Ammonia As a Marine Fuel
– Bunkering Operation and Dispersion Simulations

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Agenda

- Overview of Alternative Fuels
- Safety Property Study of Alternative Fuels
- Ammonia Pros and Cons
- Ammonia Bunkering Operations
- Scenario Based Bunkering Operation Simulation
- Ammonia Dispersion Mitigation Measures
- Conclusion and Findings

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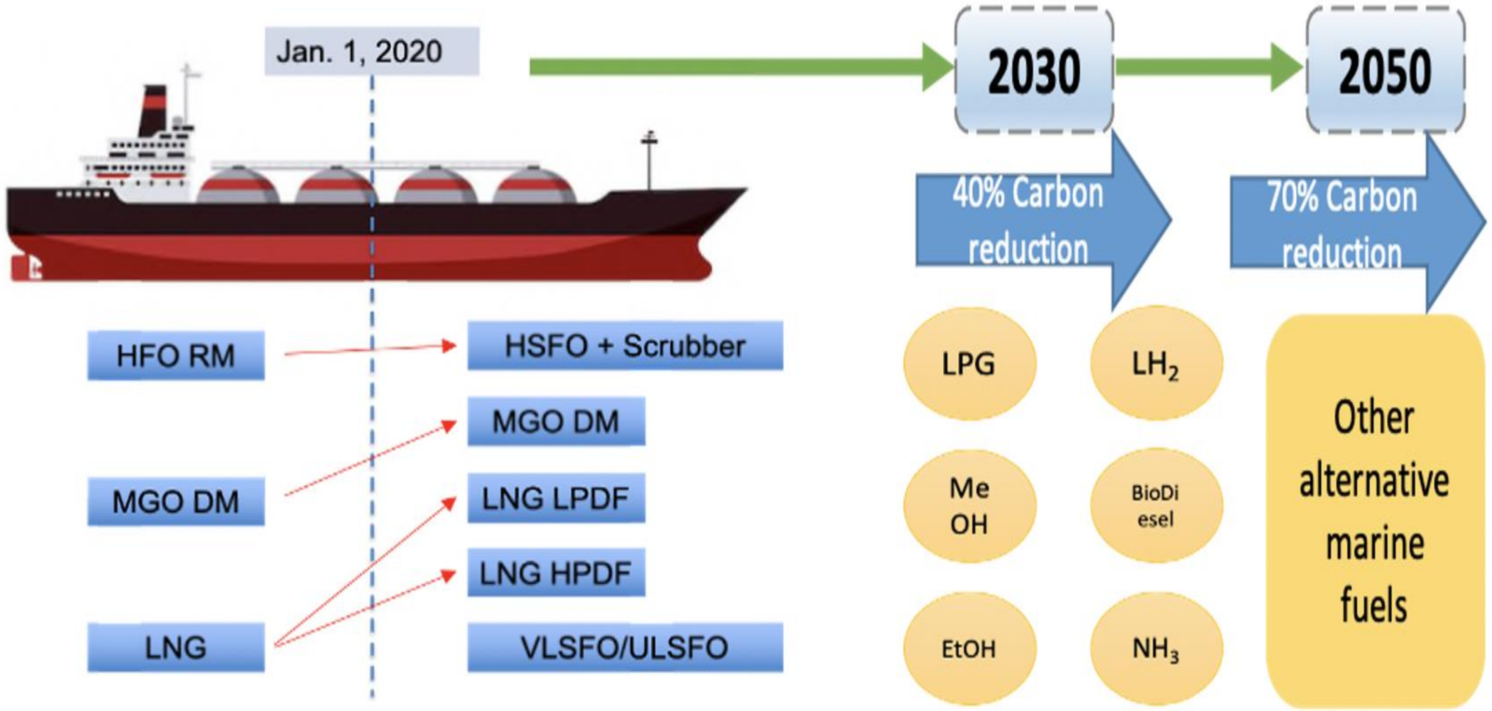
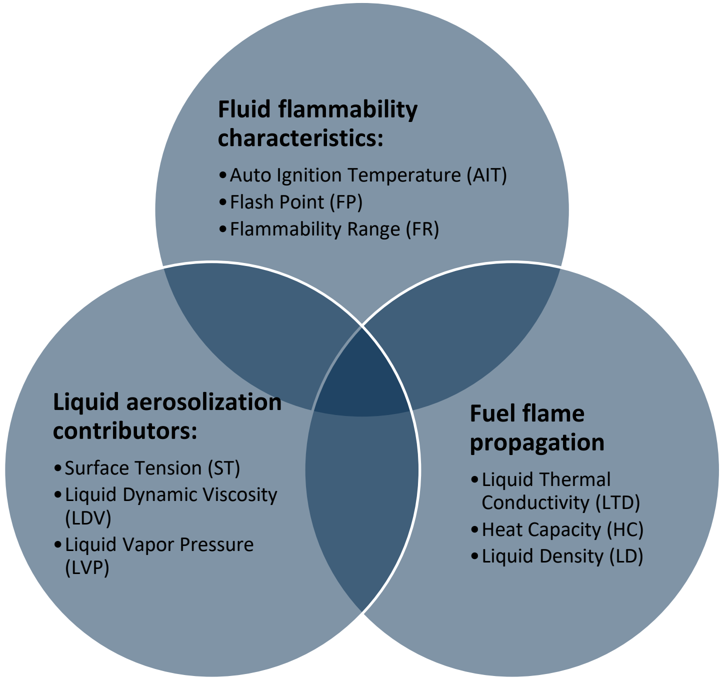
IMO strategy for reduction of GHG emissions from shipping

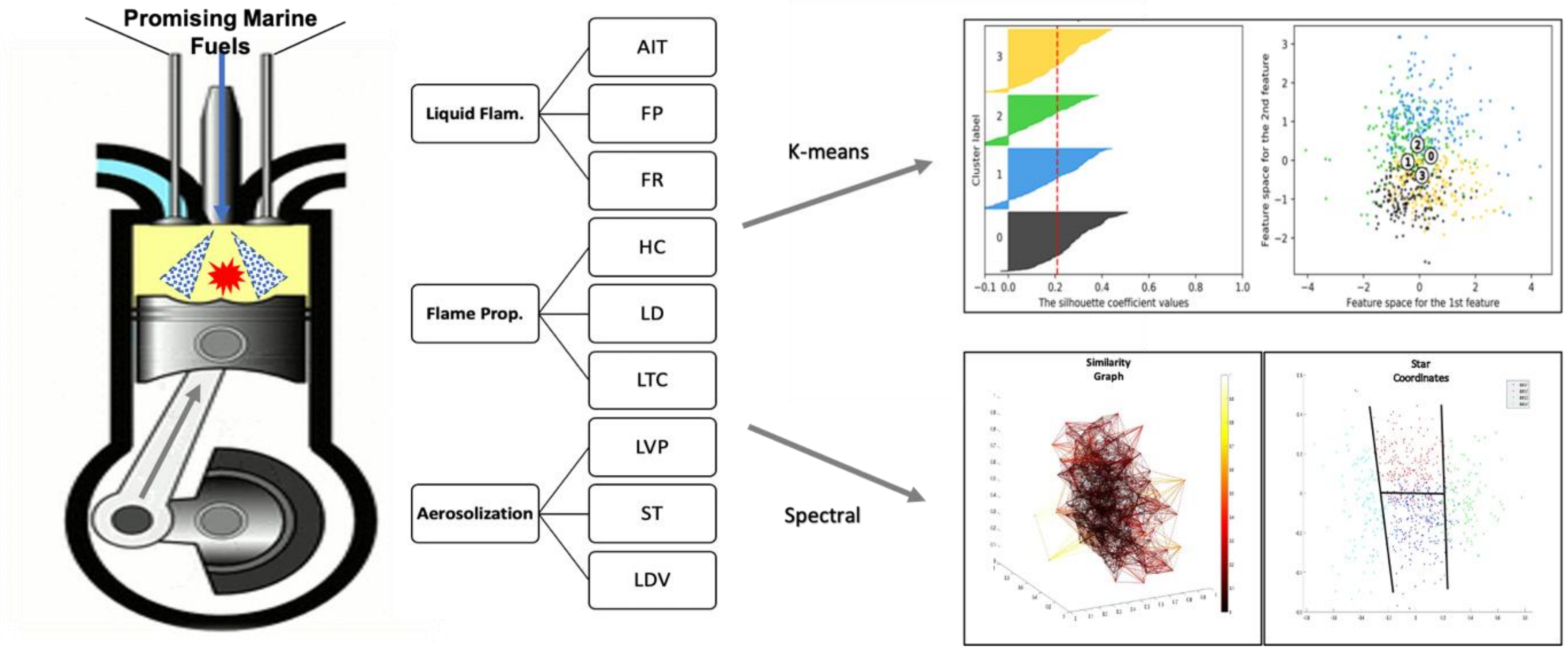
IMO Initial Strategy set ambitious goals for future pollution reduction targets compared to 2008 levels:

- Implement further phases of EEDI for new ships
- Reduce carbon intensity by 40% by 2030, 70% by 2050
- Reduce GHG emissions 50% by 2050
- Currently working on revising IMO initial GHG strategy



Safety Property Study* - Novel Combustion Risk Index





* Ji, C., Jiao, Z., Yuan, S., El-Halwagi, M. M., & Wang, Q. (2021). Development of novel combustion risk index for flammable liquids based on unsupervised clustering algorithms. Journal of Loss Prevention in the Process Industries, 70, 104422.

Safety Property Study*

NFPA 704 liquid flammability ratings of the promising marine fuels

Rating	NFPA Criteria	Marine fuel options
0	Materials will not burn in air when exposed to a temperature of 1500°F for a period of 5 minutes	
1	Flash point at or above 200°F	Biodiesel, Ammonia
2	Flash point between 100°F and 200°F	Heavy fuel oil, Marine gas oil, VLSFO
3	Flash point between 73°F and 100°F	Methanol, Ethanol
4	Flash point below 73°F	LNG, LPG, Liquefied Hydrogen

Novel rating system for alternative fuels

	Flammability	Flame Propagation	Aerosolization	LICRI
No. 6 Fuel Oil	2	2	3	0.342
Methane	4	4	2	0.103
Butane	3	4	2	0.160
Propane	3	4	1	0.318
Ammonia	1	3	2	0.553
Hydrogen	4	4	2	0.103
Methanol	2	4	2	0.280
Ethanol	4	2	3	0.165

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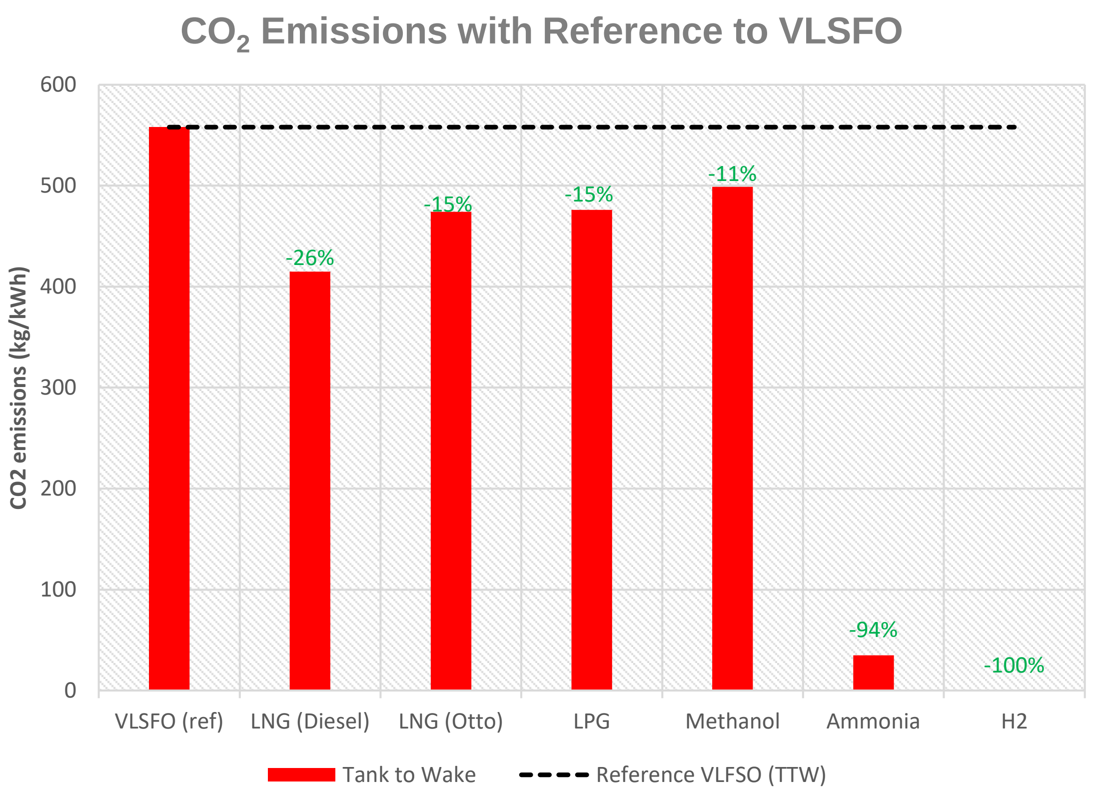
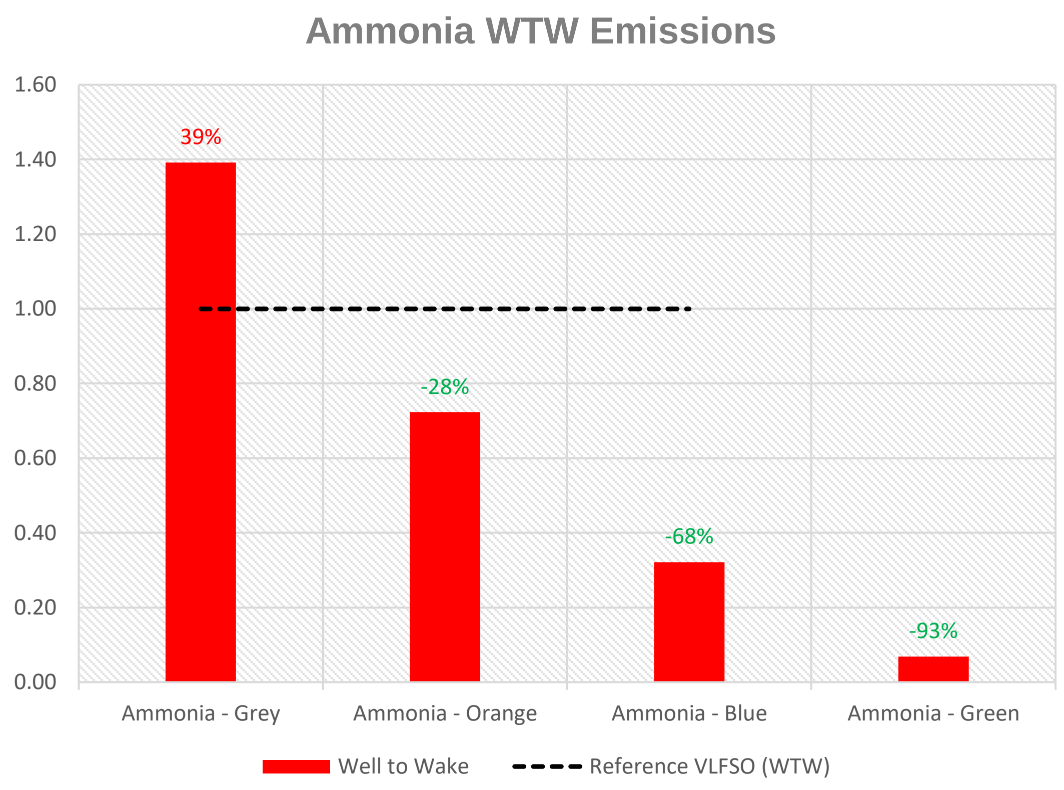
Well-to-Wake GHG Emission Comparison

- When including TTW, the Greenhouse Gas (GHG) emissions comparison changes (*see below for grey fuels)*





Source: ABS Sustainability Whitepaper: Ammonia as Marine Fuel

Ammonia as Marine Fuel

Advantages

- Carbon free - no CO_2 or soot
- Low flammability risk – 15.15% to 27.35% in air
- Can be produced from electrical energy – renewable
- Easily reformed to hydrogen and nitrogen
- Can be stored and transported as a liquid at a practical pressure and temperature
- Potential to be used in the future directly in fuel cell
- Established commercial product

Challenges

- Toxicity – No regulation for use as a marine fuel
- Engine development at design stage
- Cost
- Corrosiveness to certain materials
- Possible need for high percentage of pilot fuel
- Possible increased NOx emission
- Possible ammonia slip

Ammonia Bunkering Operation

Ship-to-ship bunkering

Ship-to-ship bunkering with cargo handling (SIMOPS)

Truck-to-ship bunkering

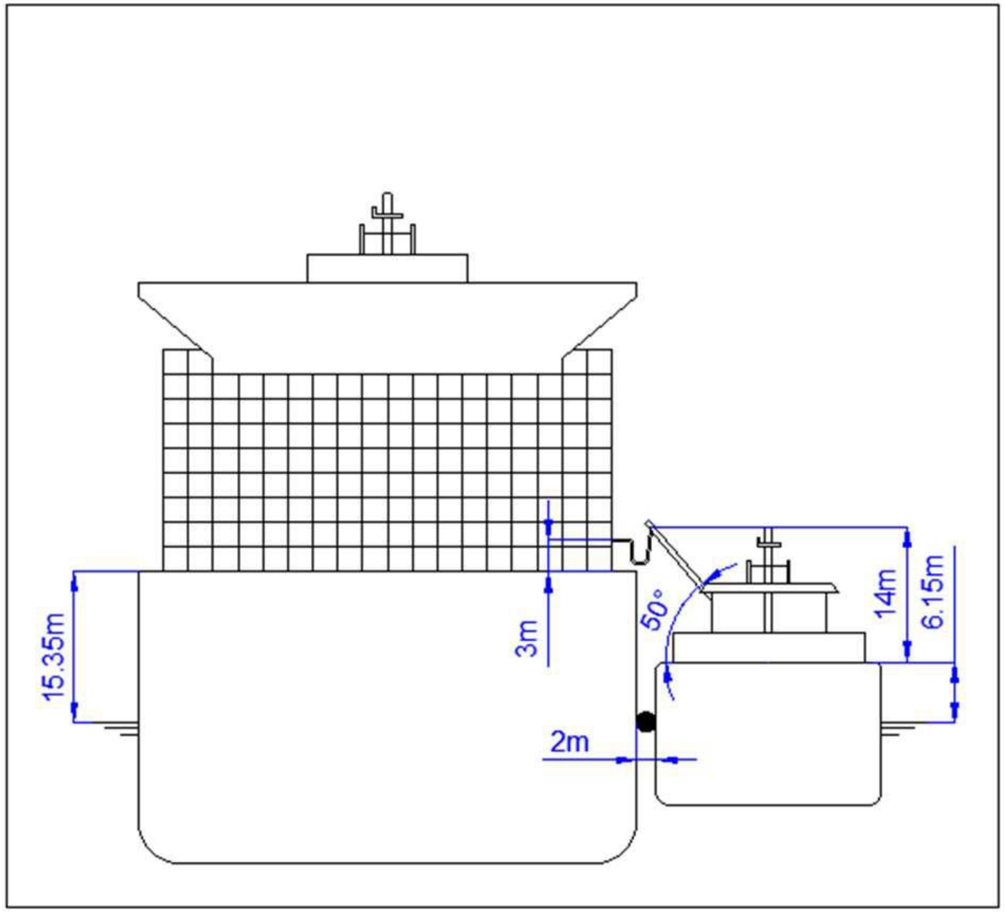
No.	Bunkering Mode	Supply Vessel/Facility	Receiving Vessel	CFD simulation of Ammonia Dispersion		
				Wind Direction	Dispersion Time	Concentration

1	Ship to ship	NH3 carrier	Container ship	• Dispersion of liquid ammonia
				  • Wind blows from bunker vessel to receiving vessel
				  • Wind blows from receiving vessel to bunker vessel
				• Dispersion of ammonia vapor
				  • Wind blows from bunker vessel to receiving vessel
				  • Wind blows from receiving vessel to bunker vessel
					• 30s
					• 60s
					• 2 min
					• 5 min
						• 30ppm (AEGL 1)
						• 160ppm (AEGL 2)
						• 1100ppm (AEGL 3)

2	Ship to ship	NH3 carrier	LPG carrier			
3	Ship to ship	NH3 carrier	Bulk carrier			
4	SIMOPS	NH3 carrier	Container ship			
5	Truck to ship	Truck (ISO tank)	Tugboat			
6	FSU to ship	FSU	Container ship			

Ammonia Leakage Scenario

Category	Parameter	Value
Ammonia release	Release location	Ammonia bunker hose connection at the receiving vessel
	Isolation time	1 min for fully automated blocking system
	Total release volume	26.29 m^3
	Release elevation	Around 18.35 m above water line
	Orifice size	203 mm
	Jet direction	Vertical up
	Liquid fraction	0.999805 (Simulated by PHAST software)
Weather condition	Temperature	$30^{o}C$ (Singapore ambient temp.)
	Relative humidity	85%
	Solar radiation	1 kW/m^2
	Wind speed	3 m/s



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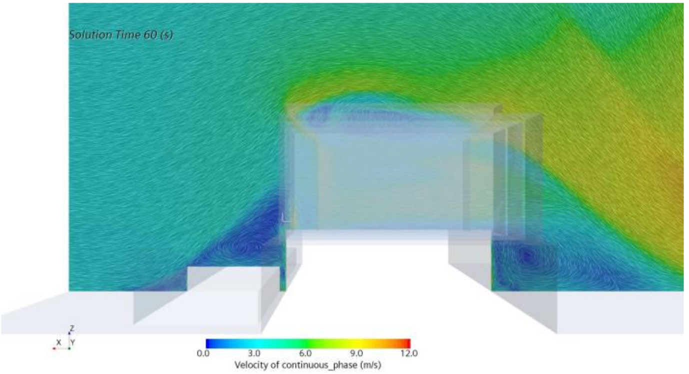
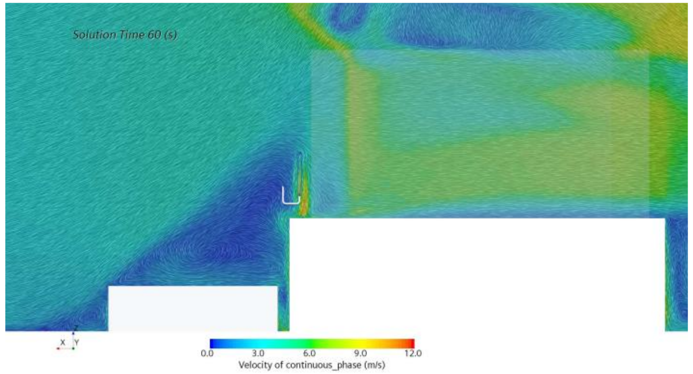
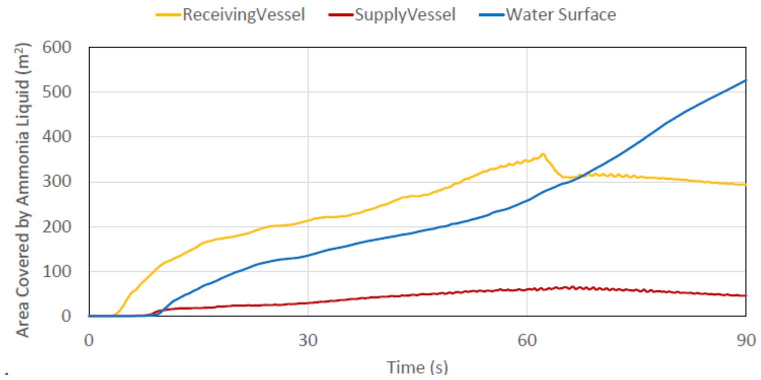
CFD Bunkering Operation Simulation

Inlet velocity = 12.78 m/s, Wind = 3 m/s (from the supply vessel to the receiving vessel)







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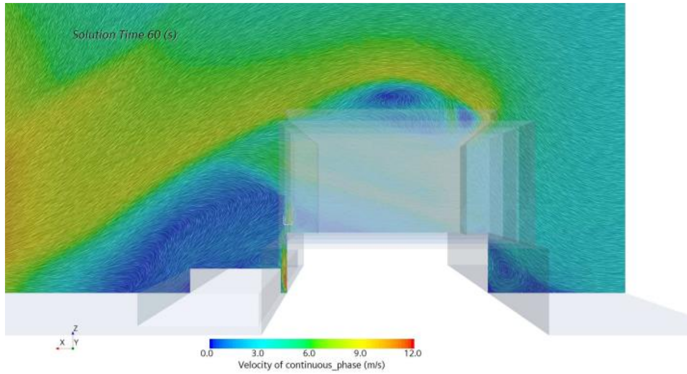
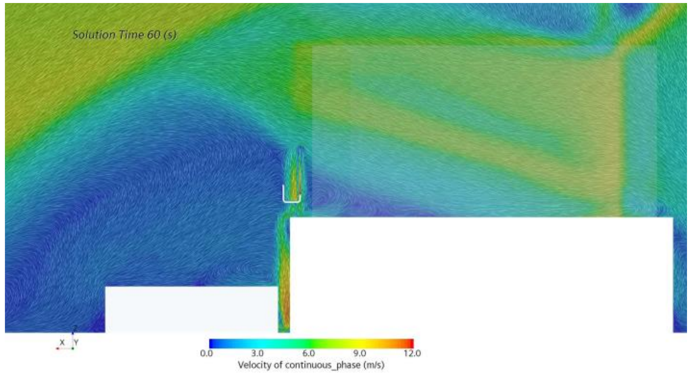
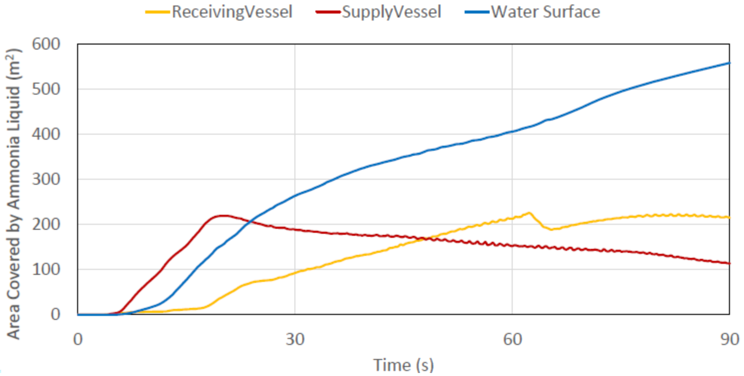
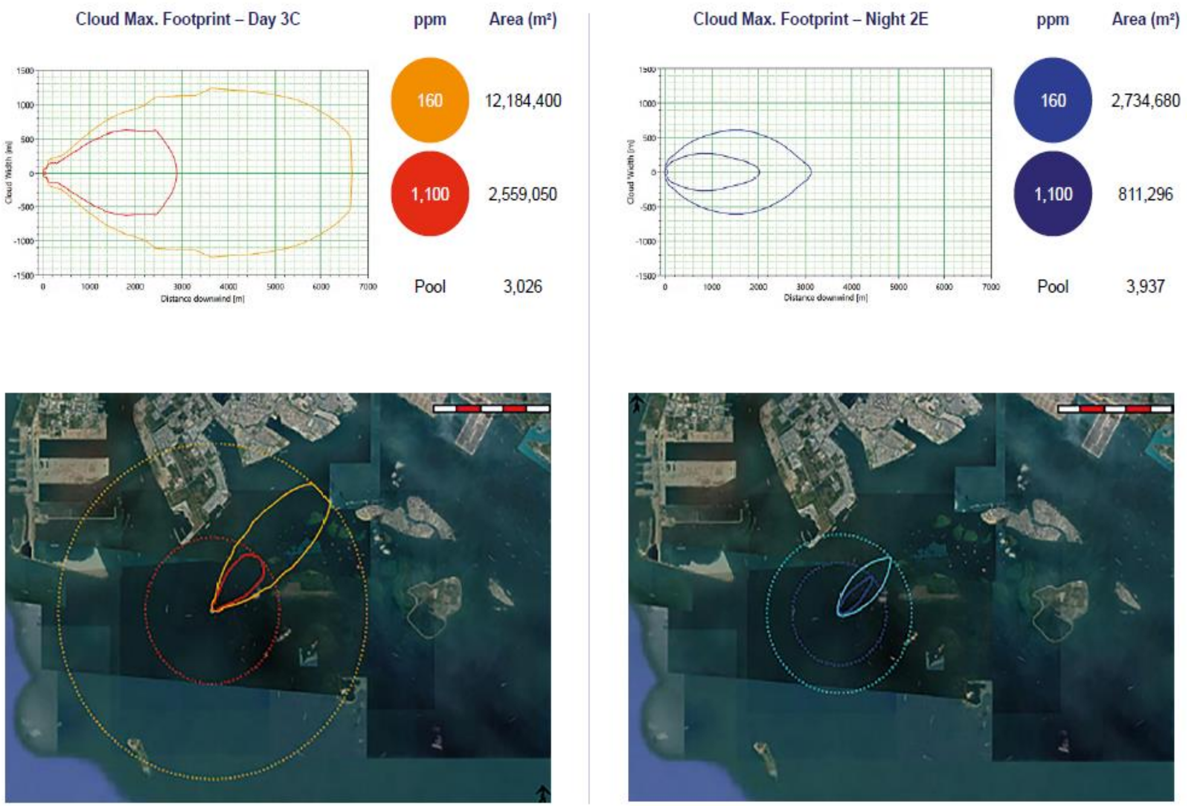






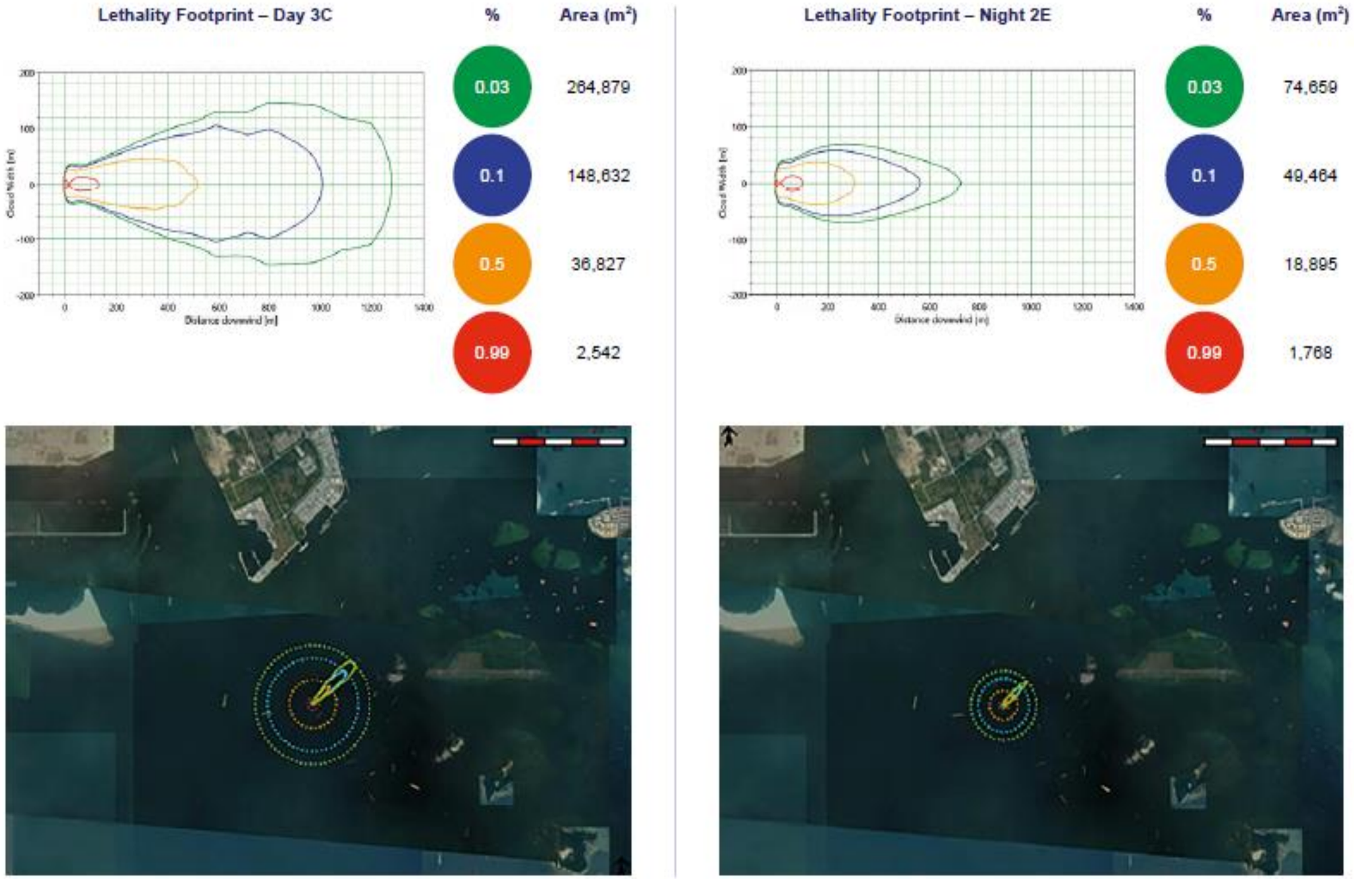
Consequence Analysis

Parameters	Atmospheric Stability	Wind Speed	Humidity	Ambient Temperature	Surface Temperature	Solar Radiation
Day	Class C	3 m/s	70%	33°C	38°C	1 kW/m²
Night	Class E	2 m/s	90%	24°C	26.5°C	0



Maximum cloud footprints for ship-to-ship bunkering

Consequence Analysis



Lethality footprints for ship-to-ship bunkering

Ammonia Dispersion Mitigation

- Absorption and Separation
  - Water Curtain
  - Absorption ($MgCl_2$, $CaCl_2$, and $BaCl_2$)
  - Neutralization

- Physical Barriers
  - Solid Physical Barriers to Limit the Dispersion
  - Isolation Room
  - Blower to Change Release Direction

Conclusion

- Ammonia is a carbon-free option with good combustion risk performance
- Toxicity is of the utmost concern during ammonia bunkering
- Bunkering operation safety distances: 370 m and 400 m (Ship-to-Shore); <100 m (Truck-to-Ship); 1.3 km and 700 m (Ship-to-Ship); 310 m and 340 m (SIMOPS)
- Various types of mitigation measures can be applied together to enhance performance

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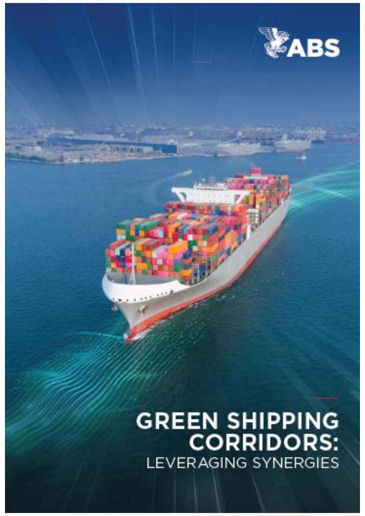
Our Recent Publications

Zero Carbon Outlook (2022): Low Carbon Shipping

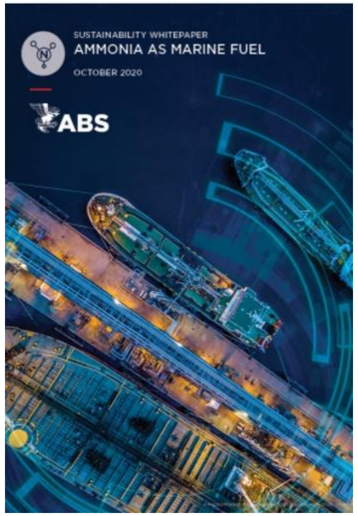


Sustainability Whitepaper 2022: Green Shipping Corridor

View of the Value Chain (2021): Low Carbon Shipping

Sustainability Whitepaper 2021: Hydrogen as Marine Fuel

Sustainability Whitepaper 2021: Methanol as Marine Fuel



Sustainability Whitepaper 2021: Ammonia as Marine Fuel

Please visit: www.eagle.org/sustainability

References

[1] NFPA 704 Fire Diamond Ratings

[2] Ji, C., Jiao, Z., Yuan, S., El-Halwagi, M. M., & Wang, Q. (2021). Development of novel combustion risk index for flammable liquids based on unsupervised clustering algorithms. Journal of Loss Prevention in the Process Industries, 70, 104422.

Sustainability Performance are based on the from

[3] Olmer, N., Comer, B., Roy, B., Mao, X., Rutherford, D., 2017. Greenhouse gas emissions from global shipping, 2013-2015. Int. Counc. Clean Transp. 1–25.

[4] Pavlenko, N., Comer, B., Zhou, Y., Clark, N., Rutherford, D., 2020. The Climate Implications of Using LNG as a Marine Fuel.

[5] Ji, Chenxi, and Mahmoud M. El-Halwagi. "A data-driven study of IMO compliant fuel emissions with consideration of black carbon aerosols." Ocean Engineering 218 (2020): 108241.

[6] Maritime Energy and Sustainable Development (MESD) Centre of Excellence. METHANOL AS A MARINE FUEL– Availability and Sea Trial Considerations. 2021

Thank You

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