Determining the impact and role of onboard vessel emission reduction

An introduction to onboard emission sources, main risks, and solution mapping

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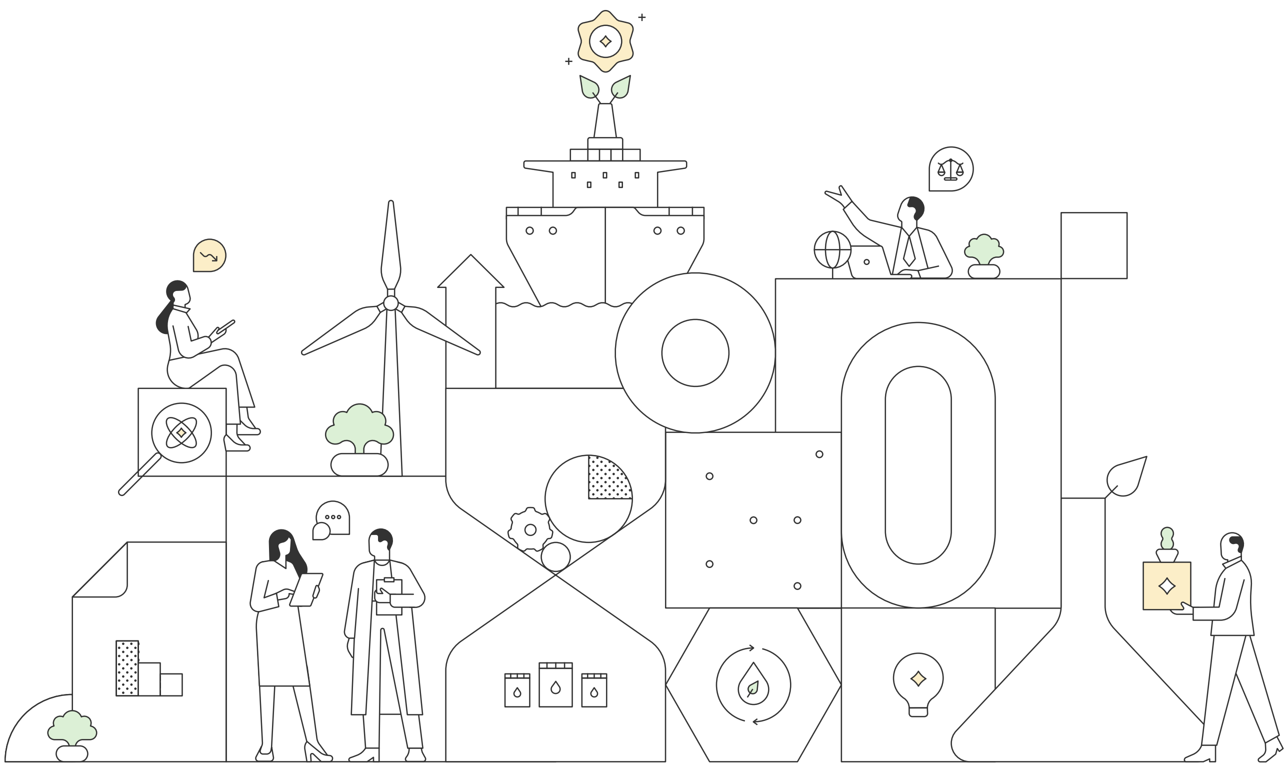
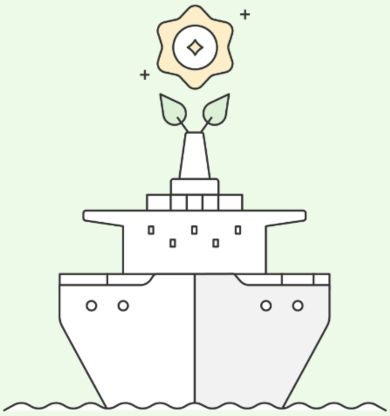




This paper is part of the Onboard Vessel Solutions Paper Series:

Vessel Emission Reduction Technologies & Solutions

The paper series covers the impact and role of vessel greenhouse gas and air pollutant emission reduction in maturing alternative fuel pathways. Onboard impact is defined in terms of tank-to-wake global warming potential with the role of onboard emission reduction either being for regulatory compliance or as an option to reduce emissions. Fuel pathway maturity is an assessment of solution readiness across the entire value chain including if vessels, fuel production plants or bunkering vessels can be ordered without technical risk, at realistic price levels and with underlying regulation in place.

Based on identified vessel emission risks, the paper series deep dives into specific emissions that need to be addressed to increase alternative fuel pathway maturity. The objective of these deep dives is to understand current or potential emission levels, set reduction targets, and identify and map applicable technologies and solutions. Emission reduction potential is then determined, and recommendations given to mature the selected fuel pathways. Finally, areas or concepts for further research and development are identified including recommended future project topics.

Papers are based on work completed as part of Center projects and working groups consisting of Center partners and external participants and contributors. Working groups provide a collaborative framework facilitated by the Center to jointly engage partners and external experts and companies on specific topics to deliver clear and impactful results.

01 Acknowledgements

We would like to thank the following working group members who have made major contributions to the work used as a basis for this paper.

The working group and paper series development has been led by Thomas McKenney and Giorgio Guadagna with sub-group leaders Ioannis Dimakopoulos, Sam Nivin Deepa Rosaline and Daniel Barcarolo. Working group participants and contributors include Jens Peter Hansen, Marcel Somers, Søren Molgaard, Anthony McCarey, Deepak Vaikkath, Janus Emil Münster-Swendsen, Jun Kato, Kei Kato, Hidehiro Nagata, Peter Nerenst, Koichi Matsushita, Tadashi Inoue, Miu Hatamura, Florian Badel, Lars Bo Andersen, Keld Johansen, Rene Laursen, Hans-Philipp Walther, Kevin Lappage, Mirko Bugsch, Dorte Kubel, Henrik Røjel, Bruno Griffaton.

02 Introduction

Along with alternative fuels and energy efficiency, vessel technologies and solutions are either required for regulatory compliance or can be used to reduce onboard emissions. While carbon dioxide (CO_2) is the main source of shipping's climate impact with over 90% of total greenhouse gas (GHG) emissions[1], non-CO_2 GHGs and air pollutants can also contribute to climate impact and regulatory risk of alternative fuel pathways. For example, the 100-year global warming potentials (GWP) of methane (CH_4) and nitrous oxide (N_2O) are 28- and 265-times CO_2, respectively.[2]

GHGs have a global impact on the climate while air pollutants have a local impact on human health and the environment. Emissions can generally be categorized into GHGs and air pollutants, however, air quality and climate change research has shown that these are not mutually exclusive. For example, different types of

[1] In terms of 100-year global warming potential (GWP) as defined within the Fourth IMO Greenhouse Gas Study (voyage-based calculation)

[2] GWP values from IPCC Fifth Assessment Report

particulate matter (PM) can have either warming or cooling effects on the climate.[3] Air pollutants, such as nitrogen oxides (NO_X) and sulfur oxides (SO_X), can contribute to global cooling and would have a negative GWP. When considering onboard vessel emissions for alternative fuels, both climate impact and regulatory risks should be assessed to ensure a holistic perspective.

Well-to-wake (WTW) and lifecycle assessment (LCA) methodologies are currently being developed to clearly define the climate impact of fuels including what emissions should be included and the quantification of their impact.

The diversity of alternative fuel options makes it difficult to agree on a common pathway, which is why emissions from multiple fuels need to be considered. Currently, the Center has identified four main alternative fuel pathways: ammonia, methanol, methane and bio-oils. Current emissions from shipping are a result of predominantly fossil fuel combustion, emitting mainly CO_2, NO_X, SO_X and PM. In line with the highest emissions, current regulations target mostly SO_X, NO_x and PM. With new fuel options comes new emissions and associated risks such as methane emissions from methane-based fuel combustion and N_2O, NO_x and ammonia (NH_3) emissions from ammonia combustion. Existing and potential future NO_X regulations will continue to be an important design limit for all fuels.

Emission regulations and restrictions can be applied at the global, regional or local level based on where a vessel is flagged or operating. Table 1 provides a general overview of vessel emission regulations. The International Maritime Organization (IMO) has agreed to include CH_4 and N_2O as GHG contributors in draft LCA Guidelines, which are under development. Black carbon (BC), a subset of PM, has also recently been in focus as having a climate impact and will be considered further at the IMO level. While the IMO is considering incorporation of new emission types, regions like the European Union are already ahead in implementing more restrictive regulations through FuelEU Maritime.

Local regulations mostly apply to domestic shipping or vessels flagged in a particular country; however, some can impact all vessels visiting certain countries, states or ports. For example, the California Air Resource Board (CARB) applies the California Code of Regulation (CCR) to control NO_X and PM emissions from vessels while docked at berth at a California port. Originally applying to container vessels, passenger vessels and refrigerated cargo vessels, it is now being extended to include car carriers and tankers. The rules require either use of shore power or a CARB-approved control technology when running auxiliary engines or boilers while docked. The local regulations identified in Table 1 should only be considered as examples of the types of restrictions introduced at the local level.

With the potential increase in non-CO_2 GHGs associated with alternative fuels along with slow-paced global regulation, future regional and local regulations and restrictions could become limiting factors and risks when selecting alternative fuels instead of global IMO regulations. Additionally, it is critical to address these new emissions upfront as the alternative fuels are being developed and implemented instead of post-fuel introduction, ultimately reducing fuel selection risk and uncertainty today. The introduction of liquified natural gas (LNG) as a fuel without fully understanding and addressing methane slip upfront highlights the importance of evaluating both climate and air quality impacts of new alternative fuels.

[3] United States Environmental Protection Agency (https://www.epa.gov/air-research/air-quality-and-climate-change-research)

Table 1: Vessel emission regulation overview

	GLOBAL	REGIONAL			LOCAL	
Air Emission	IMO	United States	European Union	China	California	Norway
Black Carbon (BC)	👥					
Nitrous Oxide (N2O)	👥		⚙			
Methane (CH4)	👥		⚙			
NOx	✓	✓	✓	✓	✓	✓
SOx	✓	✓	✓	✓	✓	✓
PM					✓	✓
VOCs	✓				✓	✓

✓ Currently applied ⚙ To be implemented 👥 Under consideration

03 Vessel technology pathways and emission sources

In addition to the selected primary fuel, emissions are directly related to the main onboard energy storage and conversion technologies. Onboard energy demand can be met in different ways using various energy storage and converter technologies (see the "Supply Side" of Figure 1). Up to 90% of the total onboard energy demand is for propulsion and typically supplied by the main energy converter(s), which contribute the most to a vessel's emissions. Internal combustion engines are predominantly used onboard vessels today and will continue to play a role in the future, which is why they are the focus of this work. Other energy converters, such as fuel cells, are available or under development and could play a larger role in the future. The emissions from fuel cells are important to understand and will be covered in a dedicated working group at the Center.

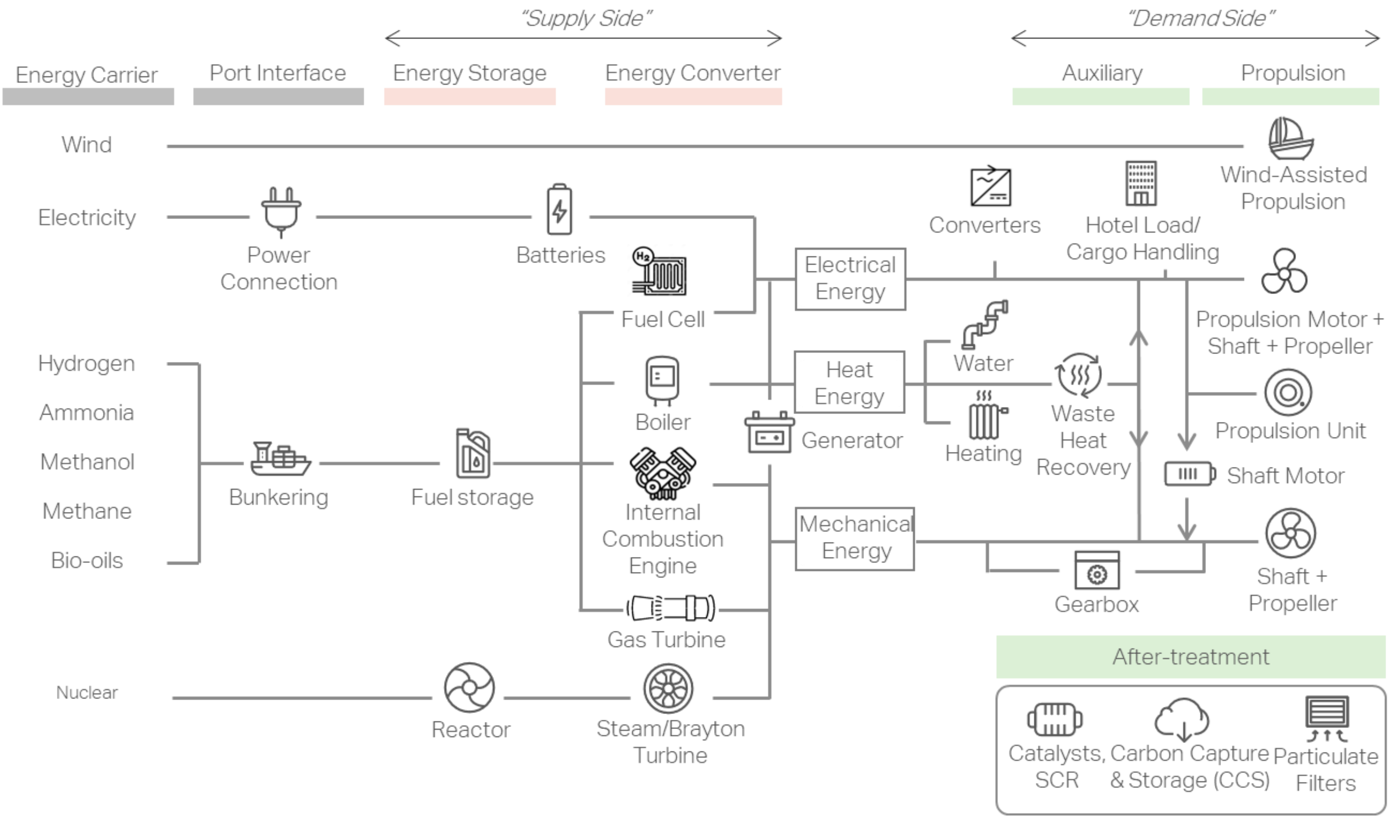
For some alternative fuel pathways, emissions related to pilot fuels also need to be considered. To ensure proper ignition of some primary fuels in internal combustion engines, a pilot or secondary fuel is injected into the combustion chamber to ignite the fuel mixture. The amount of pilot fuel needed depends on the primary fuel's ability to ignite. Methane, methanol and ammonia engine-based vessel pathways can require a pilot fuel depending on the specific engine technology. LNG/methane engines are the most developed with the lowest pilot fuel percentage while ammonia engines are still under development with higher uncertainty. Alternatives to fossil-based pilot fuels exist to reduce or eliminate GHG and air pollutant emissions including various biofuels.

While most onboard emissions come from engine combustion, other potential sources from normal operation should be considered. Exhaust gas and slip from energy converters out the funnel during normal running conditions are the primary sources of onboard emissions. Other sources include:

- **Operational releases:** Emissions from other parts of normal operation including fuel switching and gas start-up as well as gas-freeing before maintenance.

- **Fugitive emissions:** Leakages during normal operation, for example, from piping, safety valves and pump or compressor shaft seals can occur, but overall emission impact is limited.
- **Accidental releases:** Emergency situations that cause vapor releases, for instance in case of fuel tank pressure can occur due to multiple failures. Boil-off management, such as on LNG vessels, is regulated as part of control of tank pressure and temperature requirements from the IGF Code and managed such that venting of fuel vapor for control of the tank pressure is not acceptable except in emergency situations[4].

Figure 1: Vessel technology pathways



04 Emission risks

As part of the Center's efforts to understand the main energy carrier and fuel pathway maturity levels, a fuel pathway maturity map has been developed to provide a simple, interactive overview of the readiness of solutions in the entire value chain (see Figure 2). A high-level assessment has been completed utilizing three main categories: mature and proven, solutions identified, and major challenges remain. Vessel emissions is identified as one of the key considerations across the value chain and the focus on this work. Vessel emissions includes both GHGs and air pollutants. Maturity ratings are based on a combined assessment of both emission types that considers known and potential emission concerns using our current best understanding.

When assessing the maturity level of the main fuel pathways from a vessel emissions perspective, the risks of known, potential or perceived climate impact and GWP as well as impact on human health and the environment are considered. Compliance with climate and air pollutant rules, regulations and restrictions is also a main assessment criterion. The potential perceived risk of fuel usage was also considered for air pollutants including visibility of exhaust plumes and smells. There are also emissions currently regulated on shore, but not considered for vessels including particle number (PN) and NH_3. Further alignment between shore-based and vessel-based emission regulation can occur in the future. NO_X emissions remain a key design parameter for most alternative fuels to maintain regulatory compliance[4] while minimizing fuel consumption. Existing and known technologies including Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR) and direct water injection can be used to reduce NO_X emissions from alternative fuels in the same way they do for current fossil fuels. While NO_X emission levels vary by fuel, existing reduction technologies ensure regulatory compliance. NO_X emissions do not currently impact the maturity of main alternative fuel pathways.

Reduction of NO_X emissions can, however, impact an engine's fuel efficiency, which can lead to more GHG emissions, creating a situation where tradeoffs between climate and air pollution impacts need to be reached. Comparable NO_X regulations on shore are five times stricter than current Tier III levels.[5] While there is not an active focus on further reducing existing limits, there is a possibility that future reductions will be considered.

Based on the fuel pathway maturity map assessment of vessel emissions, the three alternative fuels that present the highest known or potential risks include ammonia, methane, and bio-oils.

1. **Ammonia:** Knowledge of and experience with emissions from ammonia internal combustion engines is limited. However, the potential exists for emissions of both N_2O (a potent GHG combustion byproduct) and NH_3 slip (highly toxic). Major challenges for ammonia are related to its currently unknown emission profile and the need to develop emission reduction technologies and solutions if the potential risks materialize.
2. **Methane:** For methane-based fuels, methane slip presents a GHG risk of increased CO_2-equivalent emissions. Methane slip reduction solutions are identified, but not fully developed, tested, or demonstrated.
3. **Bio-oils:** While knowledge of next generation bio-oils and their emissions is limited, varying quality and feedstock of bio-oils may lead to different emission profiles. A recent Unified Interpretation of MARPOL Annex VI related to the use of biofuels and possible implication on NO_X emissions will allow the use of biofuels and biofuel blends without assessment of NO_X emissions provided the engine can operate in accordance with the components and settings set out in its Technical File. Solutions exist to manage vessel emissions from bio-oils, however, a full understanding of what, if anything, is needed should be better understood.

From a vessel emission perspective, methanol is considered mature and proven with no further risks currently identified. NO_X regulatory compliance to be achieved using commercially available NO_X reduction technologies.

[4] Regulation 13 of MARPOL Annex VI (limits for NOx emissions from diesel engines)

[5] MARPOL Regulation 13 Tier III levels are around 2 g/kWh relative to 0.4 g/kWh for EURO VI standards for heavy-duty diesel engines

Figure 2: Fuel pathway maturity map

	Feedstock availability	Fuel production	Fuel storage, logistics & bunkering	Onboard energy storage & fuel conversion	Onboard safety & operations	Vessel emissions	Regulation & certification
E-ammonia	Mature	Solutions identified	Major challenges	Major challenges	Major challenges	Major challenges	Major challenges
Blue ammonia	Solutions identified	Solutions identified	Major challenges	Major challenges	Major challenges	Major challenges	Major challenges
E-methanol	Solutions identified	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified
Bio-methanol	Solutions identified	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified
E-methane	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified	Solutions identified
Bio-methane	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified	Solutions identified
Bio-oils	Solutions identified	Major challenges	Solutions identified	Solutions identified	Mature	Solutions identified	Solutions identified

MATURE

Solutions are available, none or marginal barriers identified.

SOLUTIONS IDENTIFIED

Solutions exist, but some challenges on e.g. maturity and availability.

MAJOR CHALLENGES

Solutions are not developed, or lack specification.

05 Emission reduction technologies & Solutions

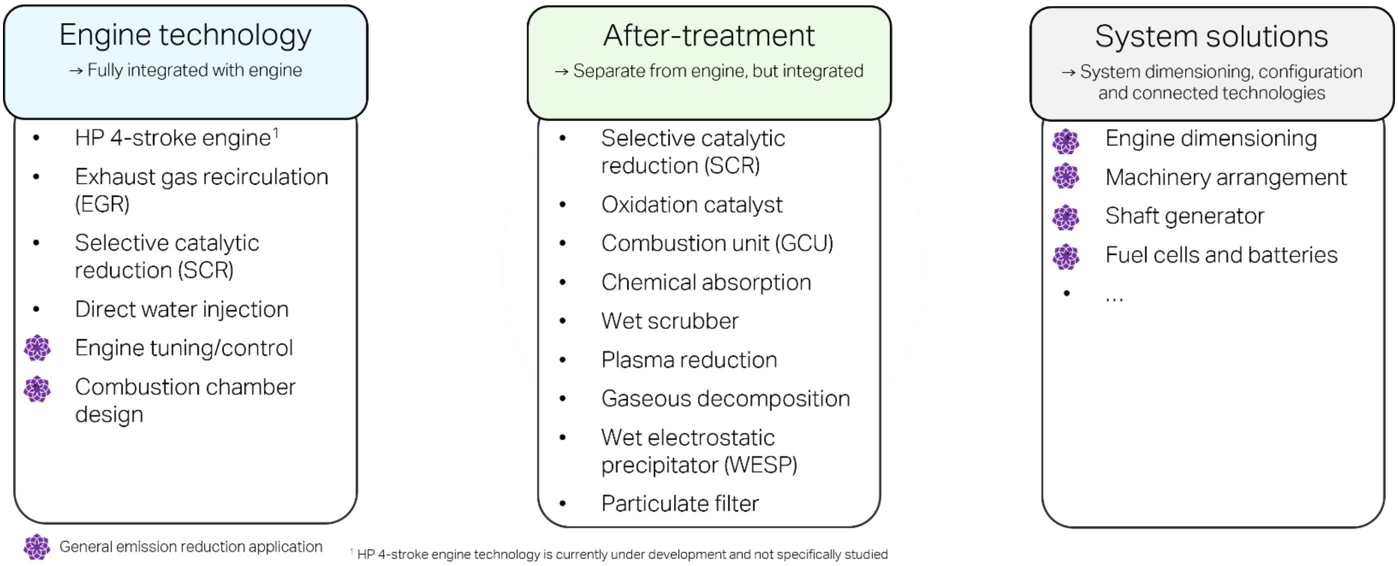
Onboard emissions are based on the ship and system design combined with how the vessel is operated for a given profile. A design could be efficient for one profile, but be inefficient for another, which can lead to higher emissions is some cases. When focusing on onboard emission reduction, technologies will play an important role, however, how these technologies and other systems are integrated together is just as critical and should be considered during design and development. Solutions include engine-related and after-treatment technologies as well as their integration together into power and propulsion concepts or system solutions.

The three main solution categories include:

1. **Engine technology:** fully integrated with the engine,
2. **After-treatment technologies:** separate from the engine, but integrated, and
3. **System solutions:** system dimensioning, configuration and connected technologies.

See Figure 3 for a representative list of the types of technologies and solutions defined under the three categories, which are provided as an example and starting point for our evaluation of applicability to specific emission types. Descriptions, results of our evaluation and applicability recommendations are provided in the papers on specific emissions. Some solutions span multiple categories based on how they are integrated. For example, an SCR can be directly integrated into an engine design or be considered as a separate technology. General emission reduction applications are also identified as solutions that can be implemented independent of a specific application. System solutions that could be considered as primarily energy efficiency technologies can also play an important role in reducing specific emissions. For example, methane slip from some internal combustion engines vary based on engine load with typically higher slip at lower loads. A shaft generator or batteries can be used to increase the engine load and reduce the specific fuel consumption resulting in less methane slip emissions.

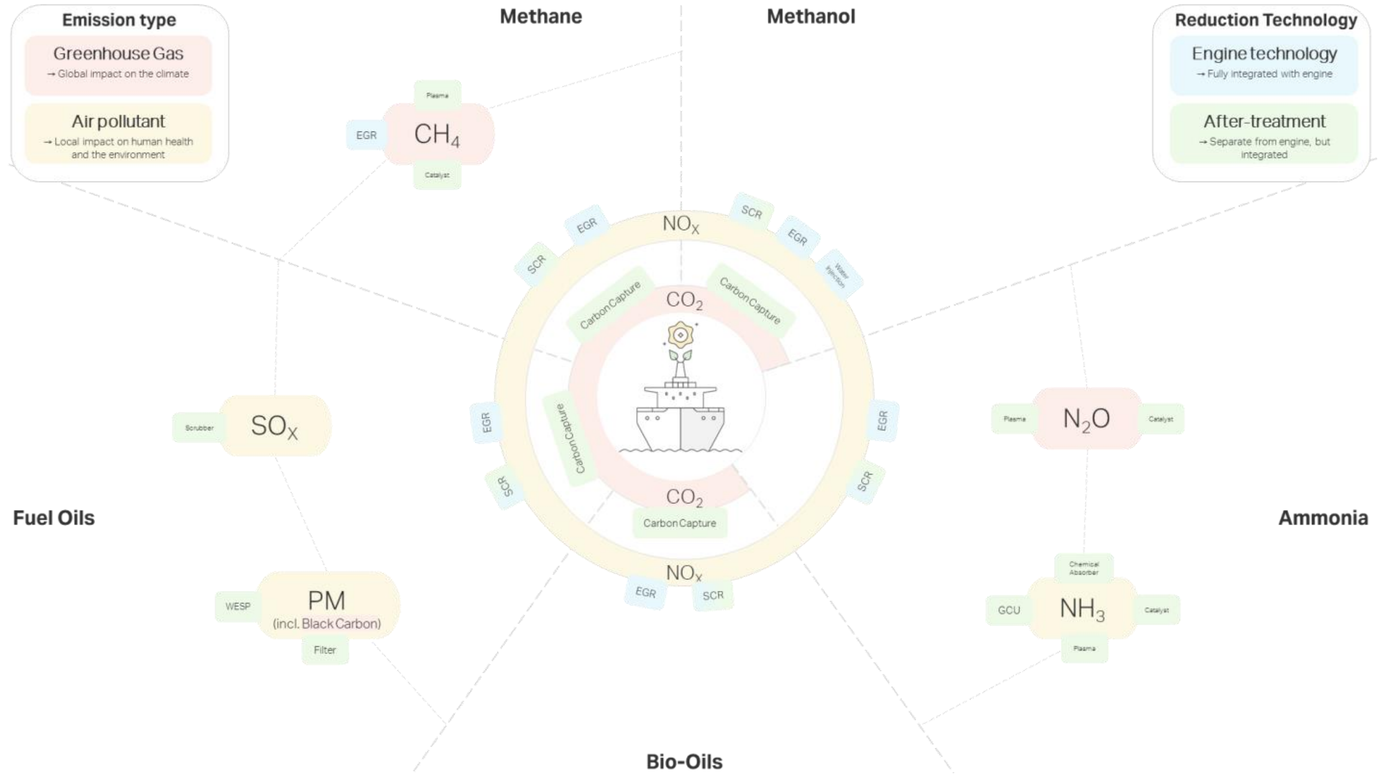
Figure 3: Emission reduction technologies and solutions



After defining the potential emission reduction technologies and solutions, a preliminary solution mapping was completed. This is visualized using an emission web (see Figure 4) that shows both the general and specific emission risks for the four main alternative fuel pathways in addition to fuel oils. The emissions web only shows the main emission risks for the fuel pathways and does not provide a comprehensive view of all emissions resulting from the combustion of each fuel. For example, all fuels will have some level of PM emissions, however it has been identified as a main risk only for fuel oils.

A mapping of applicable technologies and solutions that can reduce the identified emissions is also shown and categorized as an engine technology or after-treatment. Based on the initial mapping, there are multiple potential technologies or solutions for some emissions while others are more limited. As part of the specific emission deep dives, these technologies and solutions as well as their applicability are investigated in detail.

Figure 4: Emissions web



06 Related projects and upcoming papers

The scope of this paper series is defined considering the larger ecosystem of connected ongoing projects at the Center. Onboard carbon capture is considered an emission reduction solution focused on CO_2 emissions from a vessel. As this is a large topic on its own, it is currently being covered in a separate working group. Fuel cells, as mentioned earlier, is another main energy converter that can be used onboard to potentially increase energy conversion efficiency as well as reduce emissions. The different fuel cell technologies, systems integration and emissions impact using the main alternative fuels is currently be covered as part of a separate working group. Onboard emission measurement is a general topic that is currently being studied further to better understand actual onboard emissions including operational factors like dynamic engine loads and heavy sea states. Onboard emission monitoring is also being considered as a potential tool for emission regulation compliance assurance and enforcement

Deep dives and reviews will be covered by the individual papers on specific emissions within the paper series. The first three will focus on the red and yellow ratings related to vessel emissions from the fuel pathway maturity map. The paper topics are methane slip, ammonia combustion and biofuel emissions. Potential future topics include a broad assessment of PM including BC for all main fuel alternatives as well as a complete assessment of emissions from methanol combustion.