LNG Carbon footprint study – A comparison of GHG emissions of natural gas produced in Denmark and imported LNG and Coal

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Abstract

This study investigated what type of fuel has the lowest carbon footprint as a transition fuel between conventional energy carriers and renewables. In the Danish context, domestically produced natural gas has a lower carbon footprint than imported LNG (-12%) or Coal (-40%) over the entire value chain. Analysis was based on multiple data sources, and those that are most consistent with satellite observations were selected for final presentation. Outlier data sets were scrutinized further in order to understand the reasons for any differences. Also, an assessment was made of the GHG impact of new facilities coming on stream in the Danish offshore sector, that increase oil and gas production and thereby lower emissions per energy unit produced.

Keywords: Carbon footprint; Natural Gas; LNG; Coal; Satellite;

1. Background

The use of imported Hydrocarbons is becoming an issue in Danish politics, something that requires decision makers to be well informed of the pros and cons of the various energy carriers.

Geopolitical tensions and political decisions have caused a reduction in the use of piped Russian gas and of nuclear power in the European Union, leading to an increase of LNG and coal imports from outside the EU to address the shortfall. This has put a spotlight on locally produced natural gas as an alternative to these imported energy carriers, in particular of natural gas produced from the recently re-instated Tyra Centre in the Danish offshore sector. In the Danish context natural gas is considered a transition fuel between traditional fuels and renewables, while coal is considered a traditional fuel that is on track to be phased out.

Multiple factors are being considered in the process of prioritizing and selecting the preferred energy carriers for the energy transition in Denmark, foremost among these are energy security, environmental impact and cost.

The focus of the analysis in this study is a comparison of the environmental impact of the various energy carriers and more specifically an assessment of domestically produced natural gas (NG) against imported Liquified Natural Gas (LNG) and imported Coal, in terms of Greenhouse Gas (GHG) emissions, and Global Warming Potential (GWP).

Concerns in the Danish context are:

- Is the net contribution of Danish natural gas to global warming higher or lower than that of imported fuels?
- What aspects of the total value chain have the highest GWP impact for each fuel?
- Which GHG emissions are the main contributors to GWP?
- How sensitive is the analysis to variables such as the distance between production and consumption sites, or redevelopment of aging production facilities?

The study aims to provide clarity in addressing these GWP aspects of domestically produced natural gas and imported alternative energy carriers, in the knowledge that domestic gas already meets the energy security and economics requirements that also play a role in decision making.

2. Introduction

In September 2020, the European Commission presented a plan to reduce EU greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. The plan aims to reform the EU Emissions Trading System (EU-ETS) to make carbon emissions more costly, to put in place an EU-wide just transition mechanism to abate the social costs of phasing out coal in those areas reliant on it for power generation, and to update National Energy and Climate Plans to show how coal can be phased out more rapidly.

It is therefore important to have an objective and reliable assessment of the alternatives to coal for electrical power generation and heating (particularly relevant for Denmark), and by how much these alternatives can help to achieve the European emission reduction targets. In this study the alternatives considered are imported LNG and domestic natural gas.

For consistency purposes the study compares the full value chain emissions for delivery at the same geographical destination, which was chosen to be the Netherlands, which is host to the EU's main port, Rotterdam, and which receives gas from Danish Offshore fields via a gas export pipeline, the Northern Offshore Gas Transport system (NOGAT), that connects the Danish Tyra Centre to Den Helder in the Netherlands.

The value chain components included in the study are (Fig. 1):

- Mining, processing, transportation (by rail and ship) for Coal
- Production & processing, liquefaction, transportation and re-gasification for Liquefied Natural Gas
- Production and transport by pipeline for Natural Gas produced in Denmark.

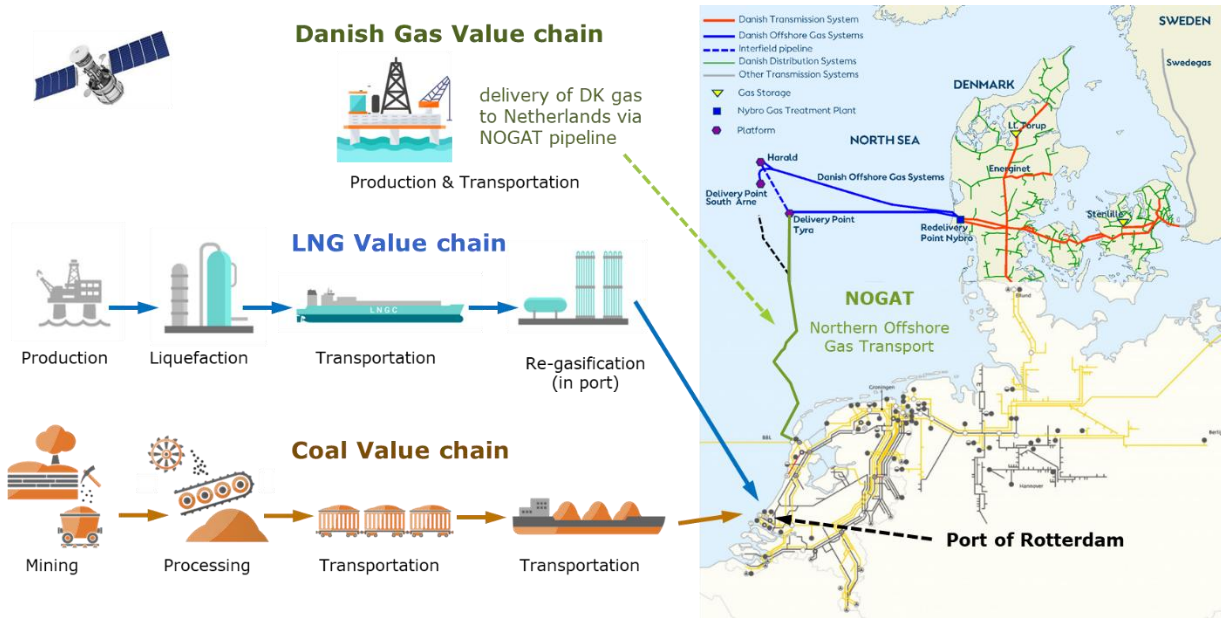


Figure 1: Overview of value chain components analysed in this study for Natural Gas produced in Denmark, Natural Gas imported as LNG into the European Union, and Coal imported into the EU.

3. Scope of investigation

3.1 Emissions of Danish Natural Gas: CO_2, CH_4 and N_2O

Operators of Oil and Gas production in the Danish offshore sector extensively report emissions of the three main GHGs, including NO_X's. DK operator reported emissions are higher than those estimated by IPCC, EPA, EDGAR and were used in the final comparison report (see Section 5.1). The proportion of N_2O in reported NO_X emissions was assessed at 0.5% for production of Danish gas, based on a mix of gas turbine [Ref. 43, 44] and diesel generator [Ref. 45, 46] emissions.

3.2 Emissions of Natural Gas imported as LNG: CO_2, CH_4 and N_2O

The main GHGs emitted by natural gas during the value chain from production to consumption are CO_2, CH_4 and N_2O. Nitrous oxide (N_2O) emissions generated by consumption of NG are more substantial than for coal, as combustion temperatures in gas turbines are typically higher than in coal driven steam turbines, leading to a higher proportion of N_2O generated. On the other hand, natural gas combined cycles are more efficient than the coal steam turbines and have a lower CO_2 emission per unit of power generated.

A considerable proportion of GHG emissions in the LNG value chain is due to liquefaction and cryogenic transport of natural gas from producing countries to consumer countries, as detailed in Sections 4 and 5.

3.3 <u>Emissions of Coal: CO_2 and CH_4</u>

The main GHGs emitted by coal, during the entire value chain from mining to consumption, are CO_2 and CH_4, with only a negligible contribution by Nitrous Oxide (N_2O). As coal is a source rock for geological accumulations of natural gas, a considerable amount of methane is released during the mining of coal. In the consumption stage coal powered steam turbines generate NO_X emissions, but the proportion of N_2O is very low due to comparatively low combustion temperatures and was hence ignored.

3.4 <u>Countries in scope</u>

Natural Gas and Coal producing countries that make up more than 80% of EU imports were included in this study, plus Denmark as a baseline reference. Australia, USA, Colombia and Kazakhstan supplied 84% of EU coal imports in 2024, while the USA, Russia, Algeria and Qatar supplied 85% of EU LNG imports (Fig. 2)

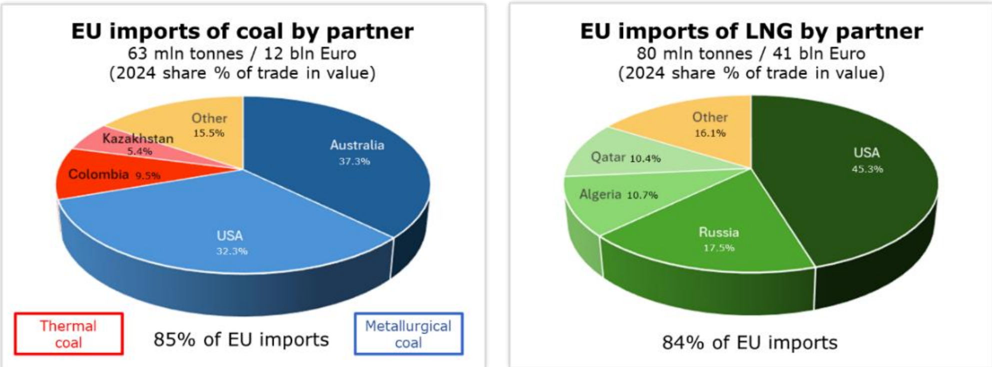


Figure 2: Source countries of fossil fuels exported to the European Union, detailing names and percentages of the 4 main source countries, providing some 85% of total EU imports. Left: coal exporting countries, with major providers of metallurgical coal in blue, and of thermal coal in red. Right: LNG exporting countries, with 4 major providers in green.

4. Methods

4.1 Bottom-up calculations were done for each energy carrier at each sector of the value chain: Production and transmission (NG)/Mining and local transport (Coal), Processing and liquefaction (LNG), Transport (Shipping: LNG and Coal; Pipeline: DK gas) and any further processing at arrival (LNG). Whenever possible, bottom-up calculations were validated by comparison with satellite observations. Data sources are shown in Figure 3.

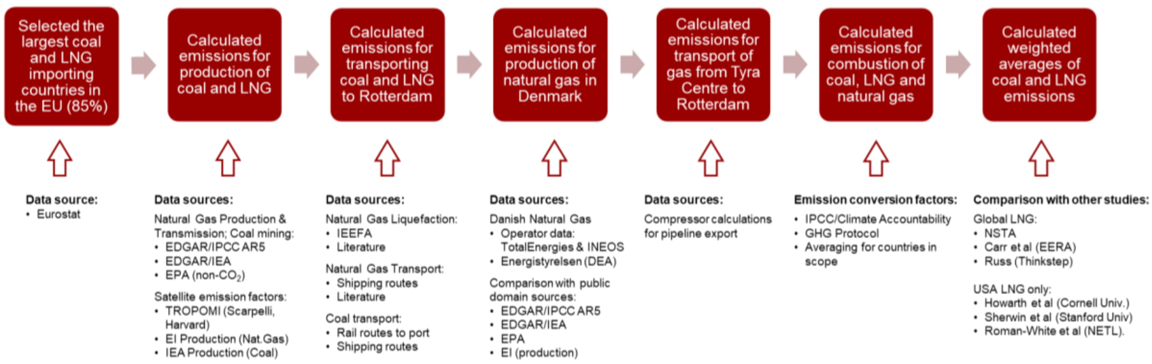


Figure 3: Overview of evaluation methods and data sources

4.2 <u>Emissions of production and transmission of Danish Natural Gas</u> are based on operator-provided reports to the Danish Energy Agency, country reports submitted to the UNFCC, and data made available by the IPCC, IEA/EDGAR and EPA (see abbreviations listing in appendix) based on a combination of bottom-up measurements, satellite observations and assumptions.

4.2.1 Operators TotalEnergies and INEOS have provided emission data separately to the study team and to the Danish Energy Agency (DEA, Energistyrelsen). Data provided to the study team were more detailed than what Danish authorities report to the public, and included a forecast of future production and emission numbers that allowed the study team to assess the impact of new facilities that have come on-stream during 2024 and 2025. Operator provided data were cross-checked with historic DEA numbers in the public domain, and with assessments by the IPCC (AR5), the EPA, IEA/EDGAR and the UNFCCC. Operator data were found to be consistent with DEA (production, CO_2 emissions), EI (production) and EPA (CH_4 emissions) numbers, but (significantly) different from IPCC and UNFCCC emission data in the public domain.

CO_2e emissions reported by the operators are circa 80% higher than those reported by the IPCC and almost five times higher than those reported by the UNFCC. This is mainly due to very low estimates of direct CO_2 emissions by the IPCC and UNFCCC, while their CH_4 emission estimates are actually higher than those of the operators. Operator numbers were used in the final comparison of Danish gas with imported energy carriers.

4.2.2 Emissions of production and transmission of natural gas for LNG were based on CO_2 emission estimates by IEA/EDGAR plus CH_4 + N_2O emission estimates by the EPA (EPA non-CO_2 emissions database), converted to CO_2e. The IEA/EDGAR estimates are recognized to be the most reliable for direct CO_2 emissions, while the EPA estimates were chosen for CH_4 and N_2O emissions, as those are more consistent with satellite observations (see Fig. 4 and [Refs. 23, 28, 32]). See Section 6.4 for analysis of satellite data.

4.2.3 Danish GHG emissions used in the analysis, based on operator provided data of CO_2, CH_4 and NO_X emissions (grey bar in Fig. 4), are higher than numbers reported by the IPCC, IEA or EPA for Denmark.

4.2.4 For production of Coal and Natural Gas the EPA emission numbers of CH_4 were selected for the final presentation, as they are more aligned with independent satellite observations than IPCC data (Fig. 4).

4.2.5 Uncertainty in reported production related emissions is circa 0.7 g CO2e/MJ (17%) and 1.1 g CO2e/MJ (20%) for coal and LNG, respectively (weighted averages).

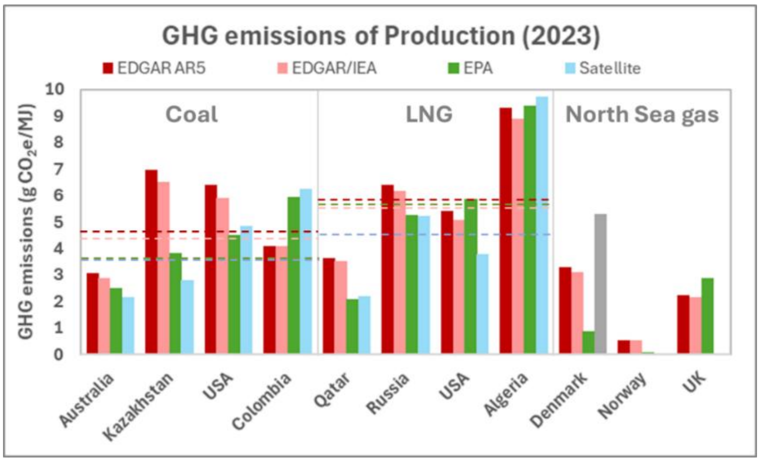


Figure 4: Comparison of normalized GHG emissions (CO_2e emitted per unit of energy produced, GWP_{100}) for four major data sources: EDGAR IPCC AR5 (IPCC fifth Assessment Report, All GHGs combined); IEA/EDGAR (sum of individual contributions of CO_2, CH_4 and N_2O); EPA (EPA for CH_4 and N_2O; IEA for CO_2) and satellite observations (Scarpelli report). Weighted averages of emissions by the 4 countries in each category are shown by dashed lines, with colours matching those of their respective data source. The Danish Gas emissions shown in grey are based on reliable operator-provided data, and are substantially higher than IPCC, IEA and EPA estimates, suggesting that actual GHG emissions uncertainty is higher than indicated by statistical analysis of IPCC, IEA and EPA data of the 8 countries studied.

4.3 <u>Emissions of Processing and Liquefaction of Natural Gas to LNG</u> were based on global LNG facility data by the IEEFA [Ref. 17] complemented by efficiency estimates by Carr et al [Ref. 2] and Jacobs [Ref. 13].

Fig. 5 shows how liquefaction of Natural Gas has become more energy efficient over time, resulting in decreasing emissions for those countries with the most recently built LNG facilities, which currently are in the USA and Russia. Additional LNG export capacity is being constructed/planned in Qatar and USA/Russia.

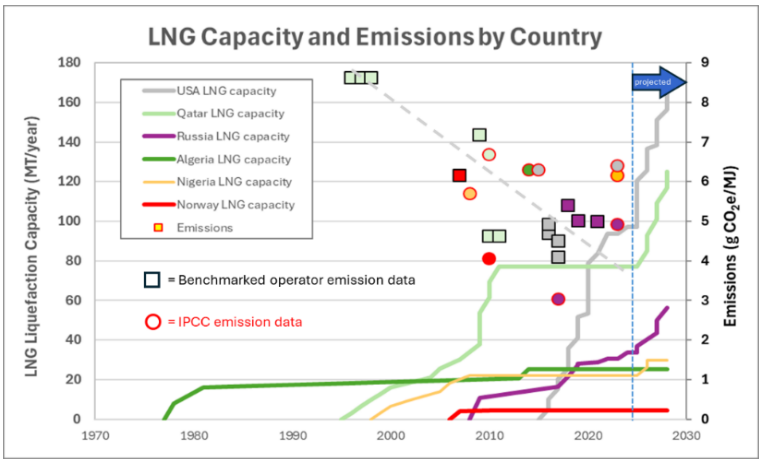


Figure 5: Historical and future development of LNG capacity and of liquefaction efficiency (expressed as CO_2e emissions per energy unit of LNG handled) over a 50-year period for a selection of LNG exporters to the EU. Liquefaction of Natural Gas is getting more energy efficient over time (grey dashed line), resulting in decreasing normalized emissions.

4.4 Emissions of Transport

4.4.1 Transport of Danish Gas takes place by compression at the offshore Tyra centre and export through either the Danish offshore gas pipeline to Nybro (DK) or through the Northern Offshore Gas Transport (NOGAT) pipeline to Den Helder (NL), see Fig. 1. For comparison reasons the longer NOGAT route was used in this study to ensure that the delivery point of all energy carriers is the same. Circa 36% of total offshore compression capacity would be dedicated to export gas via NOGAT, contributing 20% of total GHG emissions, or 1.1 g CO_2e/MJ [this study, based on Ref. 50]. See also Section 5.1.8.

4.4.2 Transport of LNG was characterized by CO_2 and CH_4 emissions of shipping from the main LNG terminal in each exporting country to the port of Rotterdam in the Netherlands, a major port in the EU with LNG processing facilities. Shipping distances and durations were determined using sea-distances.org calculations [Ref. 49]. LNG boil-off losses (with LNG being used for ship propulsion and converted to CO_2) were calculated using correlations derived by Pospisil [Ref. 1] showing that LNG boil-off rates increase with shipping duration (Fig. 6).

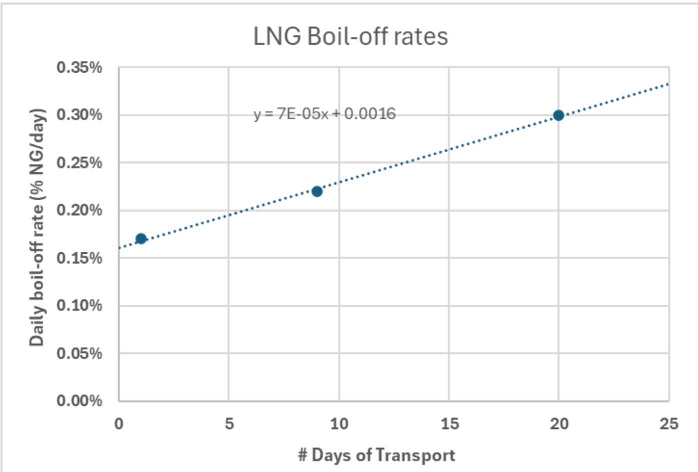


Figure 6: Daily LNG boil-off losses as a function of transportation time. The boil-off rate increases due to accumulated heat ingress, despite highly effective insulation. Boiled-off gas that is not used as fuel for propulsion, or onboard power generation, is reliquefied and returned to the tanks (from Pospisil [Ref 1]).

CH_4 leakage was based on data for two-stroke engine tankers burning LNG as fuel by Howarth [Ref. 5], with a daily leakage rate of 0.114 g CO_2e/MJ/day derived from a total methane leakage of 212 g CO_2e/kg LNG over a 38-day period. Combined outcomes of this method are shown in table 1.

From		To		Distance	Speed	Duration	Loading/Unloading		Boil-off loss	Boil-off loss	CH4 leakage	Total Loss
				(Nautical Miles	(knots)	(days)	(days)		(%)	g CO2e/MJ	g CO2e/MJ	g CO2e/MJ
Algeria	Arzew	Netherlands	Rotterdam	1.618	19	3,55	3		0,73%	0,41	0,41	0,82
USA	Sabine (LA)	Netherlands	Rotterdam	4.974	19	10,91	3		2,81%	1,57	1,25	2,82
USA	Corpus Christi (TX)	Netherlands	Rotterdam	5.111	19	11,21	3		2,91%	1,63	1,28	2,91
Russia	Yamal	Netherlands	Rotterdam	2.914	19	6,39	3		1,44%	0,81	0,73	1,54
Qatar	Umm Said	Netherlands	Rotterdam	6.365	19	13,96	3	Suez Canal	3,89%	2,18	1,60	3,78
Qatar	Umm Said	Netherlands	Rotterdam	11.098	19	24,34	3	Cape of Good Hope	8,55%	4,80	2,79	7,58

Table 1: Calculated CO_2e emissions for LNG transport from source countries to the Netherlands, based on shipping duration, boil-off losses (including propulsion and power generation) and methane leakage.

4.4.3 Transport of Coal was characterized by two components: rail transport from mining site to port and shipping transport from the main local export port to the port of Rotterdam, which handles circa a quarter of the EU's coal imports. Train/shipping distances and emissions for coal were determined using carboncare calculations [Ref. 48], verified by comparison with IEA emission standards described by Vaillancourt [Ref. 39].

Several routes were considered for coal from Australia, via the Suez Canal and a longer route around Africa, and for coal from Kazakhstan, via the Baltic Sea and a longer route via the Black Sea (Fig. 7). The geopolitical considerations behind this are described in chapter 7 (Sensitivities, Section 7.2).

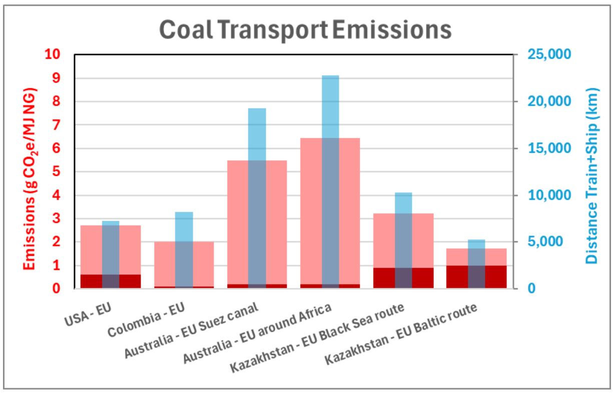


Figure 7: CO_2e emissions of coal transport from source countries to the Netherlands, for short and long shipping routes, influenced by geopolitical considerations (see Section 7.2).

4.5 Emissions of further processing at arrival are mainly relevant for LNG, since liquid LNG is re-gasified so that it can enter the gas distribution network, and can be compared to piped Danish NG and coal at a similar point in the value chain.

4.5.1 Emissions of LNG re-gasification were based on reports by Roman-White [Ref. 7,8], Gan [Ref. 21] and GIIGNL [Ref. 18]. A value of 0.6 g CO_2e/MJ was applied to each LNG supply stream, consistent with the maturity of LNG regasification facilities in Rotterdam, and the use of open rack vaporizer (ORV) technology, rather than submerged combustion vaporizers (SCV), which require more fuel.

4.5.2 The exact composition of re-gasified LNG and gas exported from Danish offshore production may still vary slightly in terms of wetness (content of C2+), but these differences are assumed to have a negligible impact in terms of GHG emissions. Also, the composition of 2023 and 2026 Danish gas is slightly different.

4.6 Validation methods: Bottom-up calculations versus Top-down (satellite observations) analysis plus verification via thermodynamics first principles.

4.6.1 Reported methane emissions (IEA, EPA, EDGAR) have been cross-checked against top-down satellite observations of CH_4 emissions, based on inversion techniques, and scrutinized in a number of recent scientific reports [Refs. 26-34]. This is an independent calibration of emissions reported to the UN and by the IPCC, based on bottom-up calculations and assumptions. While the bottom-up inventories by EPA and EDGAR are both consistent with satellite observations for total U.S. anthropogenic CH_4 emissions, with 2019 estimates by EPA (~27.3 Tg CH_4) and by EDGAR (26–29 Tg CH_4) within 15% of TROPOMI's 30.9 Tg CH_4 [Ref. 57], the EPA's detailed U.S. data and annual updates capture national trends better than EDGAR's global approach. Additionally, EPA estimates of CH_4 in other countries (those considered in this study for coal and oil & gas) are more aligned with satellite data than EDGAR's estimates, particularly for coal mining related emissions.

Leaks of CH_4 tend to be more geographically concentrated around an emission source than emissions of CO_2, creating a stronger and more localized signal that satellites can identify and quantify. Also, the CH_4 infrared spectral absorption bands at 3.3 µm and 7.7 µm suffer from less overlap with water vapour absorption bands than CO_2.

Consequently, methane emission numbers from sources that came closest to satellite observations, i.e. EPA numbers for Natural Gas in the USA and of Oil & Gas for the other countries covered, were selected for final presentation in this study.

4.6.2 Reported CO_2 emissions of Oil & Gas operations and coal mining (IEA/EDGAR, IPCC, UNFCCC) were more difficult to validate against satellite observations since background concentrations and natural variability of CO_2 are much higher than of CH_4 or N_2O, making it more difficult to differentiate between emissions by O&G activities and background emissions, as that would necessitate highly sensitive satellite sensors to detect relatively small changes in concentration caused by individual emission sources against a high background. Also, the CO_2 infrared spectral absorption bands at 15 µm, 4.3 µm and 2.7 µm suffer from overlap with water vapour absorption bands, that can obscure variations or plumes from localized CO_2 sources.

Consequently, IEA/EDGAR estimates of CO_2 emissions were used in this study, that are essentially bottom-up calculations relying on IPCC methodologies and assumptions, rather than satellite data.

4.6.3 Emissions reported by Danish Oil and Gas operators were compared with GHG emissions reported to the European Pollutant Release and Transfer Register (E-PRTR), while emissions of export gas compression were separately verified by thermodynamic calculation (see Sections 5.1.7 and 5.1.8).

4.6.4 LNG emissions obtained from literature were validated by thermodynamics modelling of a simple cryogenic liquefaction cycle, and by hydrodynamic modelling of LNG transport (see Sections 5.1.9 and 5.1.10).

4.7 The Global Warming Potential was analysed for emissions of the three main greenhouse gases, CO_2, Methane (CH_4) and Nitrous Oxide (N_2O), scaled to their 100-year warming impact (GWP_{100}).

4.7.1 GWP_{100} conversion factors for methane and nitrous oxide are: $GWP_{100}CH_4$ = 28 CO_2e; $GWP_{100}N_2O$ = 298 CO_2e.

4.7.2 Fraction of N_2O in reported NO_X = 0.5% (N_2O is a GHG, while NO or NO_2 are not).

4.7.3 An estimate of corresponding 20 year warming impact (GWP_{20}) is described in section 7.5 (Sensitivities).

5. Results

5.1 Emissions of Coal, LNG and Danish NG value chains – excluding consumption

5.1.1 Normalized GHG emissions (CO_2e per energy unit) of the first stages of the value chain, from production to delivery in the EU (Well To Tank), are higher for LNG than for coal or Danish gas, regardless of the country of origin. This is mainly due to the high energy and carbon emission footprint of gas liquefaction and cryogenic transportation (Fig. 8). GHG emissions of Danish gas are 5.3 g CO_2e/MJ (2023 data), compared to 12-17 g CO_2e/MJ for LNG, and 5.6-7.9 g CO_2e/MJ for coal.

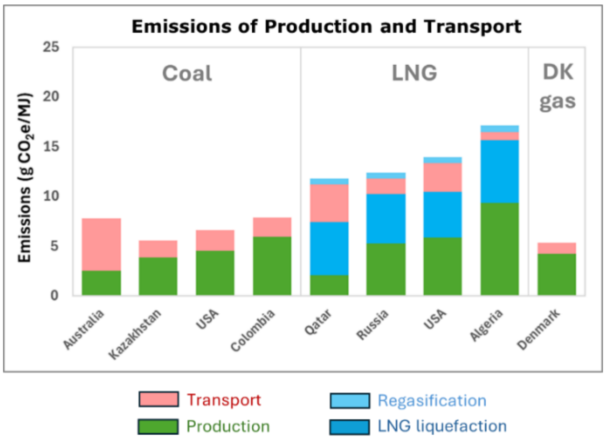
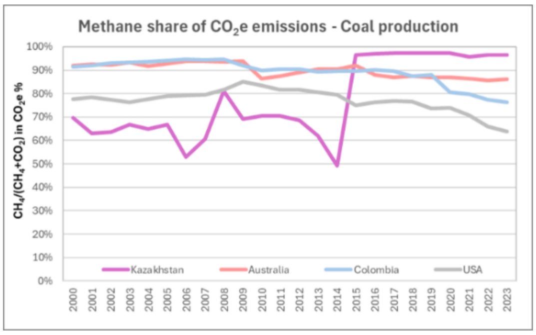


Figure 8: Comparison of normalized GHG emissions (GWP_{100}) from a production and transportation perspective. Natural gas from Denmark emits less Greenhouse Gas ($CO_2 + CH_4 + N_2O$) than imported LNG or coal. For this part of the value chain (Well-To-Tank) LNG has the highest normalized GHG emissions.

5.1.2 From a production and transportation perspective, natural gas from Denmark emits less Greenhouse Gas than imported LNG or coal. LNG emits 159% more GHGs than natural gas produced in Denmark. Coal emits circa 35% more GHGs (Fig. 8).

5.1.3 Production of coal and of natural gas (without transport) have similar GHG emissions in CO_2e terms, but are quite different with regard to the share of actual greenhouse gases emitted: the proportion of methane in total GHG emissions by coal mining (60-97%) is higher than that of (oil and) gas production (20-70%), with the exception of the USA where methane makes up circa 90% of GHG emissions by gas production (Figs. 9 and 10).



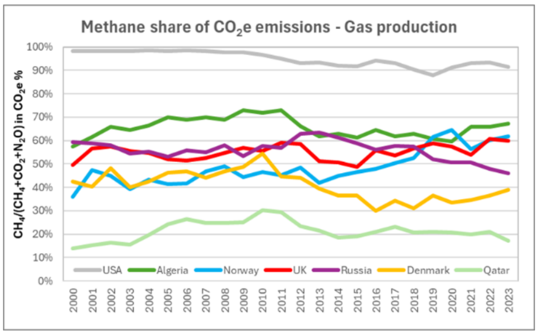


Figure 9 (left): Share of methane in total GHG (CO_2e, GWP_{100}) emissions of coal production. In geological terms coal is a major source rock for methane generation, and mining coal thus releases entrapped methane that is subsequently difficult to collect. Figure 10 (right): Share of methane in total GHG (CO_2e) emissions of gas production. Dedicated gas production can be energy intensive due to the need for compression, thus releasing CO_2, but typically aims at low methane wastage as methane is the actual commercial product. Any methane emissions are typically caused by either old infrastructure (Algeria, UK), or no access to a gas market (e.g. USA, where construction of gas export infrastructure often lags behind drilling of oil wells; or on a more permanent basis (but not applicable to this study) countries like Iraq, Iran, Venezuela that have no access to a large gas market).

5.1.4 When transport of the energy carriers is included (Well-To-Tank emissions), the GHG impact of direct CO_2 emissions surpasses that of CH_4 due to the high CO_2 intensity of coal and LNG transport relative to their production, even while methane leakage of LNG transport is similar in magnitude as direct CO_2 emissions from transport (Fig. 11).

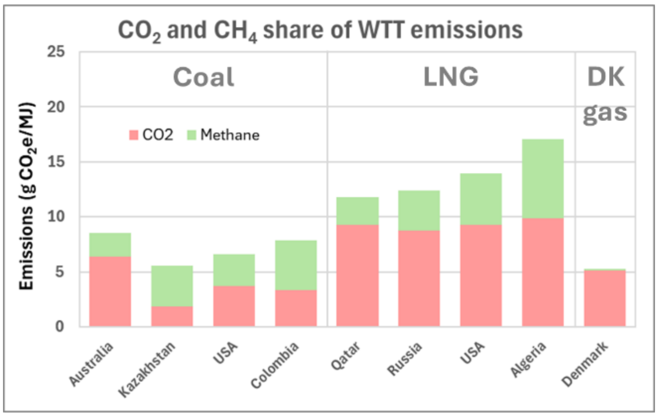
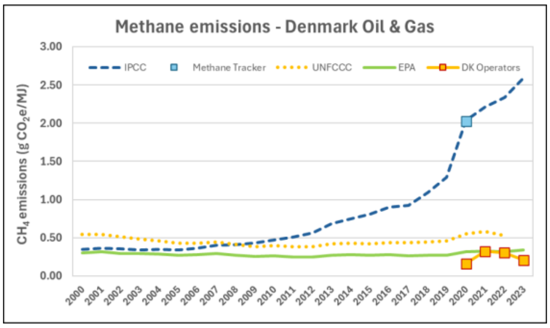


Figure 11: Share of CO_2 and CH_4 emissions (in CO2e/MJ, GWP_{100}) by coal, LNG and NG from the 8 countries studied, for the Production and Transportation stages (Well-To-Tank) of the value chain.

5.1.5 The production and transport of Danish gas has lower normalized GHG emissions (5.3 g CO_2e/MJ) than gas produced in most other countries, which is partially thanks to a remarkably low proportion of methane emissions relative to CO_2, according to Operator data (Fig. 11). This is a result of the widespread presence of effective gas gathering and export infrastructure in the Danish sector connected to an economically attractive gas sales market, that incentivizes minimization of methane losses. Note that for Coal and LNG the CH_4 numbers in Fig. 11 are by EPA, and CO_2 numbers by IEA/EDGAR, while Danish gas emissions are all based on operator-provided data.

5.1.6 GHG emissions of Danish Oil and Gas production operations provided by operators are considerably higher than those reported by IPCC and EDGAR (Fig. 13). This is mainly due to higher operator-reported CO_2 emissions (0.86 MMton CO_2/yr by operators versus 0.09 MMton CO_2/yr by IEA/IPCC in 2023). Methane emissions reported by Danish Oil and Gas operators are similar to those reported by EPA, but significantly lower than those reported by the IPCC and the IEA Methane tracker (Fig. 12). The UNFCCC country report for Denmark contains somewhat higher methane emissions than operator data, but very low total CO_2e emissions due to serious under-estimation of CO_2 emissions, inconsistent with factual amounts of fuel gas consumed by offshore O&G operations for power generation.



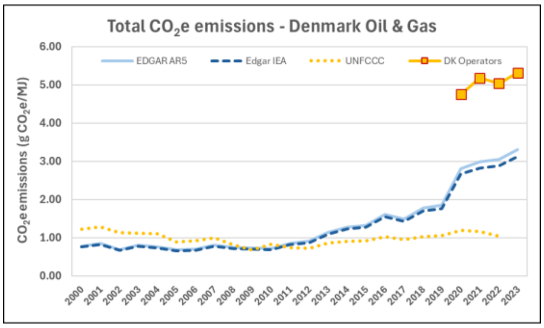


Figure 12 (left): Normalized methane emissions (GWP_{100}) of Danish Oil and Gas production as reported by external parties (IPCC, UNFCCC, EPA; continuous and dashed lines) compared with Danish Operator data (squares).

Figure 13 (right): Normalized Total CO_2e emissions (GWP_{100}) of Danish Oil and Gas production as reported by external parties (IPCC, UNFCCC, EPA; continuous and dashed lines) compared with Danish Operator data (squares).

5.1.7 The above emission numbers of Danish Oil and Gas production were also compared with GHG emissions reported to the European Pollutant Release and Transfer Register (E-PRTR), which contains data provided by the operators of any included facilities through self-monitoring and reporting, as visualized and summarized in Fig. 14 and Fig. 15.

Values for onshore and offshore emissions of methane are those from the latest reported year (2023). E-PRTR reported offshore methane emissions have dropped from 0.27 kt/year in 2018 to 0.10 kt/year in 2023, which is significantly less than the 1.2 kt/year reported by the operators or the 2.1 kt/yr by the EPA and 16 kt/yr of CH_4 reported by the IPCC for 2023.

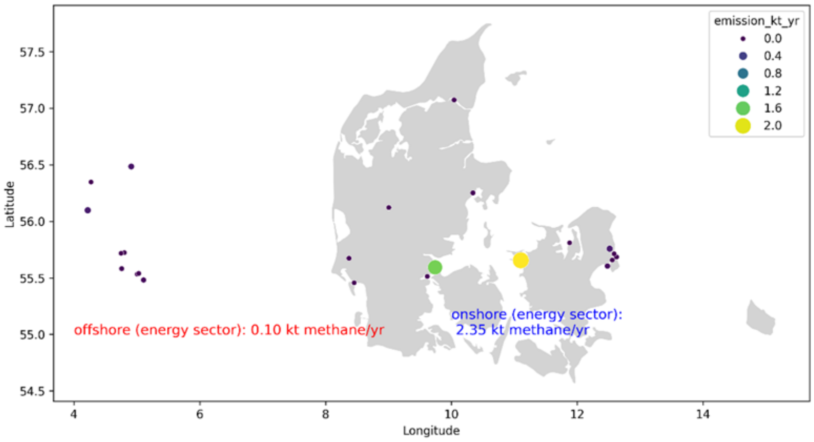


Figure 14: The latest methane emission map for Denmark filtered for the energy sector and the latest reported year. The total amount of emission from onshore and offshore are calculated and shown on the map. Note that for some facilities, the data can be outdated as some numbers are not available for the latest reported year (2023).

E-PRTR reported CO_2 emissions, however, have increased from 287 kt/year in 2028 to 736 kt/year in 2023, which is close to the 855 kt/yr reported by Danish O&G operators in 2023, or the 923 kt/yr of CO_2 derived from DEA data (see Figs. 13 and 15). This indicates that emission numbers in the public domain for Danish oil and gas operations are reliable for CO_2 but not for methane.

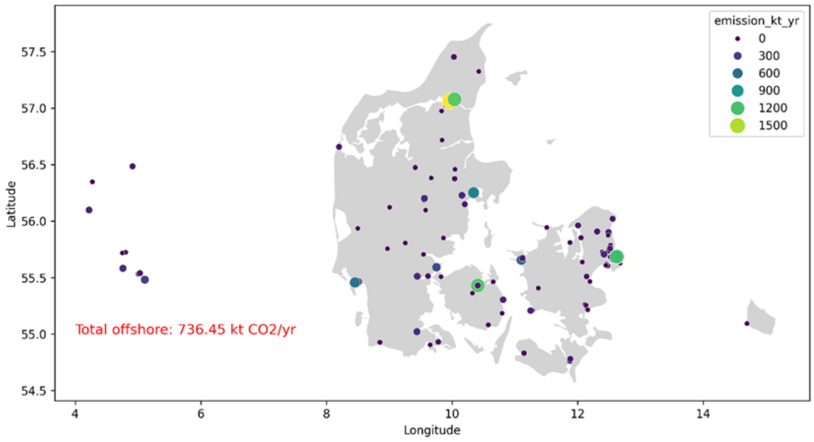


Figure 15: CO_2 emission map reported to E-PRTR filtered for the energy sector and the latest reported year

5.1.8 Separately, emissions of export gas compression were verified by thermodynamic calculation of the energy (and thus emissions) needed for the compression and pipeline transport of CH_4 from the offshore platforms to the distribution networks, which is a significant contributor to CO_2 emissions. Assuming a 500 km pipeline, a delivery pressure of 15 bar, a pipeline with a pressure drop of 0.15 bar/km, and a typical two stage compressor station, a compression energy of 0.72 MJ/kg transported natural gas (i.e. 1.5% of the natural gas heating value) was calculated, which results in a CO_2 emission of 0.8 g CO_2/MJ, which is about a fifth of the total offshore CO_2e emissions of 5.3 g CO_2e/MJ (see Fig. 13) and is close to the 1.1 g CO_2e/MJ derived from offshore power consumption calculations for export gas compression (see Section 4.4.1).

5.1.9 LNG emissions obtained from literature were validated thermodynamically by solving the mass and energy balance of a simple cryogenic liquefaction cycle, and by calculating the energy requirement of the unit. A typical coefficient of performance (COP) of 0.2 was used, in line with reported values for the Linde liquefied natural gas process. A refrigeration cycle operating at atmospheric pressure (1.01325 bar) and a temperature of -161.7 °C was used (lower than the bubble point temperature of natural gas at atmospheric pressure). A Stirling cycle, operating at a cold-end temperature of -161.7 °C (111.5 K), has a coefficient of performance (COP) of 0.14. A higher efficiency is reported in the literature for the optimized refrigeration cycles (e.g., COP of 0.22 for Linde process). The enthalpy change (ΔH) for the refrigeration cycle was calculated as 910.6 kJ/kg, with the actual refrigeration power required amounting to 6,339 kJ/kg after including all the efficiency factors, i.e. COP of the refrigeration cycle and electricity production efficiency for a natural gas combined cycle. This corresponds to a refrigeration energy demand equal to 12.7% of the lower heating value (LHV) of methane. As a result, the CO_2 emissions associated with the refrigeration process were estimated at 7.1 g CO_2/MJ of energy input, which is close to the circa 5 g CO2e/MJ for a modern LNG plant as described in Section 4.3 (Figure 5). The difference is caused by a lower percentage of methane consumed for liquefaction in modern LNG plants which is in the range of 9-10%, rather than 12.7% calculated for a simple process. Modern LNG plants use a cascade of mixed refrigerants that optimizes heat transfer across a broad temperature spectrum (from ambient to minus 162 °C), with multiple temperature steps and effective heat exchangers that reduce temperature differences between streams and enhance efficiency.

5.1.10 The energy demand of LNG transport was calculated by estimating the different forms of hydrodynamic resistances acting against an LNG carrier, in order to calculate the energy required to power a ship from A to B. The well-known model of Holtrop and Mennen was used with typical model parameters for a 140,000 m^3 LNG vessel. The distances and velocities are similar to those shown in Table 1 for shortest route from Qatar to Rotterdam. Calculations show a bunker fuel energy consumption equivalent to 0.94% of the transported LNG, which leads to a CO_2 emission of 0.7 g CO_2/MJ of methane. This value is close to the one estimated for pipeline transport (albeit for a shorter pipeline distance) but is only a fraction of the total emissions of LNG transport (3.78 g CO_2/MJ). The results shows that the main sources of emissions for LNG transport are the cryogenic cooling plus any methane leakage (see Section 4.4.2).

5.2 Emissions of entire Coal, LNG and Danish NG value chains – including consumption

Conversion factors to normalize emissions from combustion of thermal and metallurgic coal are those used by the IPCC, obtained via NGGIP and Climate Accountability reports, and the emission factor for combustion of natural gas and LNG was obtained via GHG Protocol.org.

	Combustion emissions (g CO_2e/MJ)	Heating value (MJ/kg)	CO_2 emissions (tonne CO_2/tonne)
Thermal Coal	95,3	22,35	2,1293
Metallurgic Coal	94,5	28,20	2,6659
Danish Gas / LNG	56.1		
Data Source:	GHG Protocol.org	IPCC-NGGIP	IPCC Climate Accountability

Table 2: Emission factors (GWP_{100}) for the combustion of natural gas and coal imported into the European Union. Combustion emissions for thermal and metallurgic coal are weighted averages for the mix of coal types imported.

GHG Protocol provides many different emission factors for the various types of coal (in kg CO_2/TJ), but for this study it was necessary to determine a weighted average emission factor for the mix of coal types imported into the EU from the main source countries Australia, the USA, Colombia and Kazakhstan. In order to achieve this, country-specific heating values of coal by NGGIP were combined with coal type specific CO_2 emission data (per tonne of thermal or metallurgic coal) from Climate Accountability, to calculate average emission factors for the types of coal imported by the EU (see Table 2).
Emissions by combustion of LNG and Danish gas were deemed to be 56.1 g CO_2e/MJ (GHG Protocol.org).

5.2.1

Normalized GHG emissions (CO_2e per energy unit) of the total value chain (production, transport and combustion, i.e. Well To Wheel), are higher for coal than for LNG or Danish gas, regardless of the country of origin. This is mainly due to the high carbon footprint of coal combustion per energy unit, which is caused by the higher carbon to hydrogen ratio of coal (Fig. 16). GHG emissions of Danish gas are 61.4 g CO_2e/MJ (2023 data), compared to 67.9-73.2 (weighted average 69.9) g CO_2e/MJ for LNG, and 100.8-103.1 (weighted average 101.9) g CO_2e/MJ for coal.

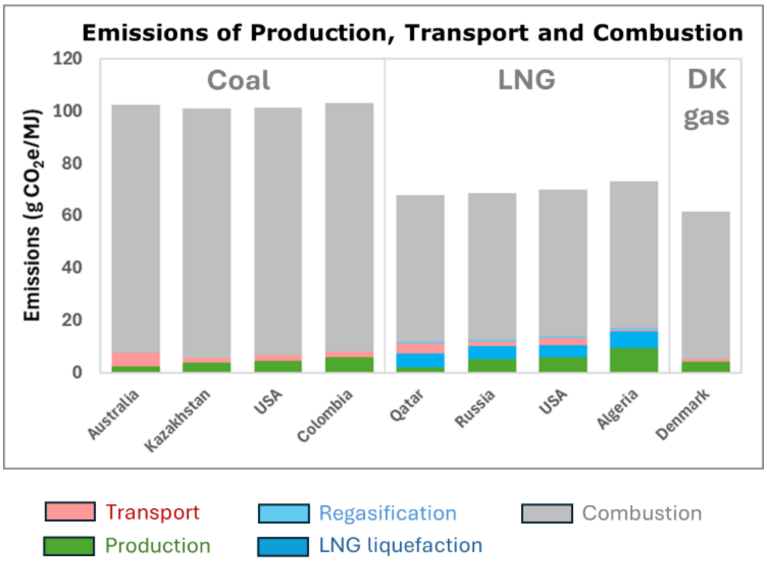


Figure 16: Comparison of normalized GHG emissions (GWP_{100}) from a Total Value Chain perspective (production, transportation and combustion, or Well-To-Wheel). Natural gas from Denmark emits less Greenhouse Gas ($CO_2 + CH_4 + N_2O$) than imported LNG or coal, while coal has the highest overall (WTW) GHG emissions.

5.2.2 Operator emission data of DK offshore sector versus external estimates

Absolute CO_2 and methane emissions of the Danish offshore oil and gas industry in 2023 were circa 855 kiloton and 1.2 kiloton, respectively, totaling 893 kiloton CO_2e/year, as reported by offshore O&G operators TotalEnergies and INEOS. This is close to the emissions independently calculated by adding DEA derived CO_2 emissions and EPA reported CH_4 emissions, of 923 kiloton CO_2e/year for 2023 (Fig. 17).

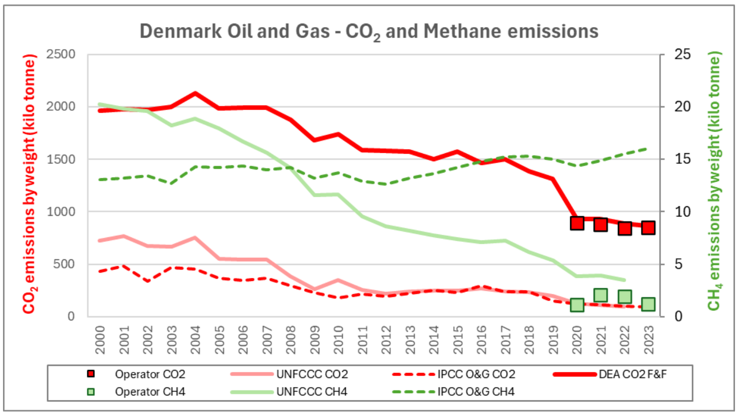


Figure 17: Comparison of Operator provided absolute CO_2 (red squares) and CH_4 (green squares) emissions against official Danish Energy Agency data (CO_2 only) and external reports (UNFCCC and IPCC). Operator CO_2 emissions are well aligned with emissions derived from DEA fuel and flare data, but are much higher than UNFCCC and IPCC estimates, while Operator CH_4 emissions are close to (but still lower than) UNFCCC estimates, and much lower than IPCC estimates.

- CO_2 emissions reported by UNFCCC and IPCC for the Danish oil and gas industry are inexplicably low as they do not even get close to the objective accounts of CO_2 generated by consumption of fuel gas offshore, reported by offshore operators and the DEA. In the final analysis operators' CO_2 emission numbers were therefore used.
- CH_4 emissions reported by UNFCCC and operators are relatively close, while the downward trend of methane emissions over time is consistent with historic efforts to reduce gas leakage through improved monitoring and retrofit projects. The different IPCC trend of constant methane emissions, even when total DUC natural gas production has decreased from 11.3 bln m^3 in 2000 to 1.3 bln m^3 in 2023, is not plausible, especially since the entire Tyra Centre has been shut in from 2020 to 2023 and was therefore unable to cause any methane emissions (Fig. 17). IPCC estimates are based on 'emission factors', which are standard estimates of the methane emissions associated with processes such as venting, flaring, processing and combustion, which are apparently assumed to be constant in the IPCC estimates, rather than tied to activity levels. The amount of leaked methane as a proportion of total Danish gas production is 1.55% for the IPCC estimate compared to 0.12% for the operators' estimate. Similar assessments for Norway and UK methane emissions by the IPCC are 0.16% and 0.38%, respectively, of total gas production. An independent assessment of UK production-weighted methane loss of 0.19% by Riddick et al [Ref. 53], based on plume measurements around offshore platforms, is also lower than the IPCC estimate.
  The above suggests that DK operators' methane emission numbers are more representative than the IPCC's estimate for Danish offshore production.

Comparison of Danish O&G emissions against those of the UK paints a similar picture, with IPCC under-reporting of UK emissions by 44-55%, and of DK emissions by 42-59% (Fig. 18).

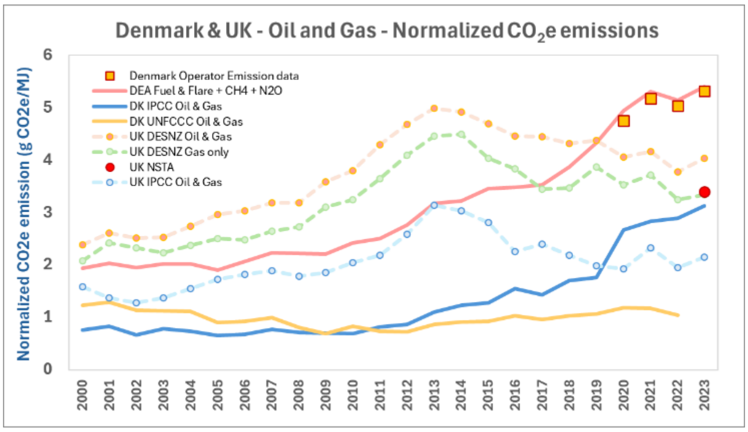


Figure 18: Similarities of IPCC under-reporting of GHG emissions (GWP_{100}) by offshore O&G industries in Denmark and UK, as compared to operator provided and government (DEA and DESNZ) data.

5.2.3 Geopolitics impact: long vs short shipping routes
Given the current geopolitical climate, optimum transport routes are not necessarily the shortest but rather the most cost-effective option from a combined time, fuel and insurance risk perspective, as described in more detail in Section 7.2.

Sensitivities		Production & Transport (WTT) (g CO2e/MJ)	Production, Transport & Combustion (WTW) (g CO2e/MJ)
Coal	Short route	7.21	101.9
Coal	Long route	7.73	102.4
LNG	Short route	13.77	69.87
LNG	Long route	14.24	70.34
DK Gas	Tyra 2023	5.32	61.42
DK Gas	Tyra 2026	4.01	60.11

Table 3: Impact of long and short shipping routes on normalized GHG emissions (GWP_{100}) of coal and LNG transport. Longer shipping routes generate more CO_2 for coal transport (propulsion), but more CO_2 as well as more CH_4 for LNG transport (propulsion, cooling and CH_4 leakage). Also shown is the impact of Tyra Centre redevelopment on emissions by Danish gas production.

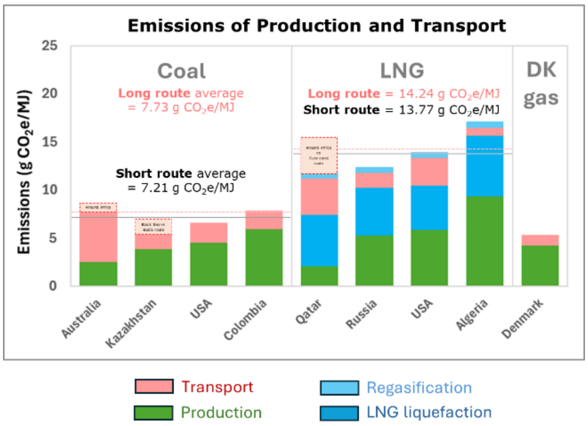


Figure 19: Graphical representation of shipping route sensitivities impact on normalized GHG emissions (GWP_{100}). The long-route weighted average emissions increase for coal and LNG is circa 0.5 g CO_2e/MJ for EU imports.

5.2.4 From a total emissions perspective, i.e. production, transportation and combustion, coal emits most GHGs (+66%), followed by LNG (+14%) compared to natural gas produced in Denmark. If long transport routes are required for geopolitical reasons, coal and LNG will emit 67% and 15% more, respectively, than Danish gas (Table 3).

5.2.5 Conversely, if coal has index 100 in total GHG emissions, then LNG's index is 68.6 and index of natural gas produced in Denmark is 60.3 for short transport routes. If long transport routes are required for geopolitical reasons, then LNG's index is 69.0 and index of natural gas produced in Denmark is 59.0.

6. Comparisons with other studies (LNG).

6.1 "UK imports: North Sea Transition Authority (NSTA) [Ref. 51]

6.1.1 The results of the DTU study are aligned with an independent study of Well-To-Tank emissions titled "Carbon footprint of UK natural gas imports" by the UK North Sea Transition Authority (NSTA), a government institution responsible for regulation of UK Oil & Gas and Carbon Storage industries (Fig. 20).

6.1.2 Results in the NSTA report are reported in different units (kg CO_2e/boe). The weighted average LNG carbon intensity of the 4 countries studied by DTU (EU imports) is 84 kg CO_2e/boe (13.8 g CO_2e/MJ), compared to NSTA's estimate for 10 countries (UK imports) of 79 kg CO_2e/boe (12.9 g CO_2e/MJ). When comparing just the 4 countries studied the NSTA average for LNG is 11.8 g CO_2e/MJ and the DTU average is 13.8 g CO_2e/MJ, with an overall DTU/NSTA average of circa 13 g CO_2e/MJ (Fig. 20). The higher DTU estimates are mainly due to the impact of methane leakage during the production and transmission stages for USA/Russia/Algeria/Qatar, prompted by satellite observations.

6.1.3 Emissions of DK oil and gas are 5.3 g CO_2e/MJ, i.e. higher than the 3.4 g CO_2e/MJ (21 kg CO_2e/boe) quoted for UK gas in the NSTA report [Ref. 51], or the 4.0 g CO_2e/MJ for UK Oil and Gas derived from UK Department for Energy Security & Net Zero data [Ref. 54].

6.1.4 Danish offshore energy consumption (and thus CO_2 emissions) is low in a global context, but on the high side in the North Sea offshore context due to high water cuts in the production of natural gas from oil wells. Emissions for DK oil and gas are projected to be lower in 2026 thanks to the redevelopment of Tyra Centre (see Section 7.3) at ca. 4.0 g CO_2e/MJ, similar to that provided by DESNZ for the UK.

6.1.5 Broader comparison of DTU study results with other LNG Value Chain investigations (Fig. 21) reveals that there are a number of studies, for instance by Carr/EERA [Ref. 2] and Howarth [Ref. 4], that show markedly higher emissions for LNG than the NSTA and DTU studies. The following sections will explain this in more detail.

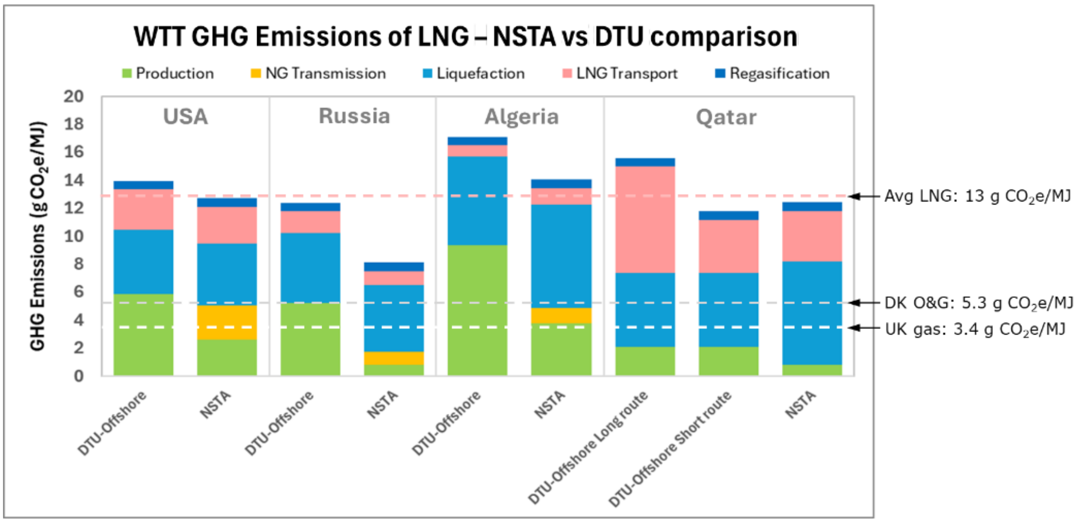
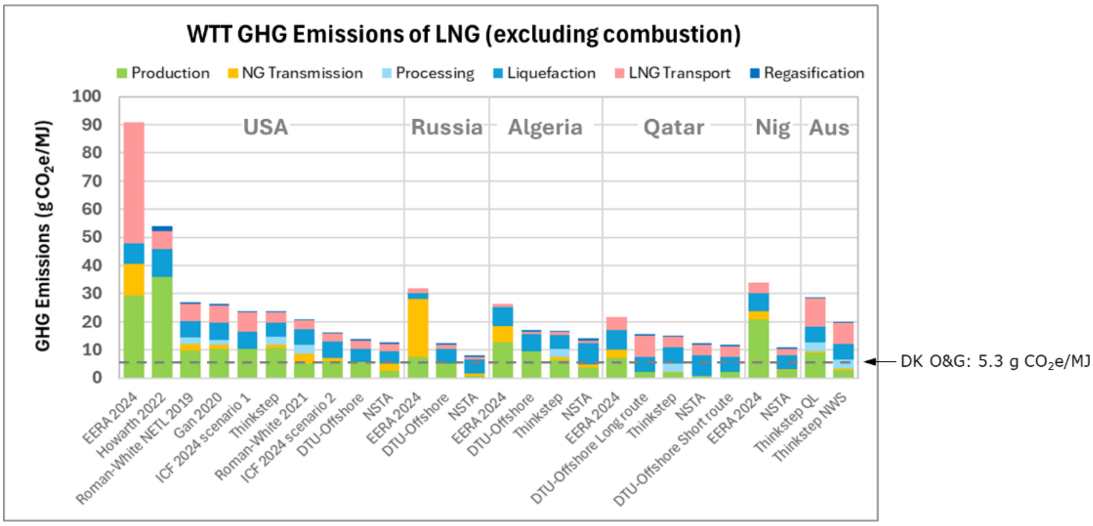


Figure 20: Comparison of DTU study Well-To-Tank emissions and NSTA study results (GWP_{100}). Results are similar overall, but the DTU assessments are higher in production related emissions, due to new insights on methane leakage prompted by satellite



observations.

Figure 21: Broader Well-To-Tank greenhouse gas emissions comparison of DTU study results with other LNG WTT investigations (GWP_{100}). Normalized GHG emissions of Danish Oil and Gas (dashed line) are lower than any assessment of imported LNG.

6.2 <u>"Well-to-Tank Carbon intensity of European LNG Imports" by Carr et al. (EERA: Energy & Environmental Research Associates)</u> [Ref. 2], also published as "Literature review of Well-To-Tank carbon intensity of European LNG imports" for the Intersessional Working Group on Reduction of GHG emissions from ships (ISWG) [Ref. 3].

6.2.1 The report summarizes regional and national variations in WTT emissions from the LNG production and supply chain of eight countries, and exhibits consistently higher emissions than any other single study. It contains GWP values from the Fourth, Fifth, and Sixth IPCC Assessment Reports (AR4, AR5, AR6).

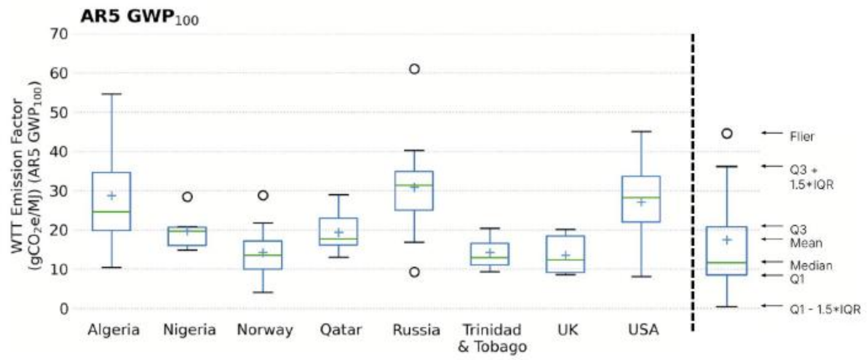


Fig. 22: Boxplot of country-level well-to-tank carbon intensity (gCO_2e/MJ, AR5, GWP_{100}), as represented in surveyed literature by percentile [From Ref. 3]. Apart from USA data, probabilistically calculated mean emissions in this figure correspond to deterministically calculated emissions shown in Figure 21.

6.2.2 The study concluded that the weighted average WTT GHG intensity of LNG was 24.40 gCO_2e/MJ (AR5 GWP_{100}) – or 34.87 gCO_2e/MJ (AR6 GWP_{20}) for the eight countries studied. WTT emission ranges shown in Fig. 22 (from [Ref. 3]) are probabilistic additions of the various value chain components, whereas the emissions in Fig. 21 are straight deterministic additions of the mean individual value chain components as quantified for AR5 in the EERA report, which results in higher numbers for the USA due to outlier data in the LNG transport component estimates.

6.2.3 The higher (and more variable) emission estimates of the Carr et al. study stem mostly from the effects of methane leakage, in particular on the production and transmission sides (and exceptionally also for LNG tanker transport, but from the USA only). There appears to be a bias in the available literature (as documented by Carr et al) to make assumptions that overestimate the potential for baseline methane leakage, since much research is incentivized by governmental initiatives to prioritize methane reduction efforts (Global Methane Pledge, launched at COP26 [Ref. 55]). Methane reduction targets (in CO_2e) are easier to achieve than direct CO_2 reduction targets, and are thus a focus area for governments.

6.3 USA LNG exports: Howarth (Cornell) & Sherwin (Stanford, aerial surveys) [Ref. 5]

6.3.1 "The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States" publication by Howarth [Ref. 5] contains widely quoted emission numbers of the Oil and Gas sector in the USA that are higher than most other publications, except for the IPCC AR4, AR5, AR6 reports. A major reason for the high overall emission numbers by Howarth (Fig. 21) is his use of an assessment by Sherwin [Ref. 6] that 2.8% of US gas production leaks out to the atmosphere, implemented by Howarth as a base assumption. Section 6.3.2 contains an alternative view on the Sherwin assessment.

6.3.2 Critical review of the Sherwin assessment [Ref. 6], which had formed the basis of Howarth's evaluation. The 2024 Sherwin et al study, "US oil and gas system emissions from nearly one million aerial site measurements" [Ref. 6] surveyed 6 selected areas for methane emissions by infrared imaging spectrometry on a King Air B200 aircraft, with most observations in the Permian and San Joaquin basins, which are both oil-driven basins with high CH_4 leakage rates. US LNG exports, however, come not just from the Permian Basin but also from the Haynesville Shale, Eagle Ford Shale and the Marcellus and Utica shales (via pipeline).

Methane emissions from the Permian and San Joaquin basins are higher than elsewhere, due to rapid drilling/fracking activity with incomplete (under construction) gas export infrastructure in the Permian, and aging infrastructure with idle wells in the San Joaquin basin. Data in the Sherwin report confirm that emissions in the midstream sector go down over time, as export infrastructure is being improved.

Satellite observations provide a more comprehensive, and thus more representative, overview of methane emissions over land than selective surveying from an aircraft, and in the DTU study EPA data were used that are based on recorded GHG emissions from oil production and from gas production across the USA, consistent with satellite observations. For instance, methane emissions by US oil and gas production amount to 0.9% of gas produced while emissions by just natural gas production are circa 1.1% of gas produced, based on bottom-up and satellite analysis by the EPA. This is considerably lower than the 2.8% of gas leakage estimated by Sherwin and Howarth.

6.4 <u>Global methane emissions, satellite: Scarpelli (Harvard)</u> [Ref. 23]

6.4.1 The 2022 report by Scarpelli et al [Ref. 23] titled "Updated Global Fuel Exploitation Inventory (GFEI) for Methane emissions from the Oil Gas and Coal sectors Evaluation with inversions of atmospheric Methane observations" is an independent verification of national methane emission inventories by providing spatially resolved inventory information obtained through inversion analysis of atmospheric methane observations by satellites. The study emphasizes the potential of satellite observations, particularly from the TROPOMI (TROPOspheric Monitoring Instrument) satellite, to enhance the evaluation and improvement of national methane inventories. TROPOMI data offers higher density observations, which can lead to finer-resolution inversions [Ref. 37 Lorente et al].

Methane emissions from the Scarpelli report were used in the DTU study to calculate the satellite-based emissions of oil and gas production (Tables 4 and 5) discussed in Section 4.2 and shown in Fig. 4 and Fig. 21. Coal production data by IEA and Oil & Gas production data by EI (Energy Institute) were used.

	CH_4 emissions		
Country	Oil (MMt)	Gas (MMt)	Coal (MMt)
USA	1.77	6.34	2.13
Russia	2.11	1.99	2.73
Qatar	0.10 (est)	0.05 (est)	
Algeria	0.20	1.07	
Australia		0.32	0.90
Colombia			0.35
Kazakhstan			0.28

	CH_4 emission factors		
Country	Oil (t/1000m^3)	Gas (t/mln m^3)	Coal (t/kt)
USA	2.35	5.49	3.32
Russia	3.67	2.95	
Qatar	1.40 (est)	0.30 (est)	
Algeria	3.00	12.7	
Australia			1.8
Colombia			4.2
Kazakhstan			2.44

Table 4 (left): Methane emissions of oil, gas and coal extraction operations in the countries studied, obtained via inversion of satellite data [Ref. 23].

Table 5 (right): Methane emission factors (emitted methane per unit of production) expressed in tonne CH_4/1000 m^3 oil, tonne CH_4/mln m^3 gas, or tonne CH_4/ktonne coal, for oil, gas and coal, respectively. Note: tonne = metric ton.

6.5 <u>USA LNG exports: Roman-White (National Energy Technology Laboratory)</u> [Ref. 7]

This case study [Ref. 7] provides greenhouse gas intensities for all stages of the LNG value chain for LNG exported from the USA (Sabine Pass) to China, and to a range of other countries, including the Netherlands.

6.5.1 Stages of the value chain described in the report are: Production; Gathering & Boosting; Processing; Transmission Network; Liquefaction; and Ocean Transport.

6.5.2 The 2021 article compares results with those of two earlier studies, by Gan et al (2020) and by NETL (2019), that had evaluated 40-50% higher GHG intensities. The more recent lower intensities were mainly a result of using more recent and more relevant production and transmission data (i.e. actual sources of natural gas for LNG, and pertinent compressor efficiencies for the gathering and boosting stages).

6.5.3 Main differences with the DTU study are higher emission estimates for the transmission and processing stages of the value chain, which were based by NETL on bottom-up modelling, and IPCC inspired assumptions on methane slippage/leakage (Fig. 21).

6.5.4 The case study concludes that fuel switching from coal to LNG in China can reduce GHG emissions by circa 50%, which is similar to the DTU study's assessment for Denmark, where switching from coal to LNG or domestic gas can reduce GHG emissions by 31% or 40%, respectively.

6.5 <u>Global LNG imports to EU: Russ (Thinkstep consultancy)</u> [Ref. 10]

This case study titled "GHG Intensity of Natural Gas Transport", by Russ (Thinkstep consultancy) [Ref. 10] compares natural gas imports to Europe, via the Nord Stream 2 Pipeline, with LNG imports from the USA, Qatar, Australia and Algeria.

6.5.1 Results for Qatar and Algeria are similar to those of the DTU study, but emissions for US LNG are higher, mainly due to higher emission estimates for production and transmission (Fig. 21).

6.5.2 Main conclusion of the report is that import of piped gas from Russia has a significantly lower carbon footprint (6.3 g CO_2e/MJ) than imported LNG alternatives (15-24 g CO_2e/MJ). This is similar to, but still higher than, the carbon footprint of Danish gas of 5.3 g CO_2e/MJ.

7. Sensitivities.

7.1 Impact of satellite measurement and evaluation techniques

7.1.1 Water strongly absorbs radiation in the infrared, leading to low reflectivity of the signals detected by satellites. This low return signal affects both CO_2 and CH_4 measurements. However, for the weaker methane signal, (CH_4 concentration of 2 ppm versus 400 ppm for CO_2), this reduction in the amount of light available for absorption is more critical.
The combination of water absorption in methane's spectral bands attenuating the already low CH_4 signal, the low and mirror-like reflectivity of water surfaces, the presence of significant water vapor in the atmosphere above, and the challenges in characterizing water surfaces makes it very difficult for satellites to obtain reliable and accurate methane concentration data over oceans, lakes, and rivers. Consequently, satellite quantification typically underestimates methane emissions of offshore O&G production operations (e.g. Qatar) vis a vis onshore O&G operations (e.g. USA, Russia, Algeria).

7.1.2 Over land satellites are better able to detect localized emissions of CH_4 than of CO_2 because the lower atmospheric background of methane leads to a larger relative signal increase from localized sources, and the spectral absorption features of methane can be more easily identified as anomalies against the land surface. While detecting localized CO_2 emissions is possible, the high background concentration and the focus on larger-scale measurements make it a more challenging task for current satellite technology.

7.1.3 Consequently, satellites are a reliable tool for quantification of methane emissions by onshore O&G production operations, but not so much for CO_2 emissions where more aerial resolution is required.

7.2 Impact of shipping routes (geopolitical factors)

7.2.1 The shortest route for transport of coal from Australia and of LNG from Qatar to Rotterdam is via the Suez Canal. However, given attacks on shipping in the Red Sea much of the container and bulk transportation has been rerouted around Africa, which adds some 3,500 km to coal shipping from Australia, and 4,700 nm (8700 km, 10 days) to LNG shipping from Qatar. The impact of this is quantified in Section 5.2.3 and Table 3.

7.2.2 The shortest route for coal from Kazakhstan is by train (via Kazakhstan, Russia) to Latvia, and onwards by ship via the Baltic Sea to Rotterdam. An alternative route is by train (via Kazakhstan) to the Russian Black Sea port of Taman, and onwards by ship via the Black Sea and Mediterranean Sea to Rotterdam, which has a 350 km shorter train route but adds 5,000 km to the shipping route. Currently circa half of Kazakh coal is transported to Rotterdam via the Baltic route, and half via the Black Sea route, but this may change depending on EU measures that may close the border for trade between Russia and Latvia. See Section 5.2.3 and Table 3 for quantification of its impact.

7.3 Impact of Tyra Redevelopment coming onstream

7.3.1 Platforms of the Tyra centre, a major hub in Danish offshore infrastructure for production, processing and export of natural gas, have been modernized in order to ensure sustainable production for the next two decades. The original platforms had experienced seabed subsidence of circa 5 metres due to compaction of the pressure depleted chalk reservoir, and required re-development to keep crews and facilities safe from storm waves. This was used as an opportunity to also fit new equipment to reduce GHG emissions from the facilities. The new facilities came on-stream during 2024, and production has been increasing since then.

7.3.2 CO_2 emissions of Danish Oil and Gas production were calculated based on Operator forecasts for the year 2026, when production is expected to have stabilized, while CH_4 emissions were based on extrapolated 2020-2023 operator data (this study). Total estimated GHG results for 2026 are compared to 2023 emissions, the most recent year with reliable production and emission data in the public domain for the full Danish offshore sector. See Table 3 in Section 5.2.3, and Table 8 in Section 8.1.

7.3.3 Total normalized GHG emissions of Danish Oil and Gas production of 5.32 g CO_2e/MJ in 2023 are projected to decrease by circa 25% to 4.0 g CO_2e/MJ in 2026 (Fig. 23). In case methane emissions by the new Tyra facilities are significantly lower than they were before redevelopment the reduction in normalized GHG emissions may be even more than 25%.

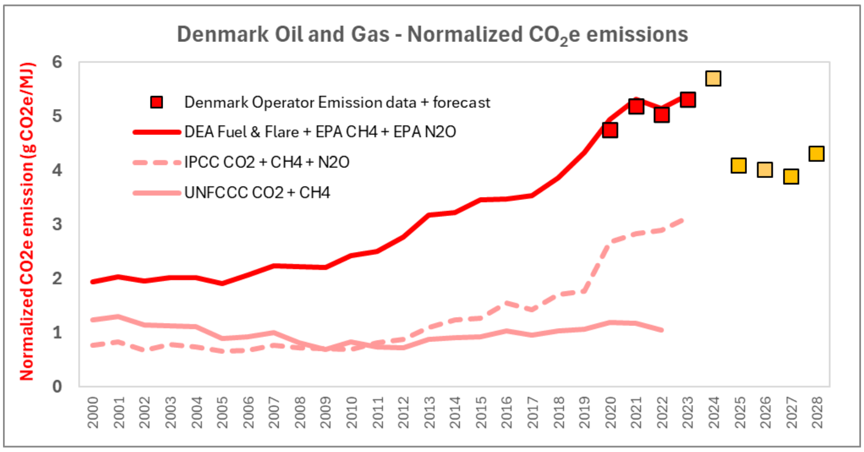


Fig. 23: Danish Offshore O&G normalized GHG emissions (GWP_{100}): comparison of historical record of emissions reported in the public domain (red lines and squares) and calculated projected future emissions based on Operator provided forecasts of production and emissions (orange squares). The new Tyra facilities are expected to reduce WTT emissions by circa 25% from 2023 to 2026.

7.4 Replacement of Coal by LNG or Danish Natural Gas

7.4.1 Replacement of coal by alternative fuels is a relevant factor to be considered in discussions regarding reform of the EU Emissions Trading System (EU ETS). Coal combustion was responsible for circa 15% of Danish GHG emissions in 2022, or an estimated 10% in 2024 [Ref. 52].

7.4.1.1 Sensitivities were carried out to quantify the impact on total Denmark GHG emissions in case coal consumption in Denmark were entirely replaced by domestic natural gas or imported LNG. If coal at 2022 consumption levels had been replaced by Danish gas or LNG, Danish scope 3 GHG emissions (i.e. emissions generated in Denmark) would have decreased by circa 6% (Fig. 24). Compared to 2024 coal consumption levels, scope 3 emissions would have decreased by 4%, but by merely 0.2% for scope 1 emissions (excluding combustion). Note that scope 1 emissions for replacing coal by LNG would actually increase, since LNG extraction and transport emits more GHGs on average than coal, causing negative savings (Figs. 24, 25, 26).

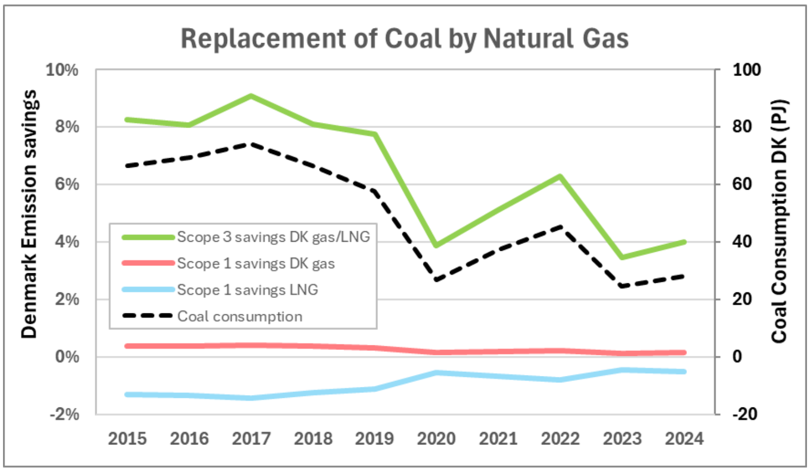
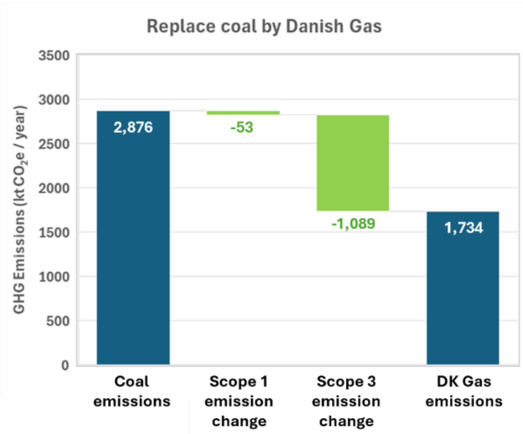


Fig. 24: GHG emissions savings of replacing coal by Danish Natural Gas or imported LNG as a percentage of total Denmark GHG emissions, and and as a function of the year the replacement takes place (GWP_{100}). Since coal consumption has historically declined the savings are decreasing accordingly and would amount to circa 4% for Danish gas in 2024 for scope 3 emissions (i.e. including combustion effects) but only 0.1% for scope 1 emissions (excluding combustion). Note that scope 1 emissions for replacing coal by LNG would actually increase, causing negative savings.



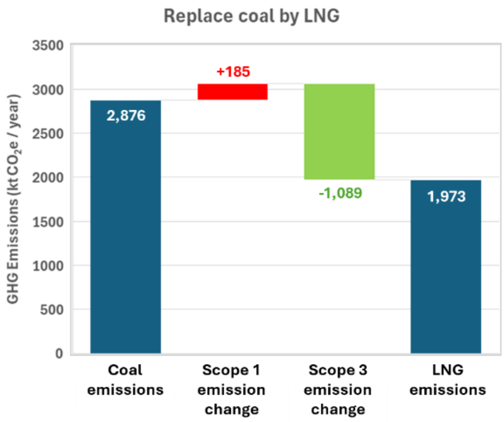


Fig. 25 (left): Wash line chart of Denmark emissions changes for replacing imported coal by domestic gas in 2024 (GWP_{100}).
Fig. 26 (right): Wash line chart of Denmark emissions changes for replacing imported coal by imported LNG in 2024 (GWP_{100}).

7.5 Impact of using GWP_{20} instead of GWP_{100}

7.5.1 Since methane has a shorter atmospheric lifespan than CO_2, the GWP of methane is different in a 20-year or 100-year reference framework. In either case methane has a higher warming potential than CO_2, but much more so in the 20-year reference framework. For this sensitivity analysis the GWP of CH_4 was assumed to be as follows: GWP_{100} CH_4 = 28 CO_2e and GWP_{20} CH_4 = 84 CO_2e, consistent with the

IPCC Assessment Report	CO_2 GWP_{20}	CO_2 GWP_{100}	CH_4 GWP_{20}	CH_4 GWP_{100}	N_2O GWP_{20}	N_2O GWP_{100}
AR4	1	1	72.0	25.0	289	298
AR5 No CC fb	1	1	84.0	28.0	264	265
AR5 With CC fb	1	1	86.0	34.0	268	298
AR6 Fossil	1	1	82.5	29.8	273	273
AR6 Non-fossil	1	1	79.7	27.0	273	273

conversion factors used in the fifth IPCC assessment report (Table 6).

Table 6: Global Warming Potentials (in CO_2e) from the Fourth, Fifth, and Sixth IPCC Assessment Reports.
CC fb = Climate-Carbon feedback, i.e. accounting for the indirect effects that warming has on
CO_2 release from e.g. soils, oceans and permafrost

7.5.2 For coal and LNG most of the methane is emitted during the production phase of the value chain, although leakage during processing and transport is still substantial.

7.5.2.1 Methane emissions during production or mining are extensively reported, verified by satellite calibration, and their contributions to the total GWP_{100} are typically 65-95% for coal mining and 20-90% for natural gas production (GWP_{100}). When recalculating these emissions over a 20-year period the methane contributions to GWP_{20} increased to 84-99% for coal mining and to 40-97% for natural gas production.

7.5.2.2 Methane emissions by liquefaction and transport of LNG were obtained from reports by Zhu [Ref. 58] and Howarth [Ref. 5], that indicate that circa 5% of the total GWP_{100} of LNG liquefaction [Ref. 58] and circa 37-50% of the total GWP_{100} of LNG transport is due to CH_4 emissions. When recalculating these emissions over a 20-year period the methane contributions to GWP_{20} increased to circa 14% for LNG liquefaction and to 64-75% for LNG transport.

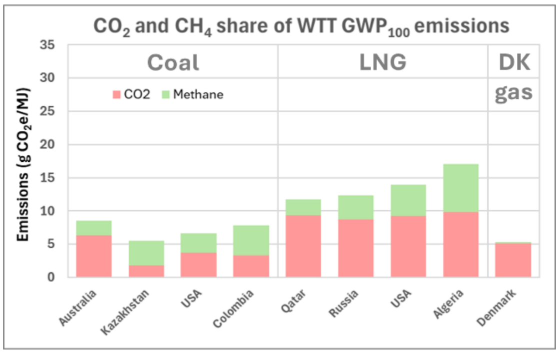
7.5.3 When including the above impacts of methane on the 20-year Global Warming Potential of the Production and Transport (WTT) part of the value chain the weighted averages of CO_2e emissions are circa 75% higher for coal and LNG, and circa 7% for Danish gas, compared to the 100-year Global Warming Potential (see Table 7).
When the entire value chain is considered (WTW) the 20-year Global Warming Potential is still circa 6% higher for coal and circa 15% for LNG (Table 7).

Sensitivities GWP_{20} / GWP_{100}		Production & Transport (WTT) (GWP_{20} / GWP_{100})	Production, Transport & Combustion (WTW) (GWP_{20} / GWP_{100})
Coal	Short route	1.78	1.06
Coal	Long route	1.73	1.05
LNG	Short route	1.77	1.15
LNG	Long route	1.77	1.16
DK Gas	Tyra 2023	1.08	1.01
DK Gas	Tyra 2026	1.06	1.00

Table 7: Ratios of the 20-year and 100-year Global Warming Potential impacts of the energy carriers studied, for different transportation routes, and for WTT and WTW value chains. The GWP_{20} is typically higher than the GWP_{100} due to methane being emitted along the value chain, which has a shorter atmospheric lifespan than CO_2 and therefore a stronger short-term impact.

7.5.4 The data clearly shows that the uncertainty in absolute Global Warming Potential as expressed in CO_2e is dominated by the assumption whether to use a 20- or 100-year GWP reference (± 77%), rather than for instance transport route uncertainty (± 7% for coal; ± 3% for LNG) or measurement uncertainty (± 17% for coal; ± 20% for LNG, see Section 4.2.5). These other sensitivities remain, of course, relevant to compare relative GWP contributions of choices that have an impact on emissions, but it should be remembered that the absolute impact is very much dependent on the time horizon being chosen.

7.5.5 Figures 27 and 28 demonstrate that the warming potential of coal and LNG Well-To-Tank emissions are dominated by CO_2 in a GWP_{100} reference framework, but by methane in a GWP_{20} framework. It is therefore a sensible short-term measure to prioritize low-cost CH_4 emission reduction efforts over high-cost CO_2 emission reduction efforts globally. Figures 29 and 30 re-iterate the benefits of replacing coal by natural gas (including LNG) from a short-term as well as long-term perspective.



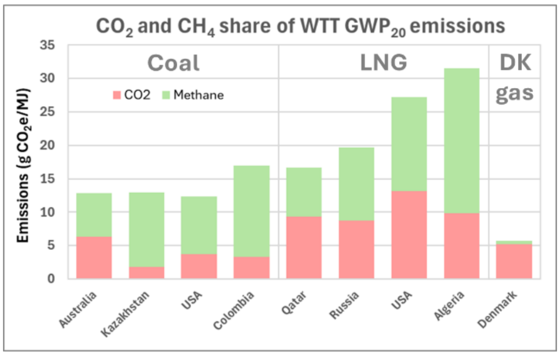
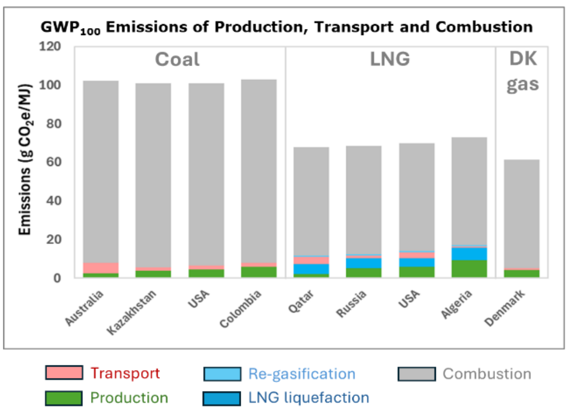


Fig. 27 (left): GWP_{100} impact of production and transport (WTT) emissions of imported coal, LNG and Danish natural gas.
Fig. 28 (right): GWP_{20} impact of production and transport (WTT) emissions of imported coal, LNG and Danish natural gas.



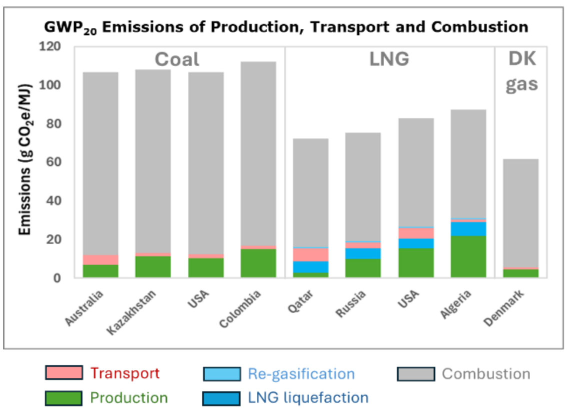


Fig. 29 (left): GWP_{100} impact of full value chain (WTW) emissions of imported coal, LNG and Danish natural gas
Fig. 30 (right): GWP_{20} impact of full value chain (WTW) emissions of imported coal, LNG and Danish natural gas

8. Conclusions.

8.1 The full value chain GHG emissions (GWP_{100}) of natural gas produced in Denmark (Production, Transport & Combustion) are circa 40% lower than of imported coal, and circa 12% lower than of imported LNG. When only considering the emissions of production and transport (i.e. excluding combustion), Danish gas GHG emissions are circa 26% lower than of imported coal, and circa 61% lower than of imported LNG (see Table 8).

Sensitivities GWP_{100}		Production & Transport (WTT) (g CO_2e/MJ)	Production, Transport & Combustion (WTW) (g CO_2e/MJ)
Coal	**Short route**	7.21	101.9
Coal	**Long route**	7.73	102.4
LNG	**Short route**	13.77	69.87
LNG	**Long route**	14.24	70.34
DK Gas	**Tyra 2023**	5.32	61.42
DK Gas	**Tyra 2026**	4.01	60.11

Table 8: Normalized GHG emissions (in g CO_2e/MJ, GWP_{100}) of the energy carriers studied, and sensitivities regarding transport routes and impact of new gas processing and export facilities in the Danish Offshore sector (Tyra Centre).

Emissions due to combustion are by far the largest contributor to GWP, with coal having the largest impact, and with natural gas emitting circa 41% less GHGs per energy unit than coal from a combustion only perspective. The emissions advantage of natural gas over coal is, however, reduced from ca. 41% to ca. 31% when gas is imported as LNG and production and transport emissions are included. Danish natural gas clearly still has the lowest overall emissions, with 40% less GWP_{100} than coal over the entire lifecycle.

Re-development of the Tyra Centre has increased gas production in the Danish sector, which has consequently led to a reduction of normalized GHG emissions (in CO_2e/MJ). The projection for 2026, when production is expected to have stabilized, is a reduction of normalized WTT emissions by 25%, compared to 2023.

8.2 Uncertainty in the estimates is significant, due to measurement challenges (for instance of satellite measurements of methane above large bodies of water), under-reporting of small or diffuse emission sources and the use of generic emission factors in the absence of reliable measurements.

CO_2 measurements by satellite can be compromised in areas with frequent cloud cover, high humidity and complex land-water interactions. CH_4 measurements are particularly challenging over large water bodies, where less infrared light returning to the satellite than over land, combined with an overall much lower atmospheric concentration of CH_4 compared to CO_2, leads to poor signal-to-noise ratios, to the point that methane emissions of offshore activities cannot be reliably verified by satellite.

According to the IPCC's AR6 report [Ref. 56] global measurement uncertainty of methane is circa 30% and of CO_2 circa 12%, which results in an emissions uncertainty of circa 20% for coal total WTT CO_2e emissions and circa 18% for LNG total WTT CO_2e emissions, for the coal and LNG suppliers considered in this study. This is similar to the observed variation of reported production related emissions described in Section 4.2.5, with coal emissions varying by circa 17% and LNG emissions varying by circa 20%.

When considering the total value chain, including combustion, the emissions uncertainties for coal and LNG drop to ±6% and ±5%, respectively, assuming a combustion emissions uncertainty of ±5% and ±2% for coal and natural gas, respectively.

8.3 Relative GWP contributions of the various energy carriers, for the various transport routes and value chain choices, are more easily visualized when indexed to just one of the energy carriers. The tables below (Tables 9, 10, 11) thus show the numbers of Table 8, but indexed to either coal, LNG or Danish gas as 100.

Sensitivities		Production & Transport (WTT) (Coal = 100)	Production, Transport & Combustion (WTW) (Coal = 100)
Coal	Short route	100.0	100.0
Coal	Long route	107.3	100.5
LNG	Short route	191.0	68.6
LNG	Long route	197.5	69.0
DK Gas	Tyra 2023	73.8	60.3
DK Gas	Tyra 2026	55.6	59.0

Sensitivities		Production & Transport (WTT) (LNG = 100)	Production, Transport & Combustion (WTW) (LNG = 100)
Coal	Short route	52.4	145.8
Coal	Long route	56.2	146.6
LNG	Short route	100.0	100.0
LNG	Long route	103.4	100.7
DK Gas	Tyra 2023	38.7	87.9
DK Gas	Tyra 2026	29.1	86.0

Sensitivities		Production & Transport (WTT) (DK gas = 100)	Production, Transport & Combustion (WTW) (DK gas = 100)
Coal	Short route	135.4	165.9
Coal	Long route	145.3	166.7
LNG	Short route	258.7	113.7
LNG	Long route	267.5	114.5
DK Gas	Tyra 2023	100.0	100.0
DK Gas	Tyra 2026	75.3	97.9

Table 9 (left): Presentation of normalized GHG emission numbers of table 8, but indexed to Coal =100 (GWP_{100})
Table 10 (middle): Presentation of normalized GHG emission numbers of table 8, but indexed to LNG =100 (GWP_{100})
Table 11 (right): Presentation of normalized GHG emission numbers of table 8, but indexed to Danish gas =100 (GWP_{100})

8.4 The 20-year impact on Global Warming Potential (GWP_{20}) associated with the WTT production & transport of imported coal or imported LNG is higher for methane emissions (72% or 57%, respectively) than for CO_2 emissions (28% or 43%, respectively) (Fig. 28). The 100-year impact of emissions (GWP_{100}) by coal and LNG production and transport (WTT) remain higher for CO_2 (53% for coal, and 67% for LNG; see Fig. 27), while the full value chain emissions (WTW) are of course completely dominated by CO_2 emissions due to the impact of combustion, with CO_2 being responsible for 93% of coal GWP_{100} and 80% of LNG GWP_{100} (Fig. 29). These full value chain (WTW) GWP numbers for CO_2 drop to 87% of coal GWP_{20} and 70% of LNG GWP_{20} when using a 20-year, rather than a 100-year, perspective (Fig. 30). This reinforces the notion that relatively quick and low-cost measures to reduce methane emissions are sensible short-term actions.

8.5 Methane emissions by the Danish offshore oil and gas industry are comparatively small, causing relatively minor differences between 100-year and 20-year Global Warming Potentials. WTT normalized emissions increase by just 8% from 5.3 g CO_2e/MJ (GWP_{100}) to 5.7 g CO_2e/MJ (GWP_{20}), while WTW normalized emissions increase by less than 1% from 61.4 g CO_2e/MJ (GWP_{100}) to 61.8 g CO_2e/MJ (GWP_{20}), Efforts to reduce the CO_2e footprint of Danish oil and gas production are therefore likely to concentrate on improving energy efficiency of operations, in order to reduce direct CO_2 emissions per produced barrel.

Abbreviations:

BP	British Petroleum, originator of the Statistical Review of World Energy
DEA	Danish Energy Agency (Energistyrelsen), provider of Danish energy related data
EDGAR	Emissions Database for Global Atmospheric Research, a European Union sponsored database that contains independent emission assessments based on satellite observations and IPCC methodology
EI	Energy Institute, current provider of the Statistical Review of World Energy https://www.energyinst.org/statistical-review
EIA	United States Energy Information Administration, provider of US gas production data
EPA	United States Environmental Protection Agency, provider of detailed US gas production and emission data, and of global non-CO_2 emission data
EU ETS	EU Emissions Trading System (EU ETS)
IEA	International Energy Agency, provider of global production data and the Methane Tracker
IEEFA	Institute for Energy Economics and Financial Analysis, provider of LNG terminal data
IPCC	International Panel for Climate Change, provider of detailed emission assessments and methodologies
TROPOMI	The TROPOspheric Monitoring Instrument on board the Sentinel 5 Precursor (S5-P) satellite, providing methane (CH_4) measurements with accurate temporal and spatial resolution.
UNFCCC	United Nations Framework Convention on Climate Change, provider of country reports

Citations:

We acknowledge the EDGAR report webpage (https://edgar.jrc.ec.europa.eu/report_2024) and EDGAR_2024_GHG website (https://edgar.jrc.ec.europa.eu/dataset_ghg2024) as a data source for this article

EDGAR (Emissions Database for Global Atmospheric Research) Community GHG Database (a collaboration between the European Commission, Joint Research Centre (JRC), the International Energy Agency (IEA), and comprising IEA-EDGAR CO2, EDGAR CH4, EDGAR N2O, EDGAR F-GASES version EDGAR_2024_GHG (2024) European Commission.

IEA-EDGAR CO2 (v3), a component of the EDGAR (Emissions Database for Global Atmospheric Research) Community GHG database version EDGAR_2024_GHG (2024) including or based on data from IEA (2023) Greenhouse Gas Emissions from Energy, www.iea.org/statistics, as modified by the Joint Research Centre.

The greenhouse gas emission data reported under the Industrial Emissions Directive 2010/75/EU and European Pollutant Release and Transfer Register Regulation (EC) No 166/2006 was obtained from here: https://sdi.eea.europa.eu/catalogue/srv/eng/catalog.search#/metadata/9405f714-8015-4b5b-a63c-280b82861b3d

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Data sets:

Coal: Production, Emissions, Transport

- Statistical Review of World Energy - https://www.energyinst.org/statistical-review
- 2024 Energy Institute Statistical Review of World Energy - https://www.energyinst.org/__data/assets/excel_doc/0020/1540550/EI-Stats-Review-All-Data.xlsx
- IEA Global Coal production - https://www.iea.org/data-and-statistics/charts/global-coal-production-2000-2025
- IEA Global Methane Tracker - Global Methane Tracker 2024 – Analysis - IEA
- EDGAR Global Greenhouse Gas Emissions - https://edgar.jrc.ec.europa.eu/dataset_ghg2024
- CH_4 emissions: Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation Potential - EPA 2025 - Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation Potential: 2020-2080 | US EPA
- Non-CO_2 report Data annex - Emission baselines by type of gas - EPA 2024 - https://www.epa.gov/system/files/other-files/2025-04/non-co2-report-data-annex-gloabl-domestic-2025.zip

Oil and Natural Gas: Production, Emissions, Transport

- Statistical Review of World Energy - https://www.energyinst.org/statistical-review
- EIA (Energy Information Administration) Natural Gas - https://www.eia.gov/dnav/ng/hist/n9010us2a.htm
- US Environmental Protection Agency: Natural Gas and Petroleum Systems - https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2022-ghg
- Non-CO_2 report Data annex - Emission baselines by type of gas - EPA 2024 - Non-CO2 Greenhouse Gas Emission Projections & Mitigation | US EPA
- LNG carbon footprint analysis – NSTA 2023 - https://www.nstauthority.co.uk/the-move-to-net-zero/net-zero-benchmarking-and-analysis/natural-gas-carbon-footprint-analysis/
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Denmark Oil and Gas: Production, Emissions

- Statistical Review of World Energy - https://www.energyinst.org/statistical-review
- UNFCCC National Inventory Document Denmark 2025 - https://unfccc.int/documents/646479
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- Non-CO2 report Data annex - Emission baselines by type of gas - EPA 2024
- E-PRTR European Pollutant Release and Transfer Register database - https://sdi.eea.europa.eu/catalogue/srv/eng/catalog.search#/metadata/9405f714-8015-4b5b-a63c-280b82861b3d

Conversion factors:

Approximate conversion factors – Statistical Review of World Energy – BP 2021
https://climateaccountability.org/wp-content/uploads/2023/10/Coal-CarbonCoefficient-8p.pdf
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