On behalf of SGMF

3rd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel

Executive Summary

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On behalf of Sphera Solutions, Inc., and its subsidiaries

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Executive Summary

This 3^rd^ *Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel* is an update of the 2nd greenhouse gas (GHG) study published by Sphera in April 2021 (*2^nd^ Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel*). It is the second in a series of regular updates of greenhouse gas (GHG) emissions to reflect ongoing technology developments in fuel supply and marine propulsion systems.

IMO GHG emission reduction targets, as well as air quality restrictions in ports and coastal areas are challenging the shipping industry to further reduce their airborne emissions. While some emission reduction may be achieved by efficiency improvements, the industry needs alternatives to continue reducing emissions. There is increasing interest in LNG is as a potential alternative lower carbon fuel in the short to medium term. Especially, since LNG can be produced from biogenic sources via anaerobic digestion (AD) or gasification or synthetically from hydrogen (H_2) and carbon dioxide (CO_2) captured using renewable electricity without changing bunkering or engine technology. Therefore, the primary motivation for this study is to use the latest primary and secondary data to evaluate the GHG and local air pollution from fossil, biogenic, and synthetic LNG compared to conventional fossil fuels used in maritime shipping.

Figure ES-1 shows the twelve LNG pathways considered in the study. Biogenic LNG is considered anaerobic digestion of manure and residuals, landfill gas, and gasification of forest residues. Synthetic LNG considered H_2 from electrolysis powered by renewable electricity and as a co-product from the chlor-alkali process. Considered CO_2 sources included direct air capture (DAC), a biomass combined heat and power plant, and a coal-fired combined heat and power plant.

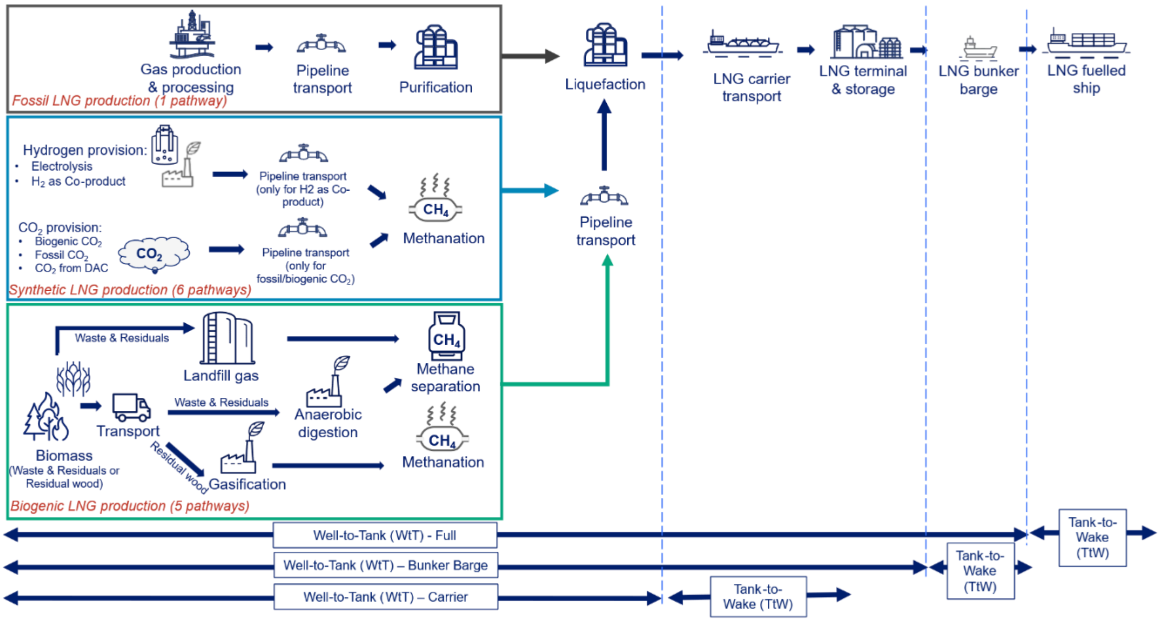

Figure ES-1: Process flow diagram for the LNG pathways considered in the study

Key Messages from the Study

Unless otherwise stated, the results reported are for the Base Case according to the ISO 14040:2006 and 14044:2006 standards. Key findings for the Well-to-Wake (WtW) analysis are separated by engine type, and the key findings of 2-stroke slow speed Otto engines are as follows:

- Using fossil LNG results (519 to 581 g CO_2-eq/kWh) in a GHG intensity that is 16 to 25% lower than $MGO_{0.1}$ (689 g CO_2-eq/kWh), depending on the fuel efficiency and emissions control technology implemented.
    - Low-pressure exhaust gas recirculation reduced WtW GHG emissions by 9%, while using a variable compression ratio reduced emissions by an additional 2%.
    - Per MJ of fuel input, fossil LNG is 11 to 16% lower than $MGO_{0.1}$ because LNG engines examined in this study have greater fuel efficiency than MGO engines examined.
    - Methane slip of the engines accounts for 5 to 10% of the WtW emissions, depending on the fuel efficiency and emissions control technology implemented.
- For each design studied, all LNG pathways, had the same TtW GHG intensity, which ranged from 406 (Design 1) to 460 (Design 3) g CO_2-eq/kWh. This represents a 19 to 29% reduction compared to $MGO_{0.1}$.
- The considered biogenic LNG pathways reduce GHG intensity compared to $MGO_{0.1}$ by 56% (AD) to 113% (LFG+CCS) based on a kWh of engine output.
- The considered synthetic LNG pathways that use ambient or biogenic CO_2 reduce GHG intensity by 45 (DAC+ICP) to 80% (DAC+Electrolysis) per kWh, while synthetic LNG using fossil CO_2 increased GHG intensity by up to 20% (FPS+ICP) compared to $MGO_{0.1}$.
- The contribution for the pilot fuel on the overall WtW GHG emissions for fossil LNG ranges between 0.7 and 0.9%, depending on the design used (different fuel efficiency and emissions control technology). For the biogenic LNG, it can be up to 12% (AD+CCS) and for the synthetic LNG up to 2.7% (via CO_2 from DAC and H_2 from electrolysis).

The key findings of the WtW analysis for 4-stroke medium speed Otto engines are as follows:

- Using fossil LNG (646 g CO_2-eq/kWh) results in a GHG intensity that is 11% lower than $MGO_{0.1}$ (725 g CO_2-eq/kWh), which is driven by a 14% reduction in TtW GHG emissions (LNG: 515 g CO_2-eq/kWh and $MGO_{0.1}$: 600 g CO_2-eq/kWh).
    - Per MJ of fuel input, fossil LNG is ~10% lower than $MGO_{0.1}$ because LNG engines examined in this study have greater fuel efficiency than $MGO_{0.1}$ engines.
    - Methane slip of the engines accounts for 12% of the WtW emissions.
- The biogenic LNG pathways reduce GHG intensity compared to $MGO_{0.1}$ by 52 (AD) to 106% (LFG+CCS) on a per kWh basis.
- The synthetic LNG pathways that use ambient or biogenic CO_2 reduce GHG intensity by 40 (DAC+ICP) to 70% (DAC+Electrolysis), while synthetic LNG using fossil CO_2 increased GHG intensity by 15 (FPS+Electrolysis) to 25% (FPS+ICP) compared to $MGO_{0.1}$.
- The contribution for the pilot fuel for fossil LNG 4%. For the biogenic LNG it can be up to 24% (AD+CCS) and for the synthetic LNG up to 11% (via CO_2 from DAC and H_2 from electrolysis).

Additional results are presented that are aligned with the International Marine Organization's (IMO's) *2024 Guidelines on Life Cycle GHG Intensity of Marine Fuel,* the European Commission's Renewable Energy Directive II (REDII) and FuelEU Maritime regulation, as well as the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping's (MMMCZCS's) LCA Methodology. Key findings associated with comparing these frameworks are as follows:

- The inclusion of waste feedstock counterfactual credits dominates the WtT and WtW GHG emissions from pathways that use manure as a feedstock. Therefore, the inclusion or exclusion of these credits should be explicitly addressed in guidelines.
    - These credits are approximately five times larger than CCS credits and lead to net negative WtW emissions.
- Considering H_2 as an industrial co-product reduces WtW GHG emissions for relevant pathways by 5 to 19%.
- Excluding infrastructure burdens from renewable electricity used for electrolysis reduces synthetic LNG pathways using DAC or BPS by 43 to 47%.

The key findings of the WtT analysis are as follows (all WtT values summarised here refer to MJ of LNG delivered to ship tank if not indicated otherwise):

- The GHG intensity of the global fossil LNG supply is 16.9 g CO_2-eq/MJ.
    - This is 15% higher than the GHG intensity from MGO$_{0.1}$. [5]
    - It represents a ~4% of reduction from the 2nd LNG Study [5] (17.7 g CO_2-eq/MJ), which is considered insignificant based on the define criteria for significance.
- In the Base Case, which excludes waste feedstock management credits, the GHG intensity of the biogenic LNG supply ranges from –22.4 to -74.3 g CO_2-eq/MJ when including biogenic CO_2.
    - Landfill Gas (LFG) reduces GHG intensity by 17.9 g CO_2-eq/MJ compared to anaerobic digestion of manure and residuals in a dedicated biogas plant because the LFG is assumed to enter the system burden free, as it is generated in each case by the decaying waste and needs to be collected regardless of its potential beneficial use as fuel.
    - Capturing the CO_2 removed during CH_4 separation reduces the GHG intensity by 34 g CO_2-eq/MJ.
    - The GHG intensity of biogenic LNG from gasification (-40.1 g CO_2-eq/MJ) is within ~2% of biogenic LNG from LFG without CCS (-40.3 g CO_2-eq/MJ) and is significantly higher than either pathway with CCS (-74.3 and -22.4 g CO_2-eq/MJ for LFG and AD, respectively).
- The GHG intensity of the evaluated synthetic LNG supply pathways ranges from -10.7 to -39.5 g CO_2-eq/MJ when including biogenic CO_2 for pathways that source CO_2 from ambient air or a biomass combined heat and power plant, and from 42.2 to 51.3 g CO_2-eq/MJ when CO_2 is sourced from a coal-fired combined heat and power plant.
    - The GHG intensity of H_2 as a co-product of chlor-alkali electrolysis (18.9 g CO_2-eq/MJ LNG or 13.8 g CO_2-eq/MJ H_2) is 87% higher than H_2 from electrolysis using wind and PV (10.1 g CO_2-eq/MJ LNG or 7.4 g CO_2-eq/MJ H_2).
    - Powering DAC from the European electricity grid (21.8 g CO_2-eq/MJ) increases the GHG intensity by a factor of 10 compared to using electricity from wind and PV (2.0 g CO_2-eq/MJ).
    - Using fossil CO_2 in synthetic LNG significantly increases the GHG intensity compared to CO_2 from a biogenic point source or the ambient air. If CO_2 from fossil FPS is treated as fossil, then these synthetic LNG pathways do not reduce emissions relative to conventional fossil LNG.

Taken in isolation, only the local air pollutants (i.e., SO_x, NO_x, PM, and BC) are relevant from the TtW component of the life cycle. TtW contributions to WtW GHG intensity are discussed in section 7.1.3. The local air pollutant emission results are directly linked to the inventory analysis and hence to the data that were collected from the engine OEMs.

The relevant findings of the Tank-to-Wake analysis are as follows:

- As new primary TtW data was only obtained for two types of LNG engines: 2-stroke slow-speed Otto dual-fuel and 4-stroke medium-speed Otto dual-fuel engines, other types of LNG engines were not considered (e.g. 2-stroke slow-speed Diesel dual-fuel).
- Methane slip in LNG accounts for 7% to 13% of engine related (TtW) GHG emissions, depending on the engine design for 2-stroke slow speed Otto engines and for around 15% of the 4-stroke medium speed engines.
- The use of LNG reduces SO_x emissions by ≥96% due to the much lower sulphur content of LNG compared to $MGO_{0.1}$.
- NO_X emissions are mainly dependent on the underlying combustion cycle and not directly on the fuel used. However, LNG engines reduce NO_x emissions compared to $MGO_{0.1}$ by 38% and ~80% in 4-stroke medium speed engines and 2-stroke slow speed Otto engines, respectively. It should be noted that different NO_x reduction targets apply to other engine technologies, and these depend on exhaust after-treatment systems.
- PM emissions are reduced by 92% for 4-stroke medium speed engines.
- No quantitative comparative statements can be made about BC due to a lack of data from engines using $MGO_{0.1}$. However, BC from engines using $MGO_{0.1}$ is almost certainly greater than engines using LNG based on emission factors from other combustion processes, and the substantially lower level of PM emissions, of which BC is a component.

Context

This 3rd GHG study analyses the life cycle GHG emissions of the use of fossil liquified natural gas (LNG) as marine fuel compared with biogenic LNG, synthetic LNG produced from hydrogen and captured carbon dioxide (CO_2). These results are benchmarked against results for conventional marine fuels (i.e., $MGO_{0.1}$ and VLSFO). In addition, air quality impacts are assessed by comparing local combustion pollutants from the operation of the engines using these different fuels.

In July 2023, the International Maritime Organization (IMO) adopted the *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, which laid out GHG emission reduction goals, guiding principles, as well as potential measures and challenges [6]. The next critical step in IMO's GHG emissions reductions plans was taken in April 2025, when they approved a draft amendment to establish a legally binding framework to achieve net-zero GHG emissions by mid-century. The proposed Net-Zero Framework include a global fuel standard as well as pricing mechanisms to encourage further reductions in GHG emissions [7]. If adopted by the Marine Environment Protection Committee (MEPC) in 2026, it will take affect at the earliest in 2028 [8].

Additionally, new vessels are required to use engines, which are Tier II compliant when operating outside Nitrogen Oxides Emission Control Areas (NECAs) and Tier III compliant whenever sailing within such NECAs. For explanations regarding the emission limit regulations, please see section 5. Where these emission limits cannot be met by the engine itself, exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) technologies must be utilised [9].

The IMO GHG emission reduction targets, as well as air quality restrictions in ports and coastal areas are challenging the shipping industry to further reduce their airborne emissions. While some emission reduction may be achieved by efficiency improvements, the industry needs alternatives to continue reducing emissions. LNG is seen as a potential lower carbon fuel in the short to medium term. Especially since LNG can be produced from biogenic sources via anaerobic digestion (AD) or gasification or synthetically from hydrogen (H_2) and carbon dioxide (CO_2) captured using renewable electricity without changing bunkering or engine technology. However, despite this potential, there are challenges associated with widespread implementation of industrial-scale biogenic and synthetic LNG including availability of feedstocks, costs, and competition for renewable electricity.

Additionally, there have been significant advancements in the use of LNG in shipping and in the potential for low-carbon alternatives such as biogenic and synthetic LNG. Therefore, there is a need to better understand the emissions performance of these fuels compared to conventional marine fuel.

This study was informed by a consortium of SGMF member companies, who are shown at the front of the report.

Study Objectives

The intention of this study is to support regulatory bodies in their work, such as the IMO and the European Commission, as well as facilitating open and transparent communications with external stakeholders such as investors, ship owners, and operators. To ensure the results are applicable as broadly as possible, life cycle GHG intensity results are generated following multiple standards and guidelines. This summary and the main body of the report provide results following ISO 14044:2006 and are critical reviewed by an external panel (Critical Review Statement can be observed in Annex A). Additional results are presented that are aligned with the International Marine Organization's (IMO's) *2024 Guidelines on Life Cycle GHG Intensity of Marine Fuel,* the European Commission's Renewable Energy Directive II (REDII) and FuelEU Maritime regulation, as well as the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping's (MMMCZCS's) LCA Methodology. As this study compares the GHG emissions associated with multiple fuel pathways, the results are intended to be used to support comparative assertions intended be disclosed to the public.

Methodology and Approach

This study is a Well-to-Wake Life Cycle Assessment of LNG as a marine fuel in accordance with ISO 14044:2006 for a single impact category: global warming. In the Well-to-Tank part of the study primary data was collected for the LNG supply chain (natural gas production, purification & liquefaction, transport, storage, and bunkering). These data are supplemented by data from Sphera's Managed LCA Content (MLC) and literature.

Figure ES-1 shows the twelve LNG pathways considered in the study. The selection of pathways began with the thirteen LNG pathways proposed by the International Marine Organization (IMO) in Appendix 1 of *2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels.* Three pathways using fossil natural gas to produce synthetic natural gas were removed, and two pathways that produce biogenic LNG from landfill gas with and without carbon capture and sequestration were added. Using natural gas as a feedstock for synthetic LNG is not considered a practical option due to the high conversion losses within steam methane reforming and methanation. The two biogenic landfill gas (LFG) pathways have been added to distinguish between biomethane produced from manure and other residues in an anaerobic digestion (AD) plant and burden-free LFG from a landfill.

Tank-to-Wake (TtW) primary data such as LNG consumption, pilot fuel consumption, methane slip, and combustion emissions were collected from engine manufacturers and vessel operators. Table ES-1 shows the engines and fuels considered in this study. New primary TtW data was only obtained for two types of LNG engines: 2-stroke slow-speed Otto dual-fuel and 4-stroke medium-speed Otto dual-fuel engines. No new data could be collected for other engine types (e.g. 2-stroke slow-speed Diesel dual fuel). Furthermore, the results of the study are only compared with MGO-powered engines in Tier III, as the engine technologies for which new data were provided are directly Tier III compliant and therefore the comparison is made with MGO, the most commonly used fuel for Tier III compliant usage. Detailed findings for VLSFO- and HFO-powered engines are available in the *2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel*. Furthermore, the difference in WtW GHG emissions was previously found to be negligible (i.e., ≤1.7%).

Table ES-1: Overview of engines technologies and fuels evaluated[a]

Engine type	Speed	Cycle	$MGO_{0.1}$	LNG
2-stroke	Slow	Diesel Dual-Fuel	**X** no update	no update
	Slow	Otto Dual-Fuel	n/a	**X**[b] new data
4-stroke	Medium	Diesel Dual-Fuel/Compression-Ignition	**X** no update	n/a
	Medium	Otto Dual-Fuel	n/a	**X** new data
	Medium	Otto Spark-Ignition	n/a	no update
	High	Diesel Compression-Ignition	no update	n/a
	High	Otto Spark-Ignition	n/a	no update
Gas turbine		Simple Cycle	no update	no update
		Combine Cycle	no update	no update

a. Engine-fuel combinations marked with an "**X**" are presented in this study. Those marked with "no update" are included in the 2nd GHG study but have not been updated. Those marked with "new data" have been updated. Those marked "n/a" are not included in either study.

b. Primary data was provided and results are presented for three efficiency and emissions control designs: Design 1: Standard design; Design 2: Standard design with low-pressure exhaust gas recirculation; Design 3: Standard design with low-pressure exhaust gas recirculation and variable compression ratio.

As this study focuses on understanding the influence of the fuel usage on the global warming potential, GHG emissions and their impact on the global warming potential (GWP) are investigated. In addition to the GHG emissions, use phase nitrogen oxides, (NOx), sulphur oxides (SOx), particulate matter (PM), and black carbon (BC) were also requested. However, primary data was not provided for BC.

For the WtT analysis, the functional unit is 1 MJ (LCV) of fuel delivered to a marine vessel, while for the WtW results a functional unit of 1 kWh of engine output is used. This WtW functional unit was selected to incorporate differences in fuel efficiency among the considered engines since 1 MJ of fuel input may result in different engine outputs.

Well-to-Tank Results

Figure ES-2 shows the WtT GWP results including biogenic CO_2. The WtT impact of global fossil LNG is 16.9 g CO_2-eq./MJ. All biogenic pathways have negative WtT GWP due to the biogenic carbon absorbed from the atmosphere during the biomass growth, which is later released during combustion in the engines. Sensitivity and scenario analyses and their results are presented in section 4.

The specific WtT GWP depends on the production technology used (all results including biogenic CO_2):

- Gasification of biomass: This production method results in a GWP of -40.1 g CO_2-eq./MJ,
- Anaerobic Digestion (AD) of manure & residues: This process leads to values of -22.4 g CO_2-eq./MJ, which can be further reduced to -56.4 g CO_2-eq./MJ when paired with carbon capture and storage (CCS).
- Landfill gas: The GWP for the production of biogenic LNG via landfill gas is -40.3 respectively -74.3 g CO_2-eq./MJ with the use of CCS

The impact of the landfill gas is lower, as it was assumed to be burden-free, whereas the biogas produced from a mix of manure and residues require some thermal energy for the heating of the fermenter and electricity for the biogas plant.

The WtT GHG intensities of synthetic LNG using a biogenic point source (BPS) or direct air capture (DAC) using hydrogen from electrolysis feed with renewable electricity are -37.6 and -39.5 g CO2-eq./MJ, respectively. This is similar to biogenic LNG from gasification of biomass or landfill gas. The GHG intensities from synthetic LNG using hydrogen from industrial co-product (ICP) are -10.7 and -28.5 g CO2-eq/MJ for BPS and DAC, respectively. For synthetic LNG produced from CO2 from a fossil point source (FPS) the assumption was made that the fuel is fossil as well (further discussion on that will be given in section 4.3.4), which lead to 42.2 and 51.3 g CO2-eq./MJ using hydrogen from electrolysis respectively from ICP.

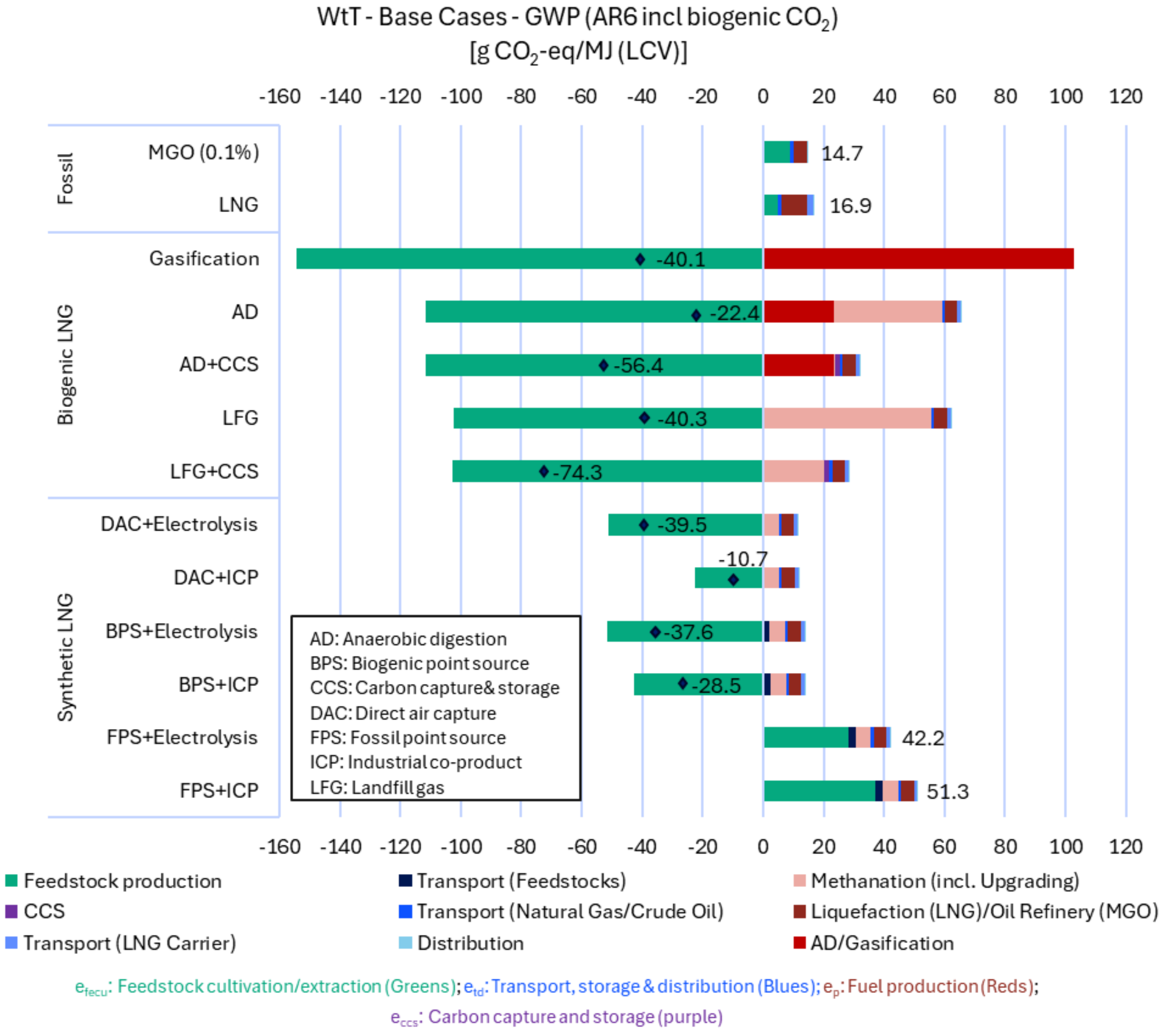

Figure ES-2: Default GHG results including biogenic CO_2 for each WtT pathway

Well-to-Wake Results

Given that the LNG engines under study meet Tier III standards directly without exhaust gas treatment, the analysis focuses on a comparison with Tier III-compliant oil-based alternatives. In this context, $MGO_{0.1}$ serves as the reference fuel due to its prevalence in SECA and NECA areas. Comparative data on engines using VLSFO or HFO in Tier II are provided in Sphera's 1st and 2nd LNG Studies

[10] [5]. Furthermore, the maximum difference in WtW GHG emissions between $MGO_{0.1}$- and VLSFO-powered engines reported in the 2nd LNG Study was ~1.7% [5].

WtW GHG intensities are presented both per total MJ of fuel and per kWh of engine output because different frameworks use different functional units. All results are presented including impacts of biogenic CO_2 removals and emissions. Three different 2-stroke slow speed Otto dual-fuel LNG engine designs were evaluated. The designs differed in their efficiency and emissions controls technology (i.e., Design 1: Standard; Design 2: Standard with low-pressure exhaust gas recirculation; and Design 3: Standard with low-pressure exhaust gas recirculation and variable compression ratio). Figure ES-3 shows the WtW GHG intensities (including biogenic CO_2) for each pathway for 2-stroke slow speed engines (Design 1) per MJ of total fuel input, while Figure ES-4 shows the same results per kWh of engine output. Sensitivity and uncertainty ranges and results for Designs 2 and 3 are shown in section 6.

Across all 2-stroke engines, the WtW GHG intensity of fossil LNG is 16 to 25% lower than $MGO_{0.1}$ when considering the engine output, but only 12 to 16% lower when only considering the fuel input. This is due to the increased fuel efficiency of 2-stroke LNG-powered vessels compared to MGO.

For biogenic LNG, the GHG intensity is 56 to 113% lower than $MGO_{0.1}$ per kWh of engine output. Biogenic LNG produced from LFG with CCS results in negative WtW GHG emissions. This is because this production process stores more CO_2 during than is released during subsequent combustion. In the case of synthetic LNG, the CO_2 source is critical. If a fossil point source (FPS) is used for CO_2 supply, per kWh of engine output GHG emissions increase by up to 20% compared to the use of $MGO_{0.1}$ and by 32 to 44% compared to the use of fossil LNG. If the CO_2 is supplied via DAC or by BPS, GHG emissions decrease by 45 to 80% compared to $MGO_{0.1}$ and 35% to 74% compared to fossil LNG.

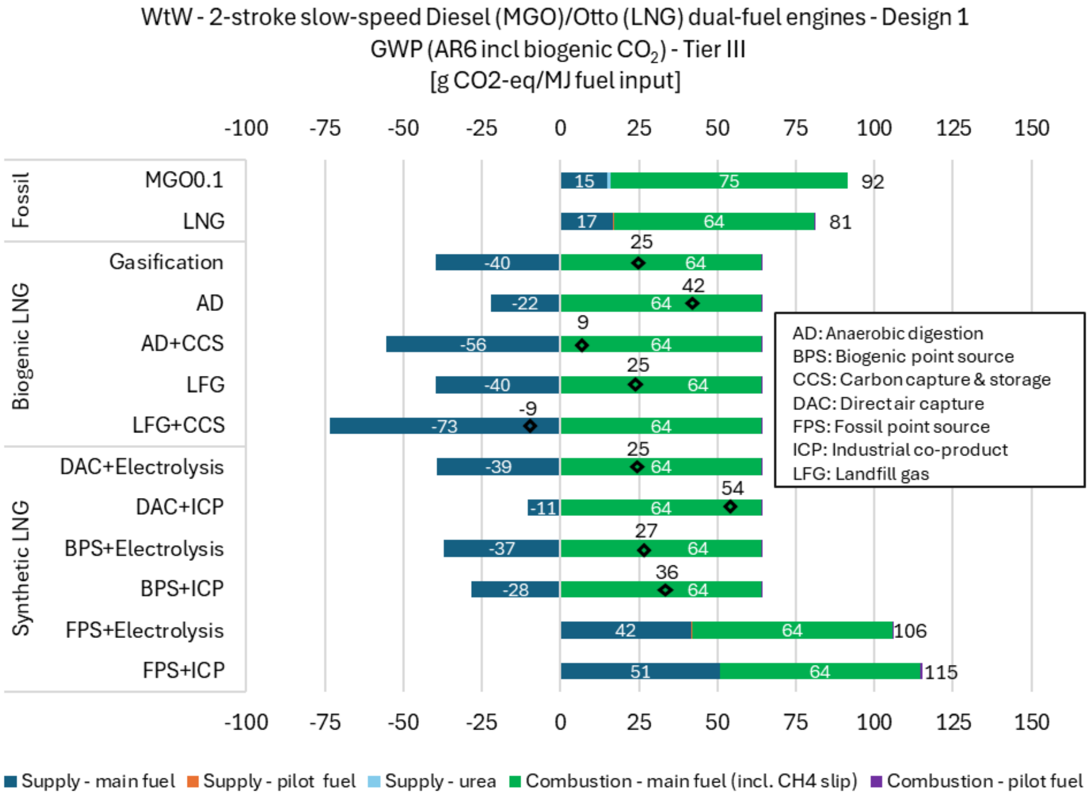

Figure ES-3: Default WtW – AR6 GHG emissions (incl. biogenic CO_2) of 2-stroke slow-speed engines (Design 1; Tier III) for each fuel pathway per MJ of fuel input

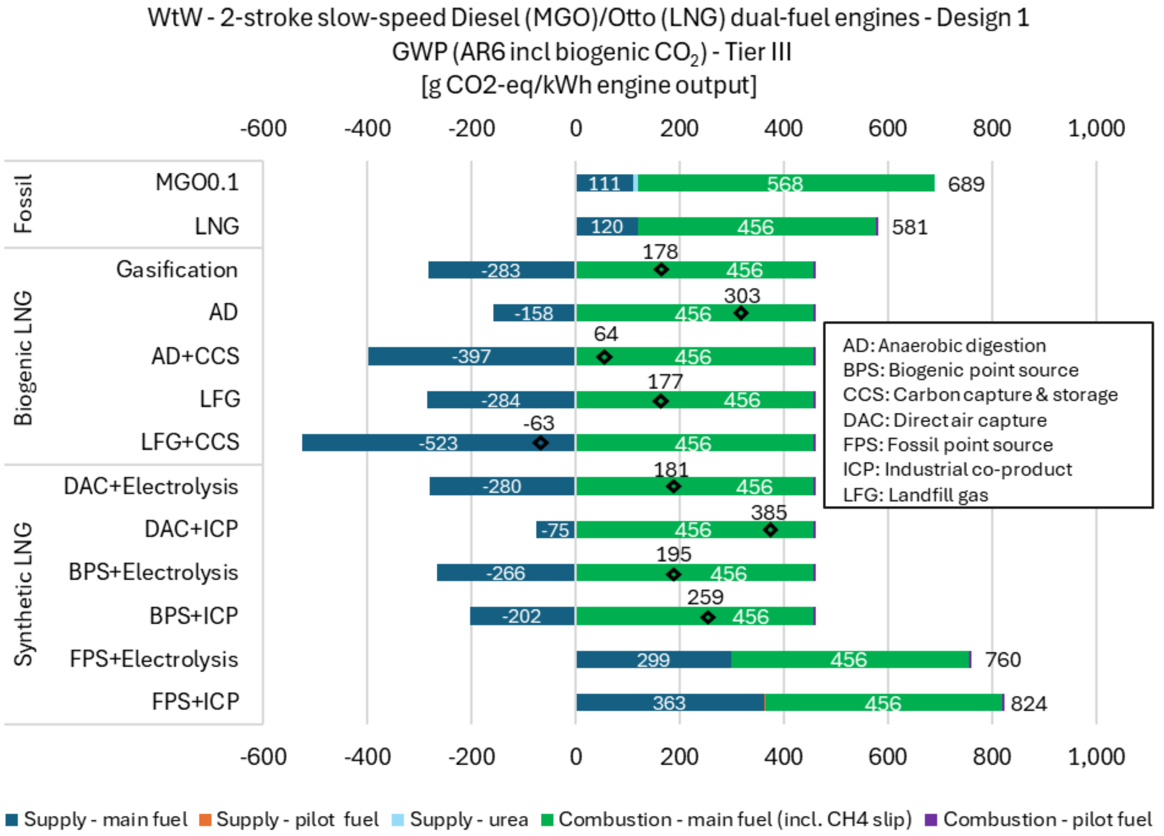

Figure ES-4: Default WtW – AR6 GHG emissions (incl. biogenic CO$_2$) of 2-stroke slow-speed engines (Design 1; Tier III) for each fuel pathway per kWh of engine output

Figure ES-5 shows the WtW GHG intensities including biogenic CO$_2$ for each pathway for 4-stroke medium speed engines per kWh of engine output. The relative rankings of the pathways are the same as for the 2-stroke slow-speed engines. In this case, fossil LNG decreases WtW GHG emissions by 11% compared to MGO$_{0.1}$. The biogenic LNG pathways reduce GHG emissions by 52 to 106% compared to the use of MGO$_{0.1}$ and by 46 to 107% compared to fossil LNG. Again, biogenic LNG produced from LFG with CCS results in negative WtW GHG emissions. This is because the production process stores more CO$_2$ than is released during subsequent combustion (for more details see section 4). In the case of synthetic LNG, the CO$_2$ source is critical. If a fossil point source (FPS) is used for CO$_2$ supply, GHG emissions increase between 15% and 25% compared to the use of MGO$_{0.1}$ and between 29% and 40% compared to the use of fossil LNG. If the CO$_2$ is supplied via Direct Air Capture (DAC) or by biogenic point source (BPS) GHG emissions decrease between 40% and 70% compared to the use of MGO$_{0.1}$ and 33% to 67% compared to the use of fossil LNG.

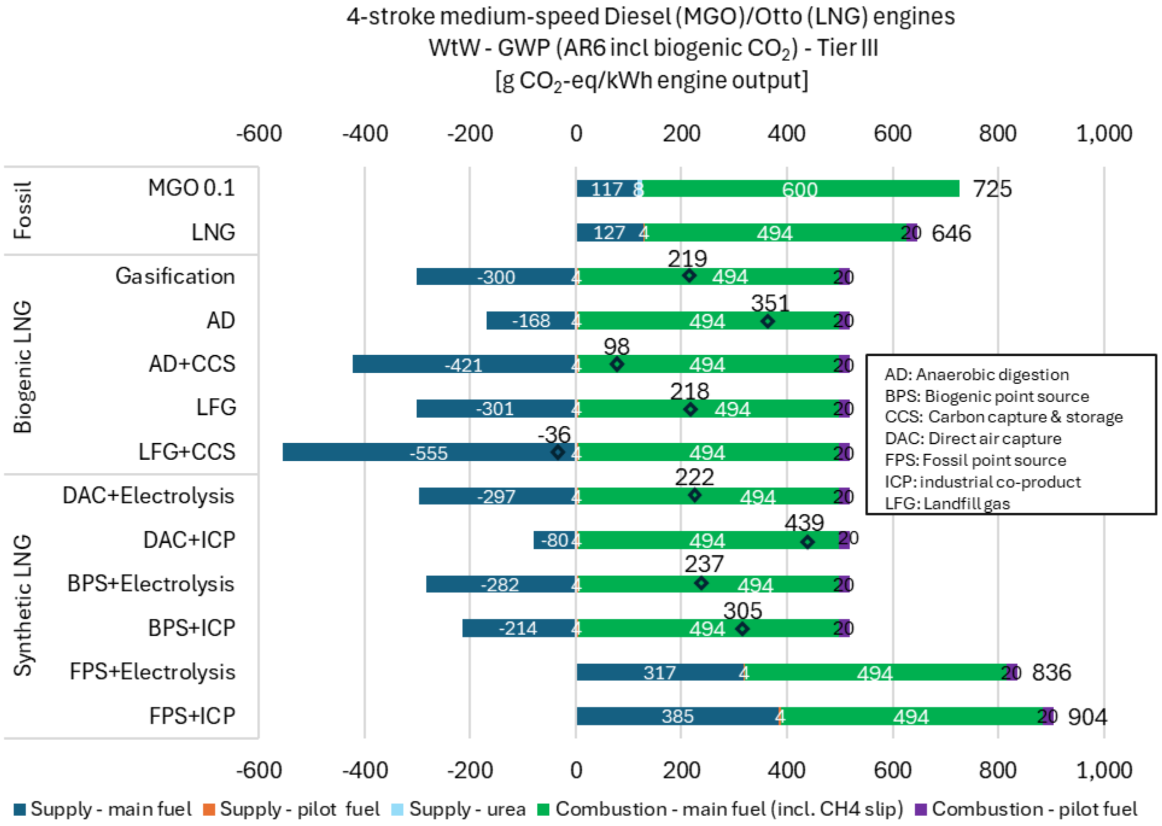

Figure ES-5: WtW – AR6 GHG emissions (including biogenic CO_2) of 4-stroke medium-speed engines for each fuel pathway

Comparisons Across Frameworks

Figure ES-6 shows the WtW results following the IMO guidelines for the evaluated 2-stroke slow-speed engines (Design 1). Results exclude biogenic CO_2 except for CCS credits, which is consistent with the IMO guidelines. The only differences between the IMO WtW results for fossil LNG and biogenic LNG compared to the Base Case is the change in CFs and functional unit (MJ of main fuel). However, the synthetic LNG pathways that use H_2 as an industrial co-product receive it burden free, which reduces the WtW GHG emissions for these engines by 5% to 19%.

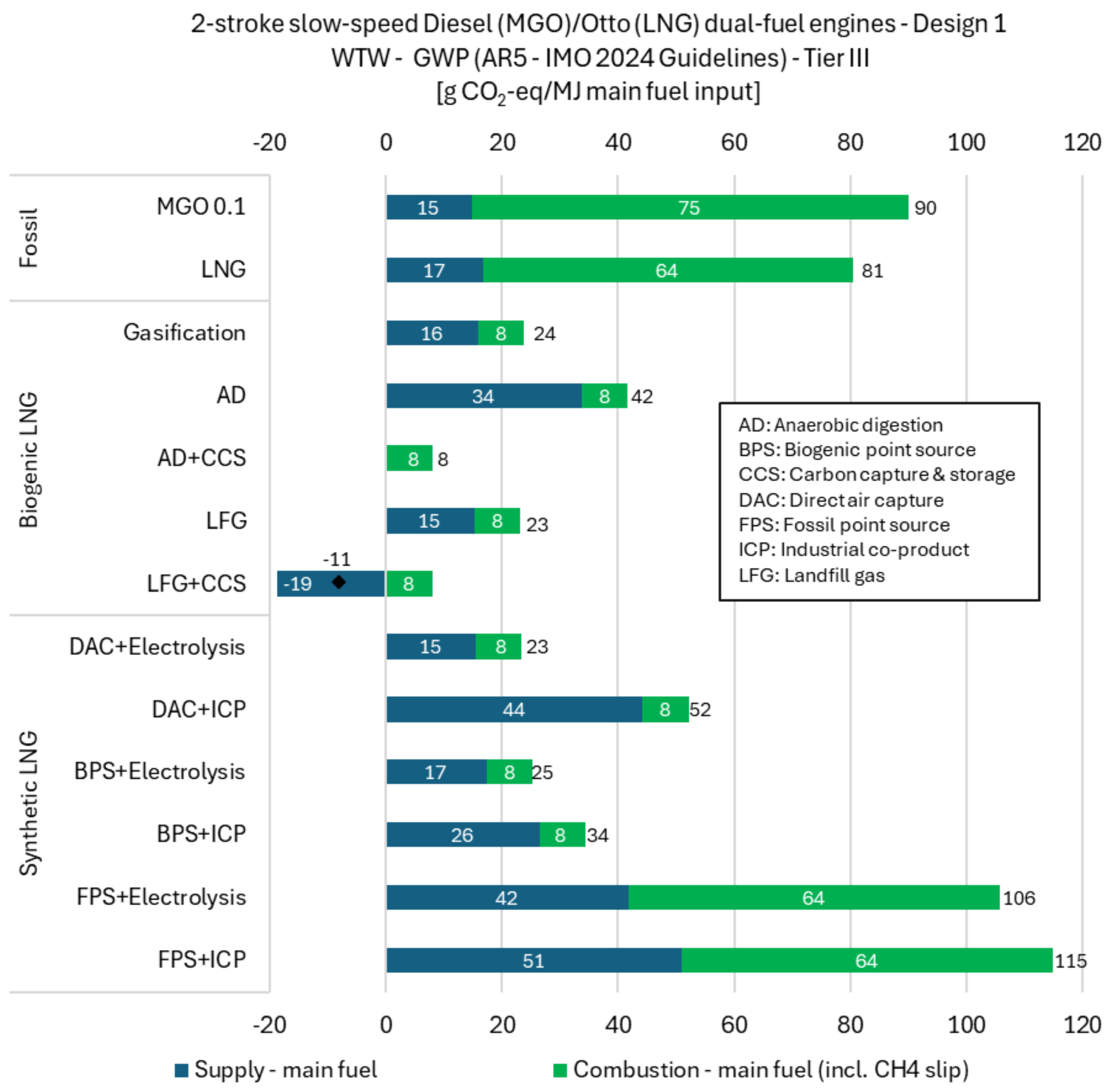

Figure ES-6: **WtW GHG results (excluding biogenic CO_2 except CCS) for all pathways following the IMO guidelines for 2-stroke slow-speed engines (Design 1)**

Figure ES-7 and Figure ES-8 compare the Base Case Results to those following the MMCZCS guidelines for the biogenic and synthetic LNG pathways, respectively for the evaluated 2-stroke slow-speed engines (Design 1). Results exclude biogenic CO_2 except CCS credits to facilitate comparisons across frameworks. The MMMCZCS guidelines are consistent with REDII/Fuel EU Maritime except for the selected CFs (IPCC AR6 versus AR4). By far the most significant difference between these pathways and the Base Case is the inclusion of credits associated with the use of manure feedstocks in AD. The other key difference is the exclusion of infrastructure, especially related to renewable electricity generation. That exclusion reduces the WtW GHG emissions of the synthetic LNG pathways using electrolysis by 9 to 48%

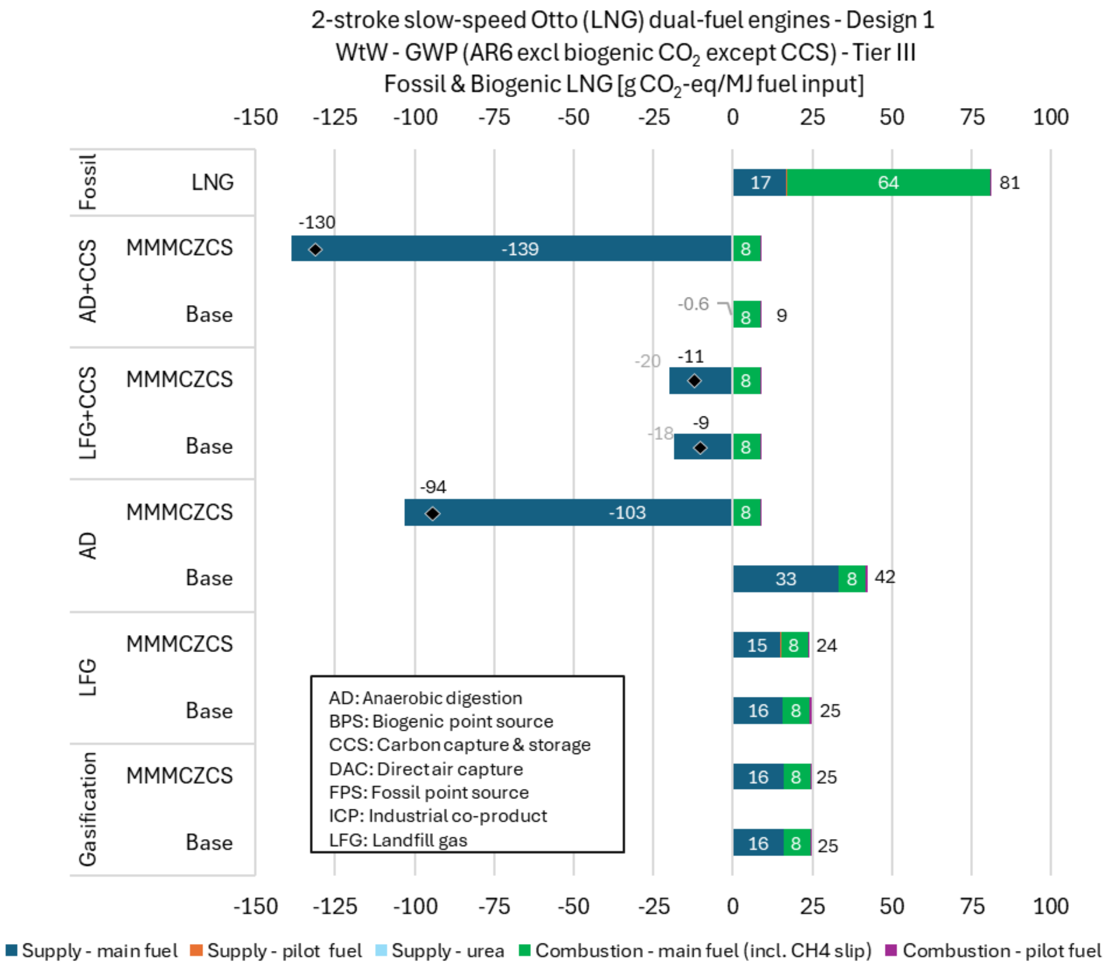

Figure ES-7: **WtW GHG results for fossil and biogenic LNG pathways following the MMMCZCS guidelines for 2-stroke slow-speed engines (Design 1)**

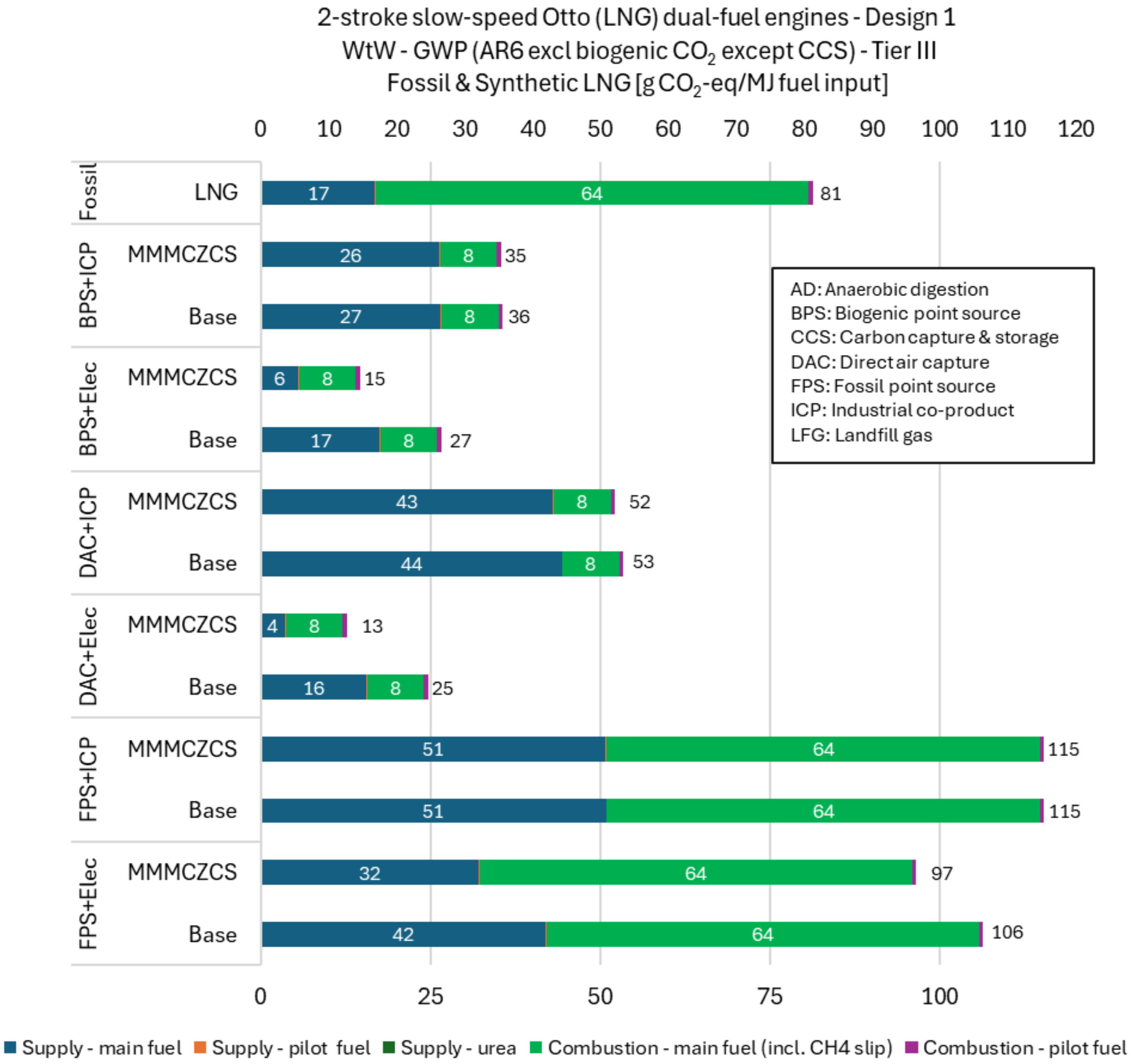

Figure ES-8: **WtW GHG results for fossil and synthetic LNG pathways following the MMMCZCS guidelines for 2-stroke slow-speed engines (Design 1)**

Conclusions

This *3rd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel* updates and strengthens the findings of the 1st and 2nd studies by incorporating new primary engine data, updated fossil LNG supply-chain information, and expanded modelling of biogenic and synthetic LNG pathways. Using the latest high-quality industry data and following ISO 14044:2006 and ISO 14071:2024 requirements, 2-stroke slow-speed Otto engines show stable, robust reductions across all regions and characterisation metrics compared to $MGO_{0.1}$, while 4-stroke medium-speed engines also demonstrate GHG improvements compared to $MGO_{0.1}$, though their performance is more sensitive to methane slip.

Biogenic LNG pathways, including anaerobic digestion, landfill gas, and biomass gasification, offer significant WtW GHG reductions and can even achieve net-negative emissions when CCS is applied to separated biogenic CO_2. Synthetic LNG produced using renewable-electricity electrolysis and DAC or biogenic CO_2 also delivers substantial reductions, while synthetic LNG derived from fossil CO_2 or high-carbon grid electricity does not. Across all engine technologies, LNG operation results in very low SO_x, significantly reduced NO_x (Tier III-compliant for Otto engines without additional emission control measures), and major reductions in particulate matter. However, primary data were not provided for BC, so no quantitative comparisons can be made. Sensitivity and Monte-Carlo uncertainty analyses show that although electricity carbon intensity, methane slip, methane leakage, and carbon-capture energy requirements introduce variability, the overall ranking of pathways remains unchanged. The key conclusions of the study—particularly the GHG and air-quality benefits of LNG and the potential of biogenic and renewable synthetic LNG—remain consistent based on the considered scenarios and uncertainties.

About Us

SGMF is a non-governmental, membership-based organisation providing independent expertise on the safe, responsible and sustainable use of low and zero carbon marine fuels. www.sgmf.info

Sphera is the leading provider of integrated sustainability and software, data and consulting services focusing on Environment, Health, Safety & Sustainability (EHS&S), Process Safety, Product Stewardship and Supply Chain Risk Management. www.sphera.com

The full study can be downloaded at: https://sphera.com/research/3rd-life-cycle-ghg-emission-study-on-the-use-of-lng-as-marine-fuel/