SMART MARITIME

PERSPECTIVES ON MARITIME FUELS AND CLIMATE CHANGE MITIGATION

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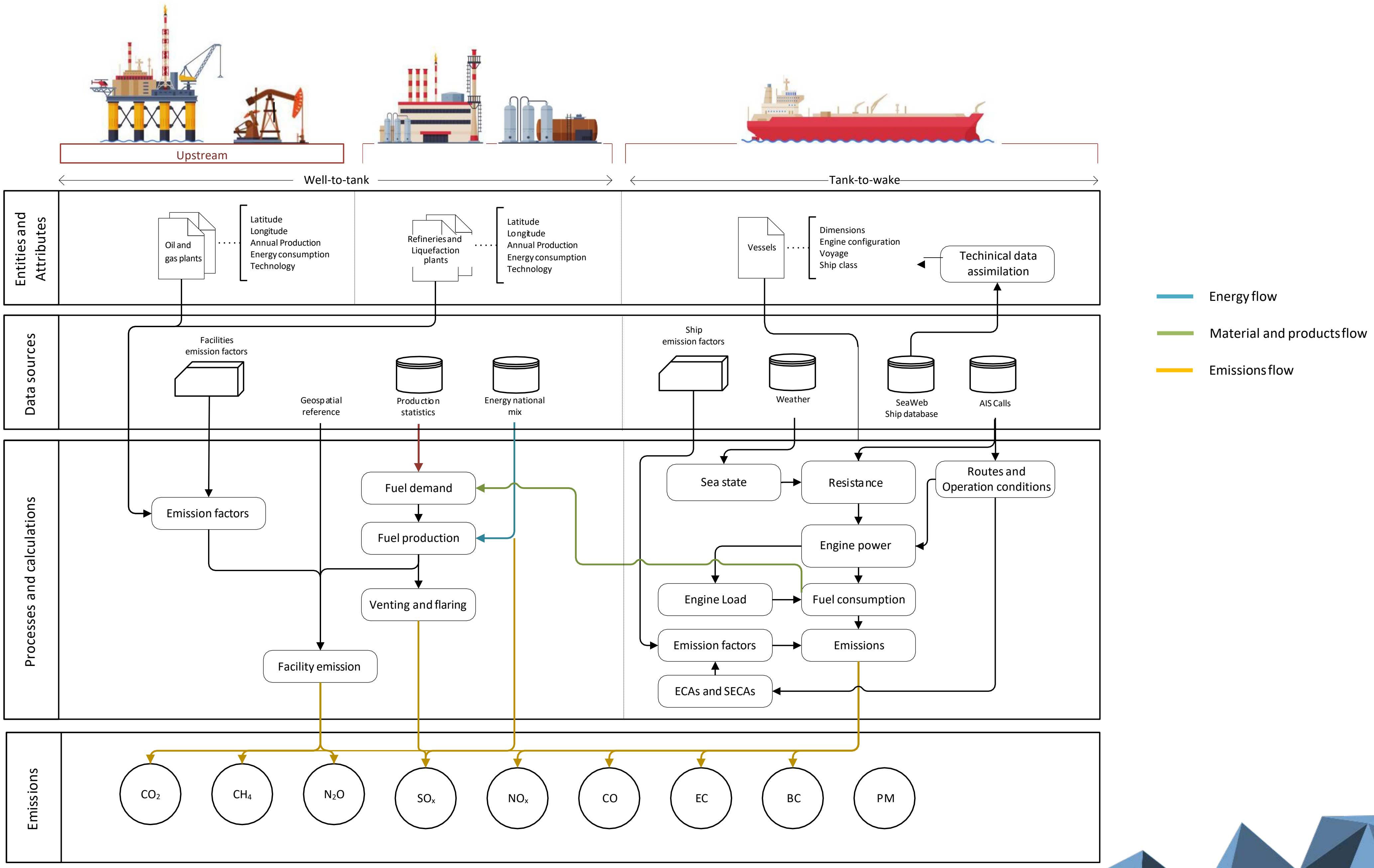
June 20, 2023 - Trondheim

The Research Council of Norway

NTNU

SINTEF

Model architecture



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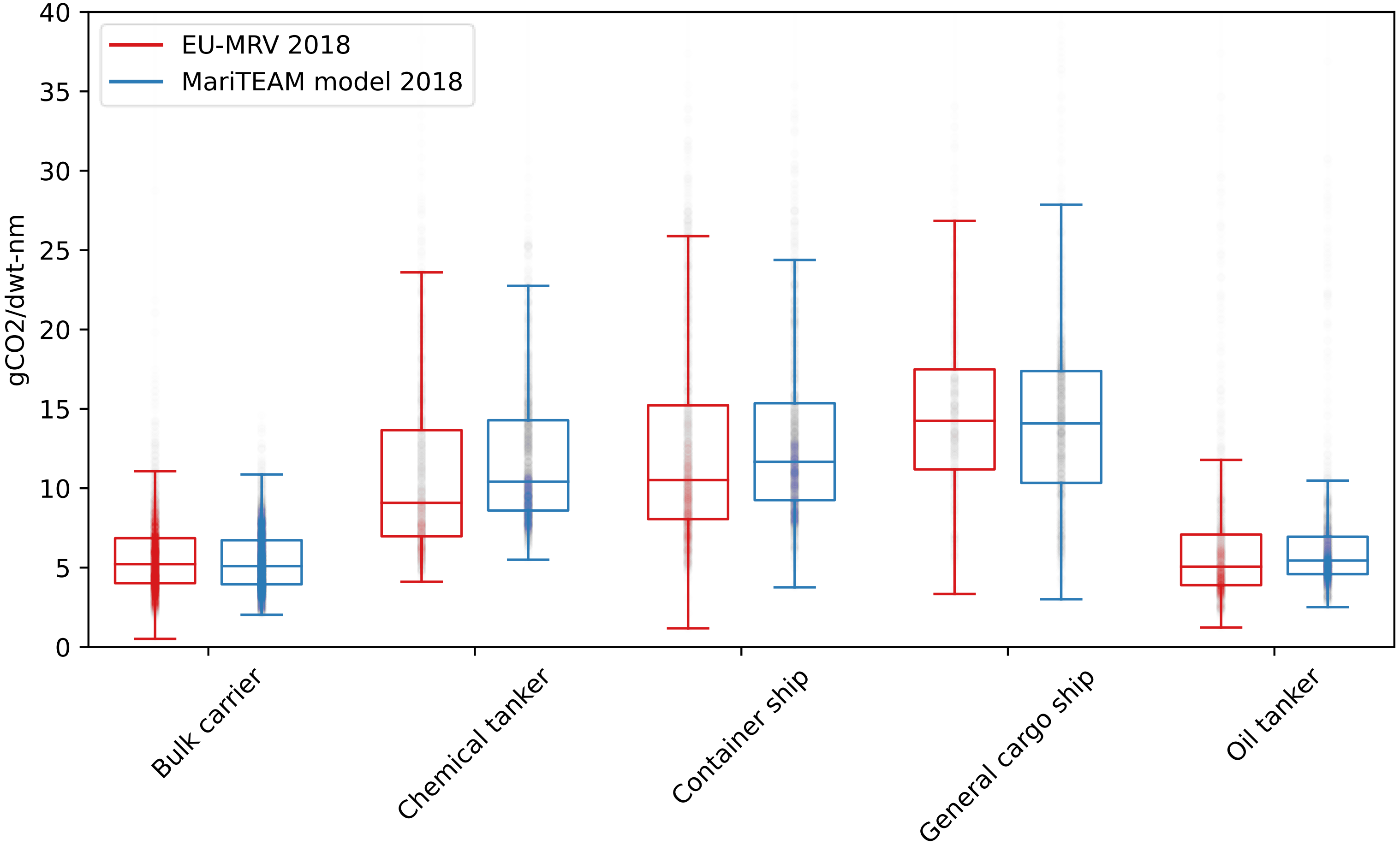
The MariTEAM model reproduces very well the AER distribution across all segments at an aggregate level



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Key assumptions for this prospective analysis

Technologies as of 2017

- HFO: Sulphur content 2.6%
- MGO
- LNG: Low-pressure

Technologies that could become available in the period between now and 2030

- HFO: Sulphur content 0.5%
- MGO
- LNG: Low and High-pressure
- Fossil Methanol
- Ammonia (blue): from Natural Gas (production on-site) with CCS (95%) , ATR H2, and biofuel as pilot fuel with conservative N_2O emissions
- Ammonia (green): Electrolysis (wind energy) and biofuel as pilot fuel with low N_2O emissions
- CCS: ~60% with FC increase of 10%
- Scrubbers: -98% SO_2 (Comer et al., 2020)

ATTENTION: Without NOx

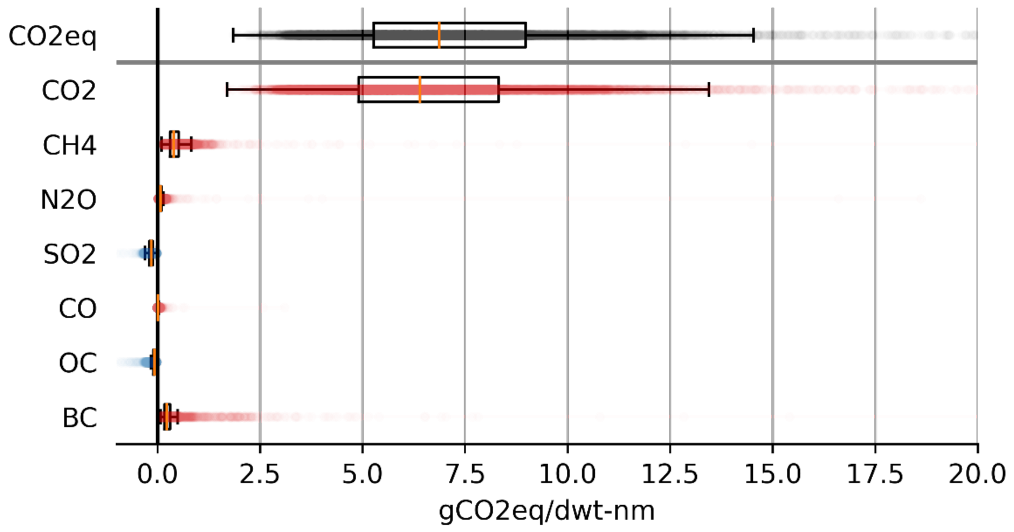
Sulphur content limit down to 0.5% (IMO2020)

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

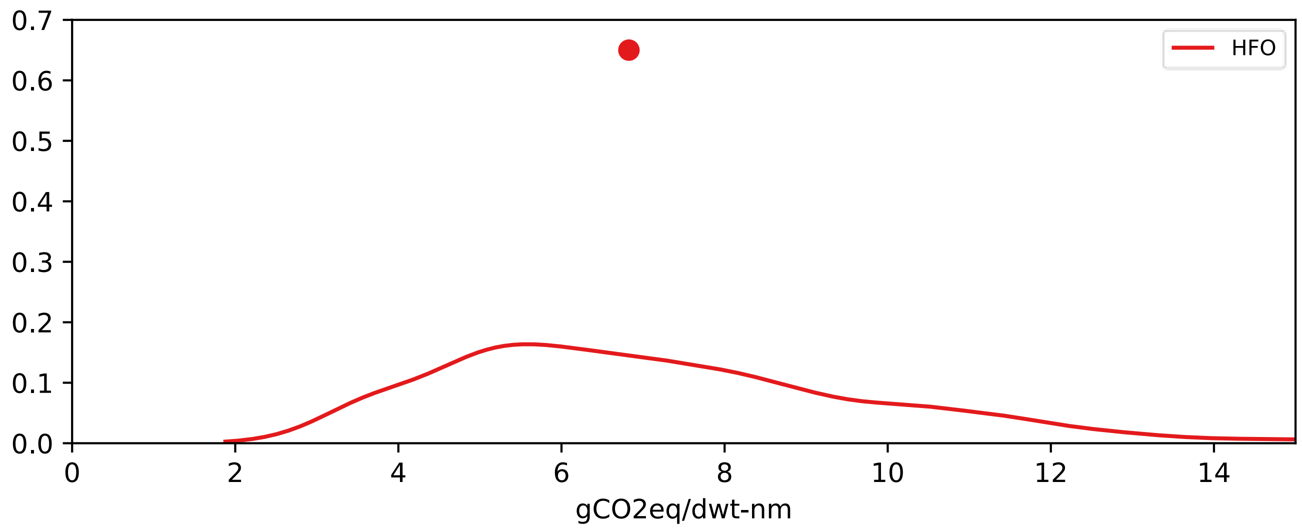
Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



Aggregate result for comparison of different cases



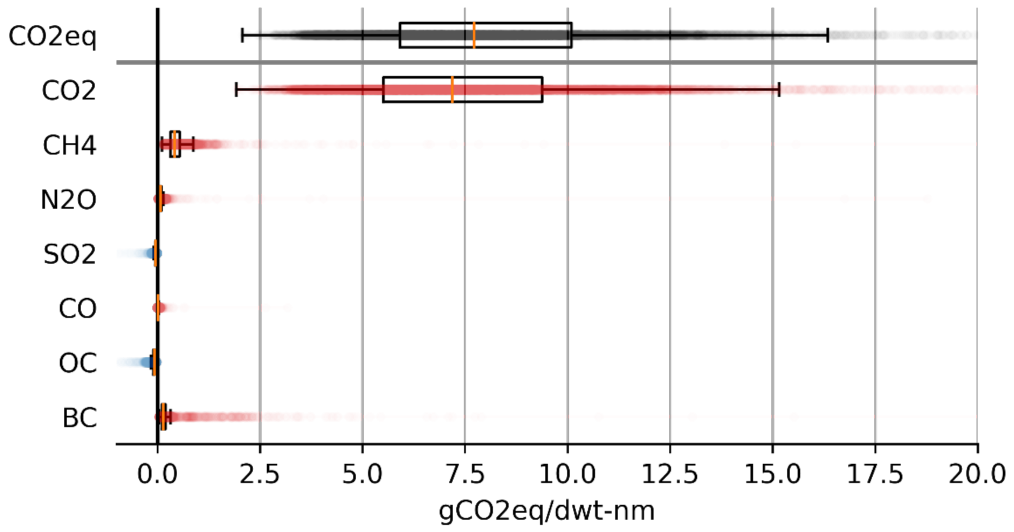
Changes in most species lead to an increase in CO2eq

HFO	**MGO**	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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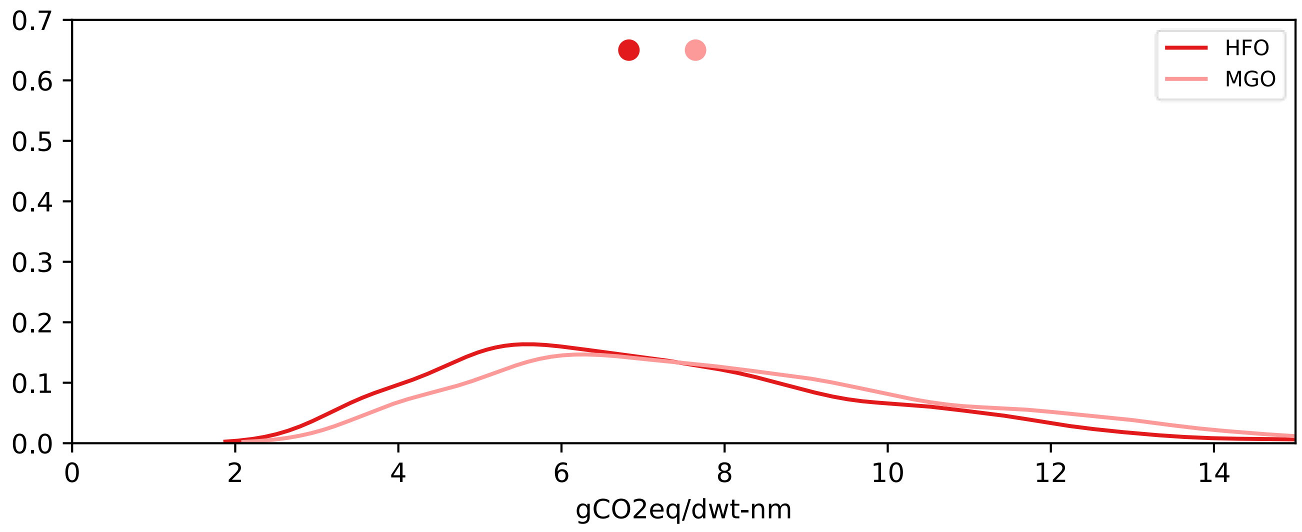


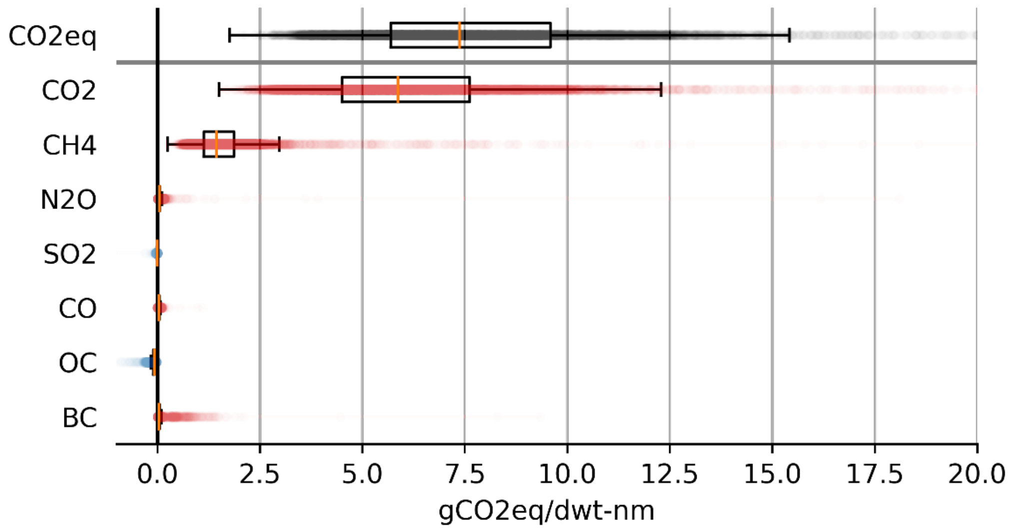
Methane nearly offsets CO2 reductions

HFO | MGO | **LNG LP** | LNG HP | Methanol | Ammonia-C-blue | Ammonia-L-green | HFO+CCS+SCRB | MGO+CCS

Bulk carriers | Chemical tankers | Container ships | Liquefied gas | Oil tankers | Ro-ro

CO2 | GWP20 | **GWP100** | GTP20 | GTP100

Individual with breakdown of contributions



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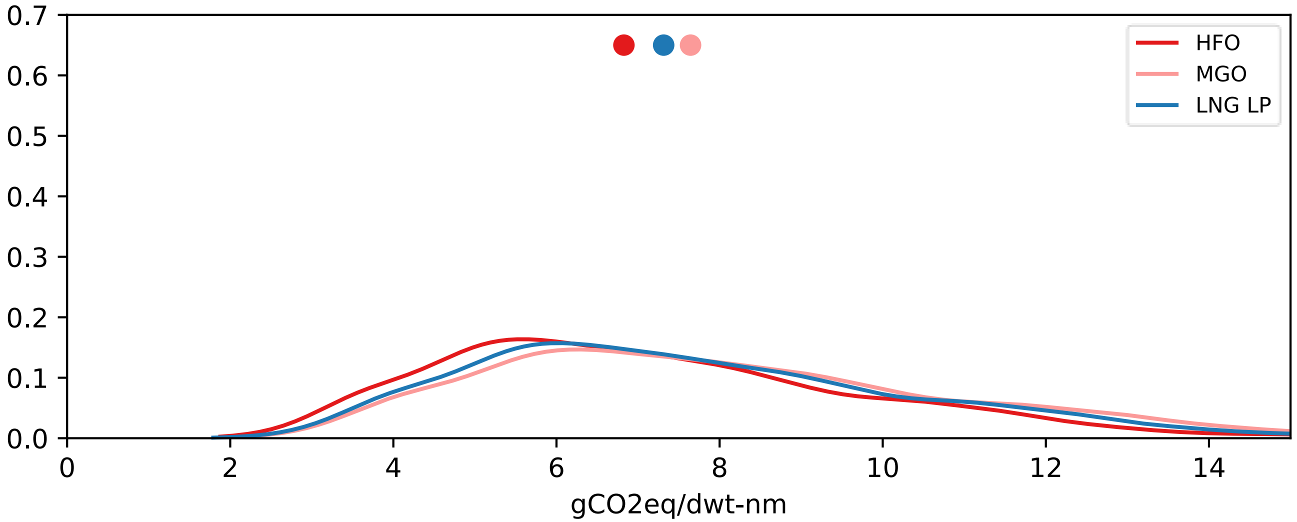

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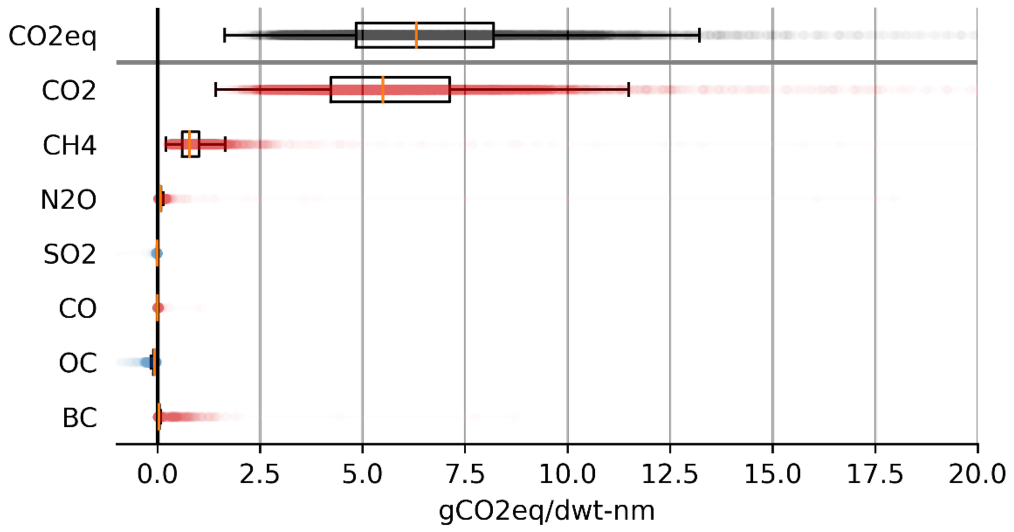
Lower Methane slip and improved thermal efficiency

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



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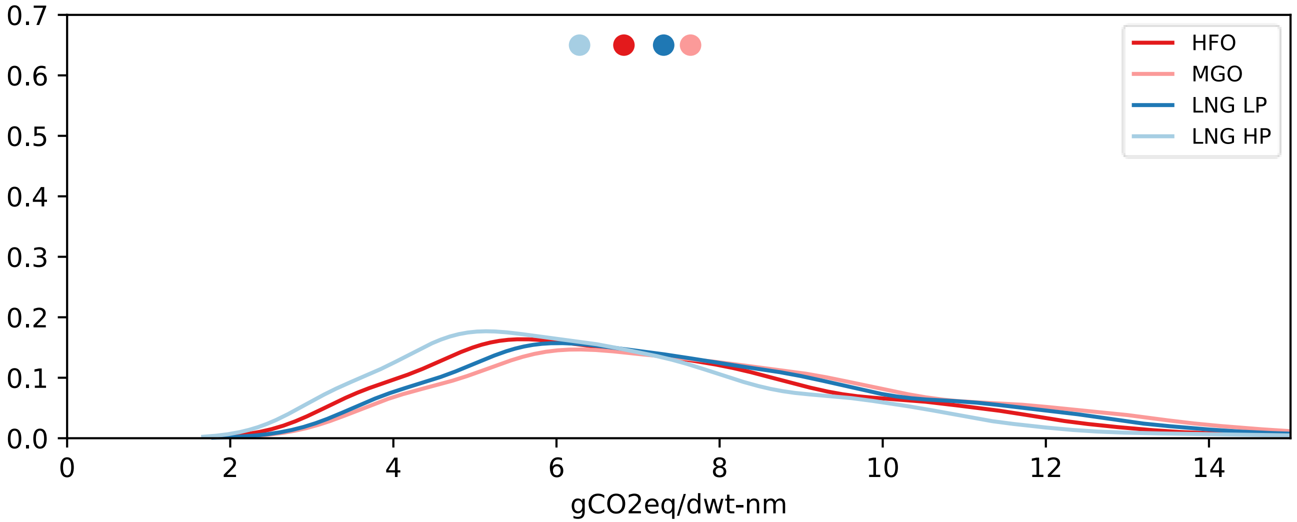

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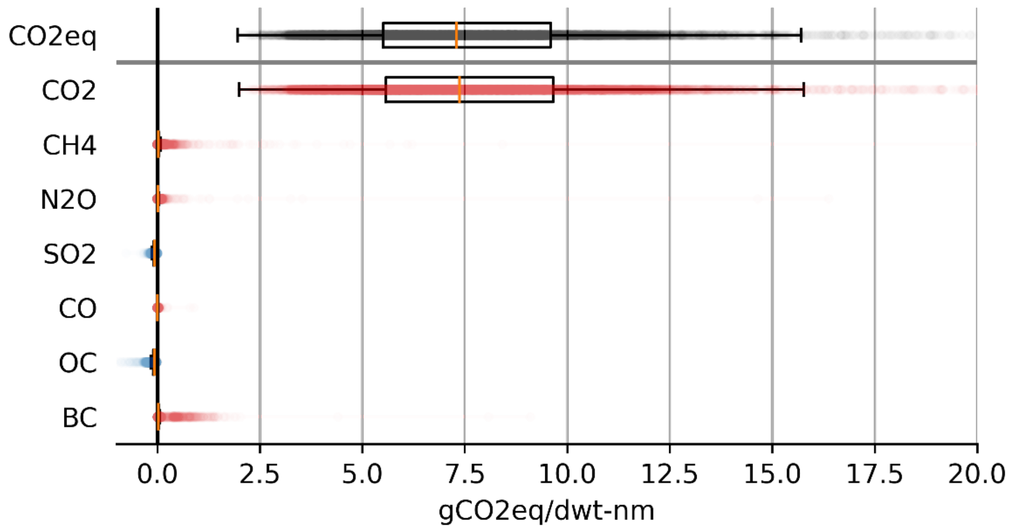
(Fossil) Methanol within range of conventional fuels

HFO | MGO | LNG LP | LNG HP | **Methanol** | Ammonia-C-blue | Ammonia-L-green | HFO+CCS+SCRB | MGO+CCS

Bulk carriers | Chemical tankers | Container ships | Liquefied gas | Oil tankers | Ro-ro

CO2 | GWP20 | **GWP100** | GTP20 | GTP100

Individual with breakdown of contributions



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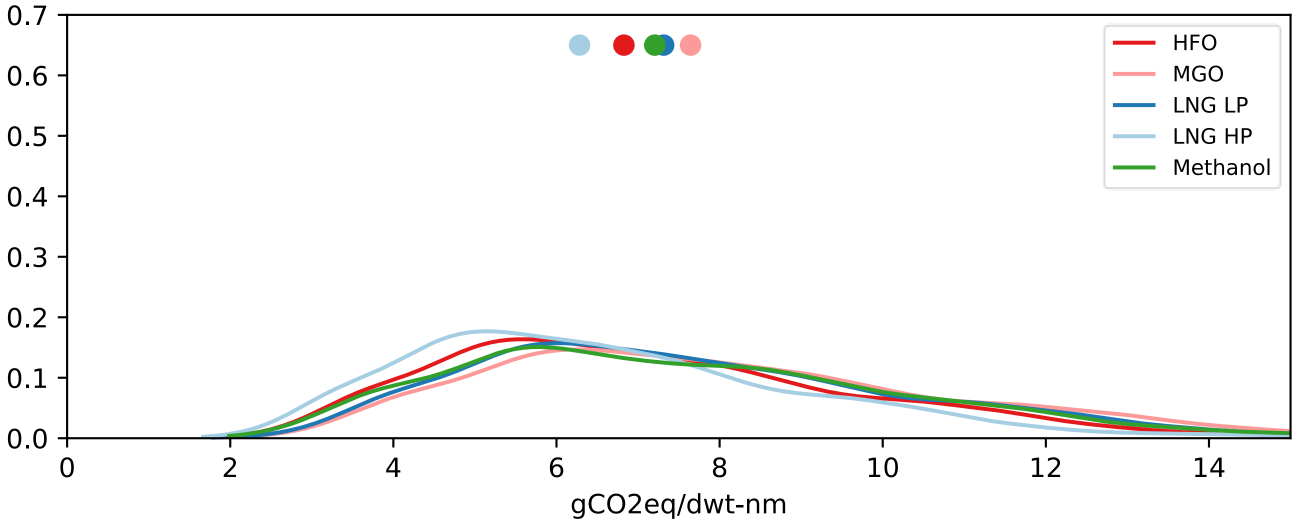

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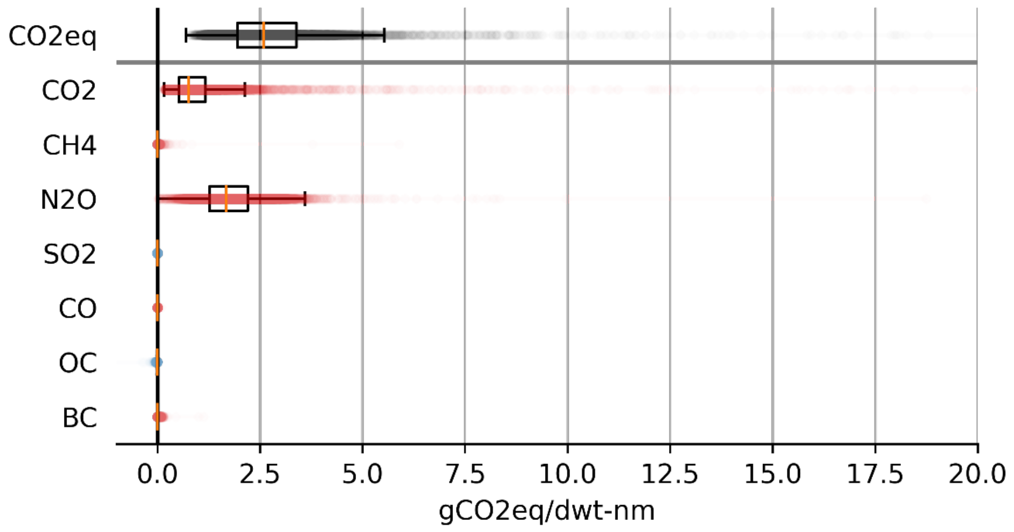
ATR H2 - NG With CCS upstream and conservative N_2O emissions levels

HFO	MGO	LNG LP	LNG HP	Methanol	**Ammonia-C-blue**	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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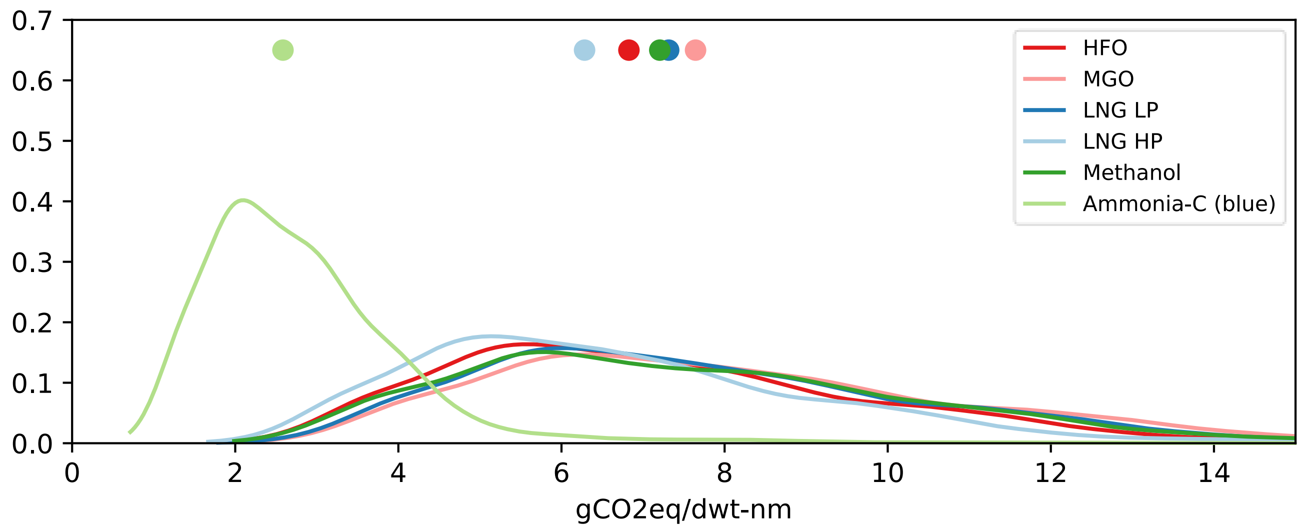


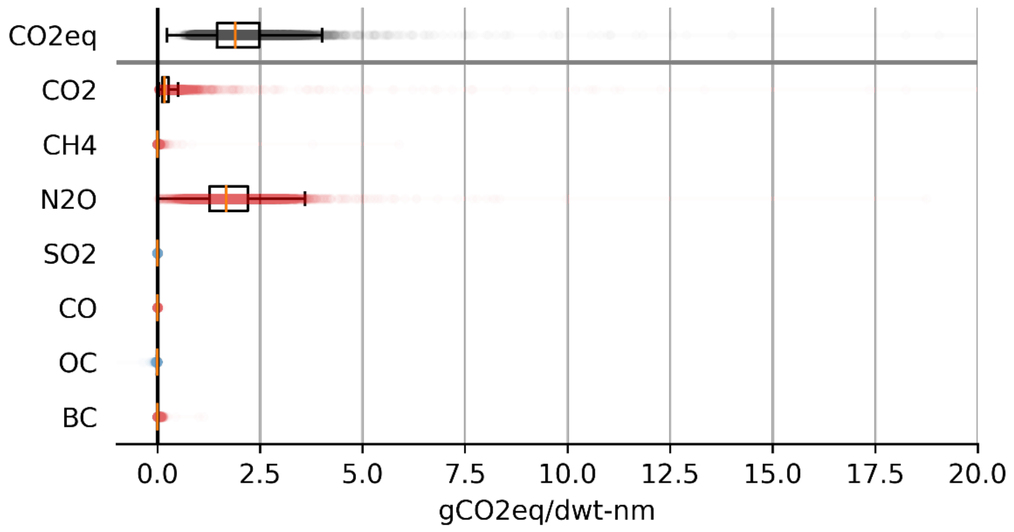
Wind Based Green ammonia and optimistic N_2O from combustion.

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



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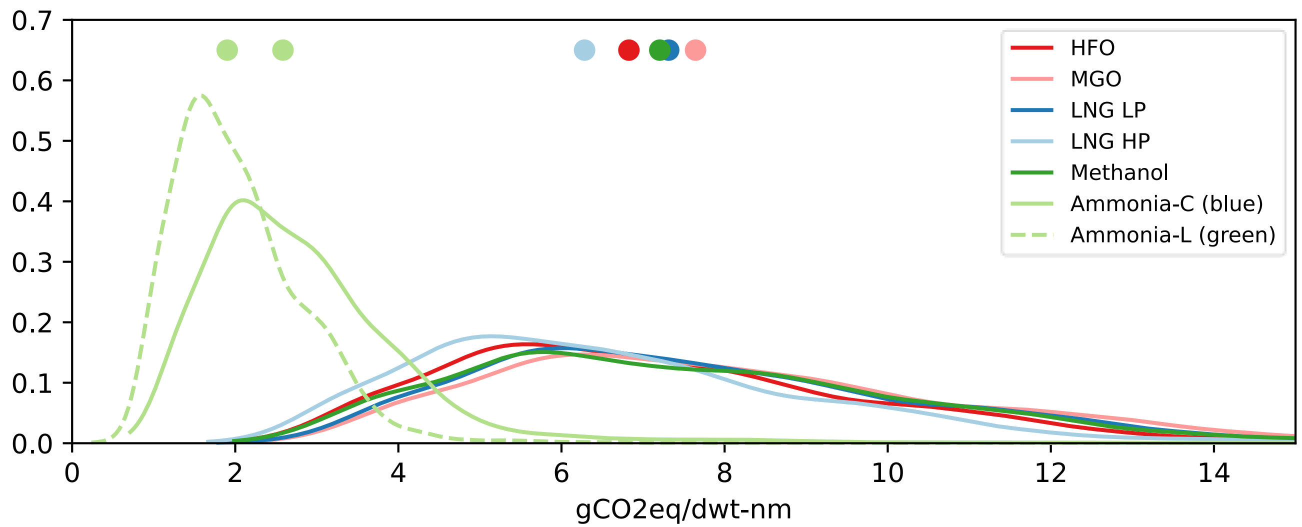


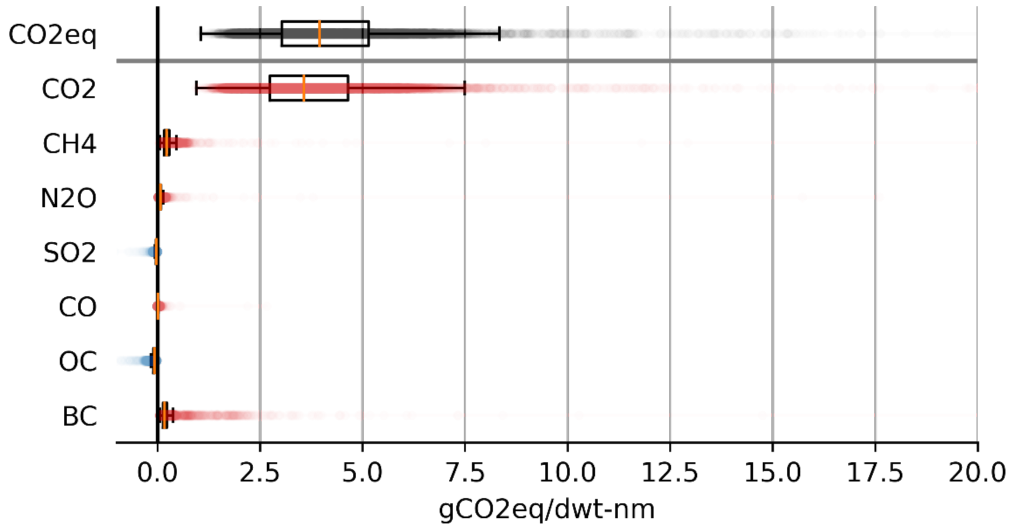
HFO with CCS

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	**HFO+CCS+SCRB**	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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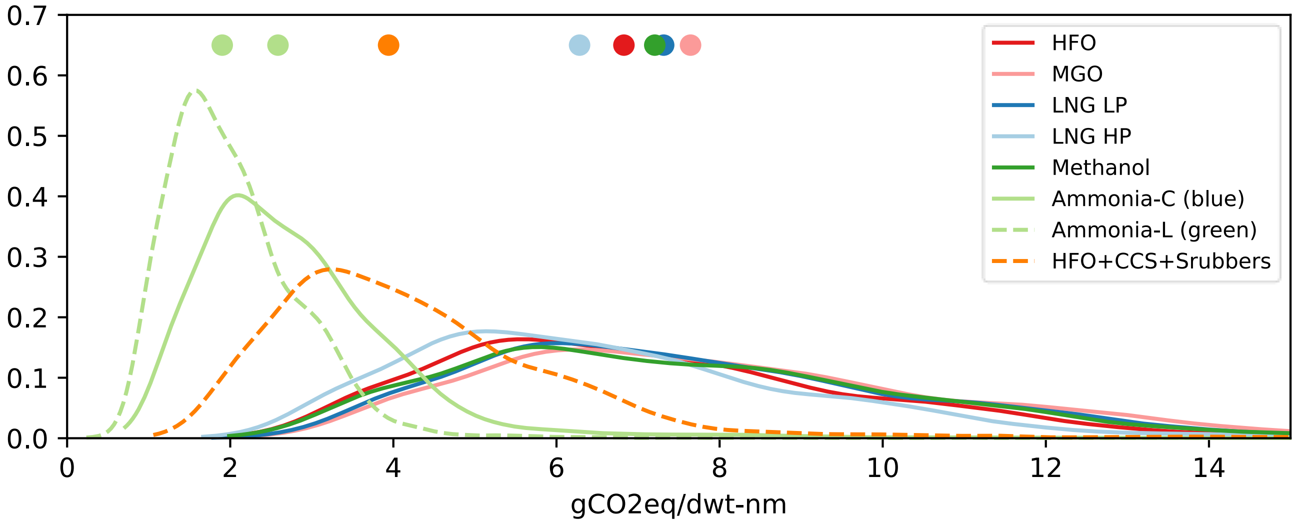

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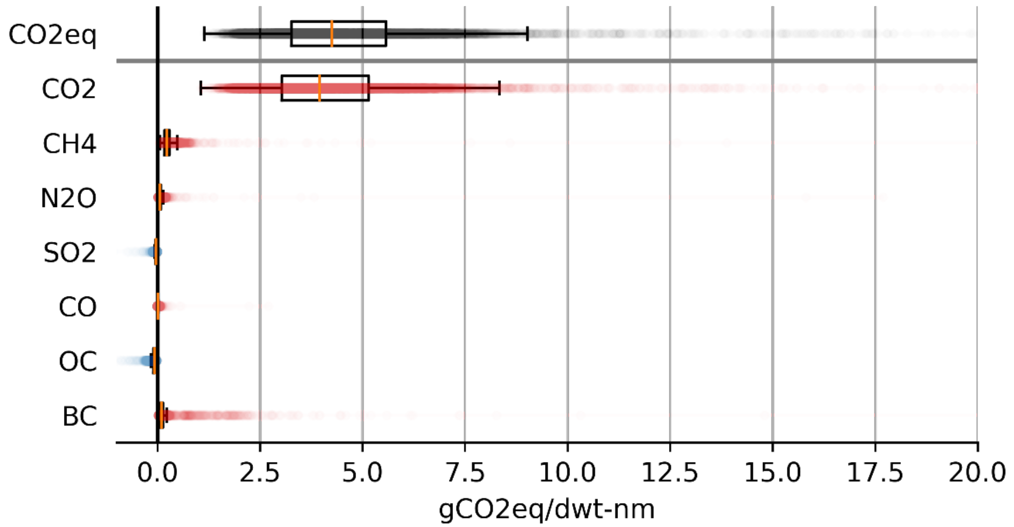
Alternative fuels across size segments.

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



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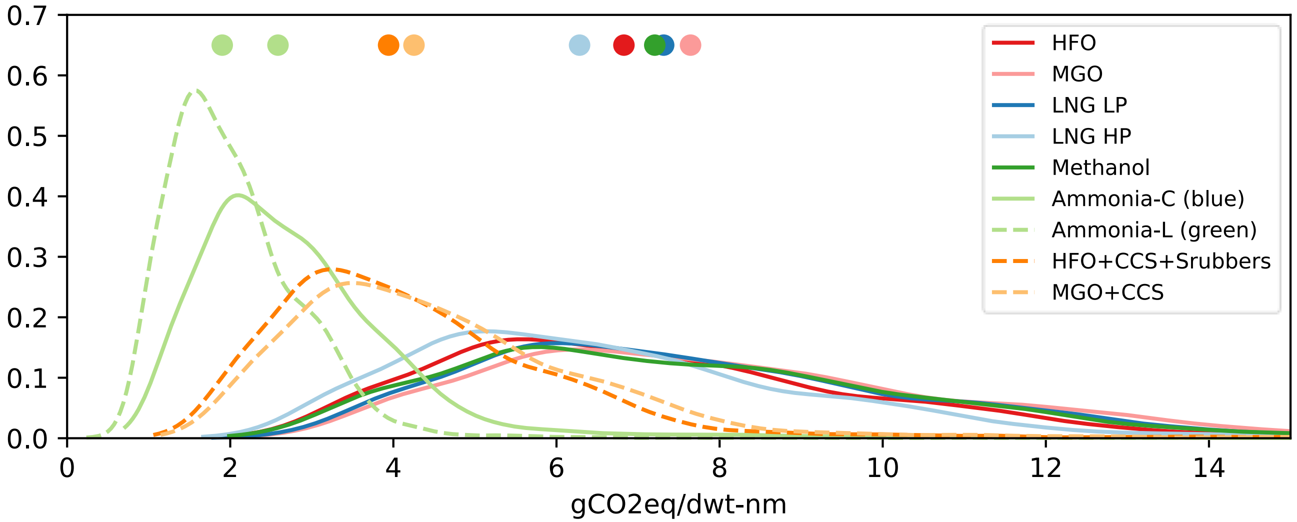

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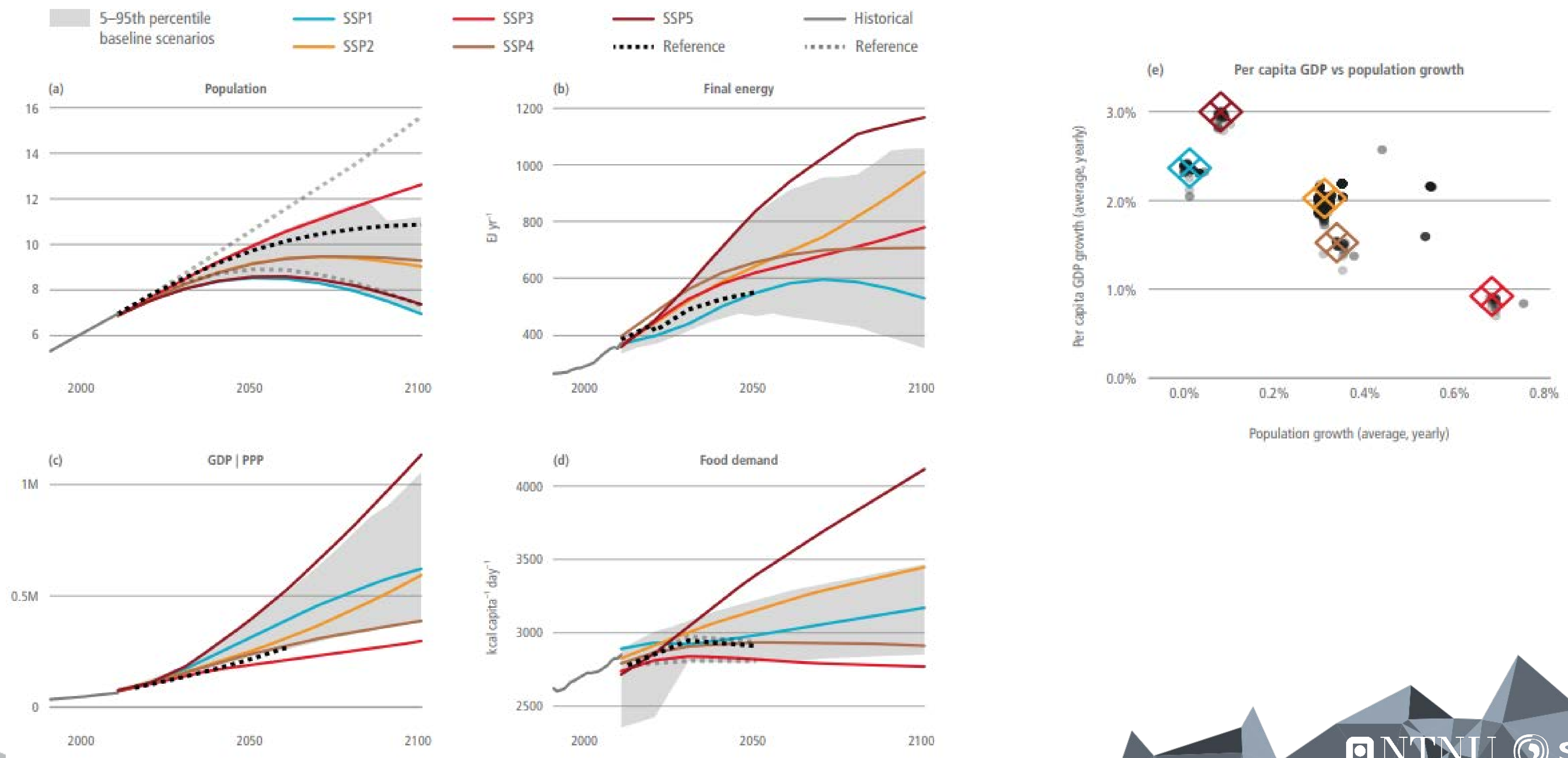
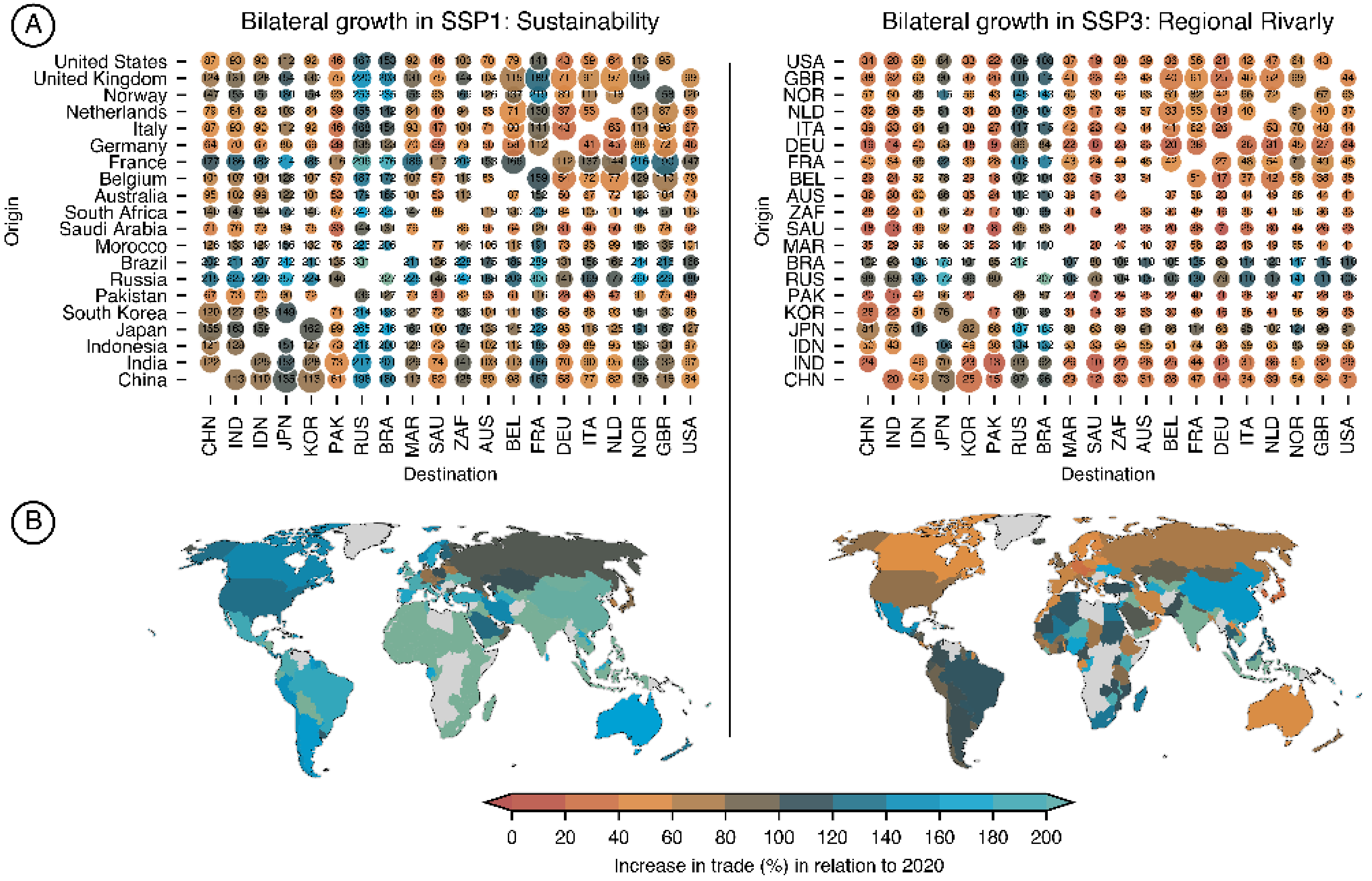
How much fuel will we need?

Shared Socio-Economic Pathways

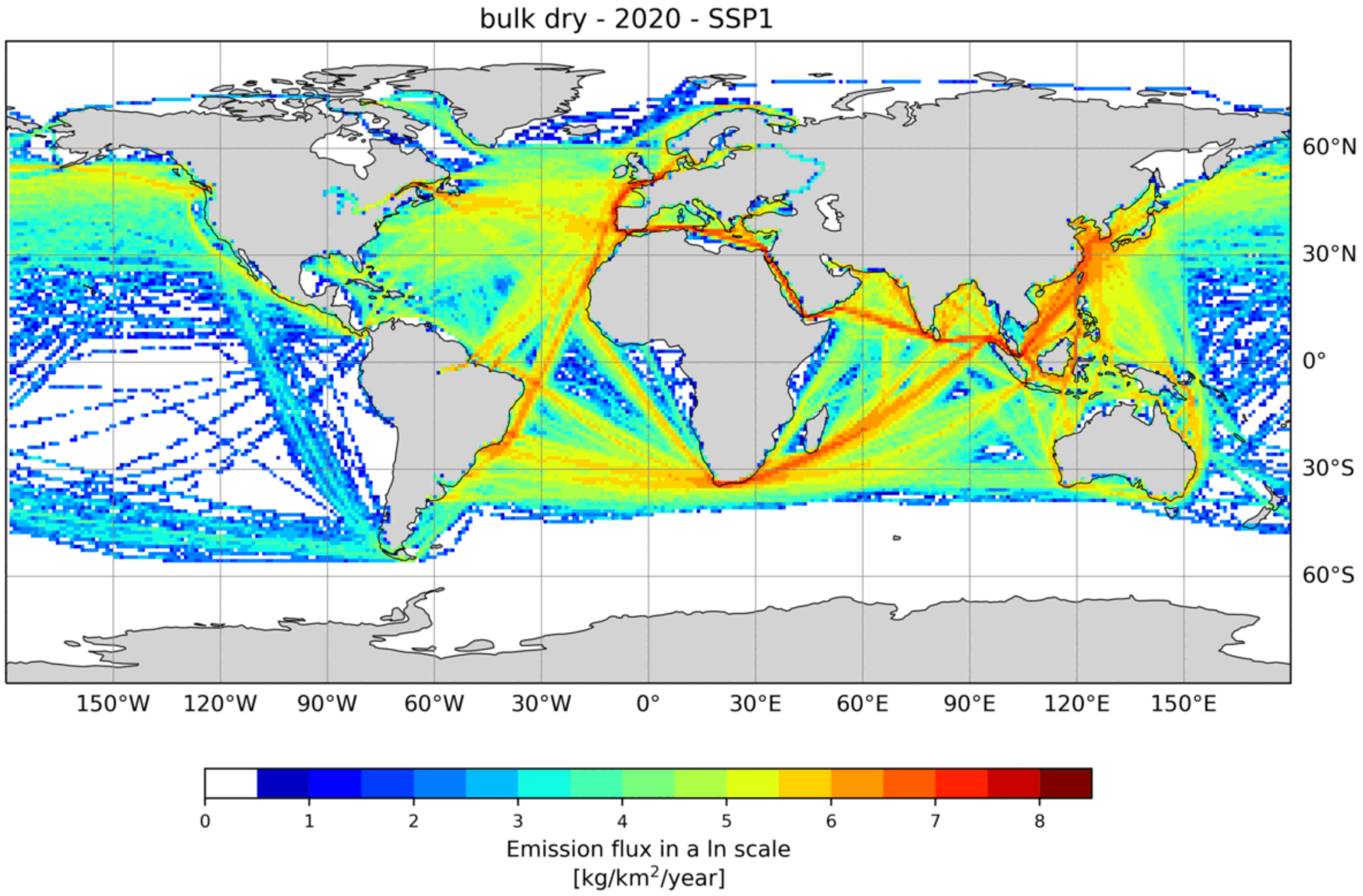


Shared Socio-Economic Pathways Gravity Modelling : Growth in Trade



Kramel et.al 2023 forthcomming

Simulation of geospatial distribution of shipping emissions – GDP Based demand Growth.



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Kramel et.al 2023 forthcomming

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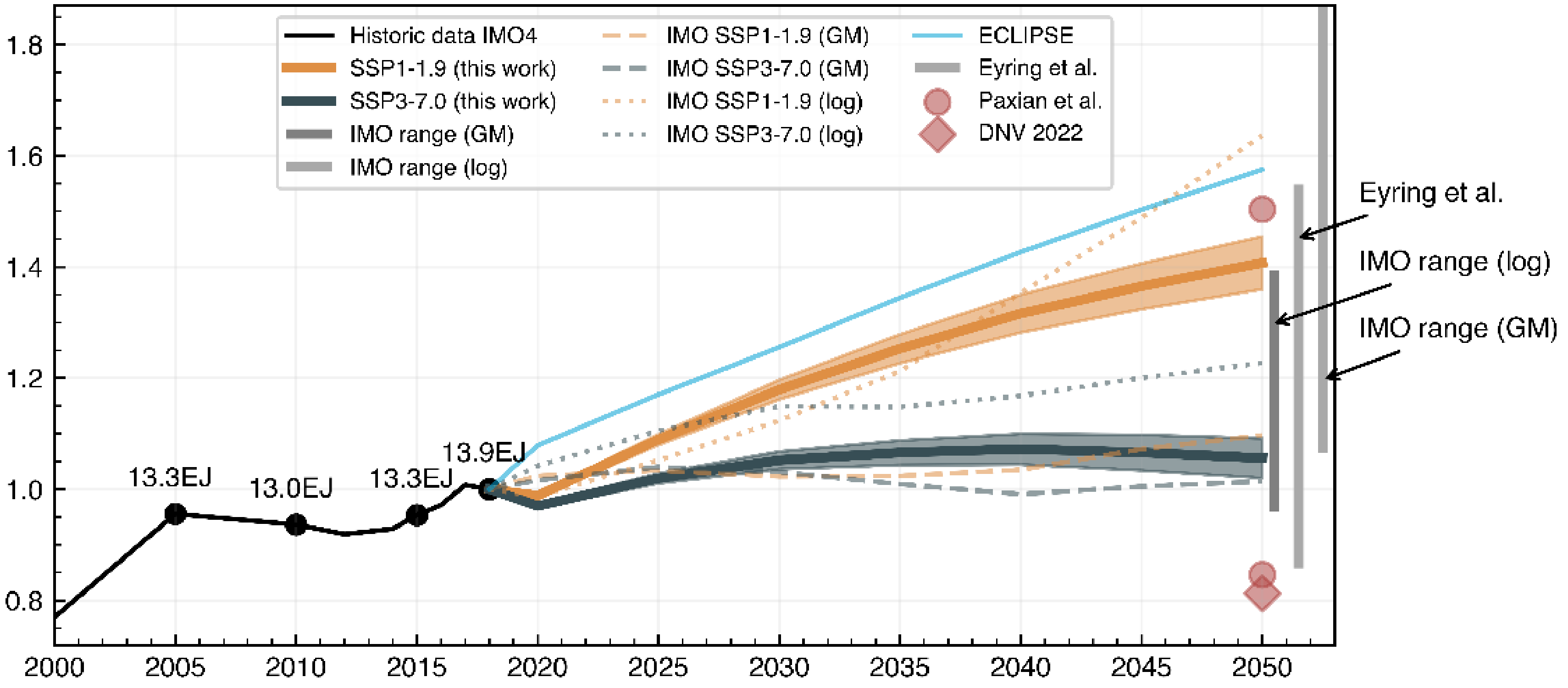
Shared Socio-Economic Pathways Gravity Modelling : Fuel Demand

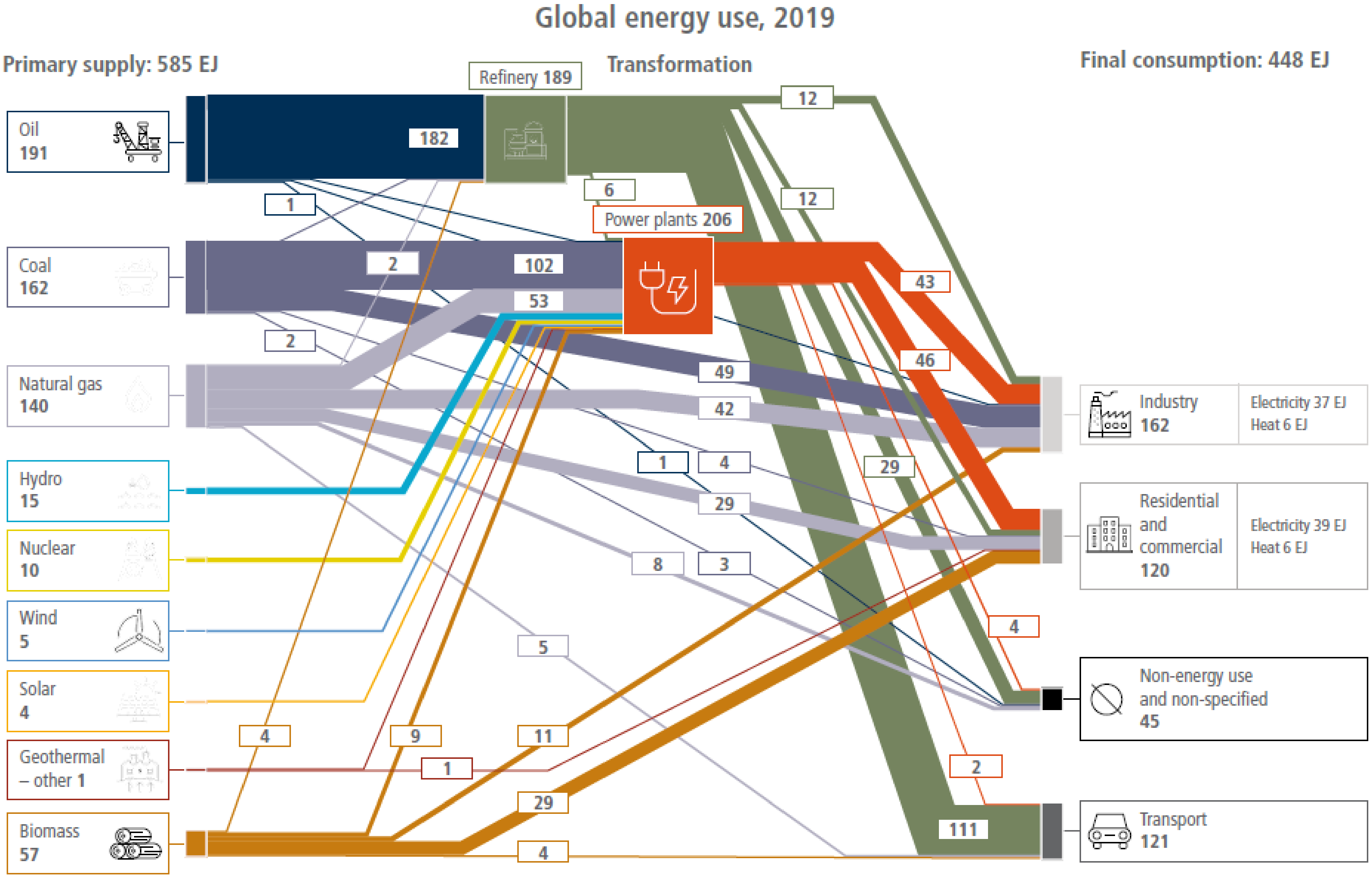


Kramel et al. 2023 forthcoming

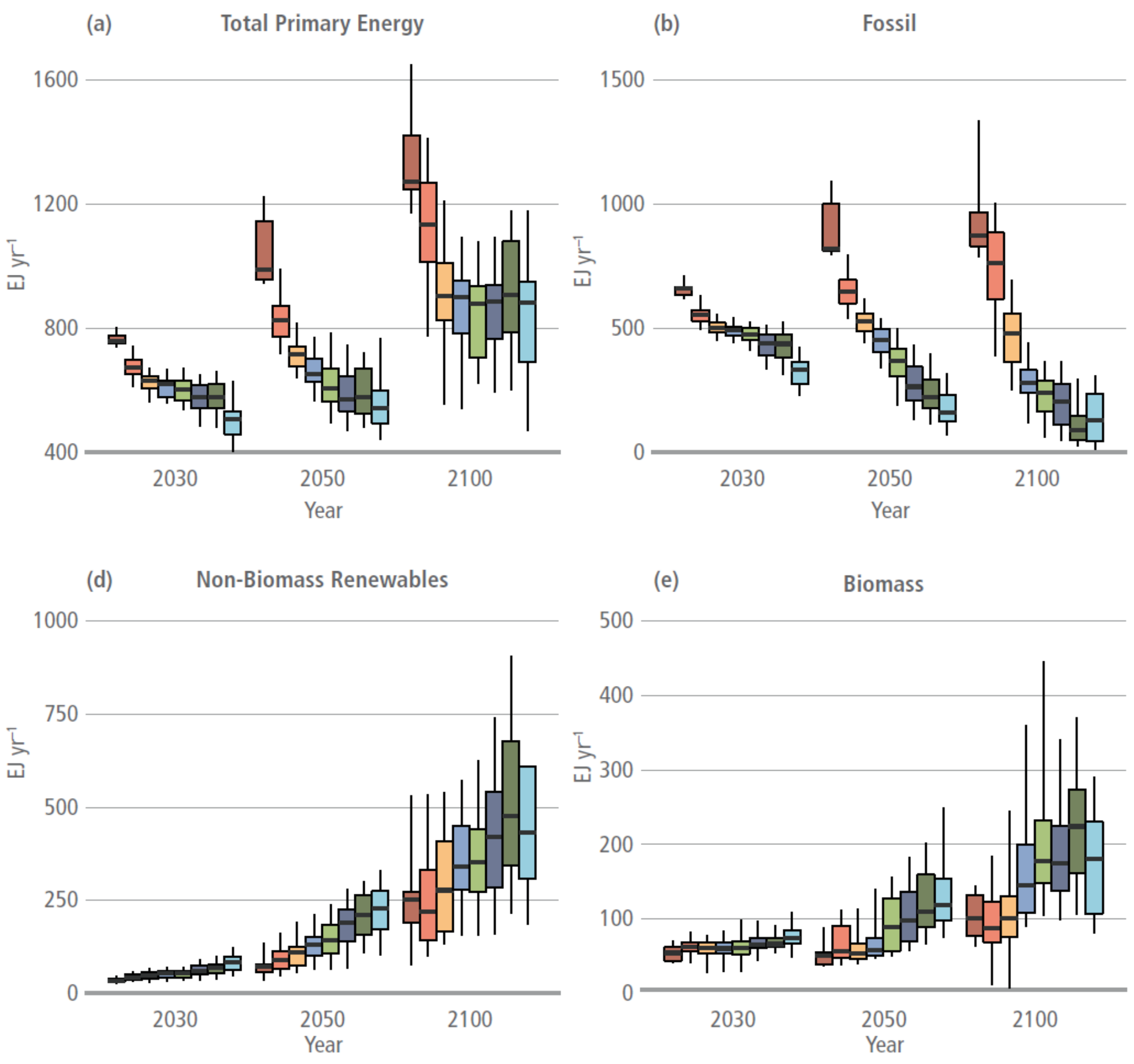
Shipping will not transform in isolation

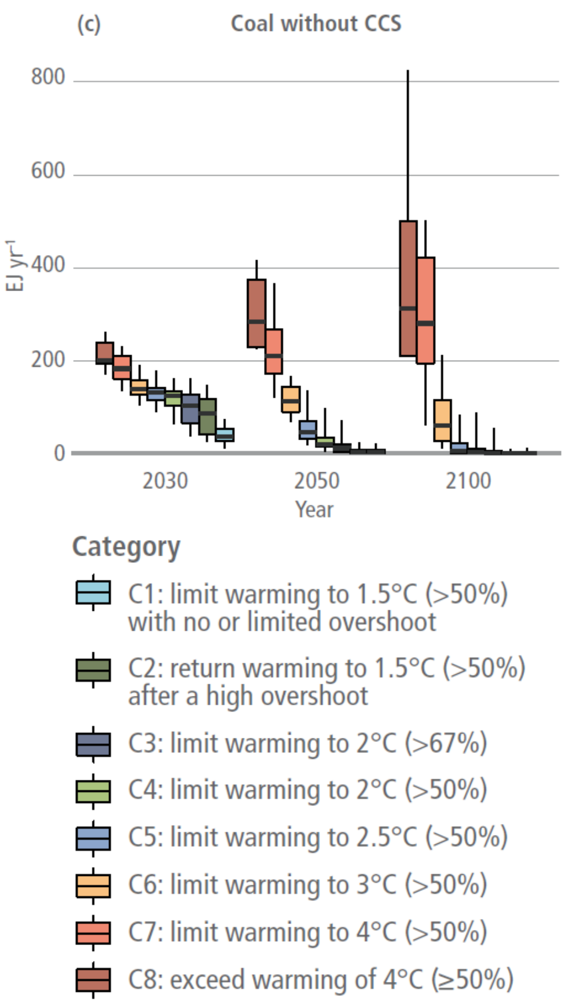
Key Insights from Global Energy Scenarios

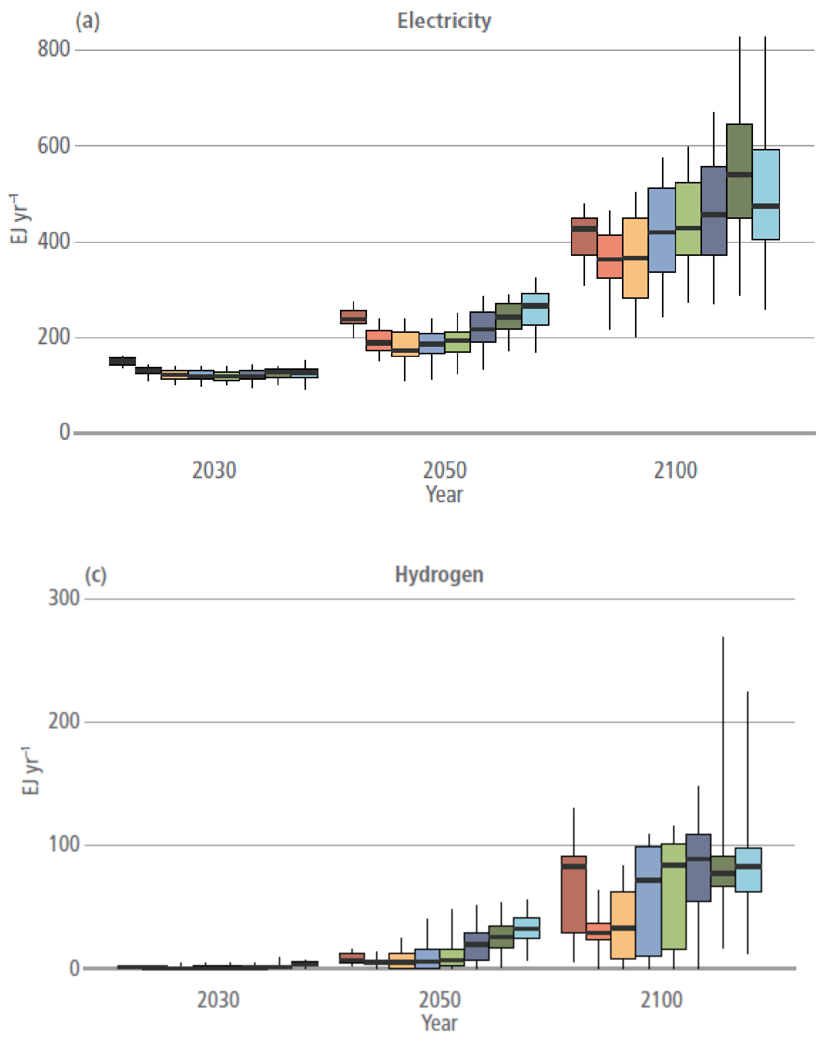
In 2019 shipping constituted 10-11% of the final consumption of energy in the transport sector



Reducing GHG emissions across the full energy sector requires major transitions. This includes a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation

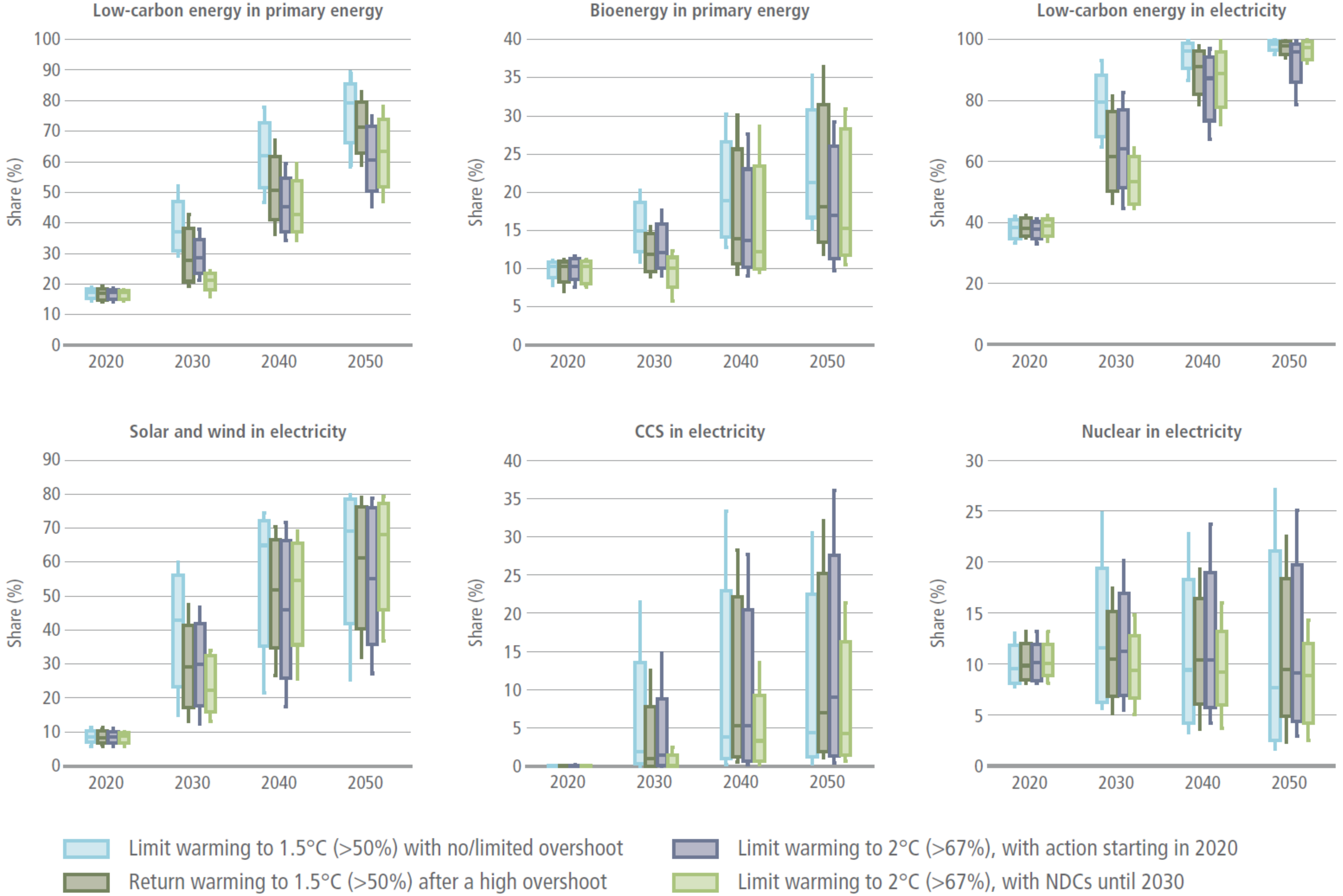






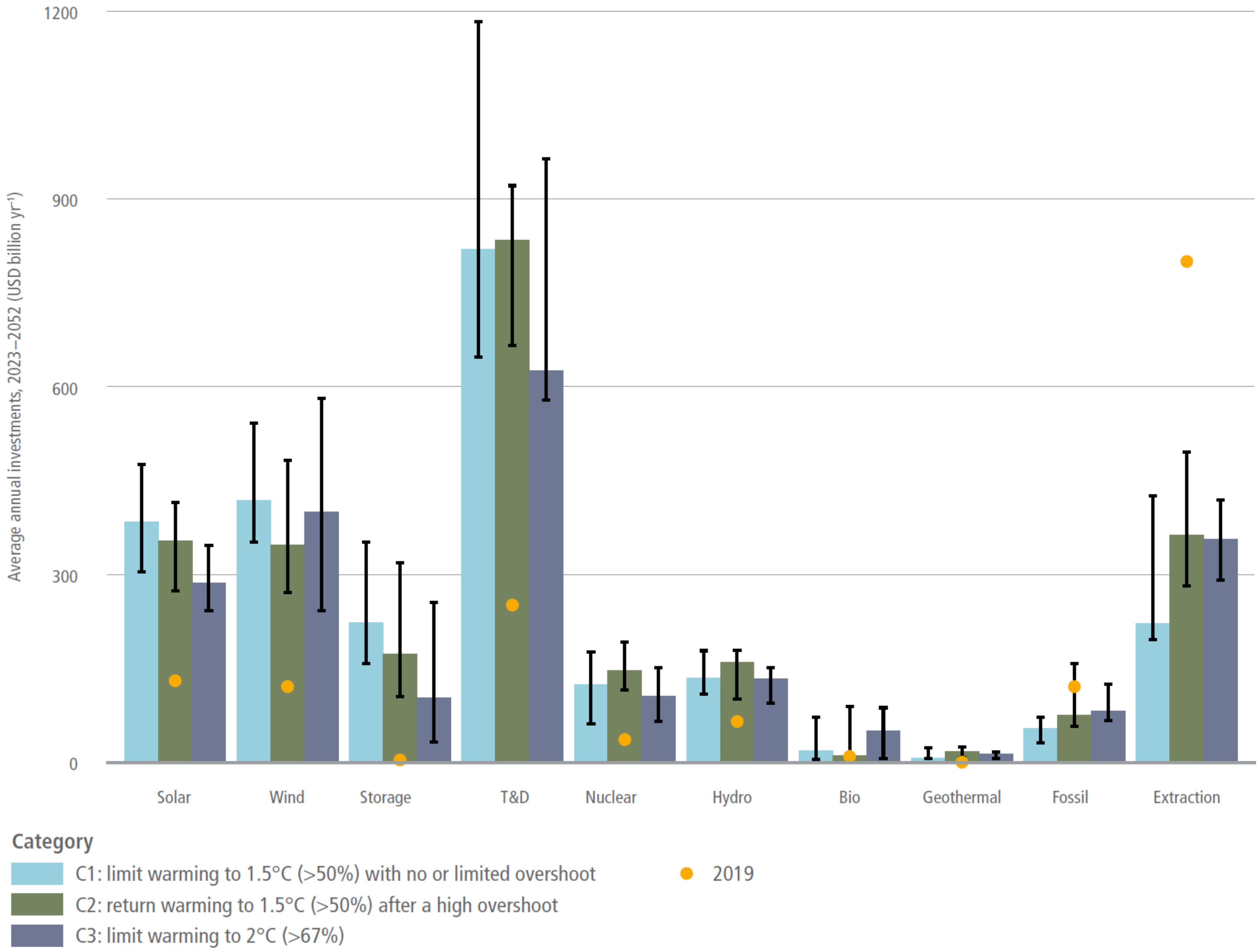
SPM C.4, SPM C3.4, SPM C4.6
Figure 3.22

Shares of Low Carbon Energy



IPCC WG3 AR6 Figure 6.30

Global average annual investments from 2023 to 2052 (undiscounted, in USD billion yr 1)



IPCC WG3 AR6 Figure 6.33

Example of Net –Zero Energy system

-

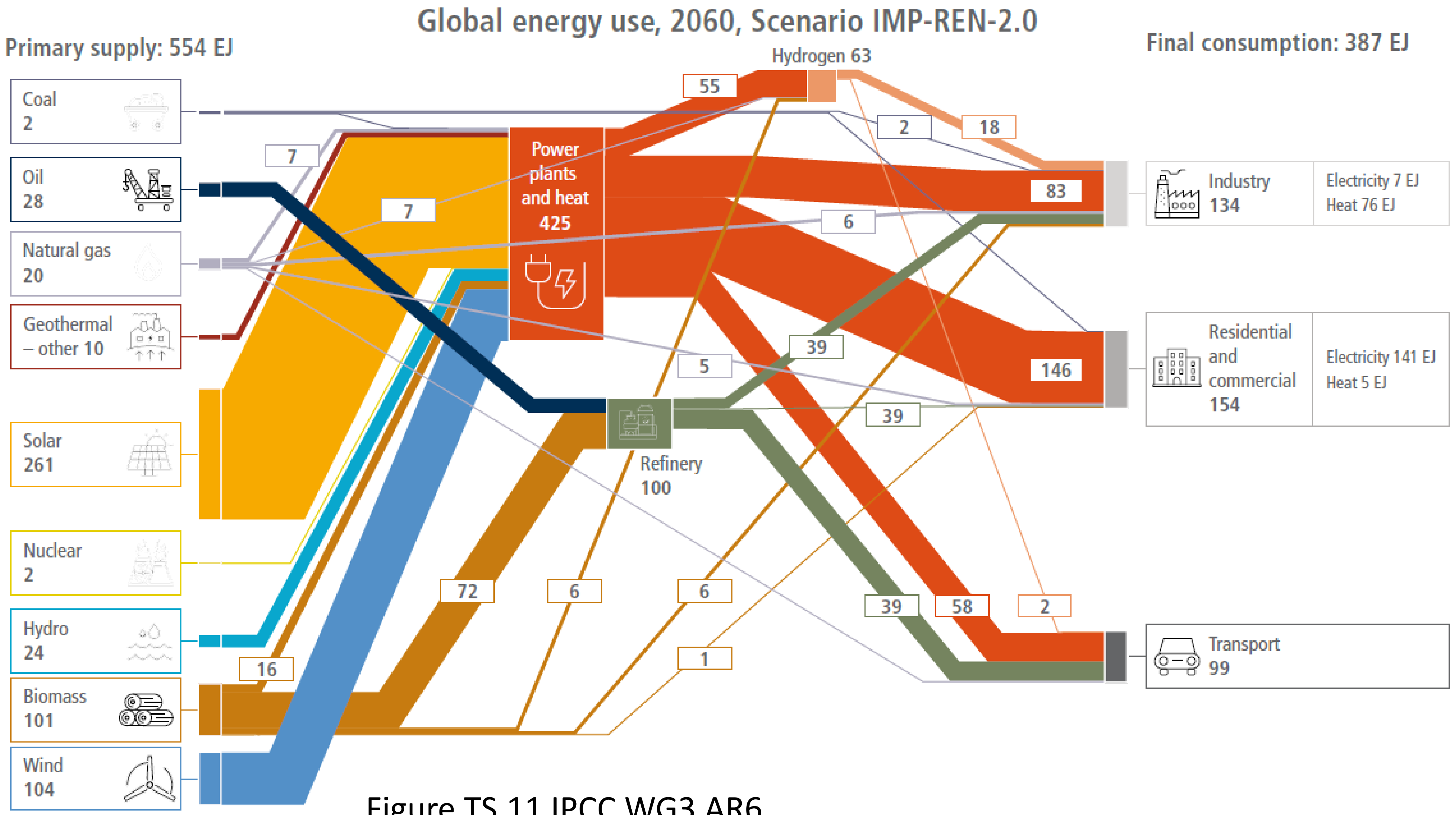


Figure TS.11 IPCC WG3 AR6

Sustainable biofuels, low emissions hydrogen and derivatives (including synthetic fuels), can support mitigating of CO2 emissions from shipping and aviation, and heavy-duty land transport

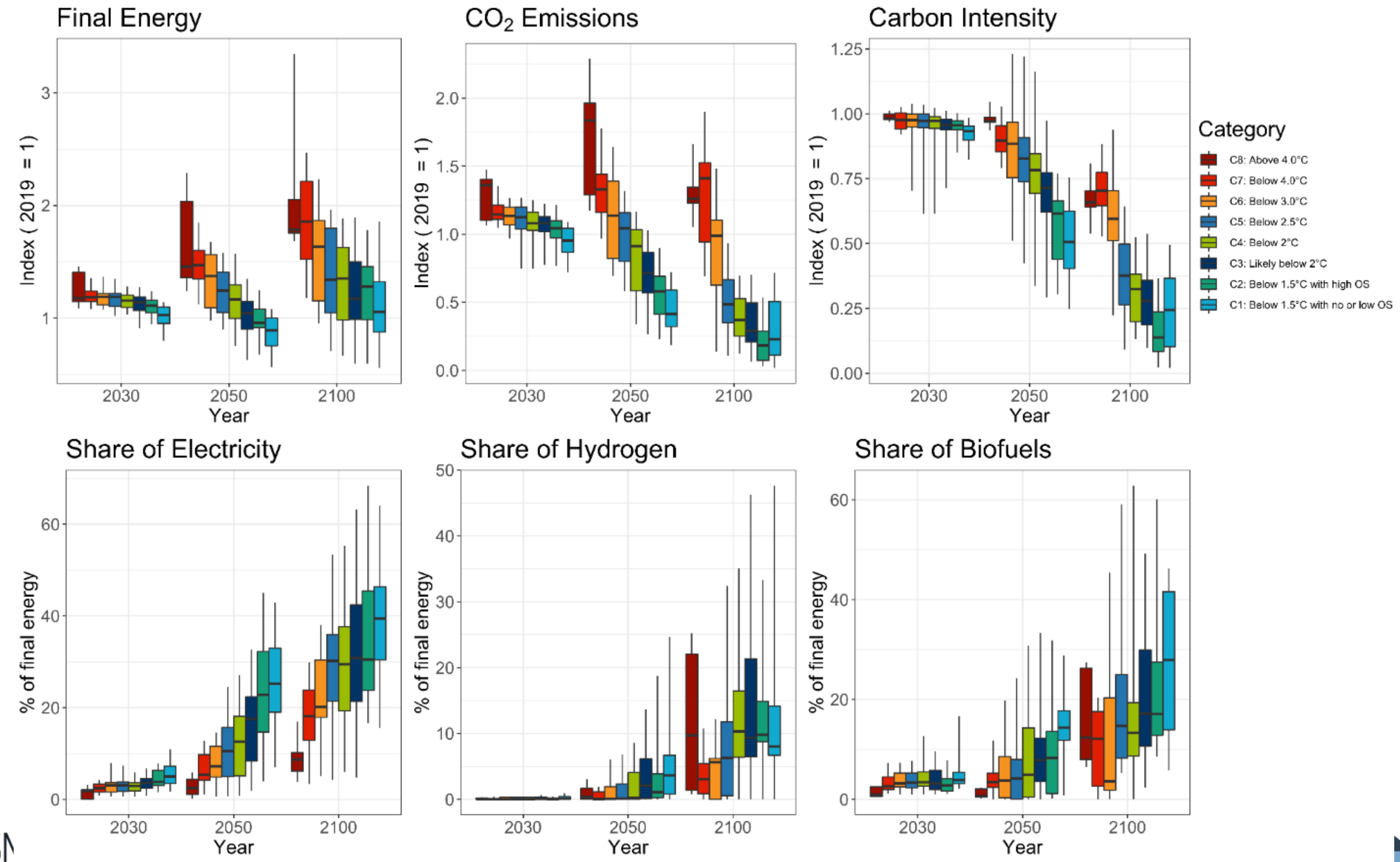
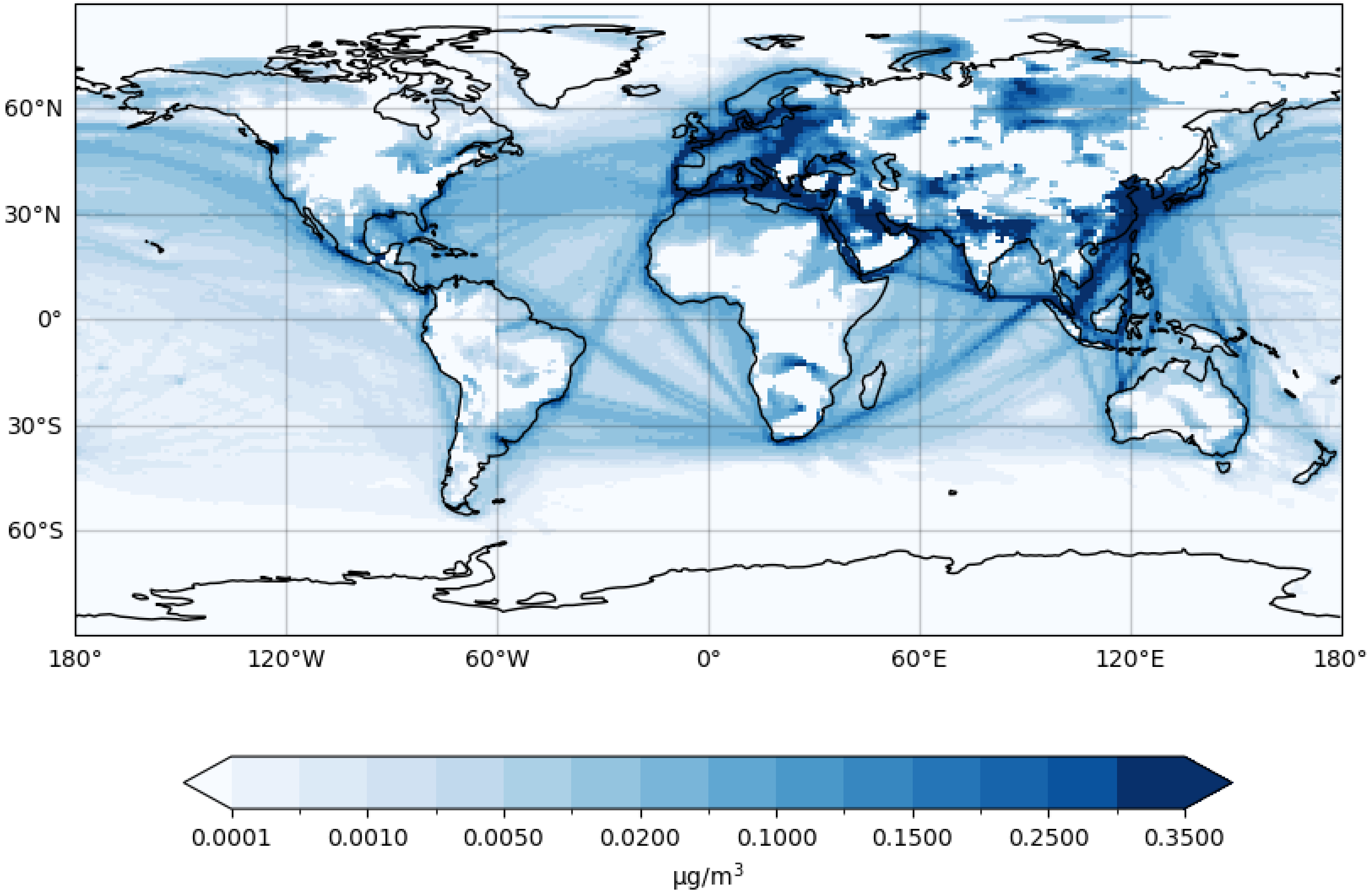


FIG 3.25 SPM C.8

Earth System Modeling

SO2 concentration in the atmospheric bottom layer due to direct emissions from the global fleet in 2019.



MariTeam

NorESM

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Thank you for the attention!

MariTeam

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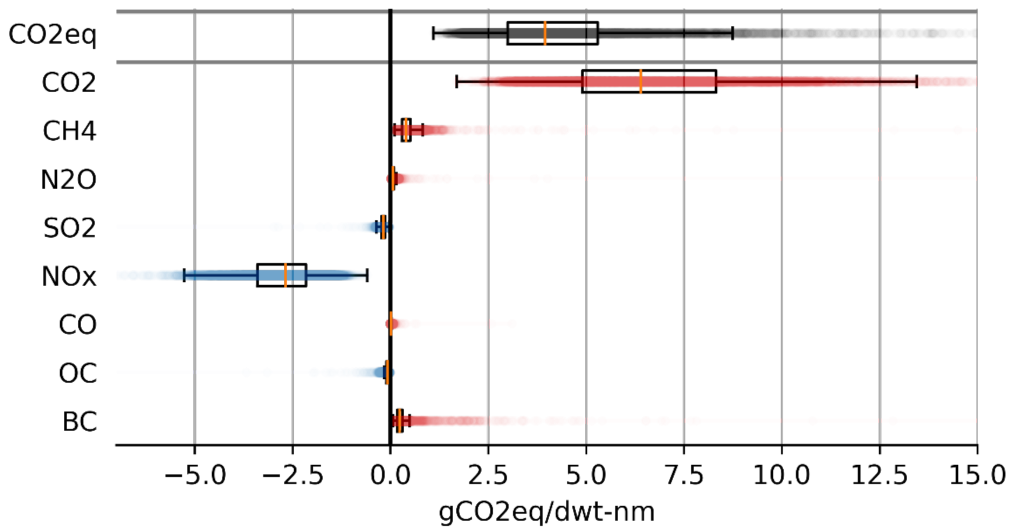
Back up Slides

ATTENTION: with NOx

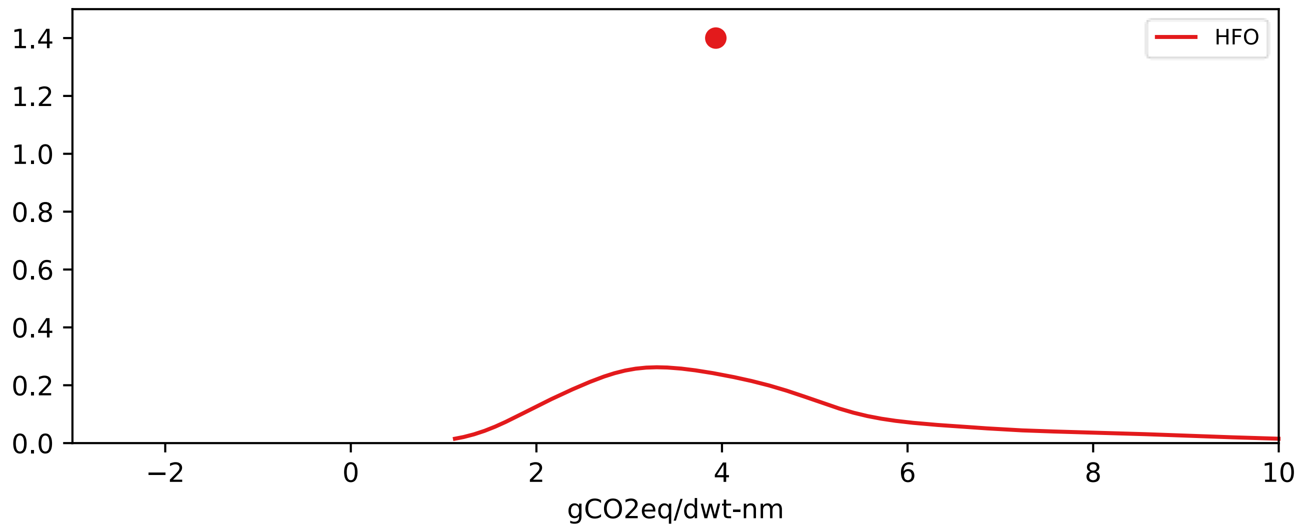
Sulphur content limit down to 0.5% (IMO2020)

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS
Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro			
CO2	GWP20	GWP100	GTP20	GTP100				

Individual with breakdown of contributions



Aggregate result for comparison of different cases



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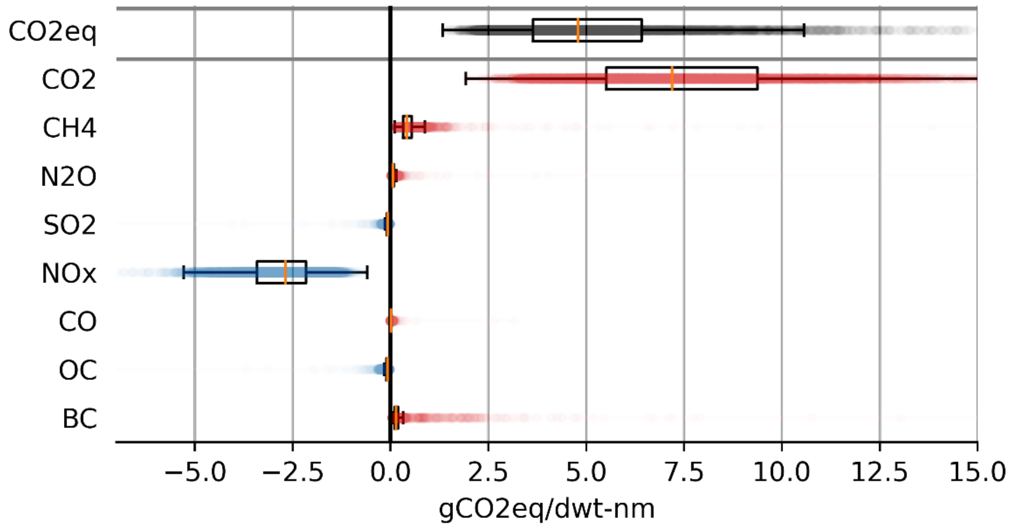
Changes in many species lead to an increase in CO2eq

HFO | **MGO** | LNG LP | LNG HP | Methanol | Ammonia-C-blue | Ammonia-L-green | HFO+CCS+SCRB | MGO+CCS

Bulk carriers | Chemical tankers | Container ships | Liquefied gas | Oil tankers | Ro-ro

CO2 | GWP20 | **GWP100** | GTP20 | GTP100

Individual with breakdown of contributions



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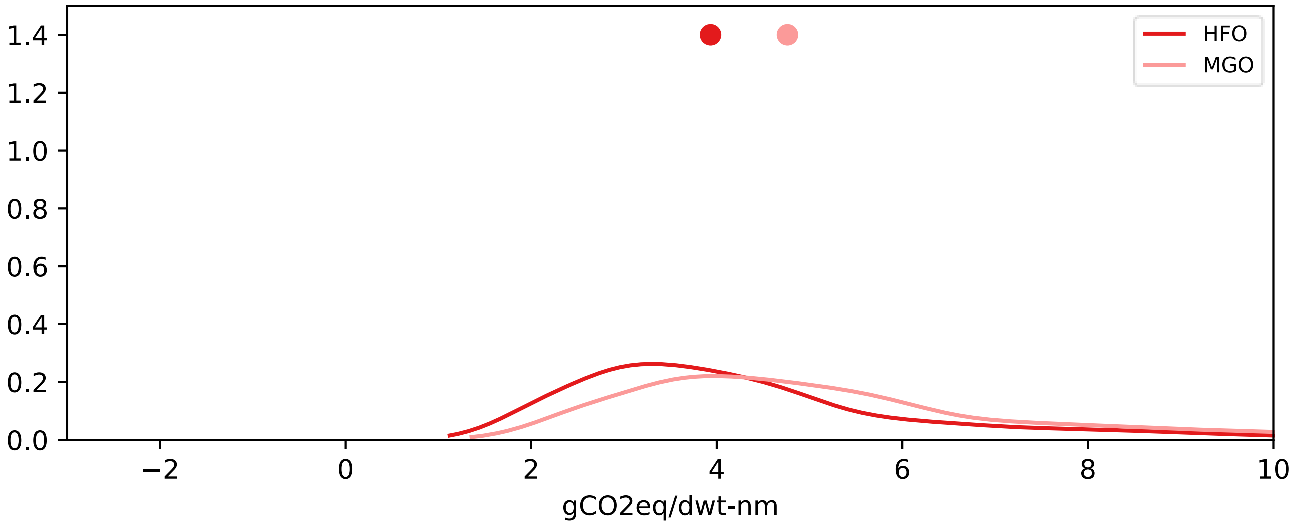

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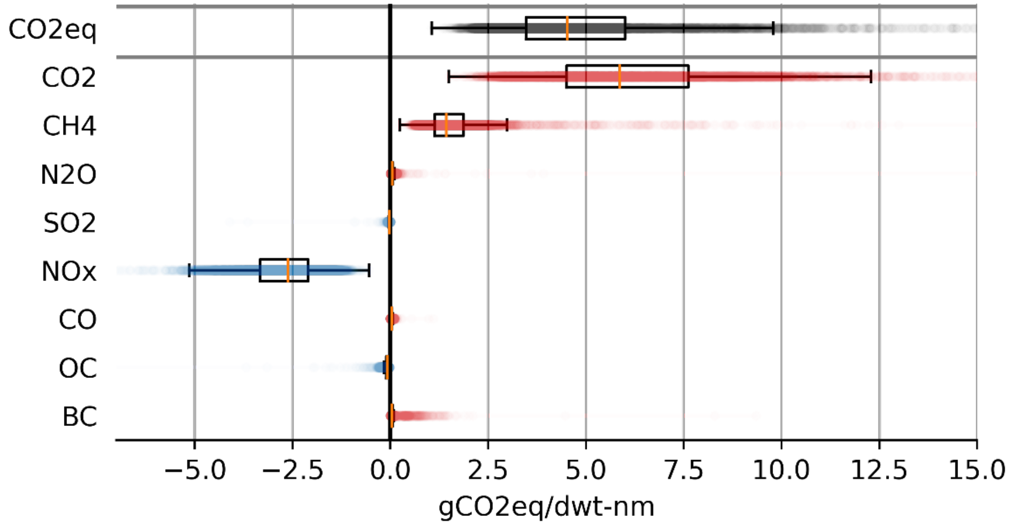
Methane nearly offsets CO2 reductions

HFO | MGO | **LNG LP** | LNG HP | Methanol | Ammonia-C-blue | Ammonia-L-green | HFO+CCS+SCRB | MGO+CCS

Bulk carriers | Chemical tankers | Container ships | Liquefied gas | Oil tankers | Ro-ro

CO2 | GWP20 | **GWP100** | GTP20 | GTP100

Individual with breakdown of contributions



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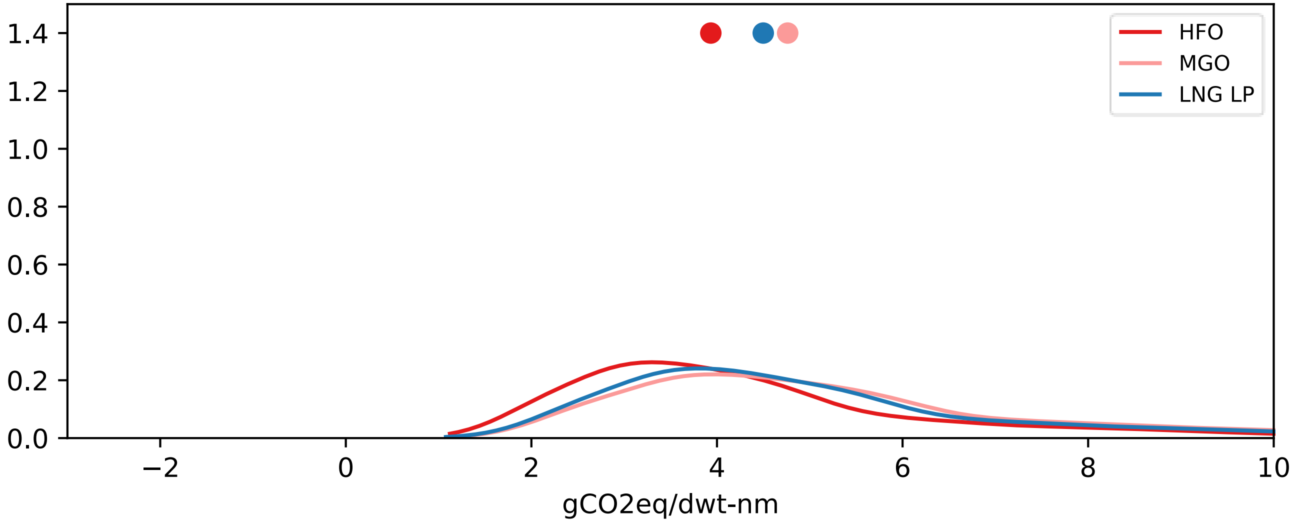


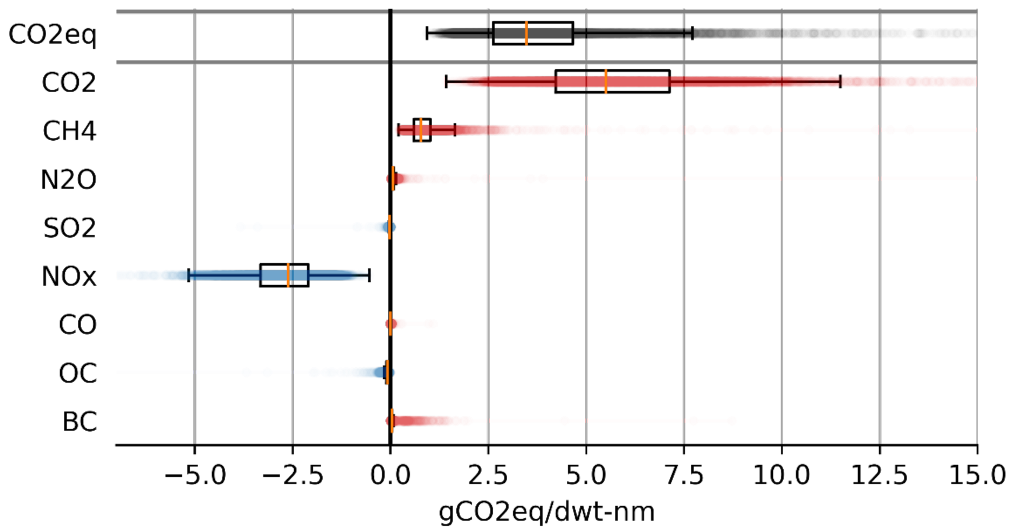
Reduction of NOx emissions by half increase the CI

HFO	MGO	LNG LP	**LNG HP**	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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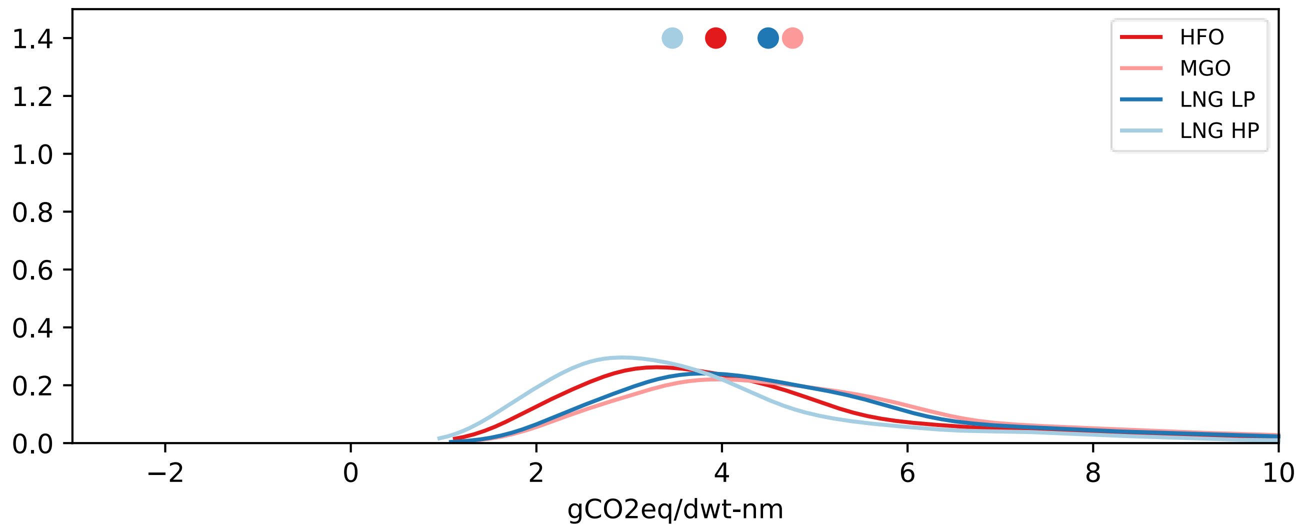

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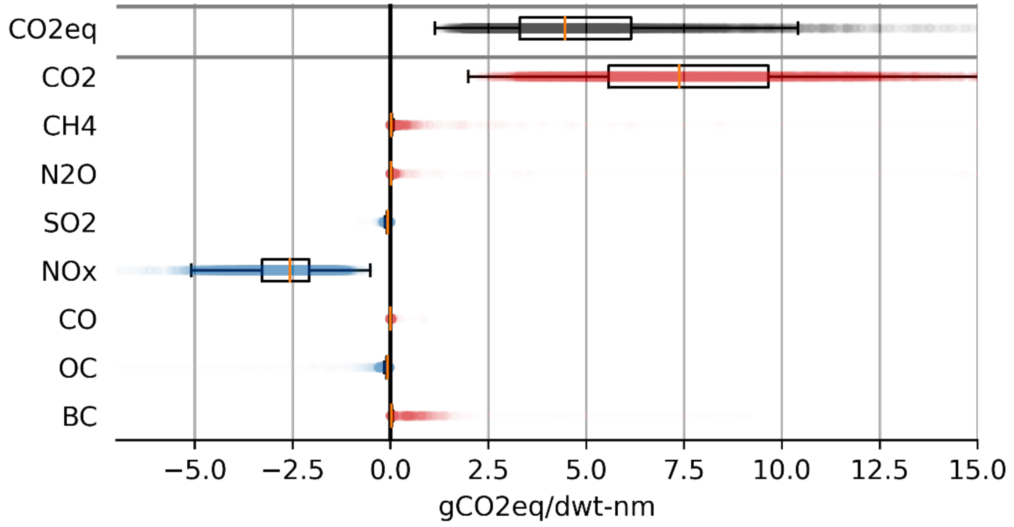
(Fossil) Methanol within range of conventional fuels

HFO	MGO	LNG LP	LNG HP	**Methanol**	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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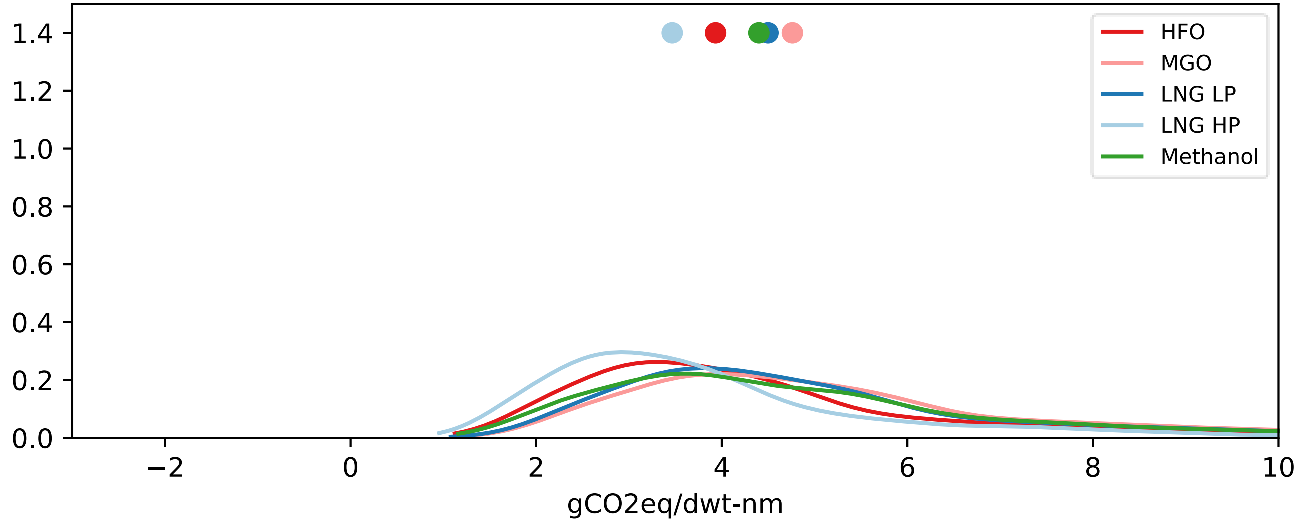

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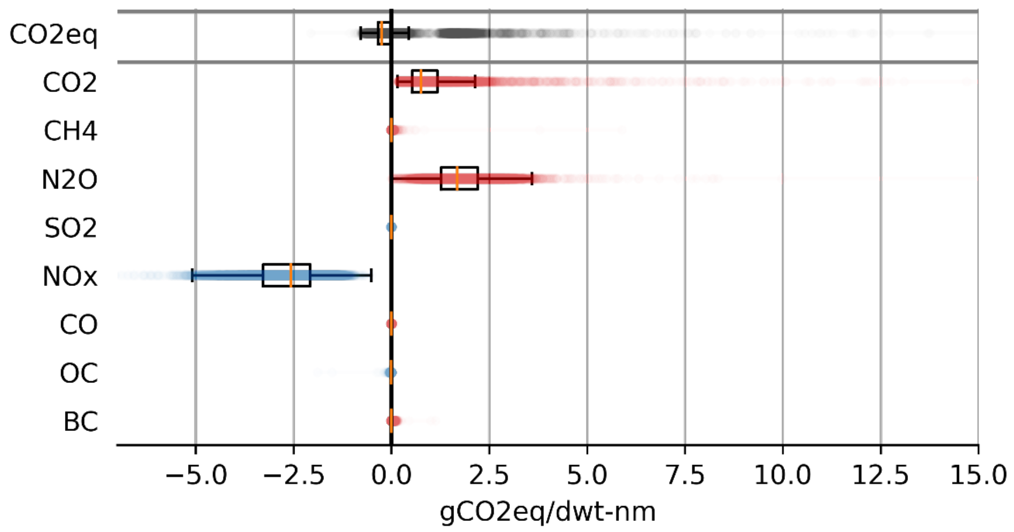
Effect of high upstream and N_2O emissions

HFO | MGO | LNG LP | LNG HP | Methanol | **Ammonia-C-blue** | Ammonia-L-green | HFO+CCS+SCRB | MGO+CCS

Bulk carriers | Chemical tankers | Container ships | Liquefied gas | Oil tankers | Ro-ro

CO2 | GWP20 | **GWP100** | GTP20 | GTP100

Individual with breakdown of contributions



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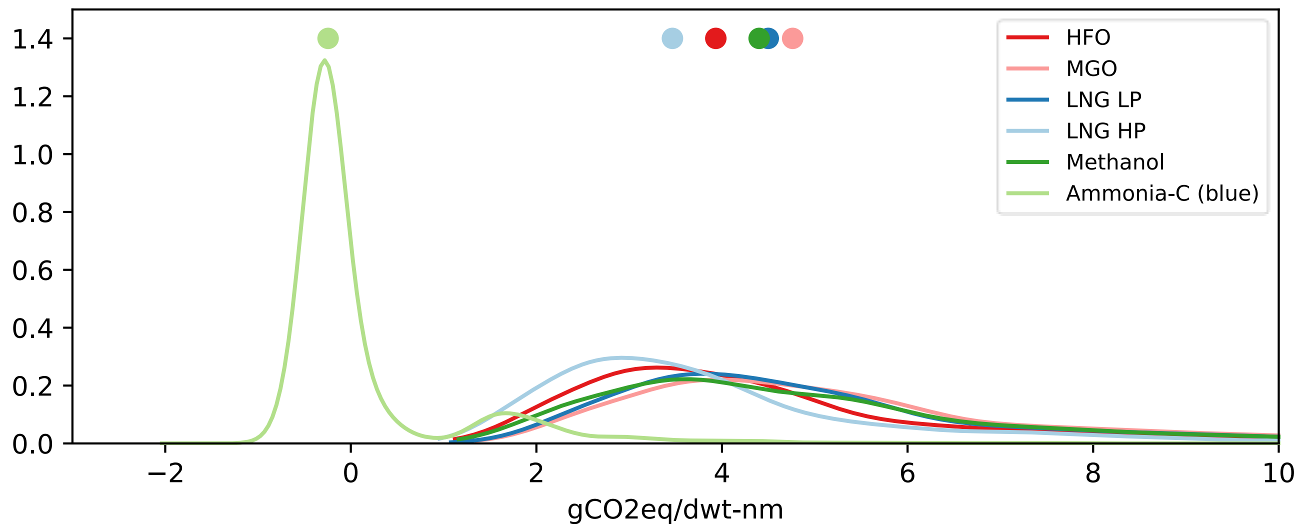

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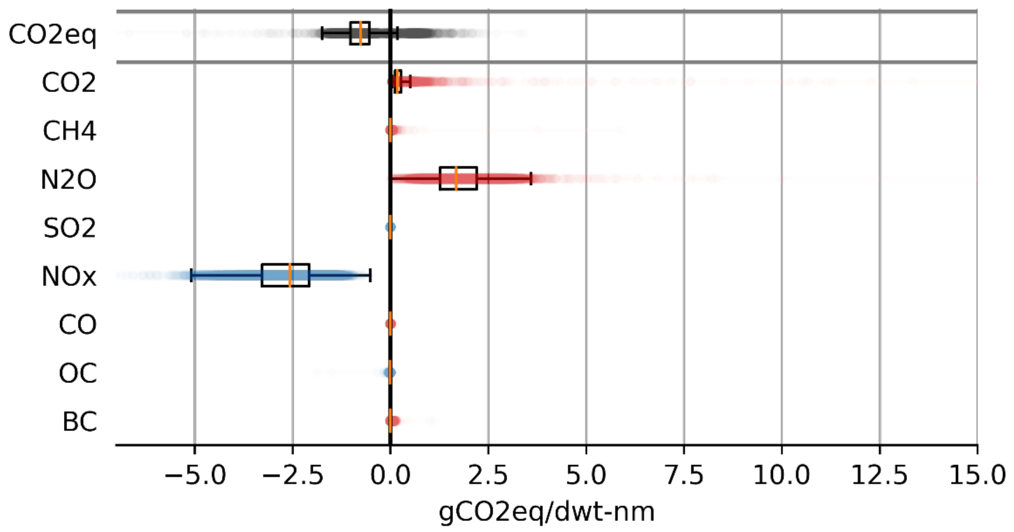
Green ammonia and halving of N_2O closer to net-zero

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	**Ammonia-L-green**	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	**GWP100**	GTP20	GTP100

Individual with breakdown of contributions



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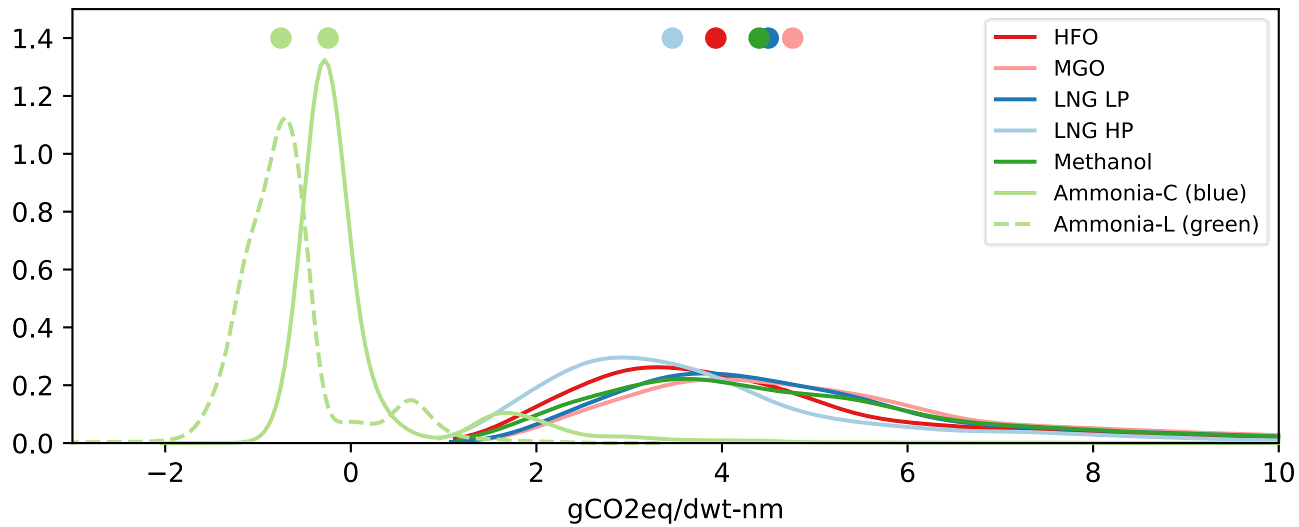


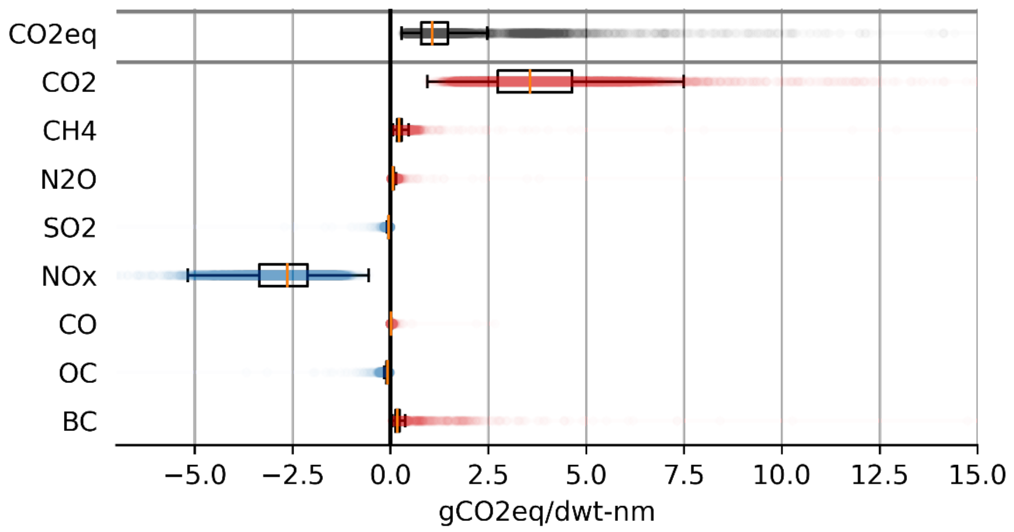
NOx emissions lead to a negative impact with CCS

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

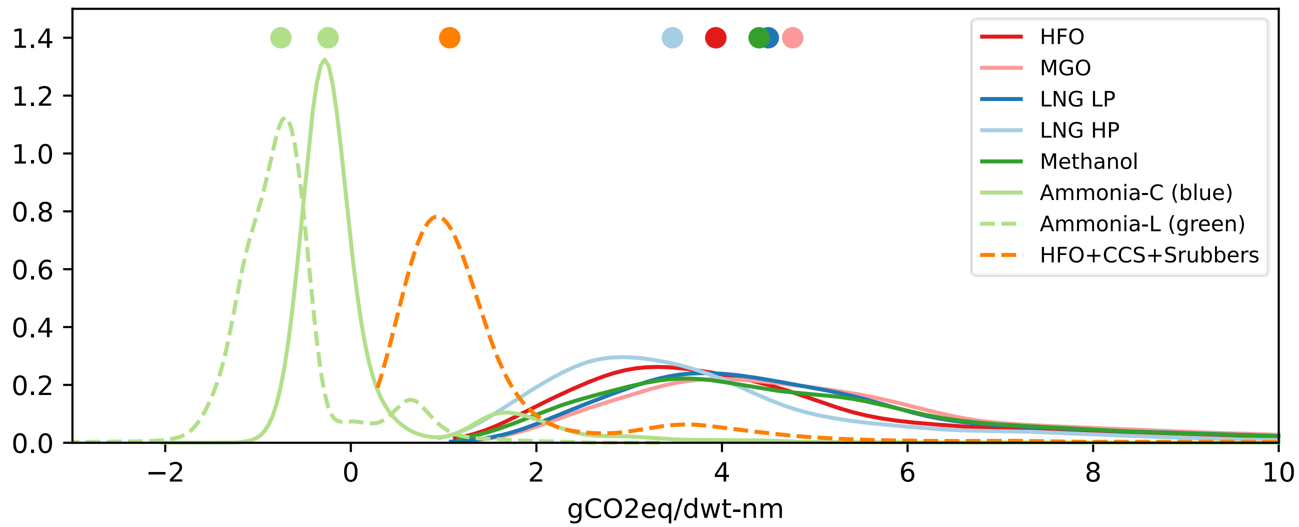
Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



Aggregate result for comparison of different cases



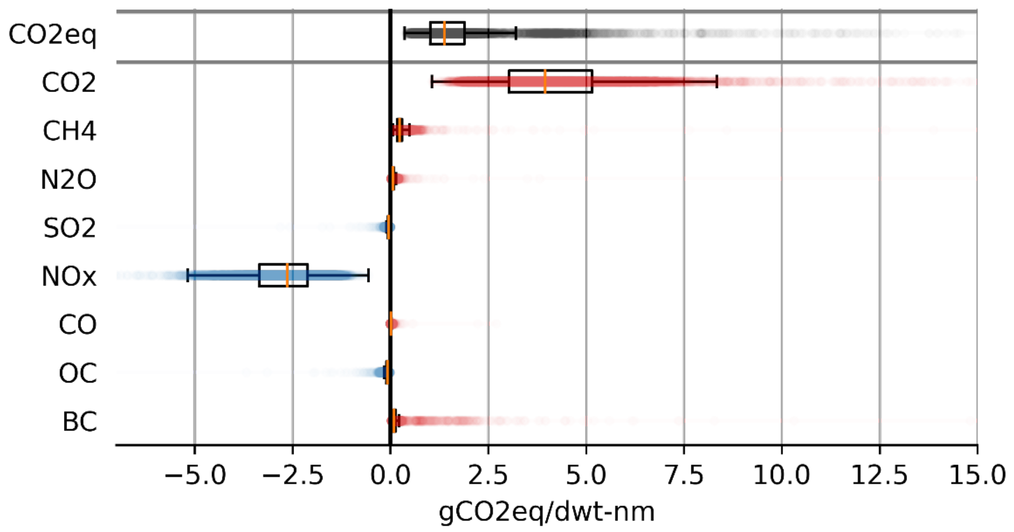
Same as MGO

HFO	MGO	LNG LP	LNG HP	Methanol	Ammonia-C-blue	Ammonia-L-green	HFO+CCS+SCRB	MGO+CCS

Bulk carriers	Chemical tankers	Container ships	Liquefied gas	Oil tankers	Ro-ro

CO2	GWP20	GWP100	GTP20	GTP100

Individual with breakdown of contributions



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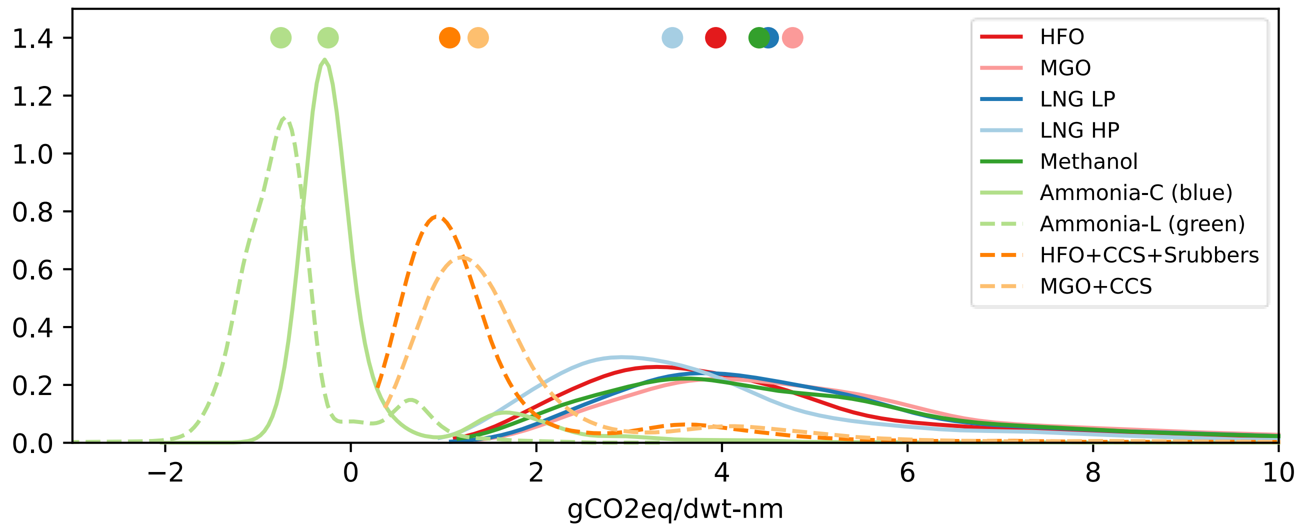
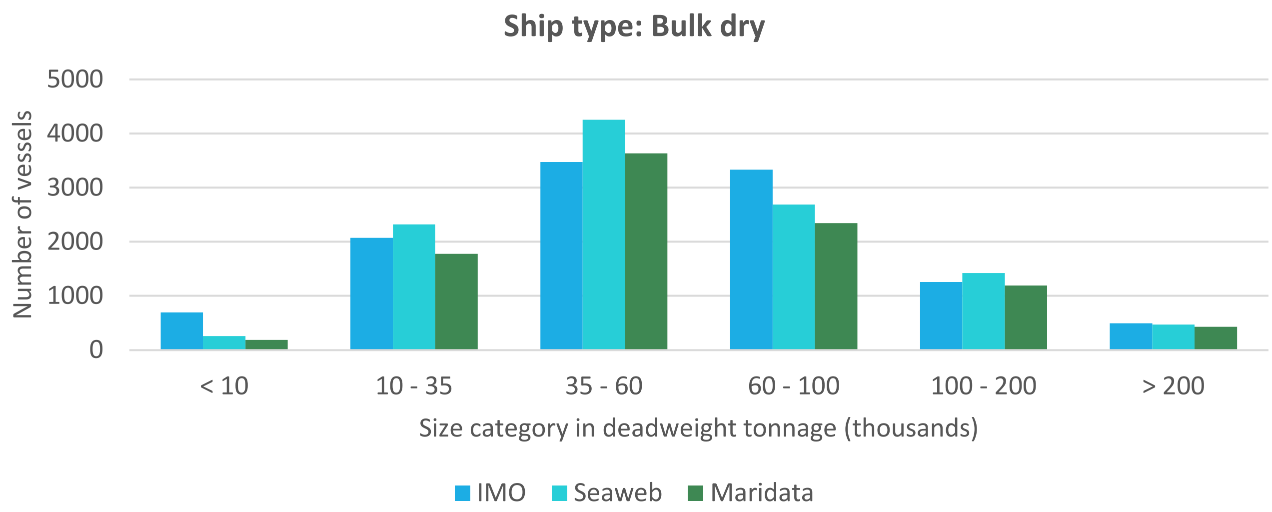
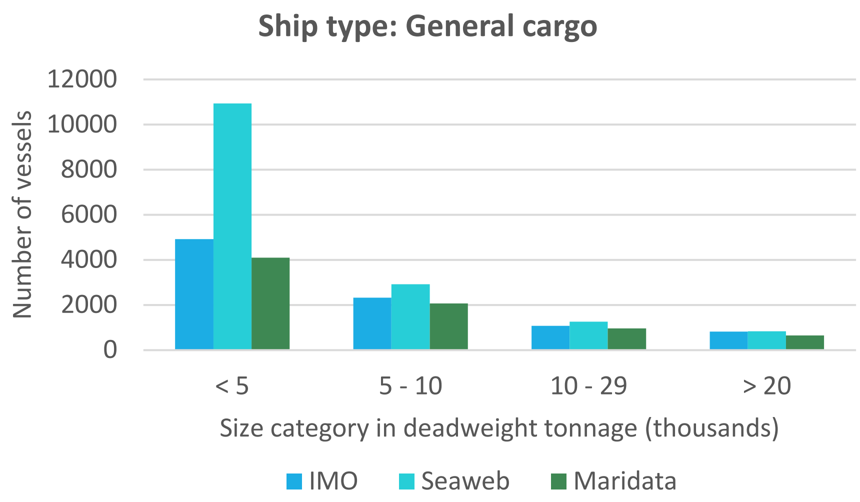


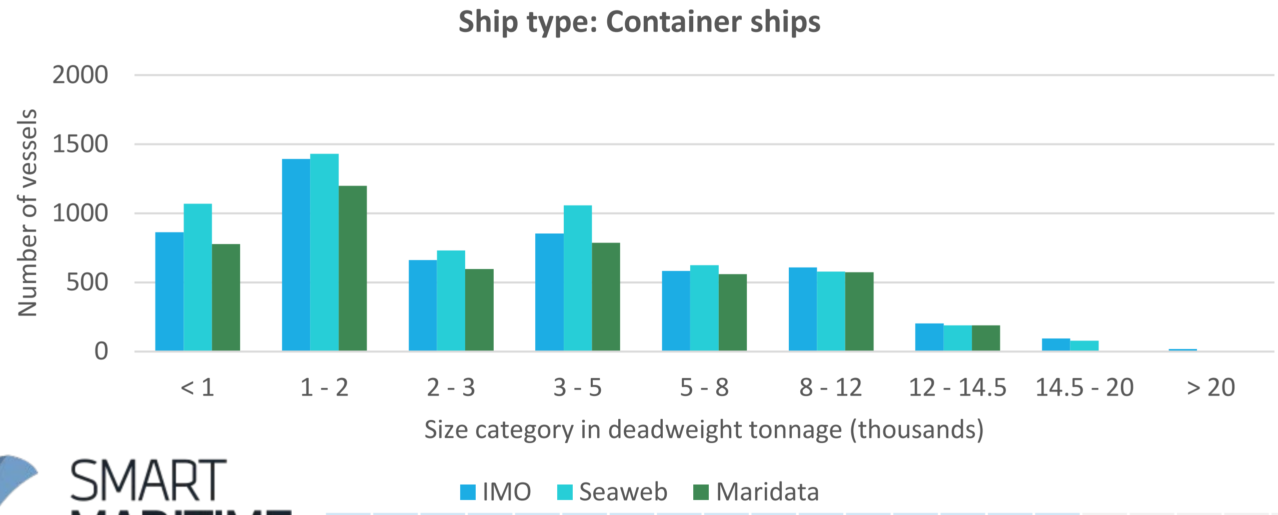
SMART MARITIME

NTNU SINTEF

Coverage

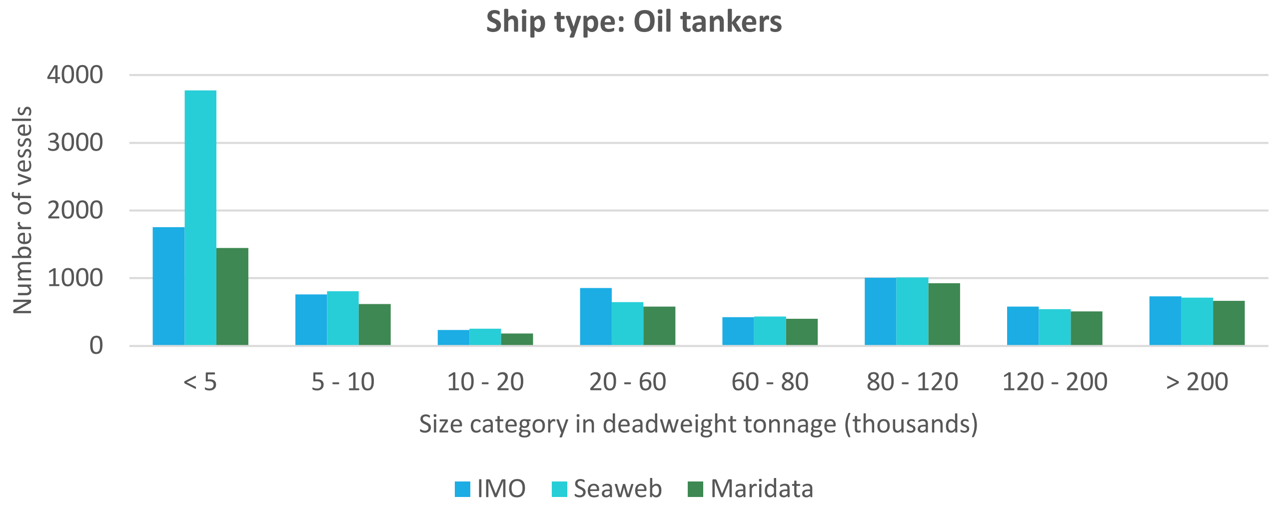


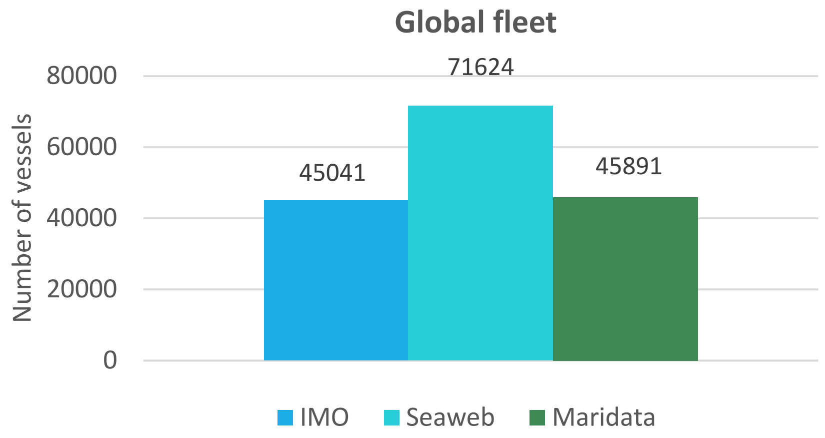


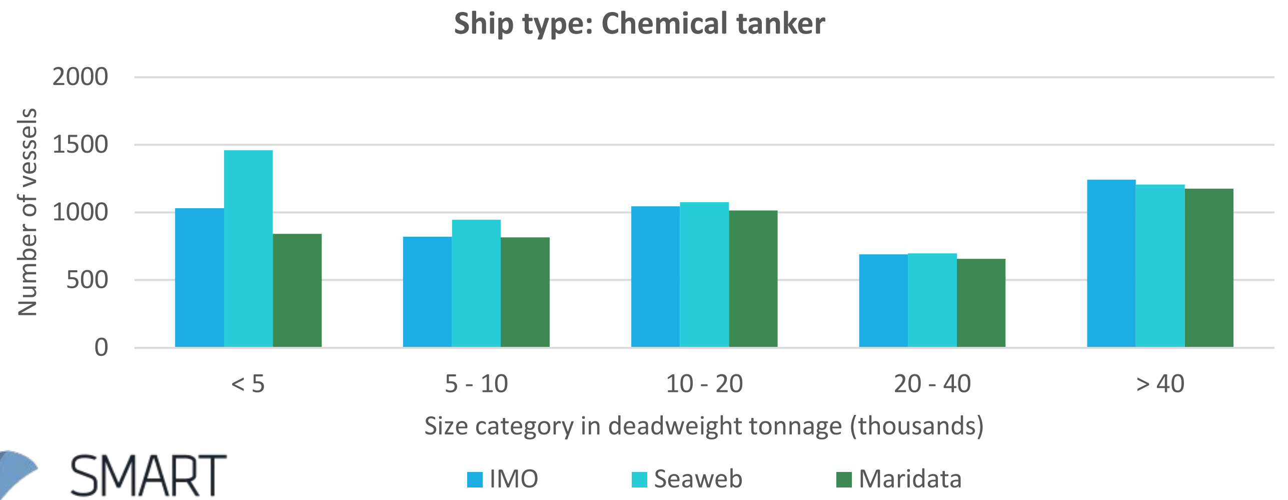


Difference to the IMO GHG study in terms of DWT
Bulk dry: +3.14%
Container: +0.56%

Coverage







Difference to the IMO GHG study in terms of DWT
Oil tankers: -4.11%
Chemical: -4.14%
Global fleet: +5.83%

Ammonia LCA

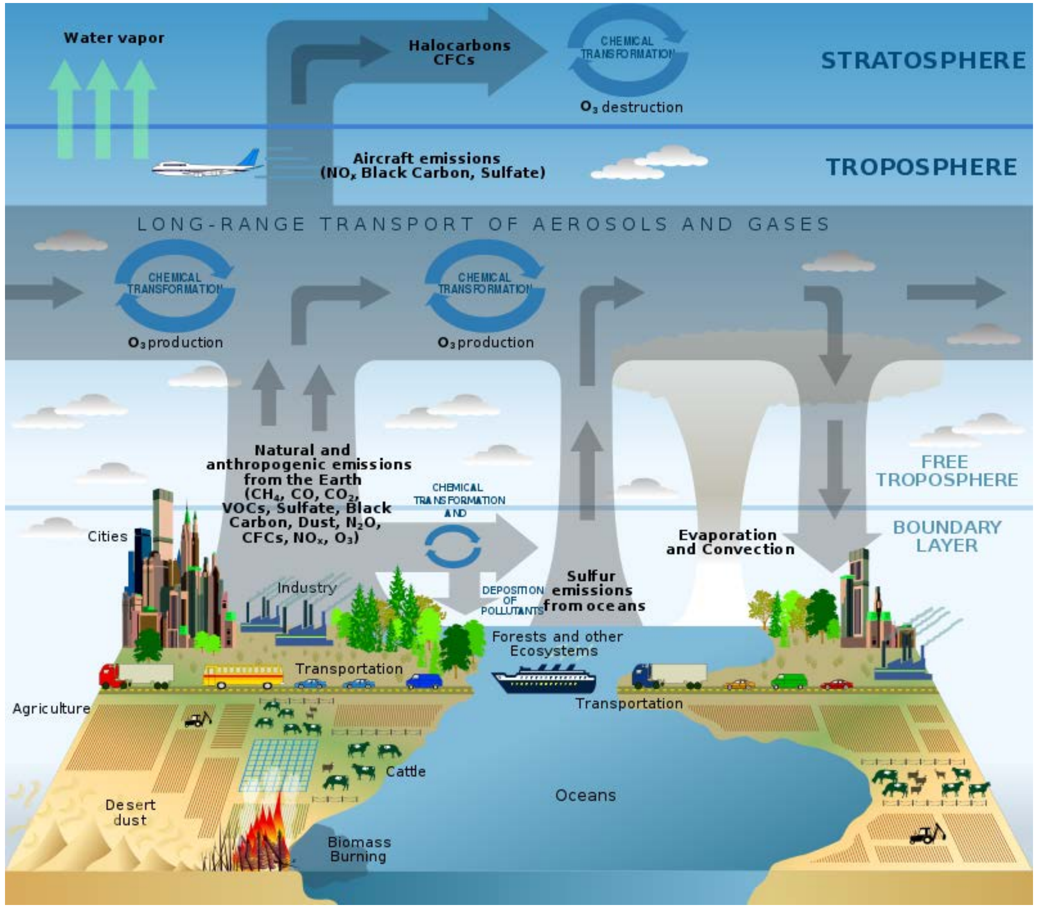
Blue H2 ATR 95+% CC		
Inputs		
CC	95 %	
Thermal effiency	75 %	
NG feedstock	3.23	kg NG/kg H2
Carbon	2.42	kg C/kgH2
CH4 leakage (upstream)	0.10 %	
Electricity ATR	3.5	kWh/kg H2
Electricity HB+ASU	0.75	kWh/kgNH3
H2	178	kg/ton NH3
N2	822	kg/ton NH3
Emission factors		
NG upstream	12.0	gCO2/MJ LNG
Electricity ATR	120	gCO2/kWh
Electricity HB+ASU	120	gCO2/kWh
Emissions		
H2 LNG upstream	1.79	kgCO2eq/kg H2
H2 electricity	0.42	kgCO2eq/kg H2
H2 on-site	0.44	kgCO2eq/kg H2
H2	2.66	kgCO2eq/kg H2
	22.13	gCO2eq/MJ H2
NH3 synthesis	0.09	kgCO2eq/kg NH3
Total	0.55	kgCO2eq/kg NH3
	24.30	gCO2eq/MJ NH3

Green NH3 via water electrolysis		
Inputs		
Electrolyzer	55	kWh/kg H2
Electricity HB+ASU	0.75	kWh/kg NH3
H2	178	kg/ton NH3
N2	822	kg/ton NH3
Emission factors		
Electricity electrolysis	12	gCO2/kWh
Electricity HB+ASU	12	gCO2/kWh
Emissions		
Total	0.12648	kgCO2eq/kg NH3
	5.62	gCO2eq/MJ NH3

	WTT (g/MJ)	TTW (g/MJ)			
	CO2eq	CO2	CH4	N2O	CO2eq
HFO	9.4	4.5E+11	7.5E+06	2.3E+07	4.5E+11
HFO+CCS+Scrubbers	9.4	2.7E+11	7.5E+06	2.3E+07	2.7E+11
MGO	13.9	4.4E+11	7.5E+06	2.3E+07	4.4E+11
MGO+CCS	13.9	2.6E+11	7.5E+06	2.3E+07	2.7E+11
LNG LP	17.9	3.2E+11	2.5E+09	1.6E+07	4.0E+11
LNG HP	17.9	3.0E+11	3.7E+08	2.3E+07	3.2E+11
Methanol	30.5	4.3E+11	8.1E+07	5.3E+06	4.3E+11
Ammonia Blue	24.3	0.0E+00	8.0E+07	5.0E+08	1.3E+11
Ammonia Green	5.62	0.0E+00	8.0E+07	2.5E+08	6.8E+10

	WtT	TtW	WtT	Comparison
	g/kWh	g/kWh	g/kWh	
HFO	67.7	605.2	672.9	100 %
HFO+CCS+Scrubbers	67.7	366.5	434.2	65 %
MGO	100.1	594.7	694.7	103 %
MGO+CCS	100.1	360.1	460.2	68 %
LNG LP	128.9	532.6	661.5	98 %
LNG HP	128.9	426.8	555.7	83 %
Methanol	219.6	576.2	795.8	118 %
Ammonia Blue	175.0	179.2	354.2	53 %
Ammonia Green	40.5	91.1	131.6	20 %

Norwegian Earth System Model



Experimental set-up

- Time-Slice Experiment: a specific time period or "slice" of the climate system is simulated. The model is run for a specific time slice, here representing the year 2019.
- The model focuses on simulating the climate conditions for those specific time periods while assuming that the “boundary conditions” (e.g., sea surface temperatures, greenhouse gas and aerosol emissions) are constant.

NorESM2 simulations:

1. Control simulation: 2019 ‘forcings’ without any emissions from the shipping sector.
2. MariTeam shipping emissions: All 2019 emissions, including emissions from shipping activities in 2019, as calculated by the MariTEAM model.

MariTeam

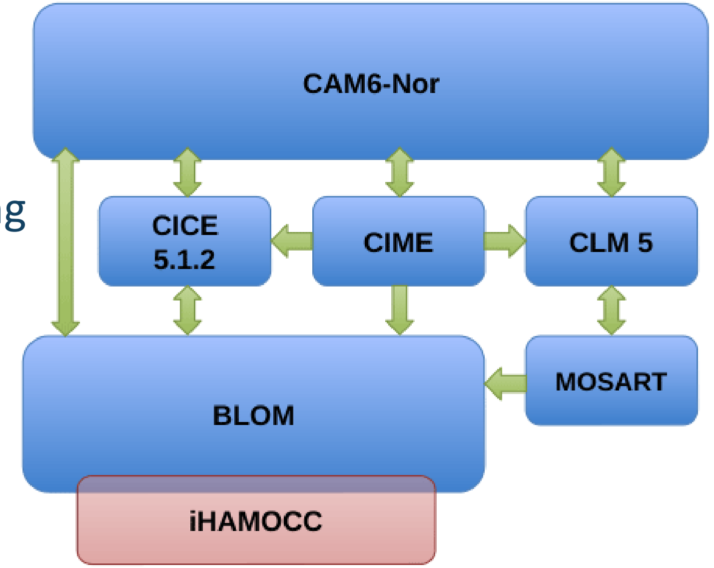
NorESM

Introduction to NorESM2: The Norwegian Earth System Model

- The Norwegian Earth System Model, NorESM2, is a comprehensive Earth system model designed to simulate the Earth's climate system. Developed by the NorESM Climate Modeling Consortium (NCC) since 2007 in collaboration between the Norwegian Meteorological Institute, the University of Oslo, NTNU, the University of Bergen, NORCE Norwegian Research Centre AS, CICERO, and Nansen Environmental and Remote Sensing Center (NERSC).
- It solves many coupled differential equations across a broad set of natural laws on a three-dimensional grid. It incorporates state-of-the-art physics and chemistry to simulate the complex interactions between different components of the Earth's system, allowing the study of how changes in one component affect the others.
- NorESM has contributed towards the reports of the IPCC and is well established within the international climate research community.

The NorESM2 components

- Atmosphere Model (CAM6-Nor): The atmospheric component is based on the Community Atmosphere Model version 6 (CAM6) but includes specific modifications that address atmospheric chemistry, aerosols, and clouds using the OsloAero6 module and improve energy and angular momentum conservation.
- Ocean Model (BLOM): the Bergen Layered Ocean Model (BLOM) is an isopycnic coordinate ocean model. It incorporates detailed simulations of ocean dynamics, including deep convection in the Southern Ocean, important for energy transport in the climate system.
- Sea Ice Model (CICE): simulates the behavior of sea ice, including the wind drift of snow over sea ice, and impacts of deposition of e.g., soot.
- Land Model (CLM5): represents terrestrial processes such as vegetation dynamics, surface energy balance, and carbon, nitrogen and water cycles.
- Biogeochemical Model (iHAMOCC): the Hamburg Ocean Carbon Cycle model (HAMOCC) is integrated with the isopycnic ocean model BLOM. This biogeochemical model simulates the ocean's carbon cycle and its interactions with the atmosphere, including the uptake and release of carbon dioxide.



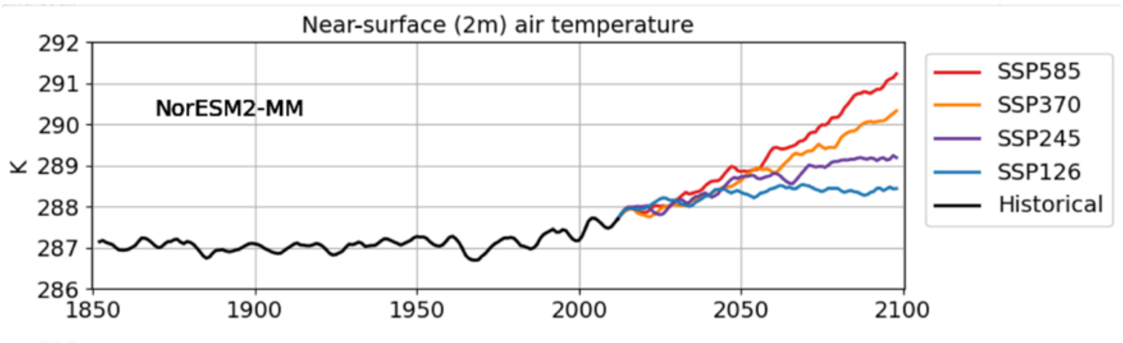
Seland et al. (2020)

NorESM2-MM discretization:

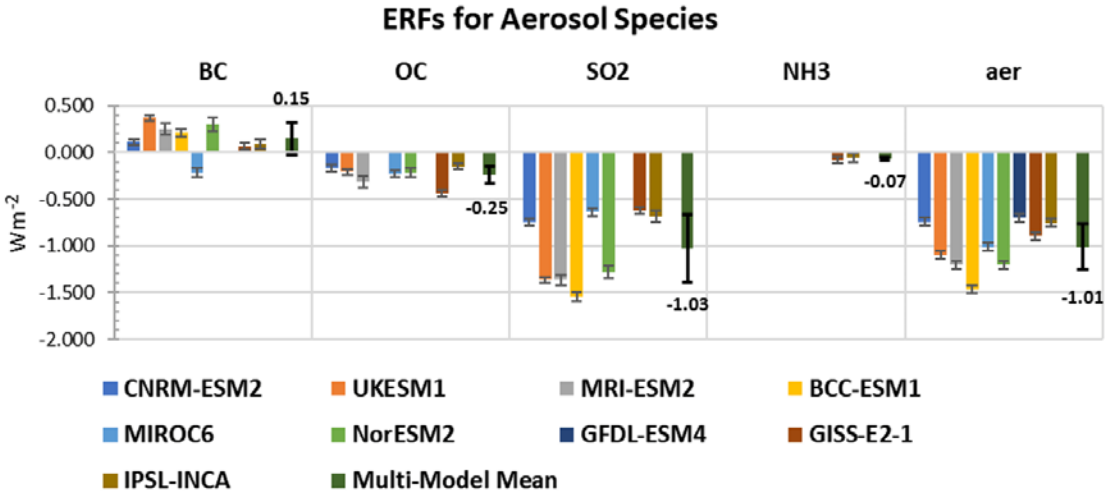
NorESM

- 1-degree latitude and longitude resolution.
- NorESM2-MM operates using specific time steps for components:
  - Atmosphere and Land: 20 minutes. the
  - Ocean and sea ice: 1 hour.
- Ocean uses tripolar gridding with isopycninc vertical coordinates, and the atmosphere finite volume with terrain-following sigma coordinates in the vertical.
- This allows NorESM2-MM to capture a wide range of climate phenomena and interactions within the Earth system, providing valuable insights into climate dynamics, projections, and potential impacts.
- Makes use of national high-performance computing (HPC) and mass – storage infrastructure.
- Takes ~20-24 hours to simulate 10 years. Generates multiple TB of data.

Benchmarking of NorESM



CMIP6: The evolution of the surface air temperature in the historical simulations and under the four SSP scenarios for NorESM2-MM, using a 5-year running mean. The model is close to the Multi-model median of the CMIP6 models that contributed to AR6 of IPCC.
(Seland et al., 2020)



NorESM is within observational and multi-model range with its calculations of effective radiative forcing from aerosol emissions.
(Thornhill et al., 2021)

MariTeam

EXPLORING THE CLIMATE IMPACT POTENTIALS OF A SHIP SEGMENT FOR DIFFERENT FUELS

SMART MARITIME

NTNU SINTEF

We have calculated results for 8 fuels across 6 ship segments x 6 size bins

We will show aggregate results for two segments and all fuels.
We will also demonstrate how we can deep dive into details of results for different size bins.

Metrics Matters

CO_2 equivalents as Global Warming Potential (GWP)

The energy absorbed over a time horizon by a unit release of a given GHG relative to CO2.

CO_2 equivalents as Global Temperature Potential (GTP)

The change in global mean surface temperature, by a unit release of a given GHG relative to CO2, at a given future time.

Both selections of time-horizon and choice of metric are debated in the literature.

We have calculated results with different metrics for different time horizons.
We will show our examples today using GWP100, but also show an aggregate comparison with GTP100

ATTENTION: Without NOx

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