BRIEFING

AUGUST 2021

Update: Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies

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INTRODUCTION

This briefing paper explains how policymakers can account for well-to-wake (WTW) carbon dioxide equivalent (CO_2e) emissions in strategies that aim to monitor or regulate climate-warming pollutants from ships. Well-to-wake emissions, or life-cycle emissions, are the sum of upstream (well-to-tank) and downstream (tank-to-wake) emissions. In addition to carbon dioxide (CO_2), carbon dioxide equivalents include greenhouse gases (GHGs) such as methane (CH_4) and nitrous oxide (N_2O), as well as particles like black carbon (BC). By focusing solely on CO_2 and ignoring other pollutants, regulators would significantly underestimate climate pollution from maritime transport which would work against achieving the Paris Agreement goal to limit global warming to 1.5°C compared to pre-industrial levels.

The European Union (EU) intends to add maritime shipping emissions to its Emissions Trading Scheme (ETS) and is currently deciding if only CO_2 emissions will be covered or if other climate pollutants, including CH_4, BC, and N_2O, should also be considered to account for CO_2-equivalent emissions. The emission factors presented in this briefing can be used by the EU and other regulatory bodies to calculate well-to-wake CO_2e emissions from marine fuel consumption. This briefing updates a previous version in order to incorporate well-to-tank black carbon emission factors and new global warming potentials from the IPCC's Sixth Assessment Report.[1]

1 Bryan Comer and Liudmila Osipova, *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*, (ICCT: Washington, DC, 2021), https://theicct.org/publications/well-to-wake-co2-mar2021.

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APPROACH FOR CALCULATING WELL-TO-WAKE EMISSIONS BASED ON FUEL CONSUMPTION

Well-to-wake CO_2e emissions (CO_2e_{WTW}) account for the amount of climate pollutants emitted upstream well-to-tank (WTT) and downstream tank-to-wake (TTW). This briefing reports CO_2e_{WTW} based on both 100-year and 20-year global warming potentials. As upstream and downstream pollutants vary according to the type of fuel and engines that are used, the analysis determines the emissions factors for four different marine fuels and multiple engine types. Fuels include heavy fuel oil (HFO), very-low sulfur fuel oil (VLSFO), marine gas oil (MGO), and liquefied natural gas (LNG). Engine types include slow speed diesel (SSD); medium speed diesel (MSD); two-stroke, slow-speed, Otto-cycle, dual fuel LNG (LNG-Otto-SS); four-stroke, medium-speed, Otto-cycle, dual fuel LNG (LNG-Otto MS); lean-burn spark ignition LNG (LBSI); two-stroke, slow-speed, Diesel-cycle LNG (LNG-Diesel), and steam turbines.

The global warming potentials listed in Table 1 represent the relative amount of heat each pollutant traps compared with the heat trapped by the same amount of CO_2 over a given period after emission.

Table 1. Global warming potentials for climate pollutants.

Pollutant	100-year	20-year	Source
CO_2	1	1	Reference level
CH_4	29.8	82.5	IPCC AR6 Table 17.5
N_2O	273	273	IPCC AR6 Table 17.5
BC	900	3200	Bond et al. and Comer et al.

As shown in Table 1, CO_2 is used as the reference and has a global warming potential equal to one. For CH_4 and N_2O, values were obtained from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6).[2] For BC, values were obtained from Bond et al.[3] and Comer, Olmer, Mao, Roy, and Rutherford.[4]

A ship's CO_2e_{WTW} can be calculated based on the mass of fuel the ship consumed and a well-to-wake carbon dioxide equivalent factor (CEF_{WTW}) for that fuel, as shown in Equation 1. Although the equation determines grams of CO_2e, the same equation can be used with any other unit of mass. For example, if one gram of heavy fuel oil results in 4.6 grams of CO_2e_{WTW}, one tonne will emit 4.6 tonnes of CO_2e_{WTW}. For the EU ETS and other policies based on the fuel consumption of large ships, tonnes will be a more appropriate unit.

2 Forster, P., T. Storelvmo, K. Armour, W. Collins, J. L. Dufresne, D. Frame, D. J. Lunt, T. Mauritsen, M. D. Palmer, M. Watanabe, M. Wild, H. Zhang, 2021, *The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)], (Cambridge University Press. 2021), www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

3 Bond, T. C., et al., Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos., 118* (2013) 5380– 5552, https://doi.org/10.1002/jgrd.50171.

4 Bryan Comer, Naya Olmer, Xiaoli Mao, Biswajoy Roy, and Dan Rutherford, *Black carbon emissions and fuel use in global shipping, 2015*, (ICCT: Washington, DC, 2017), https://theicct.org/publications/black-carbon-emissions-global-shipping-2015.

Equation 1

$$CO_2e_{WTW} = FC \times CEF_{WTW}$$

CO_2e_{WTW} = well-to-wake emissions, in gCO_2e

FC = fuel consumption, in g

CEF_{WTW} = well-to-wake carbon dioxide equivalent factor for that fuel, in gCO_2e/g fuel

Fuel consumption is reported by ship owners or operators. In the case of the EU ETS, fuel consumption will be based on EU Monitoring Reporting and Verification data. The CEF_{WTW} is calculated based on WTT emissions associated with extracting, processing, and transporting the fuel and TTW emissions associated with using the fuel on board the ship. The TTW emissions include combustion and non-combustion emissions, such as methane slip from marine engines that use LNG. Equation 2 shows that CEF_{WTW} is the sum of the WTT and TTW carbon dioxide equivalent factors, labeled CEF_{WTT} and CEF_{TTW}, respectively.

Equation 2

$$CEF_{WTW} = CEF_{WTT} + CEF_{TTW}$$

CEF_{WTW} = well-to-wake carbon dioxide equivalent factor, in gCO_2e/g fuel

CEF_{WTT} = well-to-tank carbon dioxide equivalent factor, in gCO_2e/g fuel

CEF_{TTW} = tank-to-wake carbon dioxide equivalent factor, in gCO_2e/g fuel

As shown in Equation 3, CEF_{WTT} is calculated based on the emission factors for each climate pollutant (EF_{WTT_p}) and the associated 100-year or 20-year global worming potential for each pollutant (GWP_p). The CEF_{TTW} is calculated in the same manner, per Equation 4.

Equation 3

$$CEF_{WTT} = \sum (EF_{WTT_p} \times GWP_p)$$

CEF_{WTT} = well-to-tank carbon dioxide equivalent factor, in gCO_2e/g fuel

EF_{WTT_p} = well-to-tank emission factor of pollutant p, in g/g fuel

GWP_p = the 100-year or 20-year GWP of pollutant p,

Equation 4

$$CEF_{TTW} = \sum (EF_{TTW_p} \times GWP_p)$$

CEF_{TTW} = tank-to-wake carbon dioxide equivalent factor, in gCO_2e/g fuel

EF_{TTW_p} = tank-to-wake emission factor of pollutant p, in g/g fuel

GWP_p = the 100-year or 20-year GWP of pollutant p

The EF_{WTT} and EF_{TTW} include CO_2, CH_4, N_2O, and BC. Table 2 shows EF_{WTT} by fuel type and engine type for each pollutant, as well as CEF_{WTT}, calculated in accordance with Equation 3 and the 100-year or 20-year global warming potentials listed in Table 1.

Table 3 shows EF_{TTW} for each pollutant by fuel type and engine type, as well as CEF_{TTW}, calculated in accordance with Equation 4 and the GWPs in Table 1. Summing them together, Table 4 shows well-to-wake emission factors for each pollutant and CEF_{WTW}. The following two sub-sections explain in detail how we determined EF_{WTT} and EF_{TTW}.

Table 2. Well-to-tank emission factors for each pollutant (EF_{WTT}) and associated carbon dioxide equivalent factors (CEF_{WTT}).

Fuel type[a]	Engine type	Well-to-tank (g/g fuel)					
		EF_{WTT}				CEF_{WTT}	
		CO_2	CH_4	N_2O	BC	CO_2e100	CO_2e20
HFO	SSD	0.4311	0.00399	0.00001	0.000007	0.559	0.786
	MSD	0.4311	0.00399	0.00001	0.000007	0.559	0.786
VLSFO	SSD	0.5457	0.00448	0.00001	0.000008	0.689	0.943
	MSD	0.5457	0.00448	0.00001	0.000008	0.689	0.943
MGO	SSD	0.5757	0.00460	0.00001	0.000008	0.723	0.983
	MSD	0.5757	0.00460	0.00001	0.000008	0.723	0.983
LNG	LNG-Otto-MS	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LNG-Otto-MS + crankcase	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LNG-Otto-SS	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LNG-Otto-SS + crankcase	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LNG-Diesel	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LBSI	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	LBSI + crankcase	0.5300	0.01810	0.00001	0.000006	1.077	2.043
	Steam Turbine	0.5300	0.01810	0.00001	0.000006	1.077	2.043

Table 3. Tank-to-wake emission factors for each pollutant (EF_{TTW}) and associated carbon dioxide equivalent factors (CEF_{TTW}).

Fuel type	Engine type	Tank-to-wake (g/g fuel)					
		EF_{TTW}				CEF_{TTW}	
		CO_2	CH_4	N_2O	BC	CO_2e100	CO_2e20
HFO	SSD	3.114	0.00006	0.00017	0.00019	3.334	3.774
	MSD	3.114	0.00005	0.00016	0.00049	3.601	4.731
VLSFO	SSD	3.188	0.00006	0.00018	0.00019	3.410	3.850
	MSD	3.188	0.00006	0.00017	0.00049	3.677	4.807
MGO	SSD	3.206	0.00006	0.00018	0.00004	3.293	3.389
	MSD	3.206	0.00006	0.00017	0.00026	3.489	4.090
LNG	LNG-Otto-MS	2.750	0.03526	0.00013	0.00002	3.854	5.758
	LNG-Otto-MS + crankcase	2.750	0.04167	0.00013	0.00002	4.045	6.287
	LNG-Otto-SS	2.750	0.01689	0.00014	0.00002	3.308	4.244
	LNG-Otto-SS + crankcase	2.750	0.02365	0.00014	0.00002	3.510	4.802
	LNG-Diesel	2.750	0.00148	0.00022	0.00001	2.864	2.965
	LBSI	2.750	0.02628	0.00013	0.00002	3.586	5.017
	LBSI + crankcase	2.750	0.03269	0.00013	0.00002	3.777	5.546
	Steam Turbine	2.750	0.00014	0.00007	0.00001	2.782	2.813

Table 4. Well-to-wake emission factors for each pollutant (EF_{WTW}) and associated carbon dioxide equivalent factors (CEF_{WTW}).

Fuel type	Engine type	Well-to-wake (g/g fuel)					
		EF_{WTW}				CEF_{WTW}	
		CO_2	CH_4	N_2O	BC	CO_2e100	CO_2e20
HFO	SSD	3.545	0.00404	0.00018	0.00020	3.892	4.559
	MSD	3.545	0.00404	0.00017	0.00050	4.159	5.516
VLSFO	SSD	3.734	0.00453	0.00019	0.00020	4.098	4.792
	MSD	3.734	0.00453	0.00018	0.00050	4.366	5.749
MGO	SSD	3.782	0.00466	0.00019	0.00005	4.016	4.372
	MSD	3.782	0.00466	0.00018	0.00027	4.211	5.073
LNG	LNG-Otto-MS	3.280	0.05336	0.00014	0.00003	4.930	7.801
	LNG-Otto-MS + crankcase	3.280	0.05977	0.00014	0.00003	5.121	8.330
	LNG-Otto-SS	3.280	0.03499	0.00014	0.00003	4.385	6.288
	LNG-Otto-SS + crankcase	3.280	0.04175	0.00014	0.00003	4.586	6.845
	LNG-Diesel	3.280	0.01958	0.00023	0.00002	3.940	5.008
	LBSI	3.280	0.04438	0.00014	0.00003	4.663	7.060
	LBSI + crankcase	3.280	0.05079	0.00014	0.00003	4.854	7.589
	Steam Turbine	3.280	0.01824	0.00008	0.00002	3.859	4.856

DETERMINING WELL-TO-TANK EMISSION FACTORS FOR EACH POLLUTANT

The WTT emission factors in Table 2 are obtained by multiplying the upstream energy-based emission factors for marine fuels in in Table 5 (g pollutant/megajoule) by the fuel energy content assumption in Table 6 (MJ/g fuel). The upstream (well-to-tank) emissions in Table 5 are based on the US Argonne National Laboratory's 2020 GREET model,[5] with the exception of VLSFO and the upstream CH_4 value. VLSFO is not incorporated into GREET; we therefore assume that VLSFO is an 80/20 blend of MGO and HFO, consistent with previous work.[6] The upstream CH_4 emissions for liquefied natural gas in Table 5 (0.38 gCH_4/MJ) are consistent with the findings in a previous study which finds that upstream methane leakage from liquefied natural gas production is higher than the 0.30 gCH_4/MJ assumed by the U.S. Environmental Protection Agency.[7] The energy content assumptions for HFO, MGO, and LNG are consistent with the Fourth IMO GHG Study.[8]

Table 5. Well-to-tank emissions for marine fuels (g/MJ)

Pollutant	Fuel			
	HFO	VLSFO	MGO	LNG
CH_4	0.10	0.11	0.11	0.38
N_2O	0.00018	0.00022	0.00023	0.00016
CO_2	10.72	12.93	13.48	11.04
BC	0.00018	0.00019	0.00019	0.00012

Table 6. Energy content of marine fuels

Fuel	Energy content (MJ/g fuel)
HFO	0.0402
MGO	0.0427
VLSFO	0.0422
LNG	0.0480

DETERMINING TANK-TO-WAKE EMISSION FACTORS FOR EACH POLLUTANT

The TTW emission factors for each pollutant are shown in Table 3, and CO_2 is consistent with the carbon dioxide factors used in the Fourth IMO GHG Study[9] for HFO, MGO, and LNG and Comer et al.[10] for VLSFO, as shown in Table 7.

5 Michael Wang, Amgad Elgowainy, Uisung Lee, Adarsh Bafana, Pahola T. Benavides, Andrew Burnham,... and Guiyan Zang, *Greenhouse gases, regulated emissions, and energy use in technologies model*, (US DOE EERE: Washington, DC, 2020), https://greet.es.anl.gov/net. The authors acknowledge Greg Zaimes from Argonne National Laboratory for providing us with the well-to-tank black carbon emission factors from GREET.

6 Bryan Comer, Elise Georgeff, and Liudmila Osipova, Air emissions and water pollution discharges from ships with scrubbers, (ICCT: Washington, DC, 2020), https://theicct.org/publications/air-water-pollution-scrubbers-2020.

7 Nikita Pavlenko, Bryan Comer, Yuanrong Zhou, Nigel Clark, and Dan Rutherford, The climate implications of using LNG as a marine fuel, (ICCT: Washington, DC, 2020), https://theicct.org/publications/climate-impacts-LNG-marine-fuel-2020.

8 Jasper Faber, Shinichi Hanayama, Shuang Zhang, Paula Pereda, Bryan Comer, Elena Hauerhof,... and Hui Xing, "Fourth IMO greenhouse gas study," (International Maritime Organization, 2020), https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.

9 Faber et al., "Fourth IMO greenhouse gas study."

10 Comer, Georgeff, and Osipova, *Air emissions and water pollution discharges from ships with scrubbers*.

Table 7. Carbon factors for marine fuels.

Fuel	Carbon factor (gCO_2/g fuel)
HFO	3.114
MGO	3.206
VLSFO	3.188
LNG	2.750

Black carbon TTW emission factors are consistent with those used in the Faber et al.[11] and Comer et al.[12] We assume that the BC emission factors for VLSFO are the same as for HFO. Black carbon emission factors are a function of fuel type, engine type, and engine load. The BC TTW emission factors for HFO, VLSFO, and MGO in Table 3 assume that ships operate at 50% load, corresponding to the gray shaded row in Table 8, and are divided by 1000 to convert from units of gBC/kg fuel to gBC/g fuel. Emission factors for LNG are the same as those in Faber et al. and Comer et al., as shown in Table 9.[13]

Table 8. Black carbon emission factors for oil-based fuels (g/kg fuel)

	HFO or VLSFO		MGO	
Engine load	**SSD**	**MSD**	**SSD**	**MSD**
0.05	0.44	4.54	0.10	3.48
0.1	0.34	2.32	0.08	1.60
0.2	0.27	1.19	0.06	0.73
0.25	0.25	0.96	0.05	0.57
0.3	0.23	0.80	0.05	0.46
0.4	0.21	0.61	0.04	0.34
0.5	0.19	0.49	0.04	0.26
0.6	0.18	0.41	0.04	0.21
0.7	0.17	0.35	0.04	0.18
0.75	0.17	0.33	0.03	0.17
0.8	0.16	0.31	0.03	0.15
0.9	0.16	0.28	0.03	0.14
1	0.15	0.25	0.03	0.12

Table 9. Black carbon emission factors for LNG (g/kg fuel)

Engine type	BC (g/kg LNG)
LNG-Otto-MS, LNG-Otto-SS, LBSI	0.02
LNG-Diesel	0.01
Steam Turbine	0.01

11 Faber et al., "Fourth IMO greenhouse gas study."

12 Bryan Comer, Naya Olmer, Xiaoli Mao, Biswajoy Roy, and Dan Rutherford, *Black carbon emissions and fuel use in global shipping, 2015*. (ICCT: Washington, DC, 2017) https://theicct.org/publications/black-carbon-emissions-global-shipping-2015.

13 Faber et al., "Fourth IMO greenhouse gas study;" Comer, Georgeff, and Osipova, *Air emissions and water pollution discharges from ships with scrubbers*.

Methane TTW emission factors are consistent with those use in the Fourth IMO GHG Study.[14] To calculate CH_4 TTW emissions factors, we divide the CH_4 energy-based emission factors used in Faber et al.,[15] which can be found in Table 10 and are in units of gCH_4/kWh, by the specific fuel consumption (SFC) of each fuel-engine pair in Table 11, which are in units of g fuel/kWh. This results in TTW CH_4 emission factors in units of gCH_4/g fuel. The SFC assumptions reflect 2001 and newer model year engines and are taken from the Fourth IMO GHG Study.[16] The Fourth IMO GHG Study's LNG engine SFC assumptions are consistent with Pavlenko et al., which reflects modern LNG engines built in the last several years.[17] We assume that ships using VLSFO emit the same amount of CH_4 as those using HFO. Some ships using low-pressure injection engines, including LNG-Otto and LBSI may have open crankcases; if so, Pavlenko et al. estimate that there could be an additional 1 gCH_4/kWh escaping unburned from the crankcase.[18] Therefore, in Table 3, we include rows that show the impact on CH_4 and CO_2e from these additional crankcase emissions for LNG-Otto and LBSI engines in Table 10.

Table 10. Methane emission factors (g/kWh)

Engine type	Fuel type	Methane (g/kWh)
SSD or MSD	HFO, VLSFO, MGO	0.01
LNG-Otto-MS	LNG	5.5[a]
LNG-Otto-SS	LNG	2.5[a]
LNG-Diesel	LNG	0.2
LBSI	LNG	4.1[a]
Steam Turbine	HFO, VLSFO, MGO	0.002
	LNG	0.04

[a] This table shows methane emission factors used in the Fourth IMO GHG Study; however, low-pressure injection engines, such as LNG-Otto-MS, LNG-Otto-SS, and LBSI, may have open crankcases, which could emit an additional 1.0 gCH_4/kWh.

Table 11. Specific fuel consumption (g/kWh) for marine engines.

Fuel type	Engine type	Specific fuel consumption (g fuel/kWh)
HFO	SSD	175
	MSD	185
VLSFO	SSD	167
	MSD	177
MGO	SSD	165
	MSD	175
LNG	LNG-Otto-MS	156
	LNG-Otto-SS	148
	LNG-Diesel	135
	LBSI	156
	Steam Turbine	285

14 Faber et al., "Fourth IMO greenhouse gas study."
15 Faber et al., "Fourth IMO greenhouse gas study."
16 Faber et al., "Fourth IMO greenhouse gas study."
17 Pavlenko et al., *The climate implications of using LNG as a marine fuel*.
18 Pavlenko, et al., *The climate implications of using LNG as a marine fuel*.

Nitrous oxide TTW emission factors are consistent with those use in the Fourth IMO GHG Study.[19] To calculate N_2O TTW emissions factors, we divide the N_2O energy-based emission factors used in Faber et al.,[20] which can be found in Table 12 and are in units of gN_2O/kWh, by the SFC of each fuel-engine pair in Table 11, which are in units of g fuel/kWh. This results in TTW N_2O emission factors in units of gN_2O/g fuel. We assume that ships using VLSFO emit the same amount of N_2O as those using HFO.

Table 12. Nitrous oxide emission factors (g/kWh)

Engine	Fuel	N_2O (g/kWh)
SSD or MSD	HFO, VLSFO, MGO	0.03
Steam Turbine	HFO, VLSFO, MGO	0.04
LNG-Otto-MS, LNG-Otto-SS, LBSI	LNG	0.02
LNG-Diesel	LNG	0.03
Steam Turbine	LNG	0.02

RESULTS

Table 13 presents WTW emission factors for fossil marine fuels developed according to the methodology described in this briefing. These WTW emission factors include both upstream well-to-tank (WTT) and downstream tank-to-wake (TTW) emission factors.

In Table 13, CO_2 accounts for only carbon dioxide emissions, whereas CO_2e100 and CO_2e20 account for emissions of other climate pollutants based on their 100-year or 20-year global warming potential. Comparing the three metrics, one can see that focusing solely on CO_2 and ignoring other climate pollutants can significantly underestimate climate pollution from maritime transport. We suggest policymakers consider not only CO_2e100 but also CO_2e20 for policies intended to be aligned with the Paris Agreement. In addition to reducing CO_2 emissions, reducing pollutants with large 20-year global warming potential, such as CH_4, BC, and N_2O, can help prevent additional near-term warming.

19 Faber et al., “Fourth IMO greenhouse gas study.”
20 Faber et al., “Fourth IMO greenhouse gas study.”

Table 13. Well-to-wake carbon dioxide and carbon dioxide equivalent factors (CEF_{WTW}) for fossil marine fuels.

Fuel type	Engine type	Well-to-wake (g/g fuel)		
		CO_2	CO_2e100	CO_2e20
HFO	SSD	3.545	3.892	4.559
	MSD	3.545	4.159	5.516
VLSFO	SSD	3.734	4.098	4.792
	MSD	3.734	4.366	5.749
MGO	SSD	3.782	4.016	4.372
	MSD	3.782	4.211	5.073
LNG	LNG-Otto-MS	3.280	4.930	7.801
	LNG-Otto-MS + crankcase	3.280	5.121	8.330
	LNG-Otto-SS	3.280	4.385	6.288
	LNG-Otto-SS + crankcase	3.280	4.586	6.845
	LNG-Diesel	3.280	3.940	5.008
	LBSI	3.280	4.663	7.060
	LBSI + crankcase	3.280	4.854	7.589
	Steam Turbine	3.280	3.859	4.856

DISCUSSION

To give an example of why it is important to consider not only CO_2 but also CO_2e100 and CO_2e20, consider the figures below. Each figure applies Equation 1, and fuel consumption (*FC*) is assumed to be 1000 tonnes. Figure 1 shows the CO_2e_{WTW} emissions of consuming 1,000 tonnes of LNG in the engine with the highest WTW emissions (LNG-Otto, MS + crankcase) and the LNG engine with the lowest WTW emissions (LNG-Diesel). The exercise is repeated for SSD and MSD engines running on VLSFO (Figure 2) and MGO (Figure 3). Notice that estimates of WTW climate pollution can more than double for LNG engines that have high methane slip when evaluated on CO_2e20 compared with CO_2 (left side of Figure 1). Figure 2 and Figure 3 show that the relative contribution of black carbon emissions to WTW emissions depends strongly on whether it is evaluated using 100-year or 20-year global warming potential. When BC is accounted for, using MGO results in lower WTW emissions than VLSFO.

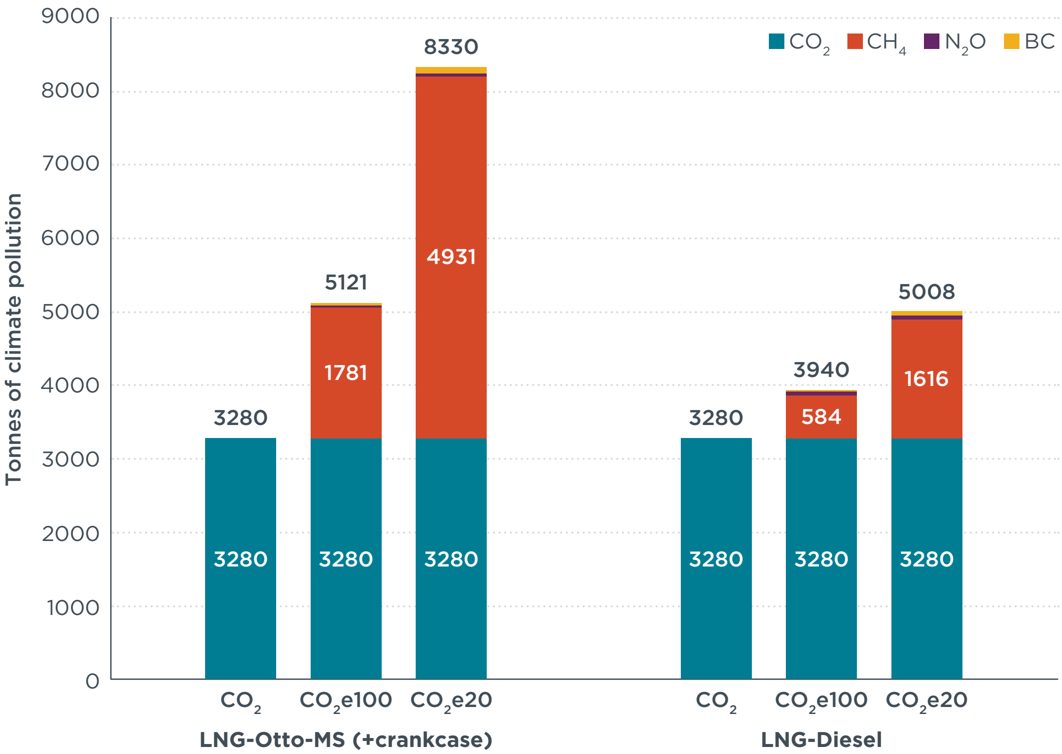

Figure 1. Well-to-wake emissions of consuming 1000 tonnes of liquefied natural gas in two engines.

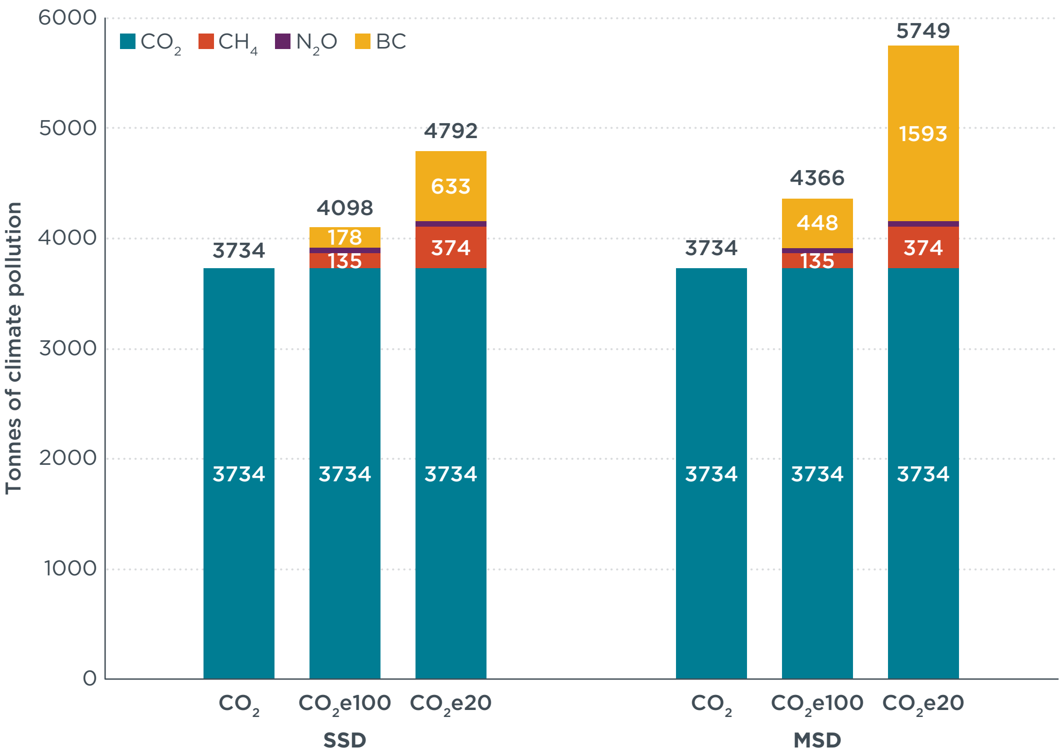

Figure 2. Well-to-wake emissions of consuming 1000 tonnes of VLSFO in two engines.

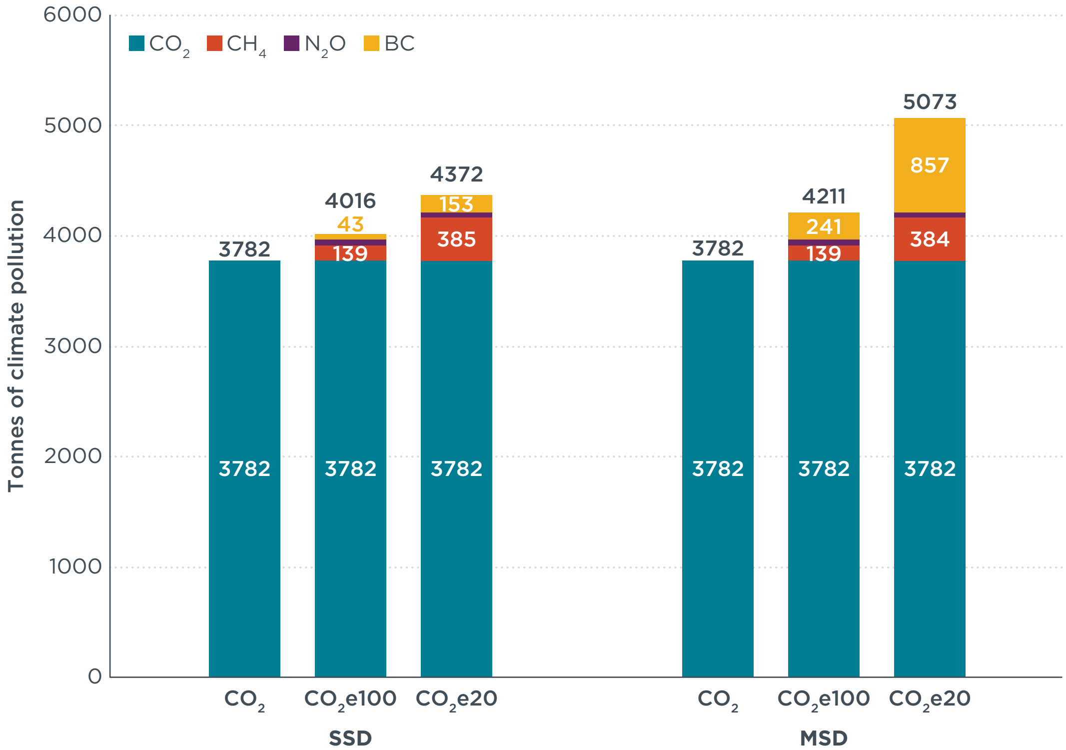

Figure 3. Well-to-wake emissions of consuming 1000 tonnes of MGO in two engines.

CONCLUSIONS

This briefing paper outlines a methodology for calculating well-to-wake carbon dioxide equivalent emissions from four fossil marine fuels: heavy fuel oil, very low sulfur fuel oil, marine gas oil, and liquefied natural gas. Well-to-wake emission factors for these fuels are presented in Table 13. While the EU Emissions Trading Scheme presents the most immediate opportunity to apply this methodology, it can also be applied to policies being developed at the International Maritime Organization and in other regions and countries that aim to reduce shipping's climate impacts.

The WTW carbon dioxide equivalent factors developed in this briefing cover existing marine fuels but could be expanded to new fuels including hydrogen and ammonia, two fuels where the WTT component is particularly important when evaluating their life-cycle climate consequences. No matter which fuel is used, WTT emissions will depend on the feedstock and production pathway. In addition, the TTW emissions will depend on whether the fuel is used in a fuel cell, combusted in an engine, or used in some other way. As new fuels and energy sources for shipping are researched and developed, it will be important to develop WTW emission factors that encompass their full life-cycle emissions in order to accurately judge their climate credentials.