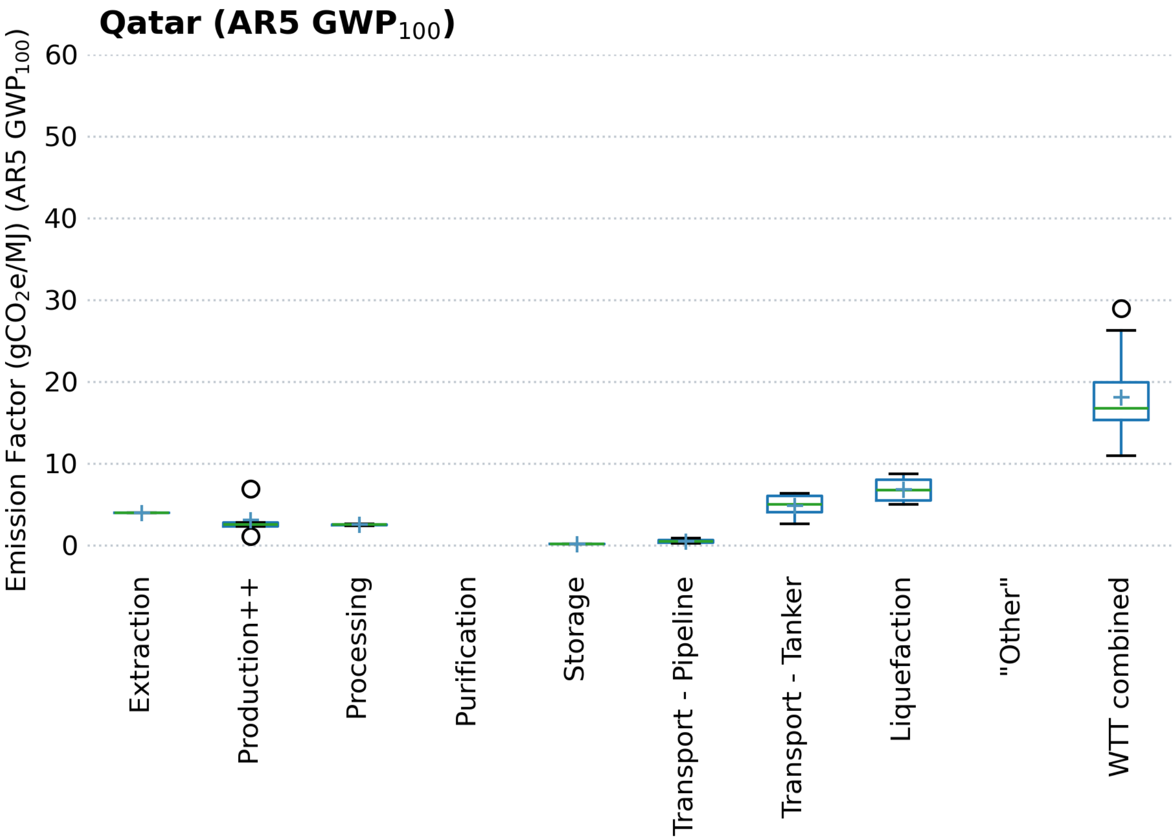
Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Qatar	Extraction	1	3.93	--	3.93	3.93	3.93	3.93	3.93
Qatar	Production++	5	3.12	2.21	1.12	2.27	2.54	2.75	6.90
Qatar	Processing	2	2.48	0.12	2.40	2.44	2.48	2.53	2.57
Qatar	Storage	1	0.18	--	0.18	0.18	0.18	0.18	0.18
Qatar	Transport - Pipeline	3	0.48	0.31	0.20	0.31	0.42	0.62	0.82
Qatar	Transport - Tanker	5	4.80	1.52	2.60	4.06	4.98	6.00	6.34

44 https://www.eia.gov/todayinenergy/detail.php?id=61483
45 https://ieefa.org/european-lng-tracker
46 https://www.rigzone.com/news/qatarenergy_now_has_over_100_lng_ships_under_construction-02-apr-2024-176267-article/
47 https://www.reuters.com/markets/commodities/qatarenergy-shell-agree-27-year-lng-supply-2023-10-18/
48 https://knowledge.energyinst.org/new-energy-world/article?id=138616
49 https://safety4sea.com/qatarenergy-inks-agreement-to-build-18-large-scale-lng-carriers/
50 https://www.rigzone.com/news/qatarenergy_now_has_over_100_lng_ships_under_construction-02-apr-2024-176267-article/
51 https://e360.yale.edu/features/undercounted-emissions-un-climate-change
52 https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report

Qatar	Liquefaction	5	6.78	1.61	4.98	5.48	6.69	8.00	8.75
Qatar	WTT combined	15	18.06	5.04	10.90	15.31	16.69	19.92	28.92

Figure 7

Emission Factors Across LNG Supply Chain in Qatar (AR5, GWP_{100}, gCO_2e/MJ)



Russia

In 2023, approximately 15% of EU imports were from Russian pipeline gas and LNG combined, dropping from nearly 40% prior to the war in Ukraine.[53,54] However, LNG imports from Russia have marginally increased to meet demand.[55] Russia was the second largest LNG supplier to the EU (Table 12). Spain, France, and Belgium continued to import the most Russian LNG to satisfy demand.[56] Despite technology and financing challenges due to sanctions, Russia is prioritizing its LNG infrastructure development to access new markets and strengthen ongoing energy partnerships, particularly with China.[57]

Historically, Russia relied on a substantial pipeline network across Europe, with minimal LNG infrastructure. Several of these pipelines have ceased operations due to damage, political conflicts and reluctance to continue energy partnerships.[58] Of the 90 emission factors identified for Russia, 32 were attributed to LNG, while 58 were attributed to natural gas (Table 3). Literature on exports to European destinations were often focused on natural gas, while much of the LNG literature was based on Asian markets.

Russia's WtT emissions were the third highest at 18.75 gCO_2e/MJ when identified by the AR6 GWP_{100} values (n=6; Table 6). At 27.96 gCO_2e/MJ, its emissions were the highest under the AR5 GWP_{100} framework, likely influenced by the greater number of emissions factors (n=16; Table 8). Many of Russia's supply chain stages were reported to be lower than other nations. Specifically, its production stage emissions, reported at 2.04 gCO_2e/MJ, were substantially lower than the emissions of the other highest emitters, the U.S.A. (18.86 gCO_2e/MJ) and Algeria (9.00 gCO_2e/MJ). This low value contradicts Russia leading the nine countries responsible for >75% of flaring emissions.[59]

Official Russian reports would suggest that its gas emissions are among the lowest. State-owned gas company Gazprom said fugitive methane emissions across its production chain "are close to zero". However, satellite data have shown several significant leaks, one of which was estimated to release approximately 395 metric tons of methane per hour. In 2019, Russia reduced its methane emissions estimate by over 90% without providing an explanation, drawing criticism from UNFCCC reviewers.[60] Russia has frequently revised its calculations and significantly lowered past estimates in recent years. The IEA estimates emissions are more than three times higher than the latest figures officially reported to the UNFCCC.[61]

Table 17

Emission Factors Across LNG Supply Chain in Russia (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Russia	Extraction	7	4.12	0.50	3.45	3.80	4.16	4.38	4.86
Russia	Production++	3	2.97	0.62	2.31	2.68	3.04	3.30	3.55
Russia	Processing	8	2.00	1.30	0.98	1.08	1.52	2.24	4.12
Russia	Storage	1	0.22	--	0.22	0.22	0.22	0.22	0.22
Russia	Transport - Pipeline	8	18.69	9.08	0.64	16.40	19.00	24.80	28.55
Russia	Transport - Tanker	3	1.55	2.68	0.00	0.00	0.00	2.32	4.64
Russia	Liquefaction	3	2.02	3.50	0.00	0.00	0.00	3.03	6.06

53 https://www.consilium.europa.eu/en/infographics/eu-gas-supply/

54 https://www.reuters.com/markets/commodities/qatarenergy-shell-agree-27-year-lng-supply-2023-10-18/

55 https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/041024-europe-is-set-to-continue-to-rely-on-russian-lng-in-short-term

56 https://ieefa.org/european-lng-tracker

57 https://www.eia.gov/international/analysis/country/RUS

58 https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/07/Insight-131-Do-future-Russian-gas-pipeline-exports-to-Europe-matter-anymore.pdf

59 https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report

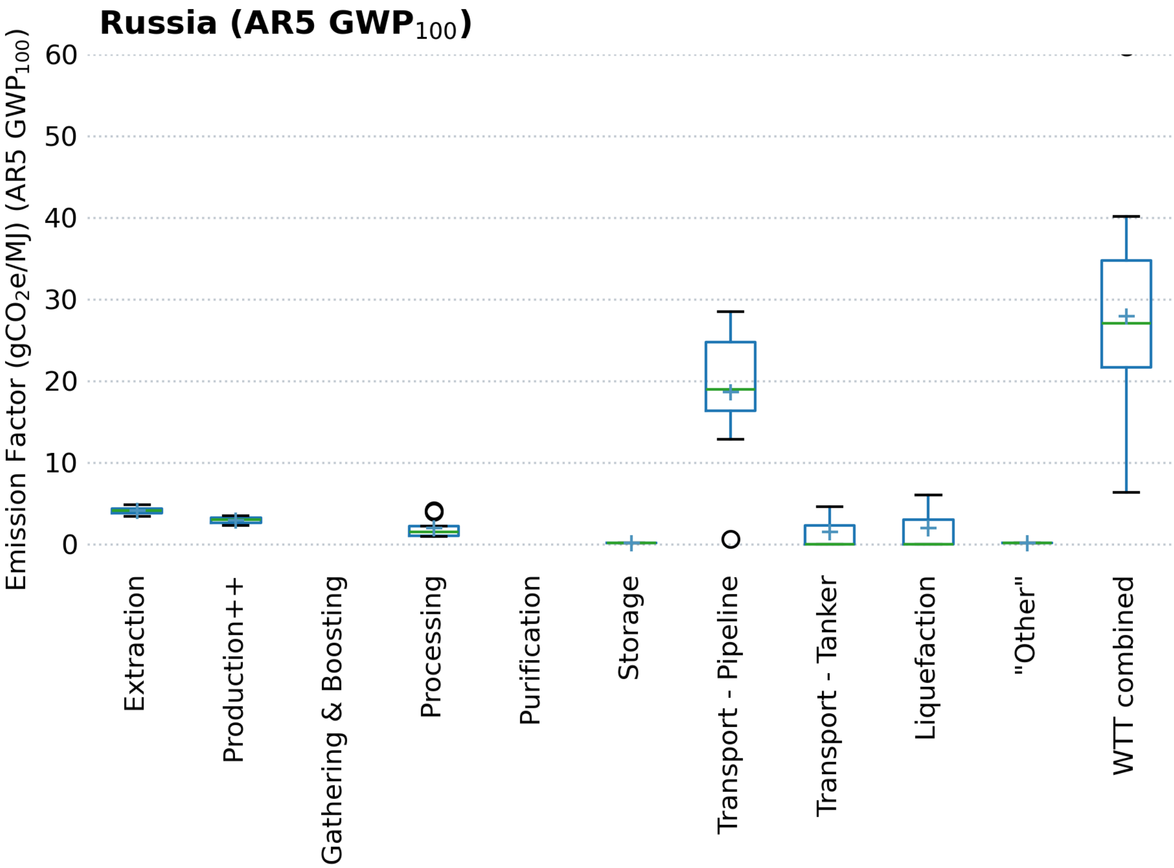
60 https://subscriber.politicopro.com/eenews/f/eenews/?id=00000180-99c8-d3ee-a392-99db2bbd0000

61 https://www.washingtonpost.com/climate-environment/interactive/2021/russia-greenhouse-gas-emissions/

Russia	"Other"	1	0.18	--	0.18	0.18	0.18	0.18	0.18
Russia	WTT combined	16	27.96	13.13	6.41	21.70	27.05	34.78	61.00

Figure 8

Emission Factors Across LNG Supply Chain in Russia (AR5, GWP_{100}, gCO_2e/MJ)



Trinidad and Tobago

Trinidad and Tobago supplies less than 5% of Europe's gas and LNG, but 40% of T&T LNG exports are delivered to Europe.[62] T&T was the seventh largest LNG supplier to the EU (Table 12), with the largest European exports shipped to the Netherlands, the UK, and Croatia.[63] The nation's domestic gas production has dwindled in recent years, meaning that there is underutilized infrastructure for liquefaction and other midstream processes. If T&T secures gas supplies from other extracting nations, such as Venezuela, it can utilize existing infrastructure to boost LNG exports and become a more substantial EU supplier.[64]

As an island nation, T&T has no active cross-border pipelines for natural gas import or export. Of the 29 emission factors identified for T&T, all were associated with LNG (Table 3). The U.S.A. granted a two-year license to bypass sanctions[65] and reinstate negotiations between T&T and Venezuela for the Dragon Gas Pipeline project, which had been shelved due Venezuela's political turmoil. By the end of 2023, the two nations signed to jointly produce and export Venezuelan gas, primarily to boost LNG capacity.[66,67]

Trinidad and Tobago the least literature references in this assessment (n=8; Table 1). T&T was found to have the lowest WtT emissions at 12.02 gCO_2e/MJ when evaluated under the AR6 GWP_{100} framework, but also had minimal emissions factors to inform this value (n=3; Table 6). When evaluating T&T by AR5 GWP_{100}, its emissions were found to be 14.86 gCO_2e/MJ, making it the sixth highest or third lowest in the assessment (n=5; Table 8). Trinidad and Tobago's second-largest natural gas producer, Shell, has set a target to achieve near-zero methane emissions by 2030 across all our operations, specifically through more efficient plant operations and shipping fleet deliveries. However, the company has also ended its previous commitment to reduce its overall carbon footprint by 2035, as it seeks to expand its LNG operations.[68]

The liquefaction (6.34 gCO_2e/MJ) and tanker transport (5.62 gCO_2e/MJ) stages had the highest emissions across the T&T observed supply chain, thus efficiency measures at these steps would be most effective at reducing WtT emissions. Potential measures could include mitigating boil-off gas during storage and liquefaction, or onboard LNG carriers, using reliquefaction technologies or other efficiency improvements to reduce venting and flaring.[69]

62 https://energynow.tt/blog/can-trinidad-amp-tobago-and-venezuela-help-fill-europes-gas-shortfall
63 https://ieefa.org/european-lng-tracker
64 https://energynow.tt/blog/can-trinidad-amp-tobago-and-venezuela-help-fill-europes-gas-shortfall
65 https://crsreports.congress.gov/product/pdf/IF/IF10715
66 https://www.gem.wiki/Dragon_Gas_Pipeline#cite_note-4
67 https://venezuelanalysis.com/news/venezuela-signs-30-year-alliance-with-trinidad-to-develop-dragon-gas-field/
68 https://trinidadexpress.com/business/local/shell-promises-more-value-less-emissions/article_f25d2cba-0b3b-11ef-afff-6b8ebc9a35c1.html
69 https://theicct.org/publication/options-for-reducing-methane-emissions-from-new-and-existing-lng-fueled-ships-oct23/

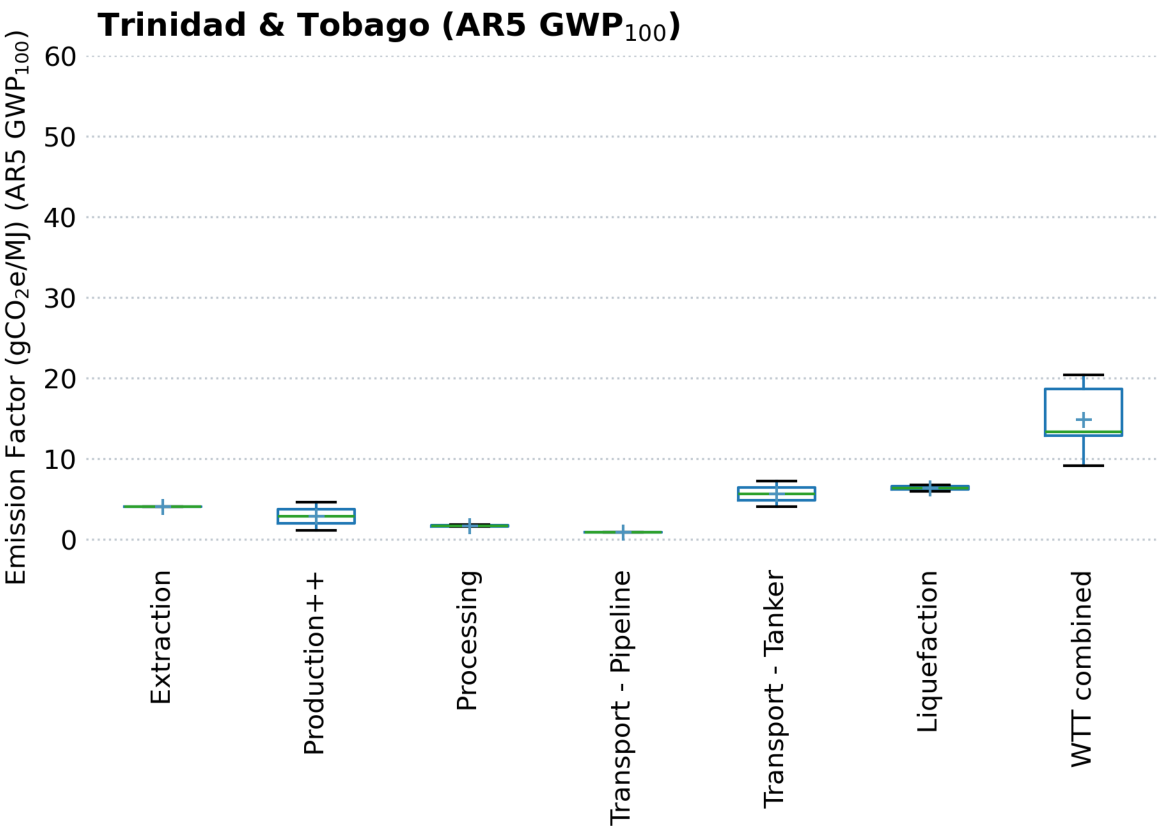
Table 18

Emission Factors Across LNG Supply Chain in T&T (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
T&T	Extraction	1	4.04	--	4.04	4.04	4.04	4.04	4.04
	Production++	2	2.84	2.43	1.12	1.98	2.84	3.69	4.55
	Processing	2	1.66	0.16	1.54	1.60	1.66	1.71	1.77
	Transport - Pipeline	1	0.85	--	0.85	0.85	0.85	0.85	0.85
	Transport - Tanker	2	5.62	2.26	4.02	4.82	5.62	6.42	7.22
	Liquefaction	2	6.34	0.57	5.94	6.14	6.34	6.54	6.74
	WTT combined	5	14.86	4.58	9.14	12.85	13.29	18.63	20.39

Figure 9

Emission Factors Across LNG Supply Chain in T&T (AR5, GWP_{100}, gCO_2e/MJ)



United Kingdom

The United Kingdom was the eighth largest LNG supplier to the EU (Table 12). The UK exports a minor amount of natural gas by pipelines, sourced from offshore production in the North Sea, but does not produce LNG domestically. Any LNG exports to the EU are re-exports of LNG that has been imported and stored and then shipped out again, as the UK often serves as a land-bridge for European imports (often through regasification).[70,71] The largest volumes of LNG imported by the UK came from the U.S.A., Qatar, and Peru. The UK did not import any volumes from Russia in 2023.[72] Consequently, there is minimal literature supporting UK LNG emission factors (n=6; Table 1). The UK has 113 natural gas producing fields, with 103 located offshore and the remaining 10 onshore.[73]

Out of the 14 emission factors identified for the UK, 8 were related to LNG and 6 to natural gas (Table 3). The UK was consistently identified in the emissions factor literature as a European LNG import destination for all countries under this project's scope. However, none of the literature specified the final destinations of LNG re-exported from the UK, only noting that it was distributed within the UK or to broader regions such as the EU, Northern Europe, or Central Europe. References classified as UK emissions factors did not identify the country of origin for the LNG, lacking details on the initial source of gas extraction, and rarely provided a breakdown of emissions by upstream and midstream stages.

AR6 GWP_{100} WtT emissions were the fourth highest in this project, at 18.32 gCO_2e/MJ; However, the UK had only a single emission factor available in AR6 GWP_{100} dataset (n=1; Table 6). Evaluating using the AR5 GWP_{100} framework decreased the mean WtT emissions to 14.05 gCO_2e/MJ and placed it as the second lowest in the assessment (n=9; Table 8).

Behind the U.S.A., the emission factor reported for UK production stages was the second highest in this assessment at 15.4 gCO_2e/MJ (Table 19). Although the UK is the world's 55th-largest producer of natural gas, it ranked 30th for its flaring volumes in 2023.[74,75] Since 2012, both the volume of gas flared and its flaring intensity have decreased by half, with the most significant reductions occurring since 2017. The UK has committed to the World Bank's Zero Routine Flaring by 2030 initiative and has made a commitment to reach a 0.25% industry methane intensity by 2025. The nation also participates in the Global Methane Initiative, the Global Methane Pledge, and the Climate and Clean Air Coalition.[76]

Table 19

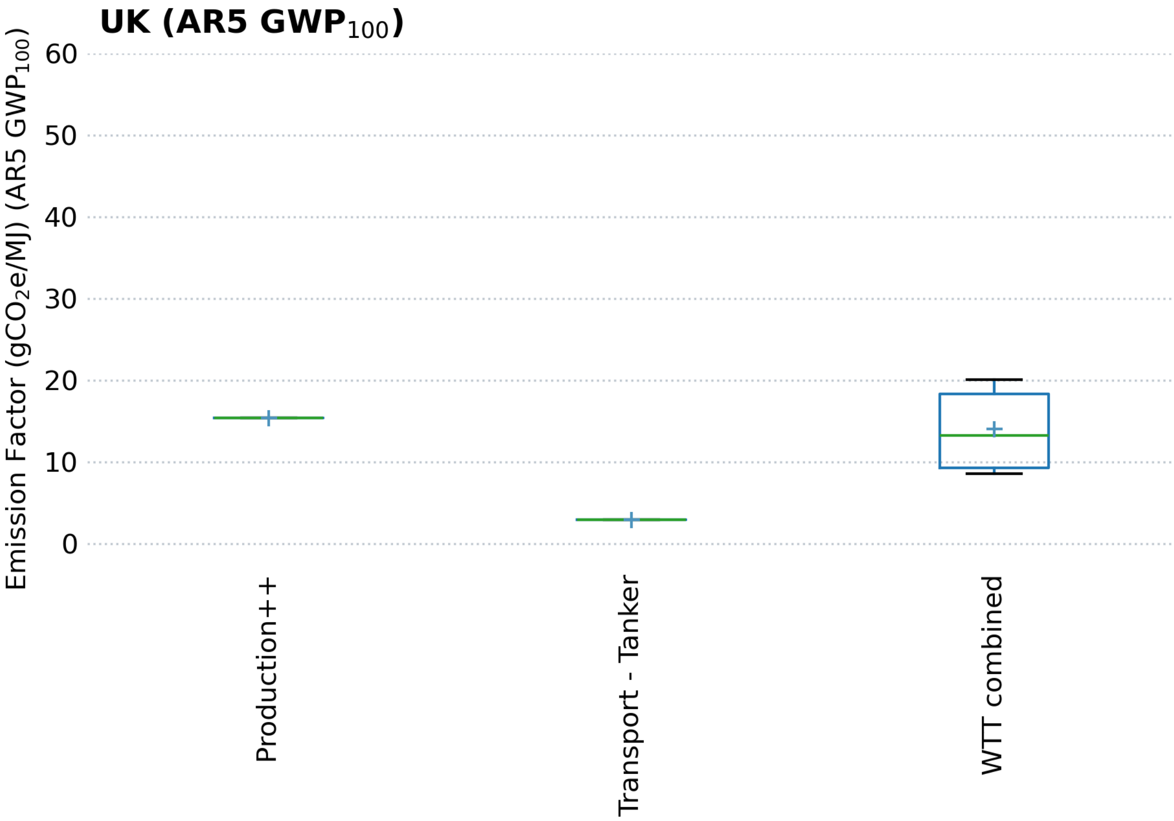
Emission Factors Across LNG Supply Chain in UK (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
UK	Production++	1	15.41	--	15.41	15.41	15.41	15.41	15.41
UK	Transport - Tanker	1	2.90	--	2.90	2.90	2.90	2.90	2.90
UK	WTT combined	9	14.05	4.75	8.57	9.30	13.26	18.35	20.04

[70] https://assets.publishing.service.gov.uk/media/5e7b4dfa86650c743803732a/Trends_in_trade_of_Liquefied_Natural_Gas_in_the_UK_and_Europe.pdf
[71] https://assets.publishing.service.gov.uk/media/642434bd3d885d000cdade0f/Supply_of_Liquefied_Natural_Gas_in_the_UK__2022.pdf
[72] https://ieefa.org/european-lng-tracker
[73] https://www.offshore-technology.com/data-insights/uk-natural-gas-production/
[74] https://www.offshore-technology.com/data-insights/uk-natural-gas-production/
[75] https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report
[76] https://flaringventingregulations.worldbank.org/united-kingdom

Figure 10

Emission Factors Across LNG Supply Chain in UK (AR5, GWP_{100}, gCO_2e/MJ)



United States of America

The United States remained the largest LNG supplier to Europe, representing nearly 50% of total imports in 2023.[77] In addition, the U.S.A. was the largest LNG supplier to the EU (Table 12), with the highest volumes of LNG received by Spain, France, and the Netherlands.[78] There are no transcontinental pipeline connections between the U.S.A. and Europe, therefore all exports to Europe must be via LNG carrier ships.

There were substantially more studies (n=32; Table 1) profiling LNG emissions in the U.S.A., particularly those with breakdowns of emissions across stages of the supply chain. This is likely due to robust environmental research and monitoring frameworks and initiatives, in addition to its extensive production and export activities. Of the 436 total emission factors assessed in the U.S.A., 300 were for LNG and 105 for natural gas (Table 3). The natural gas specific values focused on upstream emissions for regional, state, or basin-specific emissions, or evaluated the WtT stages for domestic gas use.

The WtT emissions for the U.S.A. were 27.40 gCO_2e/MJ (n=13; Table 6), highest in AR6 GWP100 rating. Under the AR5 GWP_{100} framework, the U.S.A. moves to be the third highest WtT emitter, yet its mean estimates are nearly unchanged (0.5% difference) at 27.25 gCO_2e/MJ (n=47; Table 8).

Many stages across the WtT assessment were substantially higher than those reported for other nations (Table 20), notably the values for the production stages (18.86 gCO_2e/MJ)[79] and transport by tanker (42.89 gCO_2e/MJ). Higher tanker emission factors are to be expected, due to boil-off gas, flaring and venting across the journey, given that its LNG must travel long distances compared to other nations in the project scope. Production values may be influenced by the greater number of peer-reviewed and government studies available for the U.S.A., which often offer more detailed observations and may account for a broader range of factors, including indirect emissions associated with the production and increased scrutiny of high-emitting sources.

The United States remains in the top nine countries responsible for over 75% global flaring volumes – along with Algeria, Nigeria, and Russia.[80] The U.S.A. has endorsed the World Bank's Zero Routine Flaring by 2030 initiative and participates in the Global Methane Initiative and the Climate and Clean Air Coalition. Rejoining the Paris Agreement in 2021, the U.S.A. has set a target to reduce net economy-wide GHG emissions by 50-52% below 2005 levels by 2030, specifically citing the reduction of methane emissions from gas wells and infrastructure as a priority action to meet these goals.[81]

In January 2024, the U.S.A. temporarily paused *pending* decisions on LNG exports to non-free trade agreement countries to allow the U.S. Department of Energy to update its analyses, including GHG life cycle assessments and considerations for communities surrounding LNG operations.[82] By July 2024, a federal judge ruling blocked the pause deeming it "without reason or logic". As a result, the pause is effectively lifted, pending further legal action or appeals from the U.S. administration.[83]

[77] https://www.eia.gov/todayinenergy/detail.php?id=61483

[78] https://ieefa.org/european-lng-tracker

[79] The GREET (2022) WtW Calculator's upstream (well-to-propeller) estimate is 19.31 gCO_2e/MJ, aligned with our Production++ stages, though lower than the WtT findings of this assessment

[80] https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report

[81] https://flaringventingregulations.worldbank.org/united-states-federal-offshore

[82] https://www.whitehouse.gov/briefing-room/statements-releases/2024/01/26/fact-sheet-biden-harris-administration-announces-temporary-pause-on-pending-approvals-of-liquefied-natural-gas-exports/

[83] https://www.reuters.com/business/energy/federal-judge-halts-us-governments-ban-lng-permits-2024-07-01/

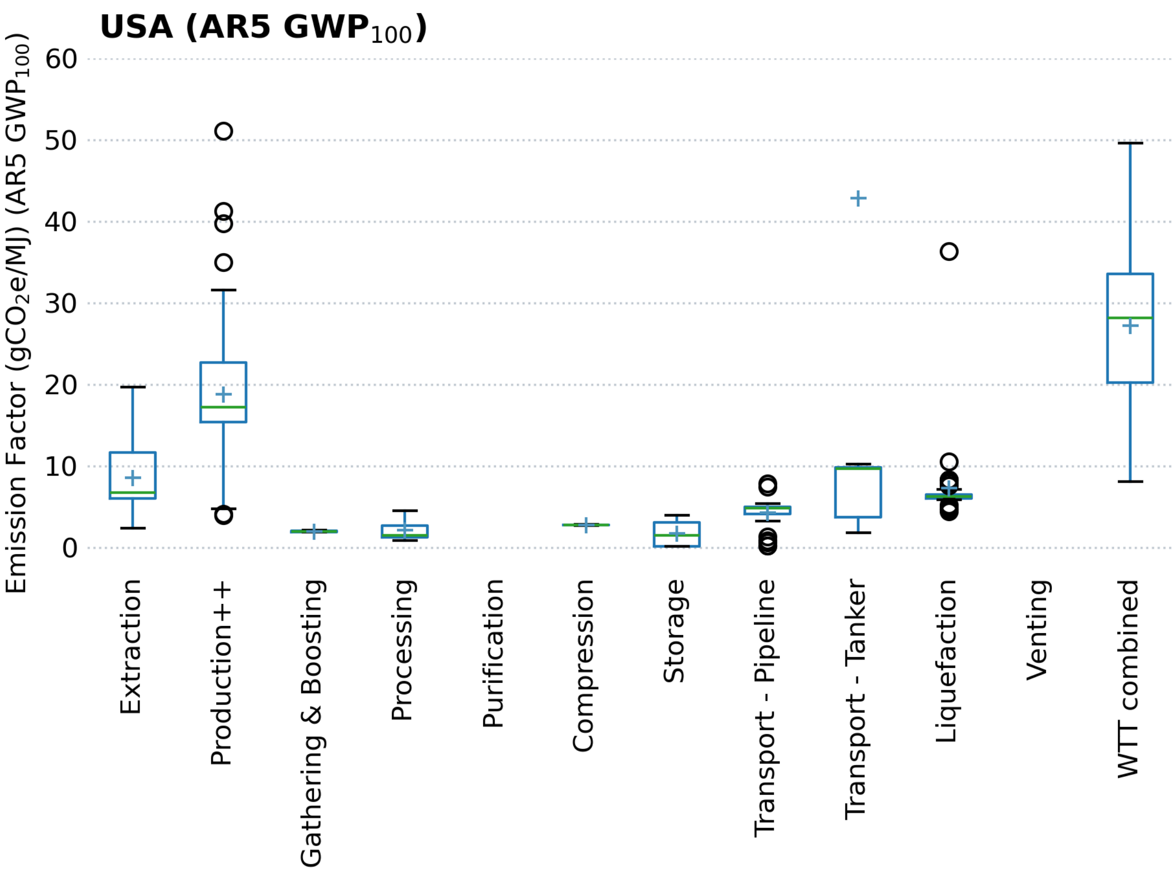
Table 20

Emission Factors Across LNG Supply Chain in U.S.A. (AR5, GWP_{100}, gCO_2e/MJ)

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
U.S.A.	Extraction	27	8.62	4.16	2.37	6.04	6.76	11.68	19.71
	Production++	81	18.86	7.89	3.97	15.41	17.23	22.73	51.11
	Gathering & Boosting	3	2.01	0.12	1.91	1.95	1.99	2.06	2.14
	Processing	31	2.16	1.14	0.90	1.28	1.56	2.72	4.52
	Compression	2	2.80	0.08	2.75	2.78	2.80	2.83	2.86
	Storage	4	1.80	1.92	0.17	0.18	1.52	3.14	3.97
	Transport - Pipeline	34	4.33	1.75	0.26	4.18	4.88	5.02	7.90
	Transport - Tanker	38	42.89	219.68	1.83	3.79	9.74	9.86	1,361.29
	Liquefaction	37	7.29	5.05	4.50	6.08	6.30	6.55	36.40
	WTT combined	47	27.25	9.99	8.10	20.23	28.18	33.60	49.66

Figure 11

Emission Factors Across LNG Supply Chain in U.S.A. (AR5, GWP_{100}, gCO_2e/MJ)



Pipelines

Emission estimates for pipelines are shown graphically in Figure 12 and in tabular form in Table 21. Estimates are presented for AR5 GWP_{100} and normalized per 1,000 km of pipeline distance. The U.S.A. had the largest sample available (n=32), though many estimates were derived from a single study, followed by Russia (n=7). Other than Qatar (n=3) most other countries only had one or two pipeline estimates, resulting in overall small sample sizes.

Results from a single study for Trinidad and Tobago show the highest mean emissions rate at 10.6 gCO_2e/MJ-1000km, followed by Nigeria (8.5 gCO_2e/MJ-1000km) and Norway (6.9 gCO_2e/MJ-1000km).

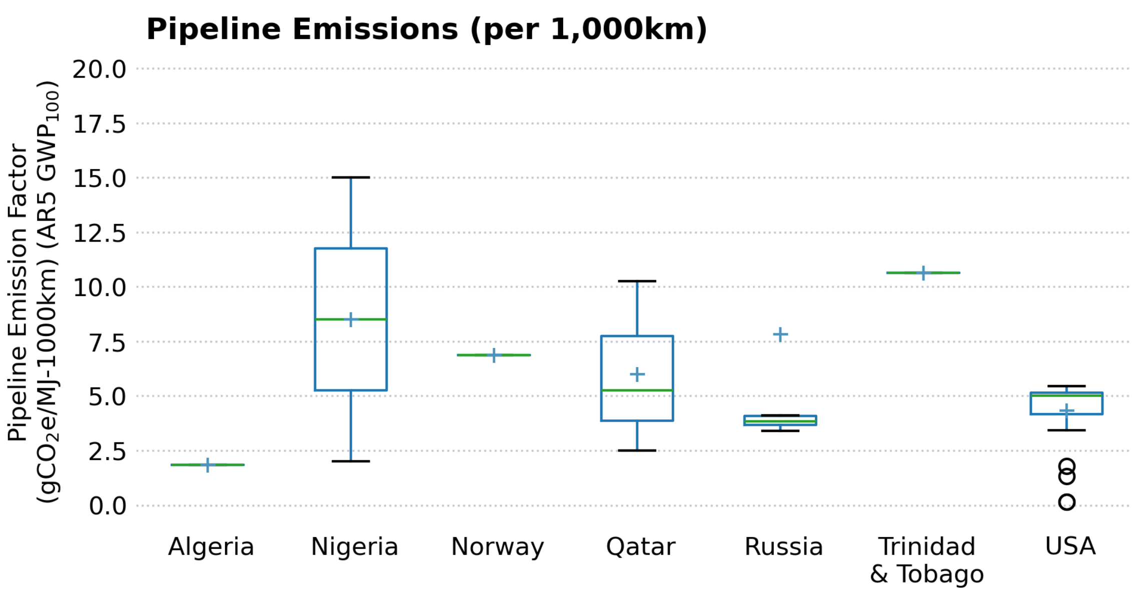
Table 21

Pipeline Emission Summary Statistics by Country (AR5, GWP_{100}, gCO_2e/MJ-1000 km)

country	count	mean	std	min	25%	50%	75%	max
Algeria	1	1.8	-	1.8	1.8	1.8	1.8	1.8
Nigeria	2	8.5	9.2	2.0	5.3	8.5	11.8	15.0
Norway	1	6.9	-	6.9	6.9	6.9	6.9	6.9
Qatar	3	6.0	3.9	2.5	3.9	5.3	7.8	10.3
Russia	7	7.8	10.7	3.4	3.7	3.8	4.1	32.0
Trinidad & Tobago	1	10.6	-	10.6	10.6	10.6	10.6	10.6
U.S.A.	32	4.3	1.5	0.2	4.2	5.0	5.2	5.4

Figure 12

Pipeline Emission Factors by Country (AR5, GWP_{100}, gCO_2e/MJ-1000 km)



IEA Upstream Methane Emissions

The literature seldom reports venting, flaring, or fugitive emissions as distinct stages of the WtT emissions, typically integrating them into broader categories or neglecting them altogether. Our literature review found only one value explicitly defining venting emissions for Nigeria (Table 14). Therefore, the IEA Global Methane Tracker[84] was utilized to offer a more detailed understanding of their role in the WtT emissions and address the gap in the literature, while also providing a top-down empirical view of emission rates.

[84] https://www.iea.org/data-and-statistics/data-product/methane-tracker-database

The IEA Global Methane Tracker combines data from publicly available sources and satellite measurements. Their estimates for natural gas fugitive and venting emissions from upstream production begin with U.S.A. emission intensities derived from the U.S. Greenhouse Gas Inventory.[85] These intensities are scaled for other countries based on data related to infrastructure age, operator types (i.e. independent, national, or international companies), flaring volumes and production volumes. Scaling also incorporates the strength of national regulation and oversight compiled by the World Bank[86] and the oil & gas sector specific policy efforts tracked by the IEA Policies Database.[87] Further refinements are based on satellite observations from Kayrros[88], which are currently limited to large emitting sources.

Methane emissions from IEA were reported in kilotons of CH_4 per year (kt CH_4/yr). For our analysis, these emissions were converted to gCO_2e/MJ using the AR6 report GWP-weighted emission intensity (GWP_{100}). The total production volumes of natural gas for 2023 were collected and converted from their original units to terajoules (TJ) to align with the energy content measurements used in our assessments.[89]

The U.S.A., Algeria, and Russia exhibited the highest WtT emissions in our assessment (Table 6; AR6 GWP_{100}). These nations also stand in the top nine countries responsible for over 75% global flaring volumes.[90] Nigeria also ranks in the top nine for flaring and has the fifth highest WtT emissions. The UK, with only one emission factor reported (Table 6; AR6 GWP_{100}), ranks fourth in WtT emissions but is not among the top nine countries for flaring.

The IEA data aligns with each of these results, also identifying these countries as having the highest levels of fugitive and vented methane emissions (Figure 13). Most of these emissions were observed from onshore gas production rather than offshore. Vented emissions had a higher emission intensity than fugitive emissions for across the countries and sources.

Table 22

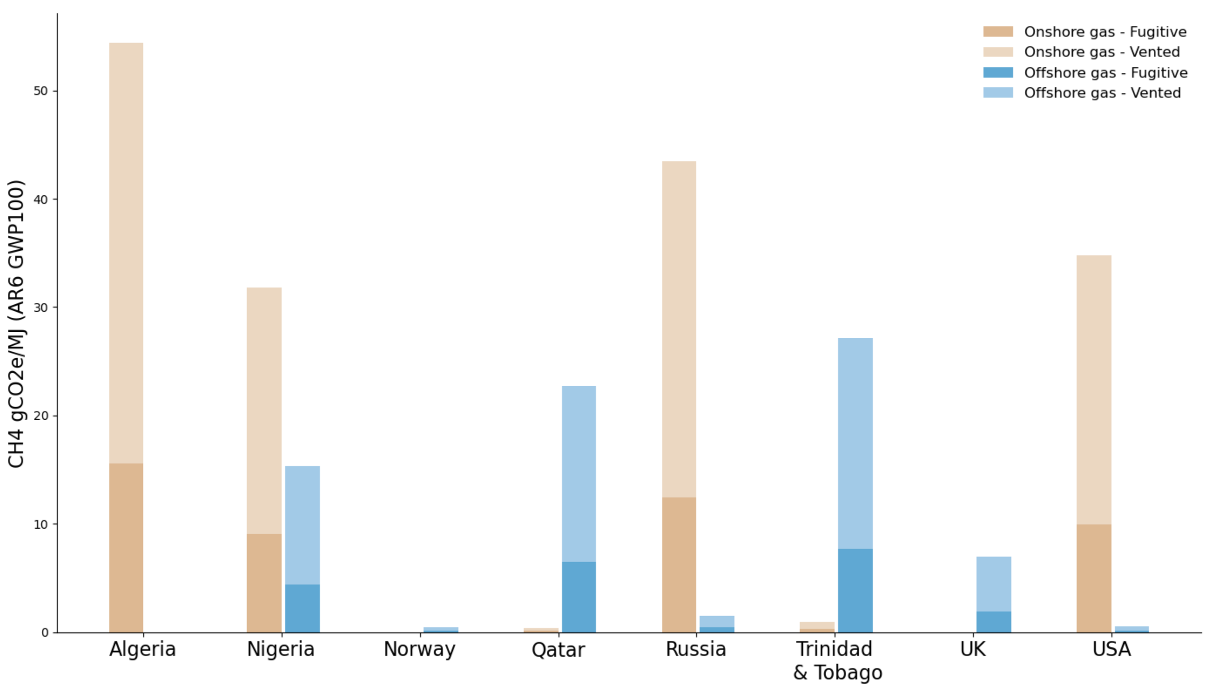
IEA Methane Tracker 2023 Measurements, Onshore and Offshore Upstream Emissions
(AR6, GWP_{100}, gCO_2e/MJ)

Country	Segment	Sub-segment	CH_4 (gCO_2e/MJ)	kt CH_4/yr	2023 Production (TJ)
Algeria	Offshore gas	Fugitive	--	--	3,654,000
		Vented	--	--	
	Onshore gas	Fugitive	15.58	191	
		Vented	38.82	476	
Nigeria	Offshore gas	Fugitive	4.36	23	1,573,200
		Vented	10.99	58	
	Onshore gas	Fugitive	9.09	48	
		Vented	22.73	120	
Norway	Offshore gas	Fugitive	0.14	2	4,197,600
		Vented	0.28	4	
	Onshore gas	Fugitive	--	--	
		Vented	--	--	
Qatar	Offshore gas	Fugitive	6.49	142	6,516,000
		Vented	16.24	355	
	Onshore gas	Fugitive	0.14	3	

85 https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
86 https://www.worldbank.org/en/publication/worldwide-governance-indicators
87 https://www.iea.org/policies
88 https://methanewatch.kayrros.org/
89 https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser
90 https://www.worldbank.org/en/programs/gasflaringreduction/publication/2024-global-gas-flaring-tracker-report

Country	Segment	Sub-segment	CH_4 (gCO_2e/MJ)	kt CH_4/yr	2023 Production (TJ)
		Vented	0.27	6	
Russia	Offshore gas	Fugitive	0.44	31	21,110,400
		Vented	1.09	77	
	Onshore gas	Fugitive	12.44	881	
		Vented	31.04	2199	
Trinidad & Tobago	Offshore gas	Fugitive	7.73	25	964,800
		Vented	19.46	63	
	Onshore gas	Fugitive	0.31	1	
		Vented	0.62	2	
United Kingdom	Offshore gas	Fugitive	1.92	8	1,242,000
		Vented	5.04	21	
	Onshore gas	Fugitive	--	--	
		Vented	--	--	
United States	Offshore gas	Fugitive	0.16	20	37,270,800
		Vented	0.41	51	
	Onshore gas	Fugitive	9.95	1245	
		Vented	24.84	3107	

Figure 13
IEA Methane Tracker, Onshore and Offshore Emissions from Upstream Production
(AR6, GWP_{100}, gCO_2e/MJ)



Conclusions

Norway had the lowest WtT emissions at 12.57 gCO_2e/MJ (Table 8; AR5 GWP_{100}), which may be attributed to stringent flaring regulations and rigorous oversight, and relatively short transport distances to the EU. In contrast, Algeria, U.S.A., Russia, and Nigeria exhibited the highest upstream LNG carbon intensities under the assessment (AR5 GWP_{100}), with Russia leading at 27.96 gCO_2e/MJ; aligning with their positions as top contributors to global flaring volumes. Notably, Russia has come under scrutiny for its reporting methods underrepresenting emissions. This assessment includes independent sources that address data gaps with satellite observations and proxy values.[91]

Taking into account the relative country contributions to European imports, the weighted mean WtT carbon intensity for the AR6, AR5, and AR4 GWP_{100} estimates are:

AR6 GWP_{100}: 21.31 gCO_2e/MJ
AR5 GWP_{100}: 24.40 gCO_2e/MJ
AR4 GWP_{100}: 18.51 gCO_2e/MJ

We identified only a handful of studies that provided estimates natively in AR6 as those values were recently released in 2023. The sample size for WtT GWP100 estimates is considerably larger for AR5 (n=124) than for AR6 (n=40) and AR4 (n=57), and therefore provides the most statistically robust sample for estimating the WtT carbon intensity of LNG imports.

Given the substantial variation in emissions across countries, continued research is essential to accurately assess and address disparities, particularly for upstream and midstream processes such as flaring, venting, and fugitive emissions, in addition to the energy-intensive liquefaction and transportation stages. Standardizing reporting is essential to ensure accurate assessments of LNG and other energy sources and to allow for updates as scientific knowledge advances, which will help in aligning with climate targets and advancing decarbonization efforts.

Correction

This version of the document corrects an error in the August 20, 2024 version where the weighting factors applied to compute the weighted mean WtT carbon intensity based on country-specific import volumes were mis-assigned. The correctly weighted values are

AR6 GWP100: 21.31 gCO2e/MJ, AR5 GWP100: 24.40 gCO2e/MJ, AR4 GWP100: 18.51 gCO2e/MJ,
AR6 GWP20: 34.87 gCO2e/MJ, AR5 GWP20: 40.59 gCO2e/MJ, AR4 GWP20: 31.96 gCO2e/MJ.

[91] Due to limited data, reports by other nations and organizations often substitute data from the U.S. industry as a proxy to represent Russian gas production and transport - https://www.eenews.net/articles/does-a-crackdown-on-russian-gas-help-or-hurt-the-climate/

Appendix

Algeria

Algeria - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Algeria	Production++	1	3.75	--	3.75	3.75	3.75	3.75	3.75
Algeria	WTT combined	3	19.02	2.41	16.90	17.71	18.52	20.08	21.64

Algeria - AR6 GWP_{20}

country	process	count	mean	std	min	25%	50%	75%	max
Algeria	Production++	1	7.1	--	7.1	7.1	7.1	7.1	7.05
Algeria	WTT combined	1	28.7	--	28.7	28.7	28.7	28.7	28.72

Algeria - AR5 GWP_{20}

country	process	count	mean	std	min	25%	50%	75%	max
Algeria	Extraction	1	40.3	--	40.3	40.3	40.3	40.3	40.3
Algeria	Production++	2	19.8	18.1	7.0	13.4	19.8	26.2	32.6
Algeria	Gathering & Boosting	1	20.6	--	20.6	20.6	20.6	20.6	20.6
Algeria	Processing	1	6.9	--	6.9	6.9	6.9	6.9	6.9
Algeria	Transport - Pipeline	2	12.8	14.5	2.5	7.6	12.8	17.9	23.1
Algeria	Transport - Tanker	2	10.9	14.1	0.9	5.9	10.9	15.9	20.8
Algeria	Liquefaction	2	9.6	1.8	8.3	8.9	9.6	10.2	10.8
Algeria	WTT combined	2	36.8	11.0	29.0	32.9	36.8	40.6	44.5

Algeria - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	25%	50%	75%	Max
Algeria	Production++	2	6.43	0.32	6.20	6.31	6.43	6.54	6.65
Algeria	Purification	1	2.90	--	2.90	2.90	2.90	2.90	2.9
Algeria	Transport - Pipeline	1	1.20	--	1.20	1.20	1.20	1.20	1.2
Algeria	Transport - Tanker	1	1.40	--	1.40	1.40	1.40	1.40	1.4
Algeria	Liquefaction	1	4.90	--	4.90	4.90	4.90	4.90	4.9
Algeria	WTT combined	3	18.44	2.72	16.74	16.87	17.00	19.29	21.58

Algeria - AR4 GWP_{20}

country	process	count	mean	std	min	25%	50%	75%	max
Algeria	Production++	1	7.1	--	7.1	7.1	7.1	7.1	7.1
Algeria	WTT combined	1	26.6	--	26.6	26.6	26.6	26.6	26.6

Nigeria

Nigeria - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Nigeria	Extraction	1	0.03	--	0.03	0.03	0.03	0.03	0.03
Nigeria	Flaring	1	1.69	--	1.69	1.69	1.69	1.69	1.69
Nigeria	Gathering & Boosting	1	0.00	--	0.00	0.00	0.00	0.00	0.00
Nigeria	Processing	1	2.78	--	2.78	2.78	2.78	2.78	2.78
Nigeria	Transport - Tanker	1	2.77	--	2.77	2.77	2.77	2.77	2.77
Nigeria	Liquefaction	1	6.15	--	6.15	6.15	6.15	6.15	6.15
Nigeria	WTT combined	1	14.81	--	14.81	14.81	14.81	14.81	14.81

Nigeria - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Nigeria	Extraction	1	0.0	--	0.0	0.0	0.0	0.0	0.03
Nigeria	Flaring	1	2.1	--	2.1	2.1	2.1	2.1	2.05
Nigeria	Gathering & Boosting	1	0.0	--	0.0	0.0	0.0	0.0	0
Nigeria	Processing	1	4.7	--	4.7	4.7	4.7	4.7	4.72
Nigeria	Transport - Tanker	1	2.8	--	2.8	2.8	2.8	2.8	2.78
Nigeria	Liquefaction	1	6.7	--	6.7	6.7	6.7	6.7	6.68

Nigeria - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Nigeria	Extraction	1	0.0	--	0.0	0.0	0.0	0.0	0.0
Nigeria	Production++	1	23.0	--	23.0	23.0	23.0	23.0	23.0
Nigeria	Flaring	1	2.1	--	2.1	2.1	2.1	2.1	2.1
Nigeria	Gathering & Boosting	1	0.0	--	0.0	0.0	0.0	0.0	0.0
Nigeria	Processing	1	4.8	--	4.8	4.8	4.8	4.8	4.8
Nigeria	Transport - Pipeline	1	0.4	--	0.4	0.4	0.4	0.4	0.4
Nigeria	Transport - Tanker	2	2.4	0.5	2.1	2.3	2.4	2.6	2.8
Nigeria	Liquefaction	2	7.9	1.8	6.7	7.3	7.9	8.6	9.2
Nigeria	WTT combined	1	34.9	--	34.9	34.9	34.9	34.9	34.9

Nigeria - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Nigeria	Extraction	1	0.03	--	0.03	0.03	0.03	0.03	0.03
Nigeria	Flaring	1	1.66	--	1.66	1.66	1.66	1.66	1.66
Nigeria	Gathering & Boosting	1	0.00	--	0.00	0.00	0.00	0.00	0.00
Nigeria	Processing	1	2.60	--	2.60	2.60	2.60	2.60	2.60
Nigeria	Transport - Tanker	1	2.77	--	2.77	2.77	2.77	2.77	2.77
Nigeria	Liquefaction	1	6.10	--	6.10	6.10	6.10	6.10	6.1
Nigeria	WTT combined	1	13.77	--	13.77	13.77	13.77	13.77	13.77

Nigeria - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Nigeria	Extraction	1	0.0	--	0.0	0.0	0.0	0.0	0.0
Nigeria	Flaring	1	2.0	--	2.0	2.0	2.0	2.0	2.0
Nigeria	Gathering & Boosting	1	0.0	--	0.0	0.0	0.0	0.0	0.0
Nigeria	Processing	1	4.3	--	4.3	4.3	4.3	4.3	4.3
Nigeria	Transport - Tanker	1	2.8	--	2.8	2.8	2.8	2.8	2.8
Nigeria	Liquefaction	1	6.6	--	6.6	6.6	6.6	6.6	6.6

Norway

Norway - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Norway	Production++	3	3.96	2.44	1.61	2.70	3.80	5.14	6.48
Norway	Transport - Tanker	1	2.90	--	2.90	2.90	2.90	2.90	2.90
Norway	WTT combined	9	12.45	8.77	1.61	6.71	9.17	16.60	28.82

Norway - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Norway	Production++	2	3.5	0.4	3.2	3.4	3.5	3.7	3.81
Norway	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
Norway	WTT combined	8	20.0	15.7	1.7	6.8	18.5	28.5	44.73

Norway - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Norway	Production++	2	3.5	0.4	3.2	3.3	3.5	3.7	3.8
Norway	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
Norway	WTT combined	8	20.2	15.9	1.7	6.8	18.7	28.8	45.1

Norway - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Norway	Extraction	1	1.39	--	1.39	1.39	1.39	1.39	1.39
Norway	Production++	5	3.42	1.38	1.30	3.12	3.80	3.80	5.06
Norway	Transport - Pipeline	1	0.30	--	0.30	0.30	0.30	0.30	0.3
Norway	Transport - Tanker	4	7.39	9.77	1.75	2.61	2.90	7.68	22.02
Norway	Liquefaction	1	5.42	--	5.42	5.42	5.42	5.42	5.42
Norway	WTT combined	15	10.36	8.72	1.60	4.39	6.70	14.82	28.83

Norway - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Norway	Production++	2	3.5	0.4	3.3	3.4	3.5	3.7	3.8
Norway	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
Norway	WTT combined	8	18.7	14.3	1.7	6.8	17.3	26.2	41.7

Qatar

Qatar - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Qatar	Production++	3	6.54	4.52	1.40	4.85	8.30	9.11	9.92
Qatar	WTT combined	4	13.88	2.35	11.03	12.48	14.10	15.51	16.28

Qatar - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Qatar	Production++	1	2.5	--	2.5	2.5	2.5	2.5	2.52
Qatar	WTT combined	3	19.4	4.9	14.6	16.9	19.3	21.8	24.4

Qatar - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Qatar	Production++	2	8.1	7.9	2.5	5.3	8.1	10.8	13.6
Qatar	Transport - Pipeline	1	0.2	--	0.2	0.2	0.2	0.2	0.2
Qatar	Transport - Tanker	1	3.0	--	3.0	3.0	3.0	3.0	3.0
Qatar	Liquefaction	1	10.1	--	10.1	10.1	10.1	10.1	10.1
Qatar	WTT combined	4	21.5	5.5	14.7	18.2	22.0	25.2	27.1

Qatar - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Qatar	Production++	3	3.44	2.27	1.90	2.13	2.36	4.20	6.05
Qatar	Purification	1	2.90	--	2.90	2.90	2.90	2.90	2.9
Qatar	Transport - Pipeline	1	0.20	--	0.20	0.20	0.20	0.20	0.2
Qatar	Transport - Tanker	1	3.70	--	3.70	3.70	3.70	3.70	3.7
Qatar	Liquefaction	1	5.90	--	5.90	5.90	5.90	5.90	5.9
Qatar	WTT combined	6	12.76	3.43	7.00	11.19	13.78	15.39	15.79

Qatar - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Qatar	Production++	1	2.5		2.5	2.5	2.5	2.5	2.5
Qatar	WTT combined	3	18.4	4.5	13.9	16.2	18.5	20.6	22.8

Russia

Russia - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Russia	Production++	4	2.46	0.77	1.81	2.05	2.22	2.63	3.56
Russia	Processing	2	0.90	0.29	0.69	0.79	0.90	1.00	1.10
Russia	Storage	1	0.21	--	0.21	0.21	0.21	0.21	0.21
Russia	Transport - Pipeline	1	13.16	--	13.16	13.16	13.16	13.16	13.16
Russia	Liquefaction	1	4.92	--	4.92	4.92	4.92	4.92	4.92
Russia	"Other"	1	0.18	--	0.18	0.18	0.18	0.18	0.18
Russia	WTT combined	6	18.75	9.75	6.47	10.99	20.21	24.85	31.31

Russia - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Russia	Production++	2	3.3	0.9	2.7	3.0	3.3	3.7	3.97
Russia	Processing	1	1.1	--	1.1	1.1	1.1	1.1	1.1
Russia	Storage	1	0.4	--	0.4	0.4	0.4	0.4	0.36
Russia	Transport - Pipeline	1	21.2	--	21.2	21.2	21.2	21.2	21.2
Russia	"Other"	1	0.2	--	0.2	0.2	0.2	0.2	0.2
Russia	WTT combined	3	23.5	14.3	8.4	17.0	25.6	31.1	36.67

Russia - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Russia	Extraction	2	37.6	0.6	37.2	37.4	37.6	37.9	38.1
Russia	Production++	2	3.4	0.9	2.7	3.0	3.4	3.7	4.0
Russia	Gathering & Boosting	2	19.3	0.2	19.2	19.2	19.3	19.4	19.4
Russia	Processing	3	4.7	3.1	1.1	3.7	6.4	6.5	6.7
Russia	Storage	1	0.4	--	0.4	0.4	0.4	0.4	0.4
Russia	Transport - Pipeline	3	87.9	60.2	21.4	62.5	103.6	121.1	138.6
Russia	"Other"	1	0.2	--	0.2	0.2	0.2	0.2	0.2
Russia	WTT combined	4	52.1	57.8	8.4	21.5	31.4	62.0	137.0

Russia - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Russia	Production++	6	2.24	0.91	1.40	1.52	1.94	2.90	3.55
Russia	Processing	1	1.09	--	1.09	1.09	1.09	1.09	1.09
Russia	Storage	1	0.21	--	0.21	0.21	0.21	0.21	0.21
Russia	Transport - Pipeline	4	6.66	4.79	1.20	3.90	6.50	9.26	12.43
Russia	"Other"	1	0.18	--	0.18	0.18	0.18	0.18	0.18
Russia	WTT combined	9	15.81	9.68	2.50	8.18	16.19	23.10	31.06

Russia - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
Russia	Production++	2	3.2	0.9	2.6	2.9	3.2	3.6	3.9

Russia	Processing	1	1.1	--	1.1	1.1	1.1	1.1	1.1
Russia	Storage	1	0.3	--	0.3	0.3	0.3	0.3	0.3
Russia	Transport - Pipeline	1	19.6	--	19.6	19.6	19.6	19.6	19.6
Russia	"Other"	1	0.2	--	0.2	0.2	0.2	0.2	0.2
Russia	WTT combined	3	22.0	13.2	8.0	15.9	23.9	29.0	34.2

Trinidad and Tobago

Trinidad and Tobago - AR6 GWP100

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
T&T	Production++	2	5.92	5.15	2.28	4.10	5.92	7.75	9.57
	WTT combined	3	12.02	2.39	9.26	11.33	13.40	13.40	13.41

Trinidad and Tobago - AR6 GWP20

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
T&T	Production++	2	7.3	3.2	5.0	6.2	7.3	8.4	9.57
	WTT combined	2	24.4	10.7	16.8	20.6	24.4	28.1	31.93

Trinidad and Tobago - AR5 GWP20

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
T&T	Production++	1	5.0	--	5.0	5.0	5.0	5.0	5.0
	WTT combined	2	24.6	10.9	16.9	20.7	24.6	28.4	32.3

Trinidad and Tobago - AR4 GWP100

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
T&T	Extraction	2	0.28	0.00	0.28	0.28	0.28	0.28	0.28
	Production++	1	4.81	--	4.81	4.81	4.81	4.81	4.81
	Processing	2	3.09	0.00	3.09	3.09	3.09	3.09	3.09
	Liquefaction	2	8.11	0.00	8.11	8.11	8.11	8.11	8.11
	WTT combined	3	13.31	4.48	8.94	11.02	13.10	15.50	17.9

Trinidad and Tobago - AR4 GWP20

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
T&T	Production++	1	5.1	--	5.1	5.1	5.1	5.1	5.1
	WTT combined	2	22.7	9.4	16.1	19.4	22.7	26.1	29.4

United Kingdom

United Kingdom - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
UK	Production++	1	15.42	--	15.42	15.42	15.42	15.42	15.42
	Transport - Tanker	1	2.90	--	2.90	2.90	2.90	2.90	2.90
	WTT combined	1	18.32	--	18.32	18.32	18.32	18.32	18.32

United Kingdom - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
UK	Production++	1	15.7	--	15.7	15.7	15.7	15.7	15.7
	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
	WTT combined	1	18.6	--	18.6	18.6	18.6	18.6	18.6

United Kingdom - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
UK	Production++	1	15.7	--	15.7	15.7	15.7	15.7	15.7
	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
	WTT combined	1	18.6	--	18.6	18.6	18.6	18.6	18.6

United Kingdom - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
UK	Production++	1	15.40	--	15.40	15.40	15.40	15.40	15.4
	Transport - Tanker	1	2.90	--	2.90	2.90	2.90	2.90	2.9
	WTT combined	2	9.90	11.88	1.50	5.70	9.90	14.10	18.3

United Kingdom - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
UK	Production++	1	15.6	--	15.6	15.6	15.6	15.6	15.6
	Transport - Tanker	1	2.9	--	2.9	2.9	2.9	2.9	2.9
	WTT combined	1	18.5	--	18.5	18.5	18.5	18.5	18.5

United States of America

United States of America - AR6 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
U.S.A.	Extraction	4	4.79	3.18	2.37	2.45	3.83	6.18	9.14
	Production++	75	19.97	8.02	2.32	15.99	18.08	23.97	53.75
	Gathering & Boosting	3	2.06	0.19	1.91	1.95	1.99	2.13	2.28
	Processing	4	3.26	0.59	2.74	2.97	3.11	3.40	4.10
	Compression	1	2.86	--	2.86	2.86	2.86	2.86	2.86
	Storage	3	2.25	1.85	0.17	1.52	2.87	3.30	3.72
	Transport - Pipeline	5	2.29	2.37	0.26	0.27	1.49	3.71	5.70
	Transport - Tanker	7	199.92	522.09	1.86	1.95	1.97	3.90	1,383.89
	Liquefaction	5	12.55	14.44	4.99	5.39	6.40	7.67	38.31
	WTT combined	13	27.40	11.60	12.89	21.50	24.59	28.56	51.81

United States of America - AR6 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
U.S.A.	Extraction	4	7.3	2.7	4.9	5.1	7.3	9.5	9.82
	Production++	94	69.2	49.0	4.9	35.2	49.4	79.9	155.81
	Gathering & Boosting	3	4.1	1.9	3.0	3.0	3.1	4.7	6.28
	Processing	4	4.5	0.6	4.0	4.1	4.5	4.9	5.19
	Compression	2	4.0	0.1	3.9	3.9	4.0	4.0	4.03
	Storage	4	3.0	3.9	0.3	0.3	1.7	4.4	8.54
	Transport - Pipeline	5	4.5	5.2	0.6	0.6	3.8	4.1	13.29
	Transport - Tanker	7	295.8	771.5	1.9	2.7	5.4	6.4	2045.47
	Liquefaction	7	19.4	33.0	4.9	6.4	7.8	8.1	94.2
	WTT combined	8	52.7	38.5	25.8	28.1	35.7	58.2	115

United States of America - AR5 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
U.S.A.	Extraction	6	7.8	2.2	4.9	6.0	8.8	9.3	10.0
	Production++	76	45.0	20.0	4.8	33.5	39.8	56.2	133.4
	Gathering & Boosting	5	10.5	8.9	3.0	3.1	6.4	20.0	20.3
	Processing	6	5.3	1.3	4.0	4.3	5.0	6.5	6.9
	Compression	2	4.0	0.1	3.9	3.9	4.0	4.0	4.0
	Storage	4	3.1	3.9	0.3	0.3	1.7	4.4	8.7
	Transport - Pipeline	8	9.0	9.8	0.6	2.0	4.0	15.9	23.6
	Transport - Tanker	12	178.1	594.0	1.9	2.4	5.5	8.9	2,064.3
	Liquefaction	11	17.4	26.3	4.9	7.8	8.3	14.7	95.8
	WTT combined	12	48.2	36.4	14.0	27.2	36.2	51.0	116.4

United States of America - AR4 GWP_{100}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max

U.S.A.	Extraction	4	4.78	3.17	2.36	2.44	3.82	6.17	9.11
	Production++	75	17.93	6.90	3.55	14.45	16.20	21.18	46.7
	Gathering & Boosting	3	1.94	0.04	1.91	1.92	1.92	1.96	1.99
	Processing	4	3.22	0.49	2.74	2.97	3.11	3.35	3.9
	Purification	1	3.00	--	3.00	3.00	3.00	3.00	3.00
	Compression	2	2.80	0.08	2.75	2.78	2.80	2.83	2.86
	Storage	4	1.73	1.83	0.17	0.18	1.52	3.08	3.72
	Transport - Pipeline	6	1.93	1.96	0.26	0.48	1.18	3.10	5.00
	Transport - Tanker	8	167.77	467.04	1.64	1.81	2.12	4.15	1323.63
	Liquefaction	8	9.33	9.73	4.80	4.94	5.64	7.72	33.22
	WTT combined	18	23.29	9.54	12.18	18.19	20.21	25.24	46.09

United States of America - AR4 GWP_{20}

Country	Process	Count	Mean	Std	Min	0.25	0.50	0.75	Max
U.S.A.	Extraction	4	7.1	2.4	4.9	5.1	7.0	9.1	9.4
	Production++	74	39.5	17.2	4.9	29.6	35.1	48.9	115.7
	Gathering & Boosting	3	3.8	1.4	3.0	3.0	3.1	4.3	5.5
	Processing	4	4.4	0.4	4.0	4.1	4.3	4.6	5.0
	Compression	2	4.0	0.1	3.9	3.9	4.0	4.0	4.0
	Storage	4	2.8	3.5	0.3	0.3	1.7	4.2	7.7
	Transport - Pipeline	5	4.1	4.6	0.6	0.6	3.6	3.8	11.8
	Transport - Tanker	7	276.8	721.8	1.9	2.6	4.7	6.1	1,913.7
	Liquefaction	7	17.7	28.9	4.9	6.3	7.6	7.7	83.1
	WTT combined	8	47.8	33.6	24.7	26.3	32.6	52.9	102.1

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