SEPTEMBER 2023

TEXAS
The University of Texas at Austin

A TIME-IN-MODE AND CARRIER TECHNOLOGY MODEL OF EMISSIONS OF METHANE AND CARBON DIOXIDE FROM LNG SHIPPING

US EPA's 2023 International Emissions Inventory Conference
Greenhouse Gas Session

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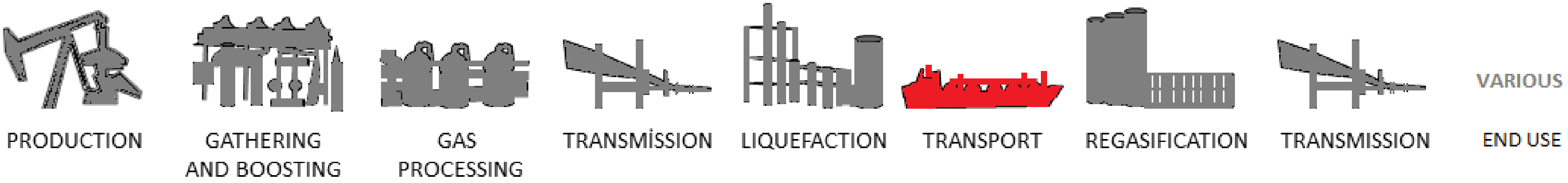
Why are we here?

What informs the best pathway for the energy transition?

Is fuel-switching to LNG a GHG win?



Do the particulars of the supply chain influence GHG emissions?

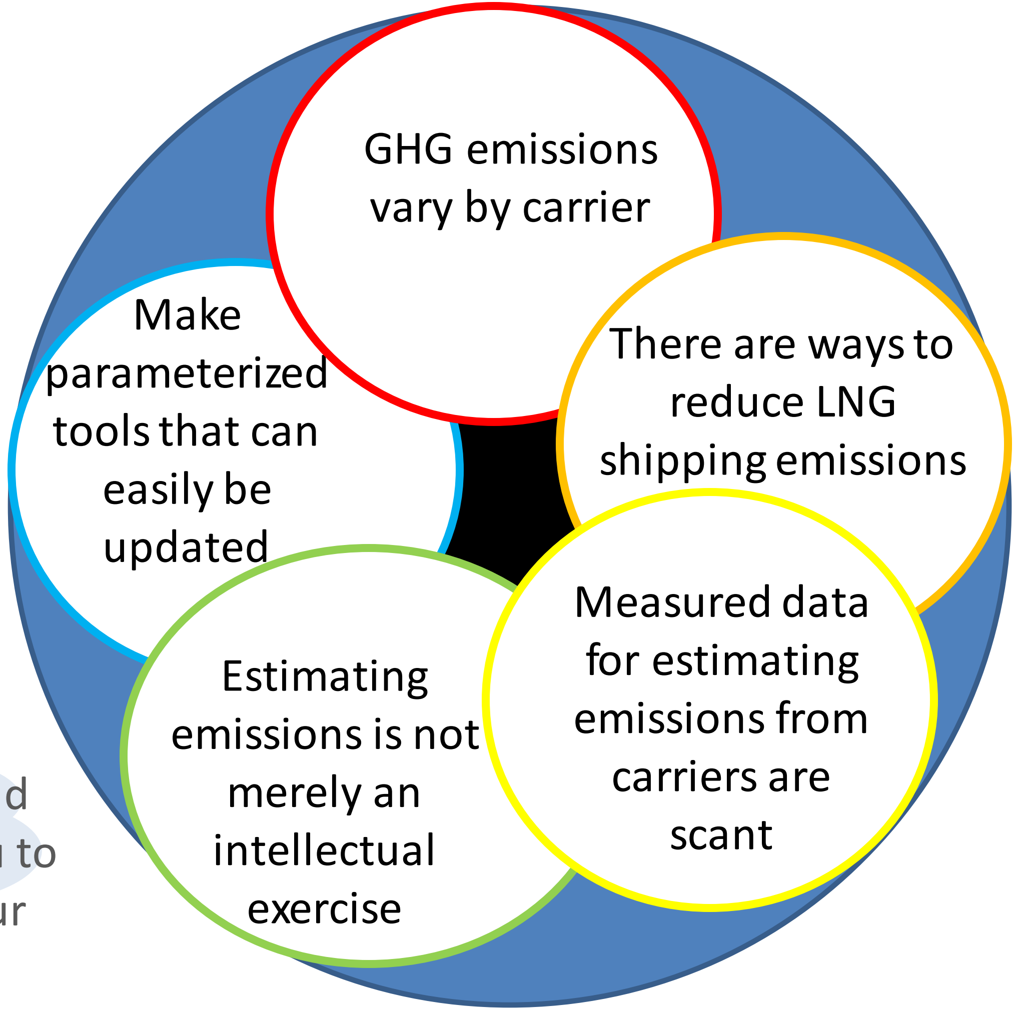
Does LNG have a long supply chain?

What's in red here?

We'll see this graphic again

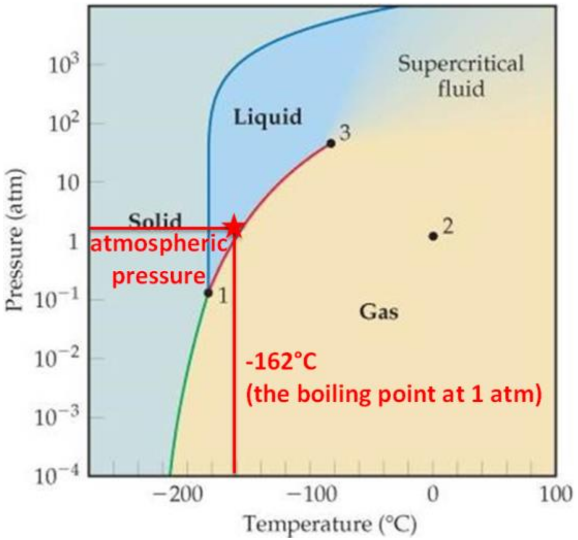
imagine that you are a policy maker in a country that has climate goals to meet and wants to minimize purchases of Russian oil and gas and you have to decide how much to incentivize construction of LNG terminals that take 5 years to build

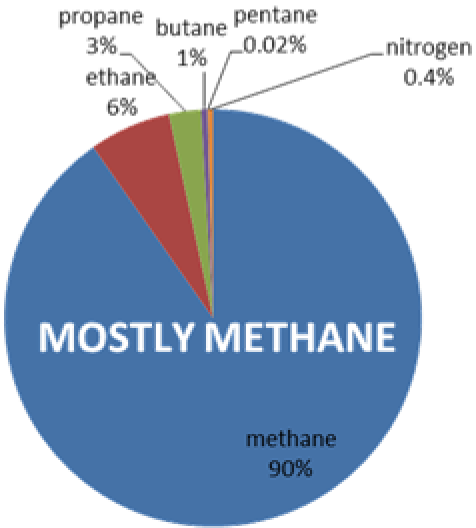
imagine that you are an LNG provider and some of your customers are requiring you to certify the supply chain emissions of your LNG



What is LNG?

What is the typical storage temperature?

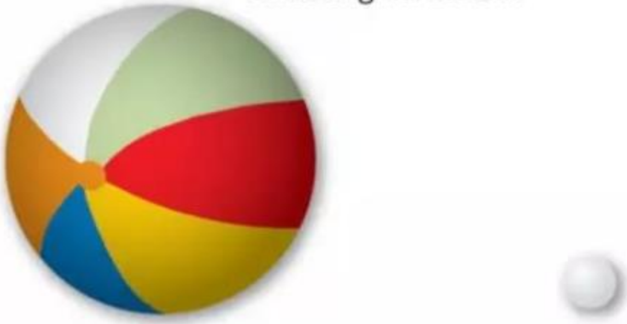




What is it mostly comprised of?

How dense is it compared to natural gas?

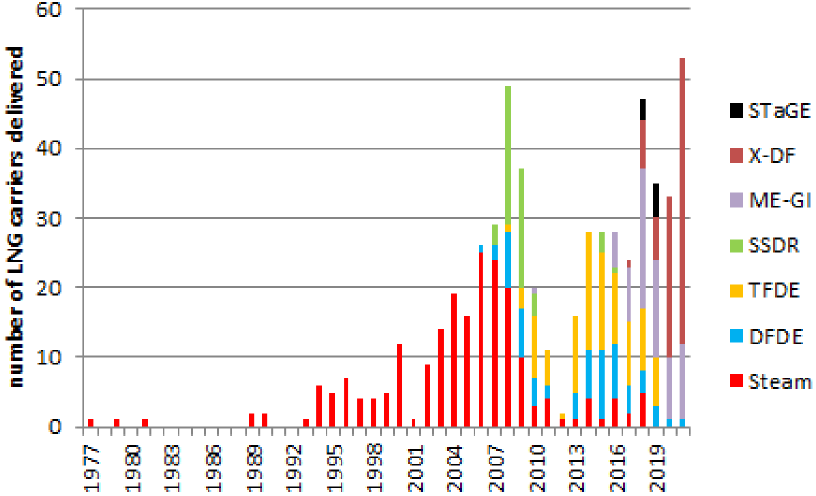
When liquefied, natural gas is 1/600th the volume of its original state…



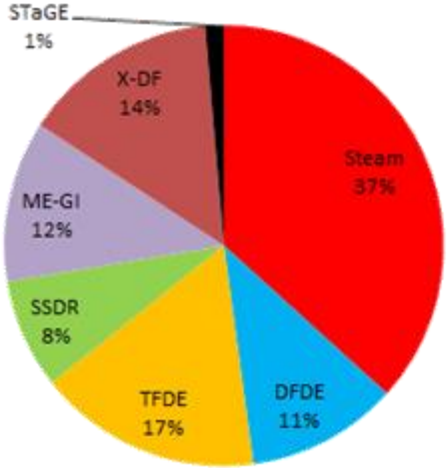
which is like a beach ball shrinking to a ping pong ball.

LNG carriers are like other mobile sources

AGE/PROPULSION TYPE



PROPULSION TYPE



Data from [IGU (2022)]

- **Steam**: steam and steam reheat
- **DFDE**/**TFDE**: dual-fuel and triple-fuel diesel electric
- **SSDR**: slow-speed diesel with re-liquefaction plant
- **ME-GI**: high-pressure MAN B&W M-type electronically controlled gas injection
- **X-DF**: low-pressure injection Winterthur Gas & Diesel
- **STaGE**: steam turbine and gas engine

What else varies?

Do carrier ages vary?

Do propulsion types differ?

What's on the right?

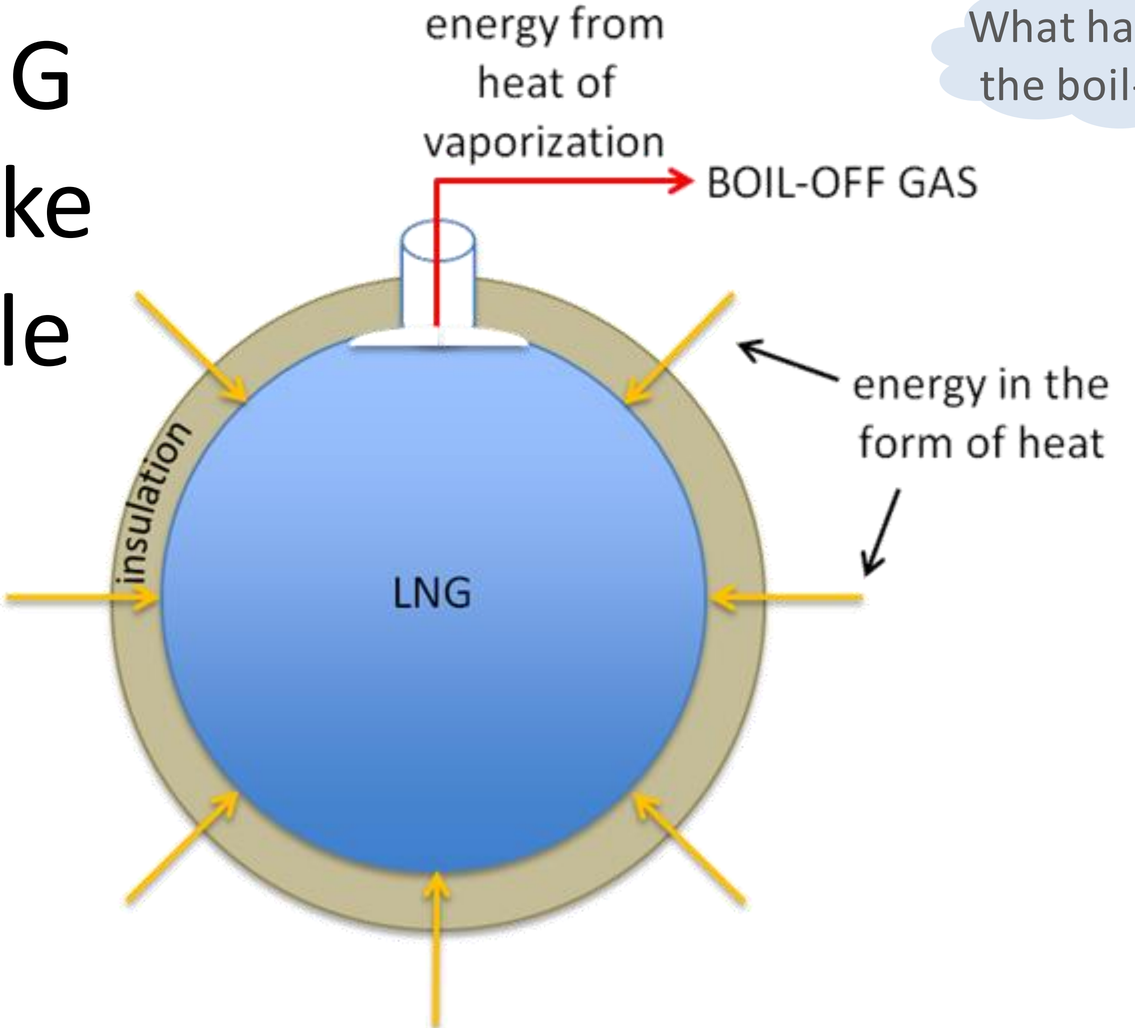
Why is SSDR circled on the right?

LNG carriers are like other mobile sources (Part II)

- Emissions are different for different stages of trips
  - Underway
  - Docked
  - Maneuvering

What sets these two apart?

How are LNG carriers unlike other mobile sources?



What happens to the boil-off gas?

How is LNG kept cold as it goes across the ocean?

3-step algorithm for developing estimated emissions

①
Estimate the boil-off gas generated and assign it to propulsion systems, generators not used for propulsion, and gas combustion units for each of three journey categories (underway by distance traveled, docked and maneuvering by time)

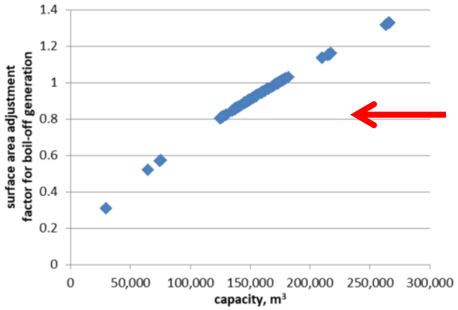
②
Estimate the ratio of methane slip to boil-off for each boil-off gas stream

③
Estimate the CO_2 by balancing the carbon
(carbon in BOG - carbon in slip = carbon in CO_2)

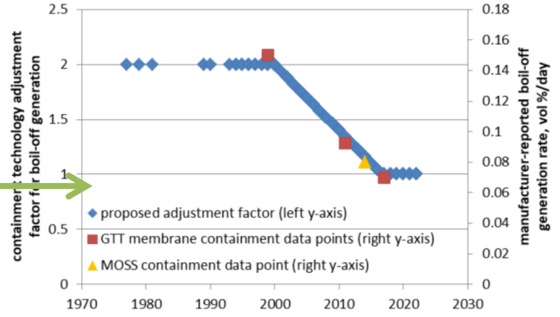
What is slip?

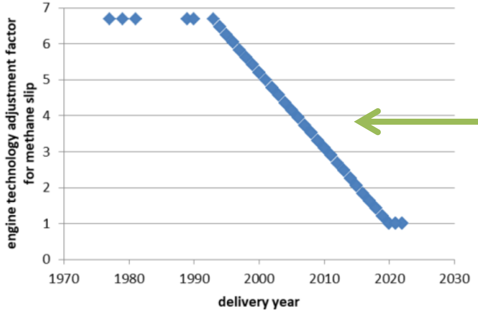
We based the numbers on on-board operational emission measurements where possible

At present, these data are only available for one modern X-DF carrier making one journey, so...

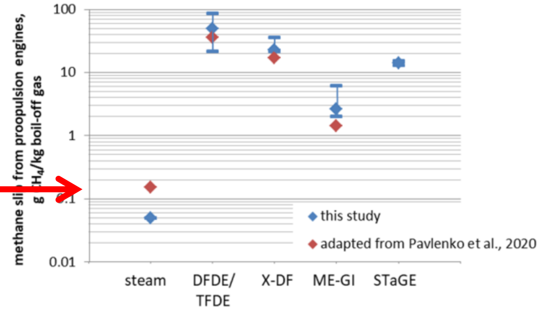


we adjusted boil-off generation by the surface area of the containment system and by the delivery year





we adjusted the slip ratio by the delivery year and in some cases by propulsion type



Make parameterized tools so that adjustments can be made as info rolls in

- Our adjustment factors weren’t pulled out of thin air but they aren’t backed up by robust volumes of data
- Our tool is designed to accommodate revised information

Example using the spreadsheet tool's user interface

FOLLOW THE NUMBERED STEPS (input fields are in yellow)

			suggested values
1)	use drop-down to select specific LNG carrier by vessel name and shipowner, or select an average carrier by propulsion type (fleet averages as of early 2022, based on all carriers taking the Gaslog Galveston's journey)	Arctic Lady Hoegh Mitsubishi	
2)	input the round trip underway voyage distance (not including maneuvering), km	20,211	Use sea-distances.org to get the one-way distance, convert from nautical miles to km, and multiply by 2.
3)	input the number of days spent maneuvering	1.7	The Gaslog Galveston spent 1.7 days maneuvering during its measurement campaign.
4)	input the number of days docked (for loading, unloading, refueling)	3.3	The Gaslog Galveston spent 3 days docked during its measurement campaign.
5)	input the ballast remaining in containment after unloading at destination (% of carrier capacity)	2.5%	The Gaslog Galveston had ballast of 2.5% during its measurement campaign.

Choose from one of 583 carriers; delivery year, capacity, & propulsion type populate automatically

		mole fraction							
		Methane	Ethane	Propane	iso - Butane	normal - Butane	iso - Pentane	normal - Pentane	Hexane+
6) revise the composition of the LNG, if desired (mole fraction)	LNG composition	0.9549259	0.0423515	0.0020167	0.0002017	0.0002017	0.0001008	0.0001008	0.0001008

7) proceed to the "EMISSION ESTIMATES" tab to review the estimated results

Example results from the tool

ESTIMATED EMISSIONS

For the Arctic Lady Hoegh Mitsubishi , taking a 20,211 km round-trip journey, with 1.7 days spent maneuvering, 3.3 days docked, and leaving 2.5% of the carrier's capacity as ballast for the return trip:

	CO_2	methane	CO_2eq*
metric tons	7,041	60.6	12,041
kg/m3 of LNG delivered	51.0	0.439	87.2

* using a $GWP_{20\text{-}yr}$ of 82.5 for methane

What does the tool tell us about ways to reduce emissions?

1. Choose the right carrier
2. Minimize the trip distance and/or the days spent maneuvering
3. Operate generators at as high a load as possible

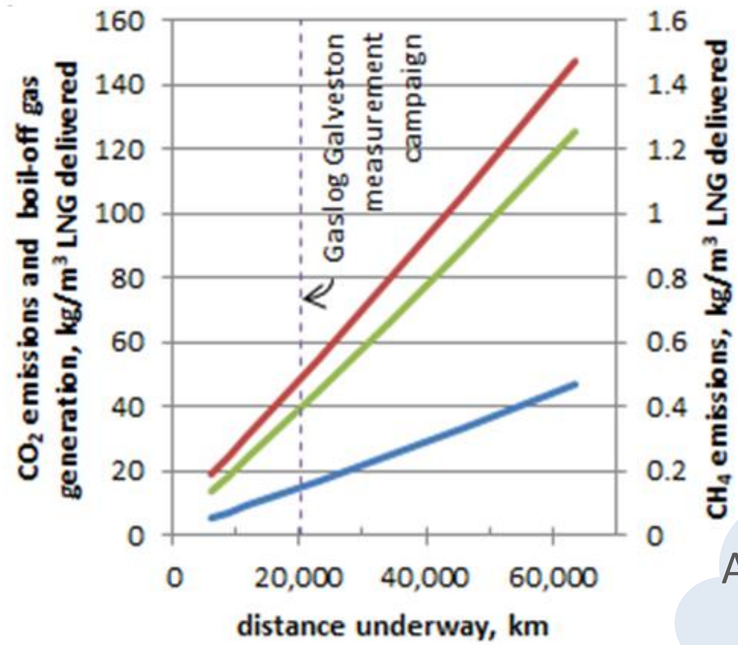
What can be done to reduce LNG shipping emissions? – Part I

carrier	number of trips each carrier can make in a year	required number of carriers	estimated emissions due to delivery of 1.8 million m^3 of LNG/y (per carrier-trip) t/y		
			methane	CO_2	CO_2eq (when $GWP_{20\text{-}yr}$ for methane is 82.5)
older carrier	12.9	2.38	1,300	150,000	260,000
hypothetical average carrier	11.2	1.08	880	71,000	140,000
recently delivered carrier	10.6	1	730	51,000	110,000

CO_2eq from end use assuming no losses in regasification or transmission and complete combustion is 2 million t/y. There's also a "compound interest effect" up the supply chain.

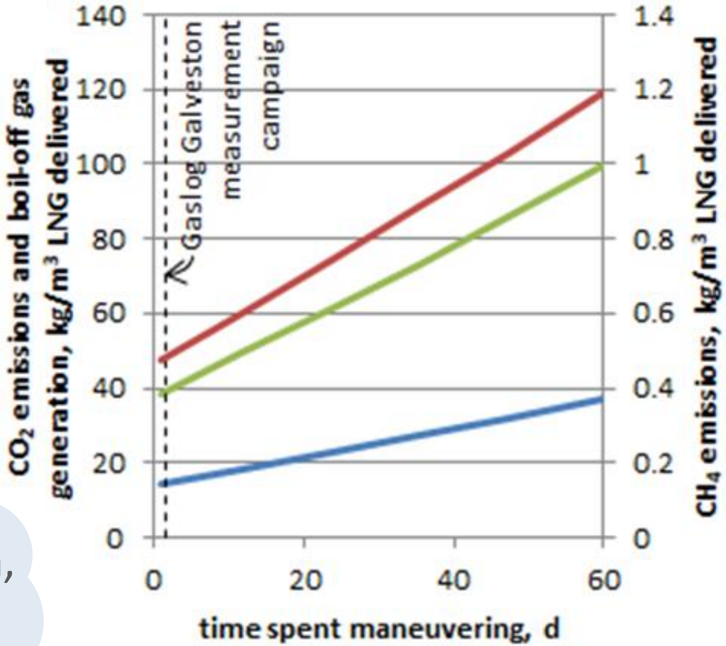
What can be done to reduce LNG shipping emissions? – Part II

What carrier is this for?



Round-trip distance between LNG terminals:

5,912 km for Oman, Algeria to Rotterdam, the Netherlands; 63,444 km for New Orleans to Shanghai

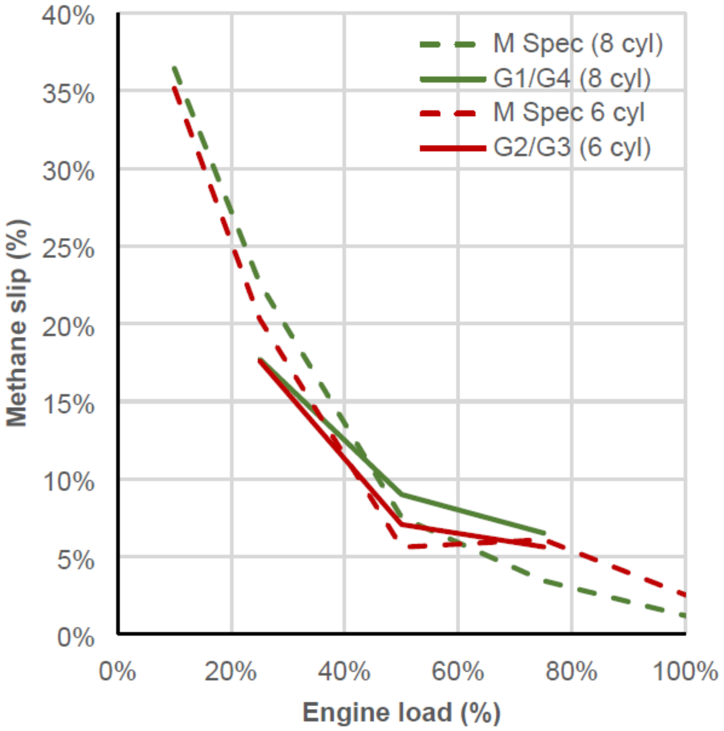


3 t CH_4 and 270 t CO_2 emitted per 1000 km

1.7 t CH_4 and 150 t CO_2 emitted per day of maneuvering

What can be done to reduce LNG shipping emissions? – Part III

Measured slip vs. engine load for generators

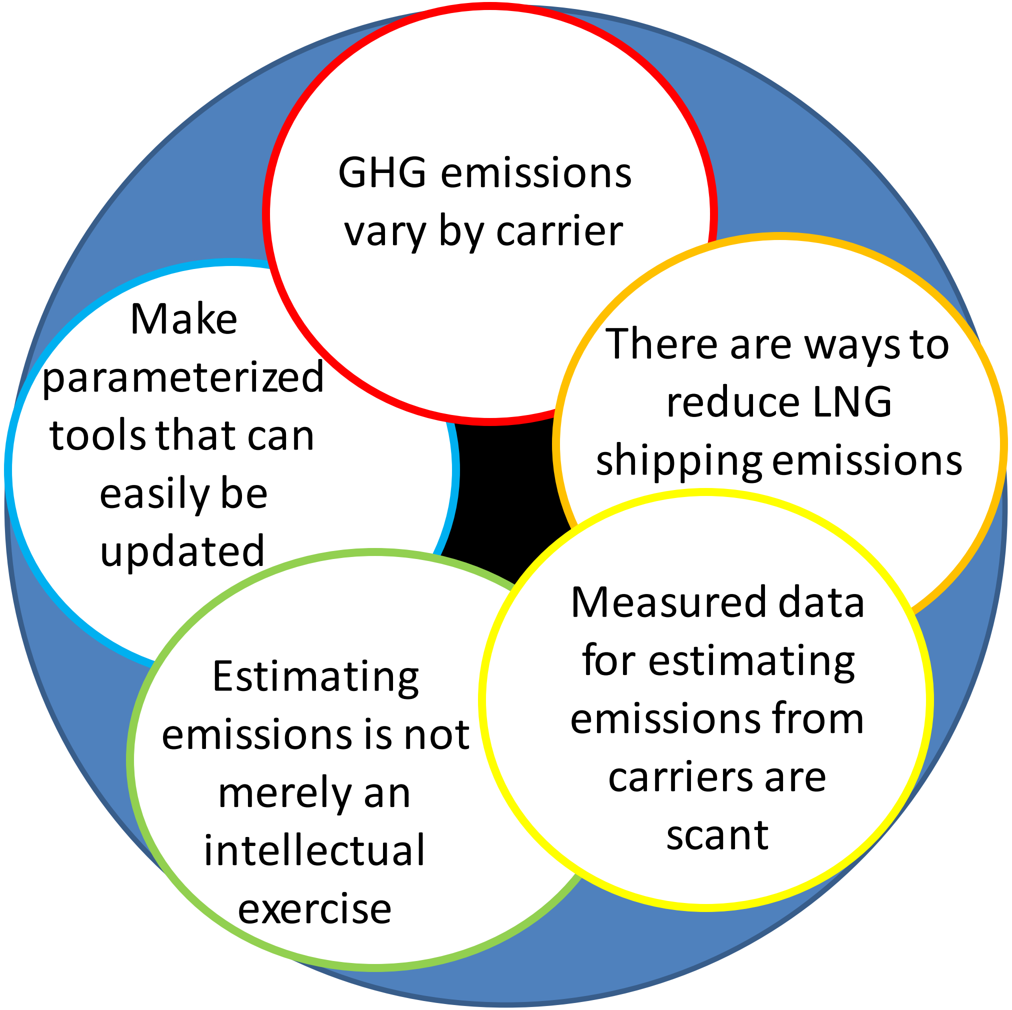


[Balcombe et al., 2022]

Takeaways

What do I want you to remember from my talk?

What do I most want you to remember?



Next steps

- Use measured emissions from other LNG carrier types that will be available soon (e.g., the FUMES project) to verify or improve estimates made by the tool
- LNG loading emissions – including containment cool-down emissions which can begin at sea – need to be measured so that a means of estimating them for varying circumstances can be developed

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This work was funded by the University of Texas at Austin

Any questions?

Step 1 – estimate and apportion boil-off gas

		Type of propulsion				
		Steam	TFDE/DFDE	X-DF	ME-GI	STaGE
While underway						
	Generators not used for propulsion while underway	0.020 t/km $\times$ d $\times$ CF_A $\times$ CF_{con}	0	0.020 t/km $\times$ d $\times$ CF_A $\times$ CF_{con}	0.020 t/km $\times$ 1.12 $\times$ d $\times$ CF_A $\times$ CF_{con}	0
	Propulsion systems (main engines/steam turbines /main generators)	Remaining	All boil-off	Remaining	Remaining	½ to the main generators, ½ to the steam turbine
While docked						
	Generators	20 t/d $\times$ t_{dock} $\times$ CF_A $\times$ CF_{con}				
	Gas combustion unit	Remaining				
While maneuvering						
	Generators	16 t/d $\times$ t_{man} $\times$ CF_A $\times$ CF_{con}				
	Gas combustion unit	Remaining				

Step 2 – estimate ratio of methane slip to boil-off gas

Type of propulsion	Generators / engines / turbines used for propulsion	Generators not used for propulsion			Gas combustion units
		Underway	Maneuvering	Docked	
Steam	0.00005	0.083	0.082	0.088	0
DFDE/TFDE	$CF_{eng} \times 0.022$	n/a	0.082	0.088	0
X-DF	$CF_{eng} \times 0.022$	0.083	0.082	0.088	0
ME-GI	$CF_{eng} \times 0.002$	0.083	0.082	0.088	0
STaGE	$0.5 \times 0.00005 + 0.5 \times CF_{eng} \times 0.022$	n/a	0.082	0.088	0

Additional considerations not modeled

- the effect of ocean and surface temperature on boil off
- the effect of engine wear and engine load on slip and carbon dioxide emissions
- higher boil-off from sloshing in partly full cargos
- higher boil-off in rough seas compared smooth seas
- load-dependent methane slip from engines and generators
- impacts of wind speed
- the effect of boil-off on composition
- the effect of nitrogen in the vapor space of the LNG containment systems due to use of nitrogen during various process and maintenance activities
- cases where boil-off is forced
- fugitive and venting emissions
- crankcase emissions
- loading and cool-down emissions