THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

MARCH 2024

FEASIBILITY STUDY OF FUTURE ENERGY OPTIONS FOR GREAT LAKES SHIPPING

AUTHORS

International Council on Clean Transportation (ICCT)
Dan Rutherford, Ph.D., Program Director - Coordinating & Lead Corresponding Author
Zhihang Meng, Researcher
Yuanrong Zhou, Researcher
Nikita Pavlenko, Program Lead
Bryan Comer, Ph.D., Program Director

American Bureau of Shipping (ABS)
Joshua Padeti, Senior Engineer II - Coordinating Author
Nathan Seward, Engineer II
Onur Semiz, Principal Engineer
Chase Ji, Senior Engineer I

Conference of Great Lakes St. Lawrence Governors & Premiers (GSGP)
John Schmidt, Program Manager - Coordinating Author

ACKNOWLEDGMENTS

Prepared for: U.S. Department of Transportation, Maritime Administration (MARAD), Office of Environment & Innovation

Recommended Citation: United States Maritime Administration (2023), Feasibility Study of Future Energy Options for Great Lakes Shipping, MARAD

Acknowledgements: We thank Hussein Basma, Ketan Gore, and Hae Joeng Cho for contributing analysis. We thank Serkan Ünalan, He Haung, Debra DiCianna and Jim Weakley (Lake Carriers Association); Professor Bryan Slack (Concordia University); Ben Hayes and Colin Henein (Transport Canada); and Galen Hon, Alyson Azzara, and Bryan Vogel (MARAD) for comments on an earlier draft. We thank Tom Klemens and Amy Smorodin for editing this work. We thank the U.S. Department of Transportation Maritime Administration for funding this work.

Edited by Amy Smorodin

International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

The Great Lakes-St. Lawrence Seaway (GL-SLS) is a vital North American economic and environmental resource, transporting more than 135.7 million tonnes (Mt) of cargo with a value of US$26.1 billion in 2022 across a 2,300 miles deep-draft inland navigation system. Awareness is also growing of the impacts of greenhouse gas (GHG) emissions and overall air pollution from shipping. Global maritime shipping emitted about 1 gigatonne (Gt) of carbon dioxide (CO_2) in 2018. According to the U.S. Environmental Protection Agency (EPA), ships and boats emitted 50 Mt of CO_2 equivalent in 2021, or equal to 2.8% of U.S. transportation GHG emissions.

This report investigates the suitability of different alternative fuels and power options in Great Lakes shipping through 2050. Via five discrete tasks, this report:

1. Profiles the Great Lakes shipping industry to characterize energy use and air pollution associated with today's ships, engines, and fuels.
2. Profiles Great Lakes ports and bunkering infrastructure to determine access to existing and potential future alternative energy supply.
3. Reviews and evaluates the suitability of alternative fuel and power options to Great Lakes vessels today.
4. Projects the suitability of those alternative fuel and power options out to 2050, taking into account different factors such as technological maturity, cost, and life-cycle emissions.
5. Identifies domestic and international environmental regulations that may influence the uptake of those alternative energy options.

In Task 1, a detailed inventory of fleet characteristics and emissions was produced using ICCT's Systematic Assessment of Vessel Emissions (SAVE) model. Bulk carriers were the most important ship type in the GL-SLS in 2021, contributing more than half of tonnage, fuel use, CO_2 emissions, and air pollution. Tugs were the second most important ship type, accounting for about 30% of activity hours and one-eighth of fuel use and CO_2 emissions. Fuel use in GL-SLS shipping is dominated by distillate fuel, with residual fuel being an important source of energy for bulk carriers in particular. Overall, ships operating in the GL-SLS region emitted about 1.5 and 1.6 million tonnes of CO_2 in 2020 and 2021, a slight decrease from 2019. Ships flagged to the United States and Canada were responsible for three quarters of those emissions, equivalent to the annual emissions from about 250,000 U.S. passenger vehicles.

In Task 2, a detailed survey was administered to regional ports to collect information on their operations, fuel supply, and existing infrastructure to support alternative marine fuels. Among the ports surveyed, Chicago supported the widest array of fuel types, including propane, gasoline, and diesel fuel. In the Port of Duluth, diesel capacity is 560,000 gallons, more than 20-times greater than the next highest port, Erie, which stores 24,000 gallons. Québec City supplies LNG as a marine fuel. Seven regional ports reported some form of electrical connections at the port but only four (Chicago, Duluth, Milwaukee, and Montréal) have onshore power supply (OPS), and the Port of Montréal was the only port with high-voltage OPS suitable for large commercial ships. The other three have low-voltage OPS suitable for harbor craft, such as tugs. All responding ports expressed willingness to engage further in alternative fuels or shore power.

For Task 3, we developed a comprehensive baseline assessment for fuel and power options suitable for GL-SLS shipping, including emissions and total cost of ownership (TCO). The results of a detailed life cycle assessment (LCA) of 32 fuel pathways using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and using 100-year global warming potentials (GWP) are shown in Figures ES1, ES2, and ES3. Results are compared to a fossil fuel baseline, marine gas oil (MGO). In Figure ES2, the yellow circles show the equivalent life-cycle GHG intensity of using hydrogen in a fuel cell or electricity in a battery, which have higher efficiency than internal combustion engines, by applying an energy intensity ratio.

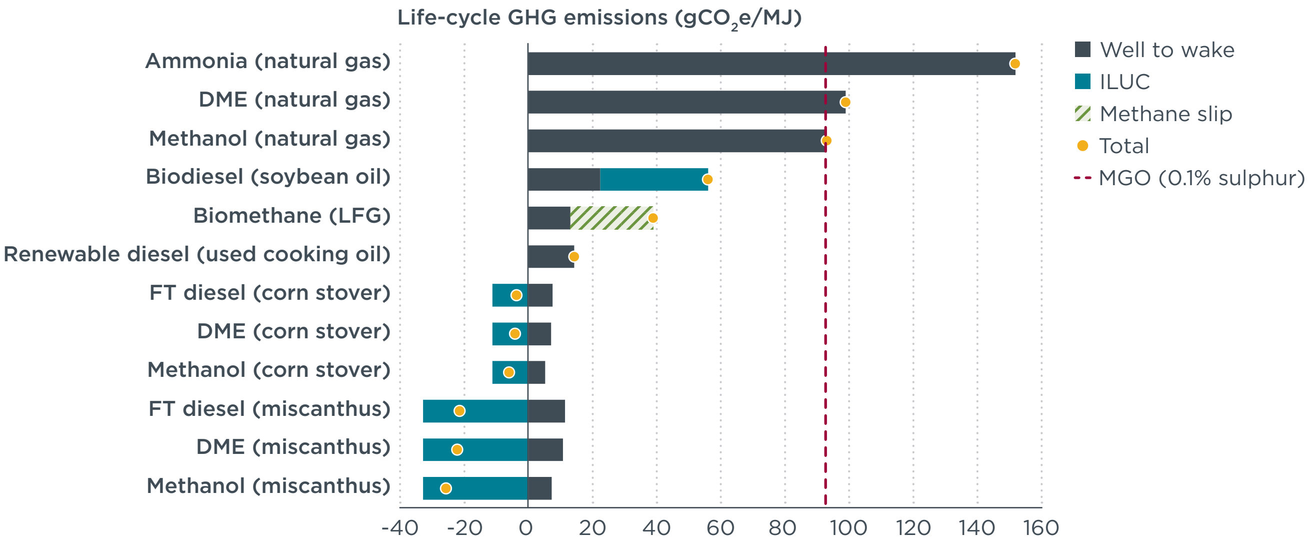


Figure ES1. Lifecycle emissions of bio-based and fossil-based fuels, 100-year GWP

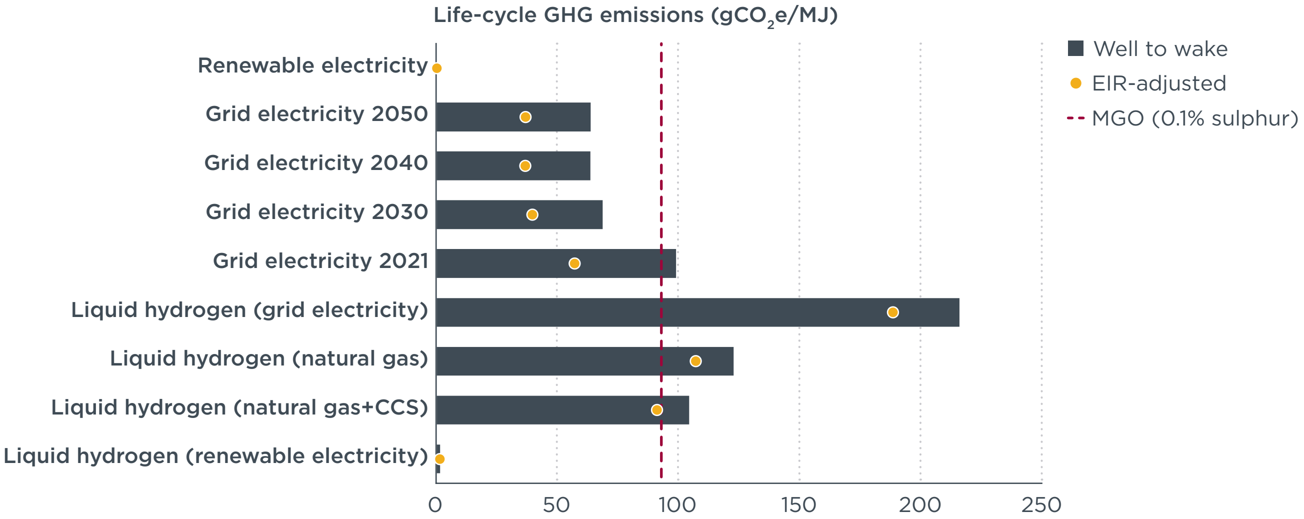


Figure ES2. Lifecycle emissions of hydrogen and electricity, 100 year GWP

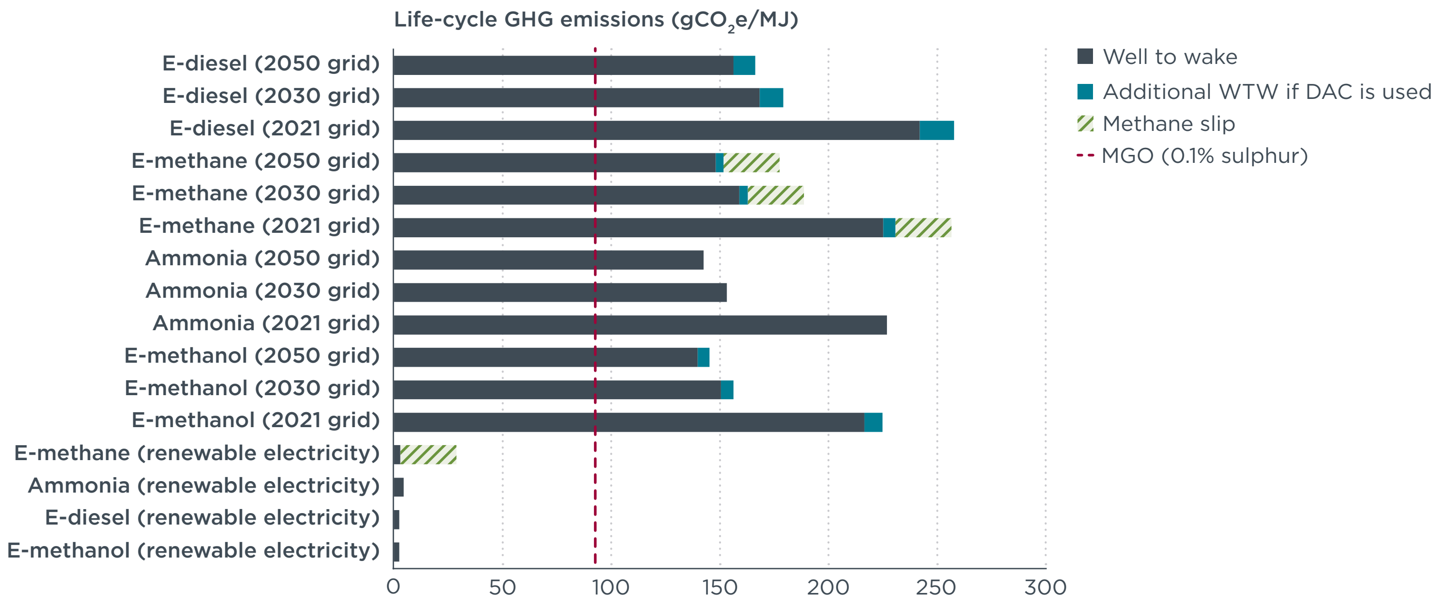


Figure ES3. Lifecycle emissions of e-fuels, 100 year GWP

As demonstrated, there are material differences in the life cycle GHG intensities of different fuels that might be used in maritime shipping in the GL-SLS region. Biofuels produced from waste biomass, such as corn stover, can provide near zero or even negative life-cycle emissions. But potentially high indirect land-use change (ILUC) emissions can limit the potential decarbonization benefits of crop-based biofuels. There is also a wide variation in the emissions performance of synthetic e-fuels, hydrogen, and electricity depending on the energy source. Nearly all methanol, ammonia, and hydrogen are produced today using fossil fuels and has high life-cycle emissions. When produced using grid electricity instead of renewable electricity, none of the fuels reduce GHG emissions relative to MGO. The use of grid electricity creates fuels with life-cycle intensities worse than MGO, whereas the use of 100% renewable electricity could generate fuels with very low life-cycle GHGs. The future viability of these fuels will thus depend on how they are produced.

Although all fuel and power options assessed have a higher TCO than the fossil fuel baseline, some variation could be seen. Biodiesel and renewable diesel had the best economic performance at less than twice the cost of the MGO baseline. Synthetic fuels are estimated to carry a substantial cost premium at more than three times that of MGO. Dimethyl ether (DME) and methanol derived from cellulosic feedstocks (miscanthus and corn stover) have somewhat better cost performance, with methanol having somewhat better economics than DME. The best economic performance was provided by gray synthetic fuels derived from fossil fuels; note that those fuels also had the worst life-cycle emissions performance.

In addition to detailed modeling of emissions and cost, five additional factors—applicability, technological maturity, compatibility, feedstock availability, and risks—were used to complete this assessment. The results are shown in Figure ES4. Results are shown for the drop-in diesel replacements (top left), ammonia and hydrogen pathways (top right), methanol and liquefied natural gas (LNG) (left and right in the middle row, respectively), DME (bottom left) and direct electrification (bottom right). In each case, a score of 5 represents very good performance while a score of 1 represents very poor performance.

Biodiesel, renewable diesel, and Fischer-Tropsch (FT) diesel showed significant diversity in the results, with both emission performance and feedstock availability varying from very poor to very good depending on feedstock. In contrast, risks, compatibility, and applicability were very good for these drop-in fuels. Cost performance ranged from very poor (e-fuels) to fair (biodiesel and renewable diesel), while technological maturity ranged from fair to good.

For ammonia and hydrogen, neither of which contain carbon but require substantial energy for production, the baseline assessment was sensitive to the input energy source. Emissions performance was either very good or very poor, depending on whether renewable electricity or fossil fuel was used for production. Costs also varied from very poor (renewable electricity) to good (fossil fuel). Ammonia and hydrogen were judged to be scalable; both present some safety concerns but are judged to be technologically mature.

Methanol demonstrated commonality across several indicators, including risks (good), compatibility (fair), and applicability (very good). Both feedstock and technology maturity were fair to very good, while cost and emissions varied widely, generally either very poor or very good depending on the feedstock and process energy used. One fuel, methanol produced from corn stover, provided the best overall performance, receiving a score of fair or better for all indicators and very good for three (emissions, feedstock availability, and applicability).

For alternative LNG, substantial commonality can be seen across fuels. LNG is a technologically mature fuel in international shipping, with few safety concerns and widespread applicability. While not a drop-in fuel, compatibility is fair due to the commercial availability of dual-fuel engines. But the cost of producing alternative LNG is high, and emissions reductions can only be ensured if it is produced using additional renewable power and if it is used in a low-methane-slip engine. A notable exception here is bio-LNG derived from landfill gas, which receives fair or better scores on all metrics but, like all LNG, the highest emissions reductions only occur when it is used in a low-methane-slip engine.

Like other fuels, there is a clear distinction between DME derived from biological feedstocks and DME produced using natural gas. Both DME derived from miscanthus and corn stover rank very good on emissions, applicability, and compatibility, fair on risks and technological maturity, but poor on cost. Fossil-derived DME excels in most categories but is very poor on emissions and only fair on risks.

The final chart in Figure ES4, for electricity (bottom right), illustrates a baseline negative assessment for direct electrification. Battery electric ships powered by either grid electricity or 100% renewable power struggle in terms of cost, applicability, and compatibility. Shifting from grid electricity to renewable electricity reduces the feedstock availability and technological maturity scores somewhat but improves the emissions performance from fair to very good. Note, however, that direct electrification of tugs was more promising, with better leg attainment rates for tugs compared with bulk carriers and chemical tankers, even at relatively low battery charging rates.

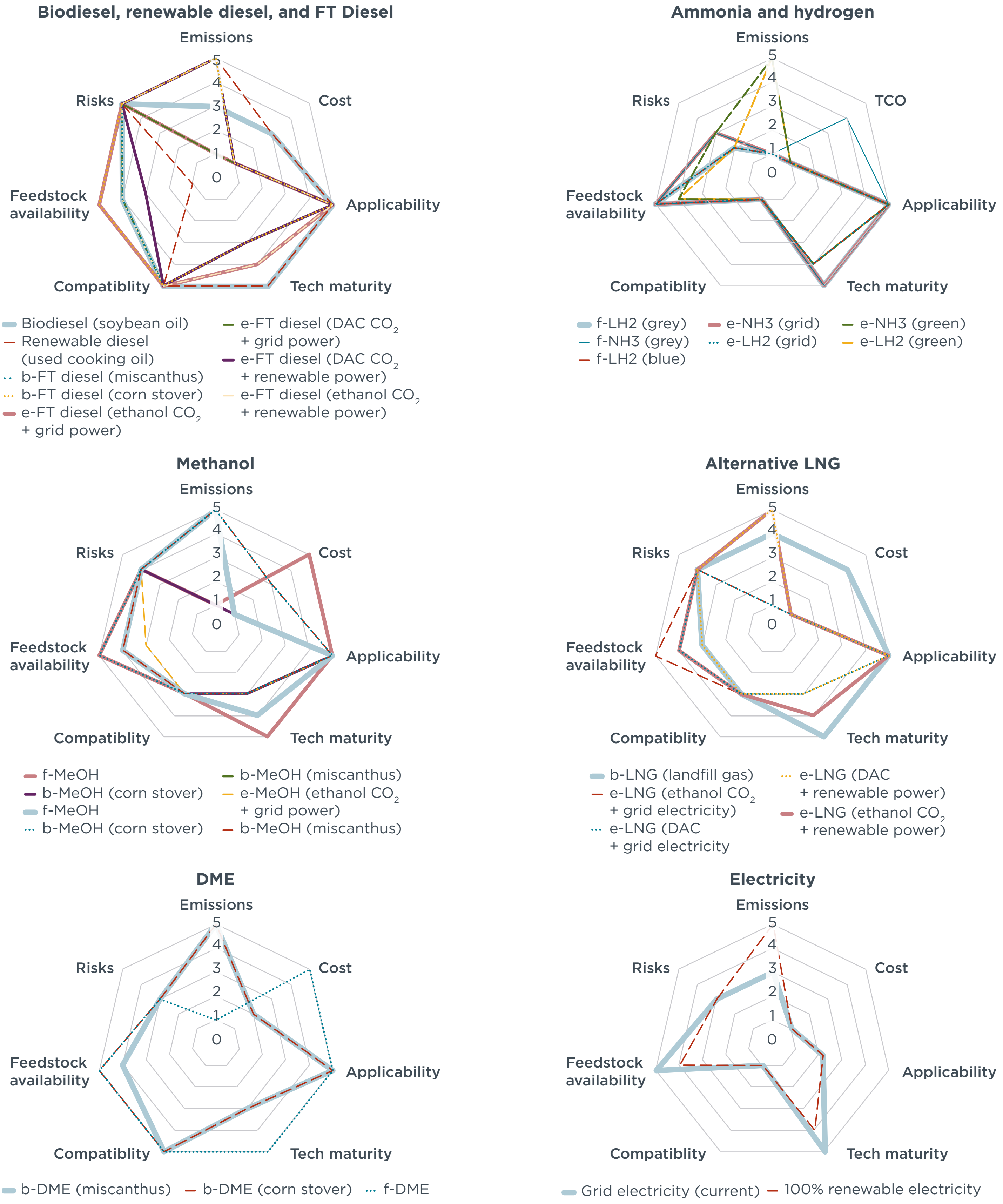


Figure ES4. Fuel and power options, baseline assessment

In summary, when produced from waste biomass or 100% renewable electricity, alternative marine fuels can provide deep reductions in life-cycle GHGs. In contrast, high ILUC emissions lead to limited decarbonization benefits from crop-based biofuels, while fuels generated from grid electricity or fossil energy can have more than double the carbon intensity of baseline fossil fuels. Alternative marine fuels carry a substantial cost premium to the MGO baseline, with cost premiums ranging from less than two-times (biodiesel and renewable diesel) to more than three-times (synthetic fuels). The lower energy density of alternative marine fuels should not be a major barrier to adoption in the GL-SLS, with the exception of battery electric cargo ships (less of a barrier for harbor craft). Most fuels investigated are sufficiently scalable to meet the energy needs of GL-SLS shipping.

Task 4 projected the baseline assessment from Task 3 to 2050. Over that period, scores on two variables—emissions and applicability—remained largely stable. The economics of most alternative fuel and power options improve significantly, although they are expected to remain more costly than fossil fuels. The compatibility of future fuel and power options should improve over time as ships, their fuel systems, and fueling infrastructure evolve to service alternatives to MGO and heavy fuel oil (HFO). The changes in the remaining four variables—applicability, feedstock availability, technological maturity, and risks—are broadly consistent with the conclusion that a variety of fuel and power options will be suitable for GL shipping.

Task 5 found that the regulatory framework for most alternative fuel and power options for shipping remains incomplete. International regulations are under development; flag states, including the United States and Canada, should continue participating in their development to prepare for their adaptation to national circumstances. All fuels investigated should be able to comply with sulfur oxide (SO_x) requirements under the Great Lakes Emission Control Area because they contain little or no sulfur; engines using those fuels should also be able to comply with national and regional standards for other air pollutants. Future regulations are expected to limit well-to-wake (WTW) GHG emissions, with limits for nitrous oxide (N_2O) and methane (CH_4) potentially impacting the uptake of ammonia and LNG, respectively.

Overall, this report concludes that all fuel options analyzed except battery electric cargo ships could be broadly applicable to GL-SLS shipping. Harbor craft, including tugs, are the exception, in that they could be more suitable for direct electrification. There is generally a tradeoff between emissions performance, technological maturity, and cost of alternative marine fuel and power options. Since the fuel pathways that provide the largest life-cycle emission reductions also tend to be the most expensive and least technologically mature, they may require targeted policy support to succeed.

All major fuel pathways identified will be more expensive than fossil fuels for the foreseeable future, although that price premium is expected to fall over time. To reduce those costs further, governments should consider implementing policies such as incentives, carbon pricing, and legally binding mandates. There was a wide variation in the emissions performance of synthetic e-fuels, hydrogen, and electricity depending on the energy source. Measures will be needed to ensure the additionality of renewable energy supply for alternative marine fuels in the GL-SLS region.

In the short term (through 2030), ports and governments can explore expanding OPS as a way to mitigate at-berth emissions for cargo ships and to recharge battery-electric harbor craft, including tugs. In the medium term (through 2040), methanol, ammonia, and liquid hydrogen are all potential fuels for use in GL-SLS shipping, but production capacity and bunkering infrastructure will need to expand to meet this demand. In the long term (through 2050), meeting both domestic and international climate targets will require the complete replacement of fossil fuels in GL-SLS shipping with fuels that have zero WTW GHG emissions.

To track technological progress and to make informed policy decisions, governments and ports should work to collect better primary data on GL-SLS vessels. One possible option is to facilitate port-to-port collaboration to collect data from common voyages and develop a central public database similar to the European Union monitoring, reporting, and verification (EU MRV) system. Additional research is recommended to further refine our understanding of potential fuel and power options for GL-SLS shipping. This includes assessments on regional e-fuel and synthetic fuel production, detailed port surveys regarding the potential for specific bunkering infrastructure (e.g., ammonia and hydrogen), regulations to ensure the safe transport of higher risk fuels, and consideration of how cargo being transported today might support the creation of alternative marine fuels at regional ports.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

A	Amperes
ABS	American Bureau of Shipping
AE	Auxiliary engine
AIS	Automatic Identification System
BC	Black carbon
BDN	Bunker delivery note
CAD	Canadian dollar
CapEx	Capital expenditure
CCS	Carbon capture and storage
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Direct air capture
DCS	Data collection system
DME	Dimethyl ether
dwt	Deadweight tonnage
ECA	Emission control area
EEDI	Energy efficiency design index
EEXI	Energy efficiency existing ship index
EGCS	Exhaust gas cleaning system, a.k.a. Scrubber
EIA	U.S. Energy Information Agency
EIR	Energy intensity ratio
EPA	U.S. Environmental Protection Agency
EU MRV	European Union monitoring, reporting, and verification system
FAEE	Fatty acid ethyl esters
FAME	Fatty acid methyl ester
FC	Fuel cell
FT	Fischer-Tropsch
FTS	Fischer-Tropsch synthesis
GHG	Greenhouse gas
GISIS	Global integrated shipping information system
GL	Great Lakes
GL-SLS	Great Lakes-St. Lawrence Seaway
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GSGP	Conference of Great Lakes St. Lawrence Governors & Premiers
GT	Gas Turbine
gt	Gross tonnage
Gt	Gigatonne (billion tonne)
GWP	Global Warming Potential
H_2O	Water
HB	Haber Bosch
HC	Hydrocarbon
HFO	Heavy Fuel Oil
HPDF	High-pressure fuel injection dual fuel engines
HSD	High speed diesel
HVO	Hydrotreated vegetable oil
Hz	Hertz
IACS	International Association of Classification Societies
ICAO	International Civil Aviation Organization

ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
IGF	International Code of Safety for Ships using gas or other low-flashpoint fuels
IJC	International Joint Commission
ILUC	Indirect land-use change
IMO	International Maritime Organization
kW	Kilowatt
LAR	Leg attainment rate
LCA	Life cycle assessment
LFAR	Leg Fuel consumption Attainment Rate
LFG	Landfill gas biomethane
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
LPDF	Low-pressure fuel injection dual fuel engines
LPG	Liquefied petroleum gas
m	Meter
m^3	Cubic meter
MARAD	Unites States Department of Transportation Maritime Administration
ME	Main engine
MGO	Marine gas oil
MJ	Megajoule
MMSI	Maritime Mobile Service Identity
MS	Methanol synthesis
MSC	Marine Safety Committee
MSD	Medium speed diesel
MSDS	Material safety data sheet
Mt	Million tonne
MTS	Great Lakes St. Lawrence Maritime Transportation System
N_2O	Nitrous oxide
nm	Nautical mile
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen oxides
OpEx	Operating expenditure
OPS	Onshore power supply
PJ	Petajoule
PM	Particulate matter
$PM_{2.5}$	Particulate matter, less than 2.5 micrometers in diameter
PM_{10}	Particulate matter, less than 10 micrometers in diameter
RFP	Request for proposals
RNG	Renewable natural gas
RoRo	Roll-on/roll-off ferry
RSO	Recognized standards organization
SAVE	Systematic Assessment of Vessel Emissions
SCR	Selective catalytic reduction
SFAR	Ship fuel consumption attainment rate
SOLAS	International Convention for the Safety of Life at Sea
SLS	St. Lawrence Seaway
SME	Soy methyl ester
SMR	Steam methane reforming
SO_x	Sulfur oxides

SSC	Ship side cost
SSD	Slow speed diesel
ST	Steam turbine
TCO	Total cost of ownership
T_{max}	Maximum draught
TRL	Technology readiness level
TTW	Tank-to-wake
ULSFO-DM	Ultra-low sulfur fuel oil distillate marine
ULSFO-RM	Ultra-low sulfur fuel oil residual marine
UCO	Used cooking oil
USD	United States dollar
V	Volt
VOC	Volatile organic compound
WTT	Well-to-tank
WTW	Well-to-wake

INTRODUCTION

In May 2022, the United States Department of Transportation Maritime Administration (MARAD) released a request for proposals to investigate future energy options for Great Lakes shipping. The Great Lakes-St. Lawrence Seaway (GL-SLS), a vital North American economic and environmental resource, extends more than 3,700 kilometers (2,300 miles) and is an important commercial waterway (*Overview of the Great Lakes/ St. Lawrence Seaway System*, 2019). There are more than 110 ports within the GL-SLS system, and vessel operators transported over 135.7 million tonnes (Mt) of cargo with a value of US$26.1 billion on the GL-SLS deep-draft inland navigation system in 2022 (Martin Associates, 2023).

Awareness is growing of the impacts of greenhouse gas (GHG) emissions and overall air pollution from shipping. Global maritime shipping emitted about 1 gigatonne (Gt) of carbon dioxide (CO_2) in 2018 (Faber et al., 2020). According to the U.S. Environmental Protection Agency (EPA), ships and boats emitted 50 Mt of CO_2 equivalent in 2021, equal to 2.8% of U.S. transportation GHGs (EPA, 2023). Maritime air pollution, including nitrogen and sulfur oxides (NO_x and SO_x) and fine particulate matter ($PM_{2.5}$), was linked to at least 64,000 premature deaths globally in 2020 (Sofiev et al., 2018).

In 2021, U.S. Climate Envoy John Kerry committed the United States to helping to achieve net zero-emission international shipping by 2050 (U.S. Department of State, 2022). In parallel, the U.S. Bipartisan Infrastructure Law passed in 2021 earmarks $2.25 billion for port infrastructure projects that could support environmental objectives like port electrification and alternative fuel bunkering.

The deep decarbonization of shipping will require switching from fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO) to alternative fuels like hydrogen, methanol, ammonia, and renewable electricity. Research is needed to identify which exact fuel and power options are appropriate for different ship types and sizes, to understand what bunkering (fueling) infrastructure is needed and where, and to estimate the production costs, feedstock supply, and life-cycle GHG emissions of these fuels. Such research could inform pilot projects and direct investments to priority technologies, vessels, and ports, including those on the GL-SLS.

This study investigates the suitability of different alternative fuels and power options in Great Lakes shipping through 2050. The report:

1. Profiles the Great Lakes shipping industry to characterize energy use and air pollution associated with today's ships, engines, and fuels.
2. Profiles Great Lakes ports and bunkering infrastructure to determine access to existing and potential future alternative energy supply.
3. Reviews and evaluates the suitability of alternative fuel and power options for Great Lakes vessels today.
4. Projects the suitability of those alternative fuel and power options out to 2050, taking into account different factors such as technological maturity, cost, and life-cycle emissions.
5. Identifies domestic and international environmental regulations that may influence the uptake of those alternative energy options.

Further information about the project partners can be found in Appendix A.

The report is arranged as follows. The first section outlines the methods used in the analysis. That is followed by a presentation of the high-level results of each task. Next, the report provides a summary of relevant domestic and international environmental regulations that will influence the uptake of these technologies. The conclusion discusses policy implications and provides suggestions for future work. Additional details about methods and results are provided in the report appendices.

METHODS

The following sections outline the methods used to complete this assessment. A detailed profile of Great Lakes fleets, ports, and bunkering infrastructure was developed first. Next a comprehensive baseline (2021) was developed and projected (to 2030-2050) ranking alternative fuel and power options applicable to Great Lakes vessels.

The individual tasks that were completed in this project are summarized in Table 1.

Table 1. Task summaries

Task No.	Task name	Summary
1	**Profiled Great Lakes shipping industry**	Using ICCT's SAVE model, an updated fuel use, emissions, and activity profile for Great Lakes shipping was developed for 2020 and 2021. Calendar year 2021 data provide a snapshot of post-COVID operations and capture recent investments to repower Great Lakes vessels.
2	**Profiled Great Lakes shipping infrastructure**	Assessed the current status of Great Lakes port infrastructure with an emphasis on fueling infrastructure and the availability of shore power and grid connections. This was performed in coordination with state and provincial staff, representatives from the maritime industry, the federal and local governments, environmental NGOs, and other regional stakeholders.
3	**Technology review and evaluation of alternative fuel and power options**	Identified and evaluated alternative fuel and power options appropriate for Great Lakes vessels. All major candidate liquid and cryogenic fuels, fuel cells, battery electric ships, and hybridization were included. An assessment of ship technologies, fuel costs, and climate impacts was synthesized into an estimate of the different technology combinations' cost and emission reductions. This was supplemented by qualitative assessments of compatibility and technology maturity.
4	**Projected alternative fuel and power options**	Projected the suitability of the technologies investigated in Task 3 to the Great Lakes fleet over time. This provided a projection of alternative fuel and power operations applicable to Great Lakes vessels through 2050.
5	**Applicable domestic and international regulations**	Identified applicable domestic and international environmental regulations driving the decarbonization of Great Lakes shipping. Also identified potential regulatory gaps for promising technologies.

PROFILING THE GREAT LAKES SHIPPING INDUSTRY

A detailed profile was assembled of the Great Lakes shipping industry, with methods drawn from the Fourth IMO GHG study (Faber et al., 2020) and the 2019 Great Lakes-St. Lawrence Seaway inventory (Meng & Comer, 2022). An updated fuel use, emissions, and activity profile for Great Lakes shipping for 2021 was developed. Updating the 2019 inventory to calendar year 2021 data provides snapshot of pre- and post-COVID operations and captures recent investments to repower Great Lakes vessels.

Meng and Comer (2022) applied ICCT's Systematic Assessment of Vessel Emissions (SAVE) model to estimate emissions from maritime shipping in 2019 in both the full GL-SLS region and on the Great Lakes only (Olmer et al., 2017). For the profile in this study, ICCT's SAVE model, a bottom-up, activity-based tool for developing high-fidelity emission inventories and activity profiles for maritime shipping, was also applied.[1] Operational data, in the form of satellite and terrestrial Automatic Information

---

[1] SAVE is a state-of-the-art, continuously improving model for estimating fuel use and emissions from ships using satellite and shore-based AIS data. AIS-based models have been used in a variety of environmental assessments, including the Second, Third, and Fourth International Maritime Organization (IMO) greenhouse gas (GHG) studies, as well as ICCT's 2019 Great Lakes-St. Lawrence Seaway (GL-SLS) ship emissions inventory. Although AIS has its limitations, it is the accepted way to generate detailed bottom-up shipping inventories. With help from reviewers, ICCT refined SAVE for this study to capture a larger share of both the GL-SLS fleet and its emissions. Additional refinements have been made during the course of this study to further improve the model and its outputs, including updated maximum vessel speed inputs from IHS Markit that improve the accuracy of fuel consumption and emissions estimates.

Service (AIS) data was provided by exactEarth (now Spire).[2] Ship specification data was provided by IHS Fairplay.[3]

Figure 1 summarizes how the emissions inventory was compiled using SAVE. SAVE used satellite and shore-based automatic identification system (AIS) data from *Spire*, which provided timestamped activity for ships that included their identification number (International Maritime Organization [IMO] number or Maritime Mobile Service Identity [MMSI] number), speed, heading, and draught.

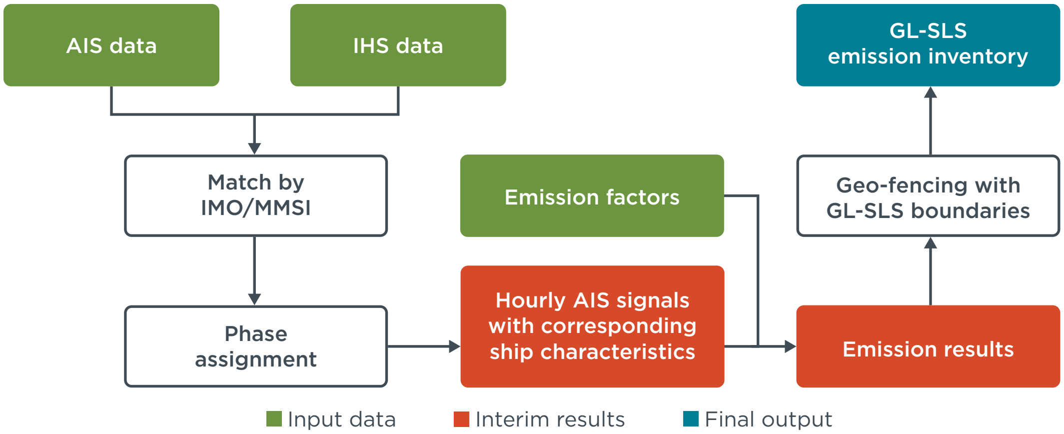


Figure 1. Emissions inventory compilation process of SAVE model

SAVE matched ships in the AIS dataset to a ship characteristics database from IHS Markit based on the ships' identification numbers.[4] The IHS dataset includes information about the ship type, size, engine power, maximum speed, and flag state. Combined with state-of-the-science emission factors by engine type, fuel type, and aftertreatment (e.g., scrubbers), SAVE generated high-fidelity inventories by ship type, size, age, engine, and fuel type. Fuel use and emissions per ship were used as an input into the baseline and projected ranking of fuel and power options, either as an absolute quantity of fossil fuel to be replaced, or via key operational routes isolated using SAVE's voyage identification algorithm (Graser, 2019).

The profile summarizes fuel use by fuel type and GHG and air pollution emissions by the Great Lakes fleet, including information on:

1. Flag state, with special emphasis on U.S.-flag and Canada-flag vessels
    - *gross tonnage* (gt) per flag state
    - *ship type* per flag state
2. Ship type
    - *Ship size* (dwt) and *gross tonnage* (gt) per ship type
    - *Maximum draught* (T_{max}) per ship type

---

[2] https://spire.com/maritime/?utm_campaign=maritime_2022_exactearth_redirect&utm_source=exactearth&utm_medium=website&utm_content=homepage

[3] https://www.shippinginsight.com/participants/ihs-fairplay/

[4] The Great Lakes shipping industry profile includes all ships that we can match using Spire AIS data and the IHS ship registry, without any minimum size threshold; however, the smallest ship able to be matched in the 2019 Great Lakes was 109 gross tonnes (gt).

- *Age* per ship type
- *Propulsion engine type* and *Power* per ship type
- *Exhaust gas aftertreatment* status per ship type (i.e., open/closed-loop scrubbers, selective catalytic reduction, exhaust gas recirculation)
- *Operating phase* per ship type (cruising speed, maneuvering, at anchor, at berth
- *Fuel consumption, type of fuel* and *emissions* per ship type and per operating phase

In the updated inventory, updated methods derived in part from IMO's Fourth GHG Study were applied (Faber et al., 2020). Air pollution emission factors for ships equipped with scrubbers were derived from Comer et al. (2020). Two other changes were made to the inventory. First, a small buffer outside of the official GL-SLS land boundary was introduced to capture missing AIS signals when ships were berthing at ports. This change increased the number of activity hours captured in the GL-SLS by about 70% and fuel consumption by 16%.[5] Second, IHS revised its database to include a more accurate estimate of the maximum speed of ships. This reduced the modeled engine load factors and therefore reduced estimated fuel use and emissions relative to the 2019 study.

Figure 2 shows the areas analyzed in this study. In 2015–2016, the Conference of Great Lakes St. Lawrence Governors & Premiers (GSGP) managed a year-long process to create the Great Lakes St. Lawrence region's Maritime Strategy (GSGP, 2019). Discussions with state and provincial officials, and alongside regional stakeholders resulted in defining the Great Lakes St. Lawrence Maritime Transportation System (MTS) as the area upstream of Les Escoumins, Québec. This location was selected because it is the regulatory extent of the Great Lakes St. Lawrence system. Accordingly, all vessel activity in the GL-SLS region, including vessels flagged to any countries and oceangoing vessels operated in the St. Lawrence Seaway, is described in the main body of this report.[6] The subset of vessels flagged to the Unites States and Canada is described in Appendix B.

---

[5] The additional buffer was added to address evidence that some AIS signals near ports or shore were being incorrectly discarded due to be being onshore. The larger buffer area included those signals which are mainly at-berth and at-anchor. Fuel consumption increased less than activity hours because most of the added hours were at berth, a low fuel consumption condition.

[6] In this study, to allow comparison with previous work all ship traffic upstream of the Saint Lawrence River from a point between Cap-St-Ignace and L'Anse-à-Gilles, Québec, was analyzed, as defined by the Great Lakes Commission. See https://www.arcgis.com/home/item.html?id=d87347457bc84e5c985db9e904b66b10. This excludes ship activity on about 150 km of the Saint Lawrence River from predominately oceangoing vessels.

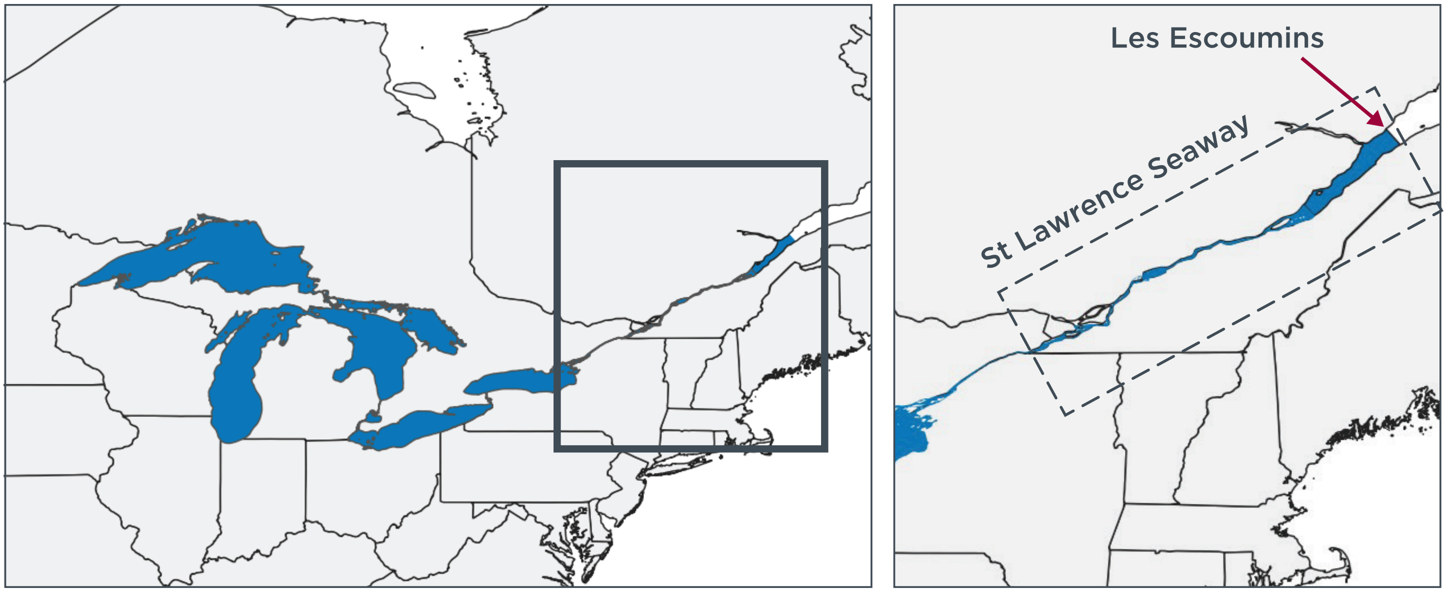


Figure 2. Regulatory definition of the Great Lakes St. Lawrence Maritime Transportation System

PROFILING GREAT LAKES PORT INFRASTRUCTURE AND BUNKERING OPERATIONS

The detailed fleet profile generated in Task 1 was complemented with matching information on Great Lakes ports and their bunkering infrastructure. This work built upon previous GSGP research, including a 2022 survey of shore power availability and 2022 and 2023 biofuel studies developed in partnership with Innovation Maritime (Great Lakes St. Lawrence Governors & Premiers [GSGP], 2022; IMAR & GSGP, 2022, 2023). This work investigated the status of existing port infrastructure with an emphasis on fueling infrastructure and the availability of shore power and grid connections for Great Lakes-St. Lawrence ports. Results were achieved through a comprehensive survey of regional port authorities' fueling infrastructure, fuel suppliers, and fuel tank systems.

GSGP, along with partners at Michigan Technological University and with input from the American Bureau of Shipping (ABS), developed a port survey on existing bunkering for key ports. The survey included questions on fuel type, volume, and means of delivery (e.g., shore-to-ship vs. bunker barge) to gauge port infrastructure readiness for alternative fuels and shore power. When performing the research and analysis, GSGP also coordinated with experts in maritime transportation from state and provincial staff and other regional stakeholders. Notably, the research team coordinated with the American Great Lakes Ports Association (AGLPA), representing many of the largest port authorities in the Great Lakes region, and the Lake Carriers' Association, representing the U.S.-flagged carriers operating on the Great Lakes.

Twelve port authorities were engaged for this survey, consisting of the largest port authority by volume of each of the 10 Great Lakes states and provinces. Additionally, two other port authorities were included, representing the next largest port authorities in the system not already included in the original 10. The research team received responses from 10 of these authorities, representing a response rate of 83%, each contributing responses of varying depths.

Topics in the survey ranged from general port characteristics (number of terminals, tonnage, port area, berths, etc.), fuel availability for vessels and other uses (storage capacity, replenishment method, suppliers, etc.), natural gas infrastructure, electricity infrastructure, and any current or planned alternative fuels or power options. Survey insights on general port characteristics, fuel and bunkering infrastructure, and future projects will inform the selection process for potential alternative power sources.

For the survey, port authorities were asked to respond to a range of questions for the port authority itself and, where possible, the “overall port.” The “overall port” encompasses the port authority, other relevant areas of the port, and privately owned terminals. Given the organizational structure of most of the Great Lakes-St. Lawrence region’s ports, port authorities could not always fully answer questions or provide exhaustive information about property not owned and managed by the port authority itself. It is important to acknowledge that these varying degrees of familiarity between port authorities and private terminals may have influenced the quality of responses given to questions regarding private terminals.

The results of the survey are summarized below; the full port survey can be found in Appendix E. In addition, a port profile by ship type was developed using ICCT’s SAVE model. The ports profile began by categorizing major U.S. and Canadian Great Lakes-St. Lawrence ports based on characteristics including maximum depth, major ship types served, annual cargo throughput, and current shore power availability.

TECHNOLOGY REVIEW AND EVALUATION OF ALTERNATIVE ENERGY OPTIONS

With the detailed fleet, port, and bunkering infrastructure profile obtained, the next step was to identify and evaluate alternative fuel and power options appropriate for Great Lakes vessels.

The transition to zero-emission shipping will be governed by both fuel and power options. Liquid hydrogen, which contains no carbon, has attracted interest as a potential marine fuel. However, due to its low energy density (up to eight times less dense, counting storage), challenges in maintaining cryogenic temperatures, and the energy intensity required for liquefaction, liquid hydrogen may be mostly suitable for shorter range ships. Ammonia, which is widely used in agriculture and industrial applications, also contains no carbon, is more easily stored than hydrogen, and can be produced from renewable sources. But ammonia is toxic, carries significant spillage and eutrophication risks, and requires aftertreatment to control combustion byproducts. Methanol, which is the simplest form of liquid hydrocarbon, burns cleanly and can be used in engines today, but contains carbon. Thus, methanol can only be produced with near-zero emissions from waste products or captured carbon, for example from power plant exhaust or direct air capture.

Table 2 summarizes the fuel and power options covered in this exercise. These included biomethane (renewable natural gas), liquid biofuels (biodiesel, renewable diesel, both hydrotreated vegetable oil [HVO] and FT diesel), bio-methanol, bio-dimethyl ether, bio-oils, bio-crude), methanol (non-biogenic pathway), and zero-carbon fuels (hydrogen, ammonia) synthesized from non-biogenic pathways. Alternative fossil fuels, including natural gas, liquefied petroleum gas (LPG), and ethane, were not analyzed. Bio-ethanol was also excluded from the analysis due to strong competition with other transport modes, notably blending with gasoline used in road transport. Onboard carbon capture and storage (CCS), which is an aftertreatment technology rather than a fuel or power option, is likewise beyond the scope of this report.

Table 2. Fuel pathways analyzed

Fuel		Feedstock structure		Fuel conversion/production	
Group	**Type**	**Nature**	**Type**	**Process**	**Energy source used in the process**[a]
Diesel	**Biodiesel (soybean methyl ester)**	Biogenic source	Soybean oil	Transesterification	Fossil energy (natural gas and methanol)
	Renewable diesel (UCO-based)	Biogenic source	Used cooking oil (UCO)	Hydrotreatment	Fossil energy (natural gas, grid electricity,[b] and methanol)
Synthetic diesel	**b-FT diesel**	Biogenic source	Miscanthus	Gasification and synthesis gas to Fischer-Tropsch synthesis (FTS)	n/a[c]
	b-FT diesel	Biogenic source	Corn stover	Gasification and synthesis gas to FTS	n/a[c]
	e-FT diesel	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and synthesis gas to FTS	Grid electricity[b]
	e-FT diesel	Nature source and captured carbon	H_2O and direct air capture (DAC)	Electrolysis and synthesis gas to FTS	Grid electricity[b]
	e-FT diesel	Nature source and captured carbon	H_2O and DAC	Electrolysis and synthesis gas to FTS	Renewable electricity (solar/wind)
	e-FT diesel	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and synthesis gas to FTS	Renewable electricity (solar/wind)
Hydrogen (liquefied)	**f-LH_2 (gray)**	Fossil source and nature source	Natural gas and H_2O (steam)	Steam methane reforming (SMR) and liquefaction	Grid electricity[b]
	f-LH_2 (blue)	Fossil source and nature source	Natural gas and H_2O (steam)	SMR with carbon capture and storage (CCS) and liquefaction	Grid electricity[b]
	f-LH_2 (grid)	Nature source	H_2O	Electrolysis and liquefaction	Grid electricity[b]
	e-LH_2 (green)	Nature source	H_2O	Electrolysis and liquefaction	Renewable electricity (solar/wind)
Ammonia	**f-NH_3 (gray)**	Fossil source	Natural gas and H_2O (steam) and air	SMR[d] and synthesis gas to Haber-Bosch (HB) ammonia synthesis	Grid electricity[b]
	e-NH_3	Nature source	H_2O and air	Electrolysis (H_2) and air separation (N_2) and synthesis gas to HB	Grid electricity[b]
	e-NH_3 (green)	Nature source	H_2O and air	Electrolysis (H_2) and air separation (N_2) and synthesis gas to HB	Renewable electricity (solar/wind)
Methanol	**f-MeOH**	Fossil source and nature source	Natural gas and H_2O (steam)	SMR and synthesis gas to methanol synthesis (catalytic process)	Grid electricity[b]
	e-MeOH	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and synthesis gas to methanol synthesis (catalytic process)	Grid electricity[b]
	e-MeOH	Nature source and captured carbon	H_2O and DAC	Electrolysis and synthesis gas to methanol synthesis (catalytic process)	Grid electricity[b]
	e-MeOH	Nature source and captured carbon	H_2O and DAC	Electrolysis and synthesis gas to methanol synthesis (catalytic process)	Renewable electricity (solar/wind)
	e-MeOH	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and synthesis gas to methanol synthesis (catalytic process)	Renewable electricity (solar/wind)
	b-MeOH	Biogenic source	Miscanthus	Gasification and synthesis gas to catalytic methanol synthesis (MS)	n/a[c]
	b-MeOH	Biogenic source	Corn stover	Gasification and synthesis gas to MS	n/a[c]
Dimethyl ether	**b-DME**	Biogenic source	Miscanthus	Gasification and synthesis gas to dimethyl ether (DME) synthesis (catalytic process)	n/a[c]
	b-DME	Biogenic source	Corn stover	Gasification and synthesis gas to DME synthesis (catalytic process)	n/a[c]
	f-DME	Fossil source and nature source	Natural gas and H_2O (steam)	Gasification synthesis gas to DME synthesis (catalytic process)	Grid electricity[b]
Natural gas (liquefied)	**b-LNG**	Biogenic source	Landfill gas	Anaerobic digestion and upgrade/ purification of biogas and liquefaction	Grid electricity[b]
	e-LNG	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and methanation liquefaction	Grid electricity[b]
	e-LNG	Nature source and captured carbon	H_2O and DAC	Electrolysis and methanation and liquefaction	Grid electricity[b]
	e-LNG	Nature source and captured carbon	H_2O and DAC	Electrolysis and methanation and liquefaction	Renewable electricity (solar/wind)
	e-LNG	Nature source and captured carbon	H_2O and CO_2 captured from ethanol plant	Electrolysis and methanation and liquefaction	Renewable electricity (solar/wind)
Electricity	**Grid electricity**				Grid electricity[b]
	100% renewable electricity				Renewable electricity

[a] This refers to external energy inputs needed to power the fuel conversion process, besides the energy provided from the feedstocks themselves when applicable.

[b] See Table 6 for grid mix assumptions.

[c] The fuel conversion process is powered by the feedstock and no external energy is needed, as explained in https://dergipark.org.tr/en/pub/ijot/issue/5774/76796

[d] N_2 is produced during secondary reforming.

These fuel combinations were supplemented by a matrix of power options including the internal combustion engine (ICE), diesel electric, hybrid electric (series and parallel), fuel cell, and battery electric. ICEs are workhorses of maritime shipping, but when powered by fossil fuels, or even some biofuels or e-fuels, they generate GHGs and air pollution. Slow speed diesel engines propel most deep-sea ships, while high speed diesel engines power smaller ships, such as port tugs and fishing vessels, and are valued in hybrid applications with very large electrical auxiliary loads like cruise ships.

ICEs can be powered by methanol today, and there are ambitions to develop and trial slow speed diesel engines powered by ammonia by 2024 (Global Maritime Forum, 2021). One alternative to an ICE is the fuel cell. Fuel cell technology combines hydrogen from fuel with oxygen from the air and converts the chemical energy to electrical energy that can be used for propulsion. Hydrogen fuel cells release only water, no climate or air pollutants, and are "modular" in how they can be operated, but are significantly more expensive than a traditional ICE for the same amount of power (Elkafas, Rivarolo, Gadducci, Magistri, & Massardo, 2022). Battery electric ships are of interest due to their high efficiencies, zero tank-to-wake emissions, and abundant feedstocks. However, they may be limited in shipping applications due to the current limits on the energy density of batteries and lack of charging infrastructure.

Criteria for baseline assessment

For this study, an integrated, multifactor approach was developed to evaluate alternative fuel and power options for Great Lakes shipping. The Great Lakes ships, their energy use, and associated operational conditions (e.g., voyage length) in 2021 served as the baseline for that assessment. The results of the baseline fleet assessment and inventory were used as an input into the analysis, namely existing fuel consumption by engine type, ship type, and ship size. Representative duty cycles, as defined by voyage length, power demand, and available bunkering times, for key ship types were also incorporated into applicability analysis.

Seven variables, three quantitative and four qualitative, were used in the baseline assessment (Table 3).

1. Life-cycle emissions: The life-cycle greenhouse gas reductions (tonnes CO_2e) per megajoule (MJ) of fuel displaced, taking into account primary energy use, ILUC and displacement effects, and shipside energy improvements.
2. Total cost of ownership (TCO): The combined cost of vessel capital expenditures (CapEx, including engines, fuel storage, fuel systems, etc.) and operational expenditures (OpEx, including fuel and maintenance) of the baseline and alternative fuel and powered vessels.
3. Applicability: The share of fuel consumption by ship type and ship size that low energy density fuels like hydrogen and electricity can displace (Mao et al., 2020, 2021).
4. Compatibility: The ease at which a given fuel and power combination can be used with existing ships/engines, taking into account combustion compatibility and current fuel supply, fuel storage, overall safety, and bunkering systems.
5. Feedstock availability: The share of current GL-SLS fuel use that could be expected to be met with current and expected future supply.

6. Risks: Shipside safety concerns that need to be addressed for a given fuel/power options, including personnel hazards, vessel hazards, environmental hazards, applicable regulations, and training requirements.
7. Technological maturity: How close a given fuel and power option is to market and ready to be deployed.

For the three quantitative metrics, the full quantitative results are presented in the appropriate metric (e.g., g CO2e/MJ or 2021 U.S. dollars) in the main body of this report and its appendices. For the qualitative assessment, a scale of 1 (worst) to 5 (best) was developed for each fuel and power option. Quantitative results were also converted to a five point scale to allow for comparison of variables on a common basis.

Table 3. Criteria included in the feasibility assessment

Type	Criteria	Metric	Primary level of analysis	Secondary level of analysis	Assessment approach
Quantitative	**Life-cycle emissions**	g CO_2e/MJ[a]	Fuel pathway	Power option (energy intensity ratio)	GREET model
	Total cost of ownership	$/dwt-nm	Power options, ship type and size	Fuel pathway	Total Cost of Ownership Calculator from the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
	Applicability	% of 2021 fuel consumption	Fuel and power options by ship type		SAVE model
Qualitative	**Compatibility**	1 to 5 scale	Fuel pathway		Secondary research Expert judgment
	Feedstock availability		Fuel pathway		
	Risks		Fuel pathway	Power options	
	Technological maturity		Fuel and power options		

[a] Energy intensity ration adjusted.

Once the baseline alternative fuel and power assessment had been completed, work turned to projecting the suitability of those technologies to the Great Lakes fleet over time. The projection was completed for the short (2030), medium (2040), and long terms (2050). The assessment of ship technologies, fuel costs, and fuel climate impacts was synthesized into a dynamic estimate of these different technology combinations' TCO and cost of GHG emissions reductions. This approach quantified the relative merits of different engine and fuel technologies on a consistent cost and sustainability basis.

Further details on the methods used for each variable in the assessment are provided below.

Life-cycle assessment methods

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model of Wang et al. (2021) was used to estimate the life-cycle, well-to-wake GHG emissions of fuels,[7] which include emissions from feedstock extraction and distribution, fuel conversion and distribution, and fuel combustion. The ILUC emissions from cultivation of the biomass were also included for biofuels. As

---

[7] Detailed information on GREET at https://www.energy.gov/eere/greet.

indicated in the fuel pathway table, the three types of biomass evaluated in this study are soybean, miscanthus, and corn stover. Their ILUC emissions and data sources are shown in Table 4.

Table 4. Indirect land-use change (ILUC) emissions of soybean, miscanthus, and corn stover

Feedstock	ILUC emissions (gCO_2e/MJ)	Data source
Soybean	33.6	U.S. Environmental Protection Agency (2016)
Miscanthus	-32.9	ICAO, 2021
Corn stover	-11.2	U.S. Environmental Protection Agency (2016)

To get the carbon dioxide equivalent emissions of methane and nitrous oxide, the global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC, 2021) Sixth Assessment Report, which are shown in Table 5, are used.

Table 5. Global warming potentials used in this study, at 100-year and 20-year time horizons

Pollutant	GWP-100 year	GWP-20 year
CO_2	1	1
CH_4	29.8	82.5
N_2O	273	273

Although default values in GREET were used for a majority of the data inputs, two main updates were made for the purpose of this study. For one, the average grid mix from Ontario and U.S. states neighboring the Great Lakes for grid electricity carbon intensity in GREET (Independent Electricity System Operator, 2023) was considered. Future grid mix projections for the U.S. states were based on the *Annual Energy Outlook 2022* (U.S. Energy Information Administration [EIA], 2022).[8] Given the uncertainties in future policies, the reference case is used as provided by EIA. However, it is likely that future grid mix can be cleaner; for example, the White House has a target of 100% carbon pollution-free electricity by 2035 and a net-zero emissions economy by 2050 (The White House, 2021). A constant grid mix for Ontario is assumed due to lack of data. Table 6 shows the average grid mix and grid carbon intensity in 2021, 2030, 2040, and 2050 assumed in this study.

Table 6. Great Lakes average grid mix and carbon intensity using GWP-100

Energy source	2021	2030	2040	2050
Residual oil	1.2%	1.1%	1.1%	1.1%
Natural gas	29.5%	17.7%	17.4%	18.7%
Coal	16.3%	12.3%	10.8%	10.2%
Nuclear power	33.0%	32.0%	32.0%	31.9%
Biomass	0.7%	0.3%	0.3%	0.3%
Other renewables (solar, wind, hydro)	19.4%	36.6%	38.4%	37.9%
Grid carbon intensity (gCO_2e/kWh)	355	246	228	228

---

[8] Including MISW, PJMC, MISE, PJMW, PJME, and NYUP regions defined by EIA.

Besides the updated grid mix in GREET, another change made is the carbon capture rate for blue hydrogen. While GREET assumes a 96% carbon capture rate at a steam methane reforming (SMR) hydrogen plant, past studies found that the general industrial practice is only around 55%, which is the value used in this study (Zhou et al., 2021).

Table 6 also denotes the grid mix assumptions that were used in the assessment of fuels that required electricity inputs. Noting that the grid mix assumptions in this study is an arithmetic average of the neighboring states, specific states can have lower or higher GHG emissions from electricity-based fuels than results shown in this study. For example, Ontario has a high share of renewables but a very low share of fossil fuels in its grid mix, as shown in Table 7 (Independent Electricity System Operator, 2023). This means that fuels produced using significant amounts of grid electricity in provinces like Ontario will have significantly lower GHG intensity than average.

Table 7. Average electricity mix in Great Lakes neighboring states and Ontario

2021 Grid mix	Great Lakes neighboring states average	Ontario
Residual oil	1.2%	4.3%
Natural gas	29.5%	4.3%
Coal	16.3%	0.0%
Nuclear power	33.0%	58.0%
Biomass	0.7%	1.0%
Other renewables (solar, wind, hydro)	19.4%	34.4%

Total cost of ownership

The TCO analysis is based on the Total Cost of Ownership Calculator from the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2021), which provides ship-side cost input and fuel cost from a variety of literatures and reports. The ship-side cost includes the cost of the engine, battery or fuel cell system, fuel tank, fuel supply system, and annual maintenance. The ship hull cost was excluded here because it will not change with the fuel/power option.[9] Incremental engine costs were assumed to be zero for the base (MGO) fuel and for fully compatible drop-in fuels, consistent with the economics of repowering an existing ship.[10]

The fuel cost includes the fuel production cost and refueling or charging cost, which can reflect the additional cost from refueling or charging infrastructure. The focus is on the TCO increment of the alternative fuel and power ships from the conventional fossil fuel ships in this research to reflect the economic challenge of fuel or power switching. The annual TCO increment is normalized by the total nautical miles (nm) traveled in a given year and tonnage (dwt) to enable comparisons across ship types and sizes.

The steps for TCO analysis are briefly described below:

---

[9] This focus on the incremental costs of the fuel and power option approximates a repowering of an existing ship. The Jones Act, which requires that ships transporting cargo between two U.S. ports be U.S.-built and owned and crewed by U.S. citizens, has been found to significantly increase the cost of newbuild ships construction in U.S. shipyards (Congressional Research Service, 2019). According to the U.S. Coast Guard, U.S. built propulsion machinery is not required on Jones Act vessels, and importation of foreign engines is common. Accordingly, we do not apply a markup for the incremental costs of alternative power options for Jones Act vessels in this study.

[10] An alternative approach, to model the TCO of all fuel pathways as a newbuild ship that includes the cost for a diesel engine, would increase the costs of the baseline MGO and drop-in replacements by 15% relative to fuels like methanol, ammonia, and hydrogen that require dedicated propulsion technologies.

1. Identify representative ship samples for the TCO analysis, with three main ship types and two ship sizes.
2. Estimate the TCO increment for each representative ship sample under each fuel and power option in 2021.
3. Project the TCO increment results of 2030, 2040, and 2050 using revised operational expenses (fuel cost) and capital expenditures (from alternative engines) over time.

Sample ship selection

The three main ship types are based on the fuel consumption results from SAVE model. Ships flagged to the United States and Canada were selected to ensure the cost results reflect the condition of the GL-SLS region. Because the TCO increment may vary for relatively smaller and bigger ships, two ships were selected for each main ship type with different gt/dwt. Table 8 shows the parameters of selected sample ships. The operating hours, trip length, and fuel consumption are estimated by the SAVE model, and the other parameters are from ICCT's bespoke IHS database.[11] The battery sizes and fuel cell volumes are estimated based on methods summarized in the next section summarizing the applicability analysis used.

Table 8. Parameters of selected ship samples for TCO analysis, 2021

Ship type	Size	Flag state	Operating hours	Trip length (km/yr)	dwt	gt
Bulk carrier	small	Canada	8,759	80,547	29,261	20,101
	large	United States	8,759	102,186	75,187	34,620
Chemical tanker	small	Canada	8,590	38,160	11,267	8,009
	large	Canada	8,733	44,811	16,775	11,290
Tug	small	United States	8,326	15,321	not available	231
	large	Canada	8,759	47,136	359	450

Ship type	Size	Fuel tank size (m^3)	Main engine power (kW)	Auxiliary engine power (kW)	Fuel consumption (tonne/yr)
Bulk carrier	small	1,499	6,637	500	2,659
	large	2,582	14,166	1,100	7,562
Chemical tanker	small	600	4,500	580	2,633
	large	624	4,800	580	2,650
Tug	small	132	1,618	210	320
	large	205	2,942	210	740

---

[11] The operating hours shown in Table 8 represent all hours for which AIS signals from a given ship were recorded. That includes both hours when a ship was actively operating (cruising or maneuvering) and when it was at berth or at anchor. A value close to 8760 (365 days times 24 hours per day) indicates that a ship's AIS signal was active throughout the year.

Ship side cost

The ship side cost (SSC) includes a variety of components and is estimated using Equation 1. Ship lifetime is assumed to be 25 years.

Equation 1

$$SSC = (\text{main engine cost} + \text{auxiliary engine cost} + \text{fuel cell/battery cost} + \text{fuel tank cost} + \text{fuel supply system cost} + \text{maintenance cost})/(DWT \times \text{trip length} \times \text{lifetime})$$

Several technologies that may be applicable to GL shipping, including wind-assisted propulsion,[12] were not directly modeled in the TCO analysis. Wind-assisted propulsion is a zero-emission propulsion technology that would reduce the energy needed from other sources, such as fuels or electrical energy in batteries. This would save on fuel and energy costs and reduce the fuel component of the total cost of ownership (Comer et al. 2022). On the other hand, there are capital costs of installing wind-assisted propulsion technologies, in addition to ongoing operating and maintenance costs that would need to be considered. The payback period for wind-assisted propulsion depends on the type and quantity of technologies that are used, operating and maintenance costs, the energy source the ship uses. However, given the costs of alternative fuels are expected to usually be higher than MGO for the foreseeable future, wind-assisted propulsion could prove to be an attractive investment for future years.

Note that not all ship types will be able to take advantage of wind-assisted propulsion. For the GL-SLS, self-unloading bulk carriers may have challenges in applying wind-assisted technologies if they interfere with unloading operations. However, new designs are being developed that allow for modular, retractable, or otherwise moveable equipment. Lastly, ship owners that directly pay for fuel costs would have a greater incentive to invest in wind-assisted propulsion because they would have a clear economic benefit of doing so. When charterers pay for the fuel, the split incentive problem can limit shipowner investment in wind-assisted propulsion and other technologies that save on fuel and improve efficiency.

Fuel cost

The fuel cost includes fuel production cost and refueling cost. These two parts of the fuel cost are all based on the fuel/power demand. For each ship sample, the real-world fuel consumptions from the SAVE model output were retrieved and converted to the fuel/power demand for each alternative fuel/power option using Equation 2:

Equation 2

$$\text{power demand}_j = \sum \text{fuel consumption}_i \times D_{fuel} \times EIR_{i,j}$$

Where:

power demand_j	power demand under the alternative fuel/power option *j*, in MJ
$\text{fuel consumption}_i$	fuel consumption baseline under operating phase *i*, in kg
D_{fuel}	energy density of the baseline fuel (40 MJ/kg for HFO; 42.7 MJ/kg for MGO; 50 MJ/kg for LNG)
$EIR_{i,j}$	energy intensity ratio of alternative fuel/power option *j* under operating phase *i*

---

[12] ICCT's method for modeling the emissions reduction potential of wind-assisted propulsion requires overlaying wind speed and direction data with AIS data on an hourly basis for each individual ship over the course of the year. The process is time- and cost-intensive for a fleet of ships and was therefore not able to be performed within the scope of this study. The limitations of using wind-assisted propulsion are explained in Comer et al. (2022) and the references therein.

The method used to estimate energy intensity ratios is explained in following section.

To estimate fuel costs for the TCO analysis, the wholesale fuel production costs and the refueling cost associated with delivery of fuels to the maritime sector were estimated separately to derive a combined fuel cost. Multiple sources were drawn upon for this study because of the wide array of fuels included, all of which have very different costs and levels of commercial readiness. For soy fatty acid methyl ester (FAME) biodiesel, costs were based on a five-year average of commercial data on wholesale soy prices collected by Neste (Neste, 2023).

Production costs of second-generation pathways without existing facilities or market data are estimated based on a literature review of techno-economic assessments, wherein the production costs of these pathways are modeled. For drop-in pathways using used cooking oil, corn stover, or miscanthus, levelized production cost estimates for middle distillates developed by Pavlenko et al. (Pavlenko et al., 2019) were used, adjusted for inflation and converted to USD. For cellulosic DME and methanol produced from corn stover and miscanthus, collected fuel production costs from previous techno-economic studies, adjusted for inflation, were used (Amaral et al., 2019; Carvalho et al., 2017; Clausen et al., 2010; Fornell et al., 2013; Haro et al., 2013; International Renewable Energy Agency, 2021; Parbowo et al., 2019; Zhang et al., 2021).

Because the cost trends of bio-based fuels are uncertain and vary based on fluctuating feedstock costs and shifts in capital costs, constant real costs were assumed for all future years. For methanol, ammonia, and hydrogen produced from natural gas, production costs were assumed to increase in the future as the natural gas price increases (Baldino et al., 2020; International Energy Agency, 2023; U.S. Energy Information Administration, 2022).

For fuels produced from electrolysis, including hydrogen, e-ammonia, e-diesel, e-methanol, and e-methane, a discounted cash flow model was used to estimate production costs. Detailed methodology and data assumptions can be found in previous ICCT studies (Comer et al., 2022; Zhou & Searle, 2022; Zhou, Searle & Pavlenko, 2022). The production cost of these fuels is assumed to decrease in the future as electrolysis technology matures. For consistency with the life-cycle GHG analysis, electricity is considered to be sourced from either 100% renewable feedstocks or from the grid average for each electricity-based fuel pathway. In this study an additional $1/kg hydrogen cost has been included for meeting additionality requirements for renewable hydrogen and its derivatives (Ricks et al., 2023). For pathways using grid average electricity, the current retail electricity price was collected for large-scale industrial users in Great Lakes neighboring states. Although it is assumed that renewable electricity prices will decrease in the future, future grid electricity prices were not projected and therefore assumed to remain constant over time.

In estimating the refueling costs, infrastructure, storage, pumps, etc., for the incumbent liquid fuels of MGO (diesel), LNG, methanol and ammonia are assumed to be made up of distribution and bunkering infrastructure costs, fuel storage costs, and the applicable liquefaction costs. The distribution and bunkering operations consist of transporting the fuels from the fuel storage location to the required port, from where it is supplied to vessel tanks through two different bunkering procedures: truck-to-ship and ship-to-ship (Nelissen et al., 2020; TNO, 2020). For this study, we do not consider bunkering via a shore-to-ship approach, which tends to be less flexible and could be hindered by complex port design. Shore-to-ship approaches also lead to comparatively slower bunkering operations becuase they require more efforts from ships to reach the fuel supply terminal (Andersson & Salazar, 2015; IRENA, 2019; Nelissen et al., 2020).

The distribution and bunkering costs in this study have been derived from TNO (2020), where the listed costs in €/GJ were adjusted accordingly to $/MJ based on appropriate unit and currency conversion standards. Further, as TNO only considered a ship-to-ship procedure for vessel fuel bunkering, the required distribution and bunkering costs for truck-to-ship approach were obtained from the estimates for fuels for road transport transported by tanker trucks. Based on the fact that ships could be refueled by two possible bunkering methods of ship-to-ship and truck-to-ship, an "average" of distribution and bunkering cost values listed for the two respective approaches was used.

The required fuel storage (i.e., fuel station) costs were also derived from TNO (2020), which were only applied to the obtained bunkering and distribution costs for truck-to-ship method. For the ship-to-ship approach, there is no additional need for fuel storage because the barge vessels in operation are already equipped with the required fuel storage facilities. For the use of conventional diesel fuels like MGO, only ship-to-ship bunkering and distribution costs were considered, because it is currently the most common bunkering procedure used across the ports for such fuel types (International Renewable Energy Agency [IRENA], 2019). Due to a lack of data, fueling costs for DME were assumed to be identical to that of LNG.

For LNG, there will be additional liquefaction costs that will emanate from its handling. Considering the fact that methane has a boiling point of -162 °C, it will require an energy intensive process to cool it to -162 °C to become liquid. The required liquefaction costs for LNG were obtained from Nelissen et al. (2020), where the mentioned costs in U.S. dollars per million Btus were adjusted to $/MJ based on the appropriate unit conversion standards. There were no applicable liquefaction costs for diesel (MGO) and methanol, as both the fuels are already in liquid state due to their higher boiling points (Andersson & Salazar, 2015). Although the use of ammonia is expected to incur some liquefaction costs due to its lower boiling point (-33°C), it can become liquid at relative low pressure and under relatively mild conditions compared to that of LNG (Nelissen et al., 2020). Hence, the energy required for the liquefaction of ammonia is expected to be relatively low (less than 0.1% by mass of ammonia) and associated liquefaction costs can be considered negligible (Nelissen et al., 2020).

The developed infrastructure for diesel fuel oil (MGO), LNG, ammonia, and methanol can further be reused for the respective carbon-neutral fuels (e-fuels) without any or negligible modifications (DNV, 2022); hence, similar fueling costs as that of incumbent liquid fuels have been considered for their respective e-fuel variant.

For both electricity and hydrogen, the cost of fueling is estimated in addition to the underlying cost of energy to assess the total cost of supplying each of these fuels to the maritime sector. For both pathways, the cost of constructing fueling and charging infrastructure, and calculating the levelized cost of that infrastructure on a per-kWh and per-kg basis, is estimated and includes amortizing those costs over the lifetime of the fueling infrastructure. The capacity of infrastructure deployed to supply the maritime sector is based on the profile of the Great Lakes shipping industry developed above, combined with the applicability analysis described below, which estimated the potential charging or bunkering demand from potential feasible ships for key ports.

To estimate the cost of infrastructure deployment for electricity pathways, this report uses the approach used by Basma et al. (2023), which estimates the combined cost of chargers and the necessary grid upgrades to deliver additional power demand. Whereas that analysis was focused on high-capacity fueling infrastructure for the heavy-duty road sector, this analysis adapts the methodology based on the fueling needs of the maritime fleet. With the applicability analysis, the portion of the fleet that could feasibly be converted to battery-electric ships was estimated. Based on the activity data of these ships, estimates are that a port will require five 1-megawatt (MW) direct current fast chargers to meet expected electricity demand, necessitating the deployment of both additional charging infrastructure and upgrades to the electricity grid. Infrastructure costs are first levelized to factor in their lifetime of use and maintenance, then amortized based on the estimated annual electricity demand at a port of approximately 9.1 GWh, to estimate the average per-kWh cost of infrastructure.

The cost assumptions for installing charging infrastructure and upgrading the grid are provided in Table 9. Charging infrastructure is assumed to have a 10-year lifetime, whereas utility grid upgrades are assumed to have a 40-year lifetime. For both investments, an 8% rate of return is assumed to estimate their levelized cost. There is a wide range of possible grid upgrade costs due to uncertainty over whether a new substation transformer is necessary, leading to a range of approximately $2 million to $4 million in upfront costs.

Table 9. Overview of capital costs for charging infrastructure and grid updates for maritime electricity charging

Component	Purchase cost	Data source
1 MW charger	$300,000	Bennett et al. (2022)
Charger installation cost	$195,000	Bennett et al. (2022)
Substation transformer addition	$0-$2,000,000	Basma et al. (2023)
Other equipment (feeders, tie, transfer switches)	$1,100,000	Basma et al. (2023)
Distribution feeder to the closest point on the grid (Point of interconnection)	$900,000	Basma et al. (2023)
Connection to the closest point on the grid to a utility meter	$100,000	Basma et al. (2023)
Utility meter and meter base	$15,000	Basma et al. (2023)
Primary transformer (converting 13kV to 480V)	$300,000	Basma et al. (2023)

For high-capacity uses such as fast charging, infrastructure costs are typically combined with demand charges levied by the utility service, which are typically charged on a per-kW basis for the peak electricity demand over a typical billing period. To estimate the contribution of demand charges, published rate schedules for electricity utilities that serve two key ports in the Great Lakes are referenced. For the Port of Duluth, estimates incorporate a demand charge for large light and power service, which includes a fixed $1,200 monthly charge for the first 100 kW of demand in conjunction with a $100/kW charge up to 10,000 kW (Minnesota Power, 2022). For the Port of Montréal, large power service for a 5 MW facility would cost approximately $13.80 CAD ($10.10 USD) per kW of demand (Hydro Québec, 2021). Together, these demand charges would add up to more than $600,000 annually, but on a per-kWh basis would be only $0.068 per kWh. Table 10 contains the combined costs for electricity fueling, on a per-kWh basis.

Table 10. Estimated infrastructure and demand charges for electricity

Cost component	Cost	Levelized cost per kWh
Infrastructure cost	$2,415,000 to $4,415,000	$0.022–$0.04
Demand charge	$10.10/kW to $10.30/kW	$0.066–$0.069

For hydrogen fueling, the incremental cost of infrastructure and liquefaction is calculated and added to the underlying hydrogen production costs previously estimated. Based on the port activity assessment, an average annual utilization is assumed of approximately 4300 tonnes of hydrogen, necessitating a station capacity of approximately 30 tonnes per day. Table 11 provides an overview of the primary cost inputs used to calculate the fueling cost of hydrogen, as well as the combined fueling cost.

Table 11. Overview of capital, liquefaction and total fueling costs for hydrogen

Year	Capital cost (individual fueling station)	Total capital costs	Lifetime infrastructure costs ($/kg)	Liquefaction electricity cost ($/kg)	Total fueling cost ($/kg)
2023	$7,700,000	$115,500,000	$3.30	$0.52	$3.82
2030	$6,330,000	$94,950,000	$2.71	$0.51	$3.22
2040	$6,020,000	$90,300,000	$2.58	$0.51	$3.08
2050	$5,720,000	$85,800,000	$2.45	$0.48	$2.93

A capital cost of $7.7 million for an individual, 2-tonne fueling station derived from European Commission figures was extrapolated, declining to about $5.7 million in 2050 (European Commission, 2021). That total capital cost was then scaled to the capacity necessary for the entire port, estimating the annual payment for the infrastructure, based on an assumption of operation and maintenance costs equal to 4% of capital costs, a lifetime of 15 years, and an 8% discount rate (European Commission, 2021). The annual cost was then divided by the quantity of hydrogen supplied at the port to estimate the per-kg infrastructure cost. Capital costs were supplemented with the energy cost associated with hydrogen liquefaction. Based on a liquefaction energy demand of 7 kWh per kg of hydrogen estimated within GREET, that was then multiplied by the cost of grid-average electricity for 2023 and each subsequent year studied (U.S. Energy Information Administration, 2023a). Table 11 illustrates the capital costs and liquefaction costs for hydrogen from 2023 to 2050.

Estimated fuel production costs, refueling costs, and total at-the-pump costs for the 2021 baseline assessment are shown in Table 12. Cost projections for 2030, 2040, and 2050 are provided in Appendix D.

Table 12. Fuel cost assumptions for 2021 baseline

Fuel pathway	Cost ($/MJ)		
	Fuel production	Fueling cost[a]	At-the-pump cost
Biodiesel (soybean oil)	$0.0331	$0.0002	$0.0332
Renewable diesel (used cooking oil)	$0.0314	$0.0002	$0.0315
FT diesel (miscanthus)	$0.0630	$0.0002	$0.0632
FT diesel (corn stover)	$0.0662	$0.0002	$0.0663
DME (miscanthus)	$0.0336	$0.0069	$0.0405
DME (corn stover)	$0.0336	$0.0069	$0.0405
DME (natural gas)	$0.0095	$0.0069	$0.0164
Methanol (miscanthus)	$0.0328	$0.0019	$0.0347
Methanol (corn stover)	$0.0328	$0.0019	$0.0347
Methanol (natural gas)	$0.0087	$0.0019	$0.0106
Liquid hydrogen (natural gas)	$0.0180	$0.0318	$0.0498
Liquid hydrogen (natural gas and CCS)	$0.0246	$0.0318	$0.0564
Liquid hydrogen (grid electricity)	$0.0342	$0.0318	$0.0660
Liquid hydrogen (renewable electricity)	$0.0393	$0.0318	$0.0711
Ammonia (natural gas)	$0.0213	$0.0032	$0.0245
Ammonia (grid electricity)	$0.0583	$0.0032	$0.0616
Ammonia (renewable electricity)	$0.0646	$0.0032	$0.0679
E-diesel (renewable electricity and point CO_2)	$0.0887	$0.0002	$0.0889
E-diesel (renewable electricity and DAC)	$0.1147	$0.0002	$0.1148
E-diesel (grid electricity and point CO_2)	$0.0792	$0.0002	$0.0793
E-diesel (grid electricity and DAC)	$0.1042	$0.0002	$0.1044
E-methanol (renewable electricity and point CO_2)	$0.0659	$0.0019	$0.0678
E-methanol (renewable electricity and DAC)	$0.0910	$0.0019	$0.0929
E-methanol (grid electricity and point CO_2)	$0.0592	$0.0019	$0.0611
E-methanol (grid electricity and DAC)	$0.0833	$0.0019	$0.0852
Biomethane (LFG)	$0.0167	$0.0069	$0.0236
E-methane (renewable electricity and point CO_2)	$0.0624	$0.0069	$0.0694
E-methane (renewable electricity and DAC)	$0.0779	$0.0069	$0.0848
E-methane (grid electricity and point CO_2)	$0.0558	$0.0069	$0.0627
E-methane (grid electricity and DAC)	$0.0707	$0.0069	$0.0776
2021 Grid electricity	$0.0099	$0.0371	$0.0470
100% renewable electricity	$0.0207	$0.0371	$0.0578

[a] Includes liquefaction costs.

Estimation of energy intensity ratios

Energy intensity ratios (EIRs) were estimated as an input into both the TCO and the emissions estimate highlighted above. EIRs are a dimensionless measure of how much energy a power option consumes relative to the baseline ICE in each of the four phases of a ship's operation—at berth, at anchor, during maneuvers, and during cruise. An EIR less than one means greater energy efficiency, whereas an EIR greater than one means worse efficiency. EIR values are expected to vary by phase. For example, a hybrid engine may have an EIR of 0.85 at berth but 1.05 at cruise due to extra energy conversion losses.

The EIRs were estimated by ABS using expert judgment using the following method:[13]

1. **Determine the key parameters and variables:** Common ones include different power options, the power option to be considered as base point,[14] ship types, and the ships' mode of operations.[15]
2. **Collect data:** Power demand by ship type at each mode of operation, thermal efficiencies of each power option, and relevant system losses.[16]
3. **Determine the system efficiency:** Efficiency of each system is calculated using the thermal efficiency of the power source by reducing the relevant system losses up to the propeller or other propulsion systems, as applicable.

Thermal efficiency of the power sources and system efficiency losses are considered based on expert judgment, but also refer to Glosten (2016).

Other references used on the analysis include Faber et al. (2020); U.S. Office of Energy Efficiency and Renewable Energy (2023); the ICCT (2011); Olmer et al. (2017); Mrzljak et al. (2017); Elkafas and Shouman (2022); and the American Bureau of Shipping (2023a, 2023b).

Comparison: The EIR provided a measure of how efficiently each marine power system converts energy into propulsion power and allows for the comparison of different marine power options. The conventional slow-speed direct diesel propulsion system is selected as our base point and its EIR is considered to be 1. Then, this ratio was compared with the calculated energy intensity ratios of each power option in each mode of ship operation.

Propulsion technologies are expected to impact different technologies in different ways. For example, hybrid diesel engines are expected to provide energy efficiency gains through auxiliary engines that dominate fuel use at berth and at anchor, but energy losses at cruise compared to direct drive engines. Therefore, a breakout of the power demand by key ship types was used to derive the EIRs. Those assumptions are shown in Table 13.

---

[13] For information regarding ABS qualifications, please see Appendix A.

[14] A conventional slow-speed direct diesel propulsion system is selected (EIR=1 for each mode of operation).

[15] Mode of operations cover at berth, at anchor, at maneuvering, and at cruise with different loads of the power sources (see Table 14).

[16] Losses vary depending on the technology and power option, but common ones include the shafting system losses, electric generation and electric motor losses, transmission system losses, battery charge, and battery system losses.

Table 13. Annual power demand by ship used as an input to deliver energy intensity ratios

Ship type	Main engine annual power demand by phase per ship type (kWh)			
	At berth	At anchor	At maneuver	At cruise
Bulk carrier	0	0	40,124	2,353,203
Tug	0	0	207,951	1,694,018
Chemical tanker	0	0	11,371	406,673
Container	0	0	16,790	1,114,672
Oil tanker	0	0	16,056	520,999
Ship type	**Auxiliary annual power demand by phase per ship type (kWh)**			
	At berth	**At anchor**	**At maneuver**	**At cruise**
Bulk carrier	93,755	159,274	59,659	188,812
Tug	235,006	187,723	55,135	73,604
Chemical tanker	138,553	136,055	13,450	92,048
Container	18,133	655,692	21,152	214,974
Oil tanker	170,283	171,350	15,210	85,247
Ship type	**Boiler annual power demand by phase per ship type (kWh)**			
	At berth	**At anchor**	**At maneuver**	**At cruise**
Bulk carrier	76,469	76,584	9,488	0
Tug	0	0	0	0
Chemical tanker	402,954	70,767	4,740	0
Container	11,947	254,065	4,051	0
Oil tanker	496,631	101,820	6,037	18,623

The estimated EIRs by power option and phase of operation are summarized in Table 14. As shown, of the power options investigated, only fuel cells and battery electric propulsion options are expected to reduce fuel use relative to direct drive ICEs during GL-SLS operations. Diesel electric and hybrid electric (series and parallel) are both expected to impose fuel efficiency penalties (EIRs greater than 1), in particular due to inefficiencies while at cruise.

Table 14. EIR comparisons for power options by phase of operation

Power option	EIR comparison table			
	Berth	Anchor	Maneuver	Cruise
Internal combustion engine (direct drive)	1.00	1.00	1.00	1.00
Diesel electric	0.86	0.87	1.13	1.39
Hybrid electric (series)	1.07	1.03	1.34	1.47
Hybrid electrical/mechanical (parallel)	0.94	0.94	1.03	1.11
Fuel cell	0.53	0.62	0.70	0.98
Battery electric	0.34	0.40	0.46	0.65

Prior to analyzing the full matrix of possible fuel pathways and power options, a scoping study was conducted to compare the TCO of small and large bulk carriers burning MGO using a conventional slow speed diesel engine, a diesel electric engine, and the two hybrid electric configurations. The modeling was conducted assuming a newbuild engine to provide a fair comparison. Incremental CapEx expenses for the diesel electric were assumed to be zero (Jeong et al., 2018) and +17% for hybrid electric engines (Ammar & Seddiek, 2021; Jeong et al., 2018). Other costs, including tank costs, supply systems costs, and maintenance costs, were held constant across all engines. Fuel costs were calculated using the methods outlined above, modified by the EIRs summarized in Table 14.

Relative to the base ICE, operating a bulk carrier on hybrid engines was estimated to increase TCO from 9% (parallel hybrid) to 42% (series hybrid) when using MGO. Those engines would have even worse economics if operated on alternative fuels, which will cost considerably more than MGO. Accordingly, diesel electric and hybrid electric propulsions options were excluded from further analysis. Instead, to simplify the analysis matrix each fuel pathway identified was matched with a key propulsion technology and analyzed as a package.

The full TCO results for 2021 and all analysis years are summarized elsewhere in this report (Table 29 and Table 57, respectively). Table 15 indicates how the five-point qualitative scale for the TCO analysis was developed.

Table 15. Five-point scale for assessing total cost of ownership

TCO metric	Designation	TCO relative to MGO baseline
1	Very poor	300%+
2	Poor	250% to 299%
3	Fair	200% to 249%
4	Good	150% to 199%
5	Very good	<150%

Applicability analysis methods

As outlined above, a high-resolution spatiotemporal ship emission inventory for 2021 was generated for the GL-SLS using the SAVE model based on AIS data from Spire. The traffic, activity, and timely location information from AIS data identified each port-to-port voyage of each ship. Based on the SAVE model output and AIS data, the applicability of fuel and power options for GL-SLS shipping was assessed, starting with battery-electric and liquid hydrogen (LH_2) fuel cell power options. This was done via the following steps:

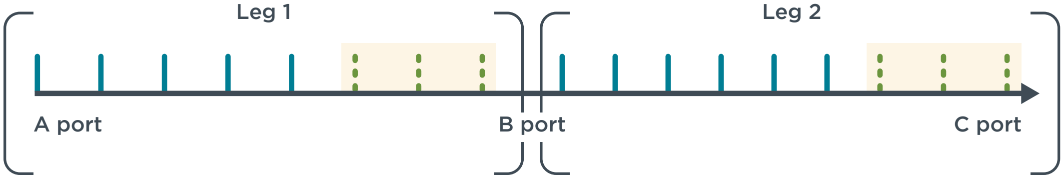
1. Identified the voyages inside the GL-SLS region of each ship included in the inventory.
2. Estimated the baseline energy demand for these voyages when they use fossil fuels.
3. Modeled the volume and mass of battery or LH_2 needed for covering those voyages, compared with the available volume and mass carrying capacity of each ship.
4. Assessed the attainment rates of ships as the percentage of voyages that could be met by battery-electric or LH_2 fuel cell options without reducing any cargo space with or adding charging/refueling stops.

Voyage identification

The voyage identification is based on the AIS data, which can reflect the location and operating phases of ships over the whole year. Each ship serves one or multiple routes, and on each route, a vessel traverses a certain number of voyages within a given time.

Each voyage is made up of one or multiple legs. Figure 3 visually describes the terms leg, voyage, and route.

- Leg: Any continuous vessel movement between two full-stop points. Full stop means the vessel shuts down its propulsion engine, and a point is usually a terminal at a port.
- Voyage: A journey between origin and destination. A voyage may consist of one or more legs.
- Route: The pathway between an origin–destination pair. Vessels sail repeated voyages along routes.



→ One voyage from A port to C port via B port, A-C pair is a route. A-B and B-C are legs

— AIS record identified at cruising/maneuvering

- - - AIS record identified at berth/anchor, and a series of continuous such signals represent the ship is berthing in a port

Figure 3. Definition of routes, voyages, and legs, and the identification procedure

Year 2021 AIS data for the GL-SLS were fed into the voyage identification algorithm summarized in previous ICCT research (Mao et al., 2020). The algorithm is based on the MovingPandas, a Python package designed for extracting trajectories from movement data (Graser, 2019). In the algorithm, AIS signals of each ship were ordered chronologically, and the operating phase of each signal was examined. The signals were split when the algorithm identified a series of continuous berthing or anchoring signals, and these split segments of AIS signals make up the legs. Figure 4 shows several sample legs identified from AIS of a typical GL-SLS region bulk carrier, *American Mariner*, with U.S. flag and operating inside the GL-SLS region. The leg identification algorithm can distinguish legs between different cities and ports, which is essential for further estimation.

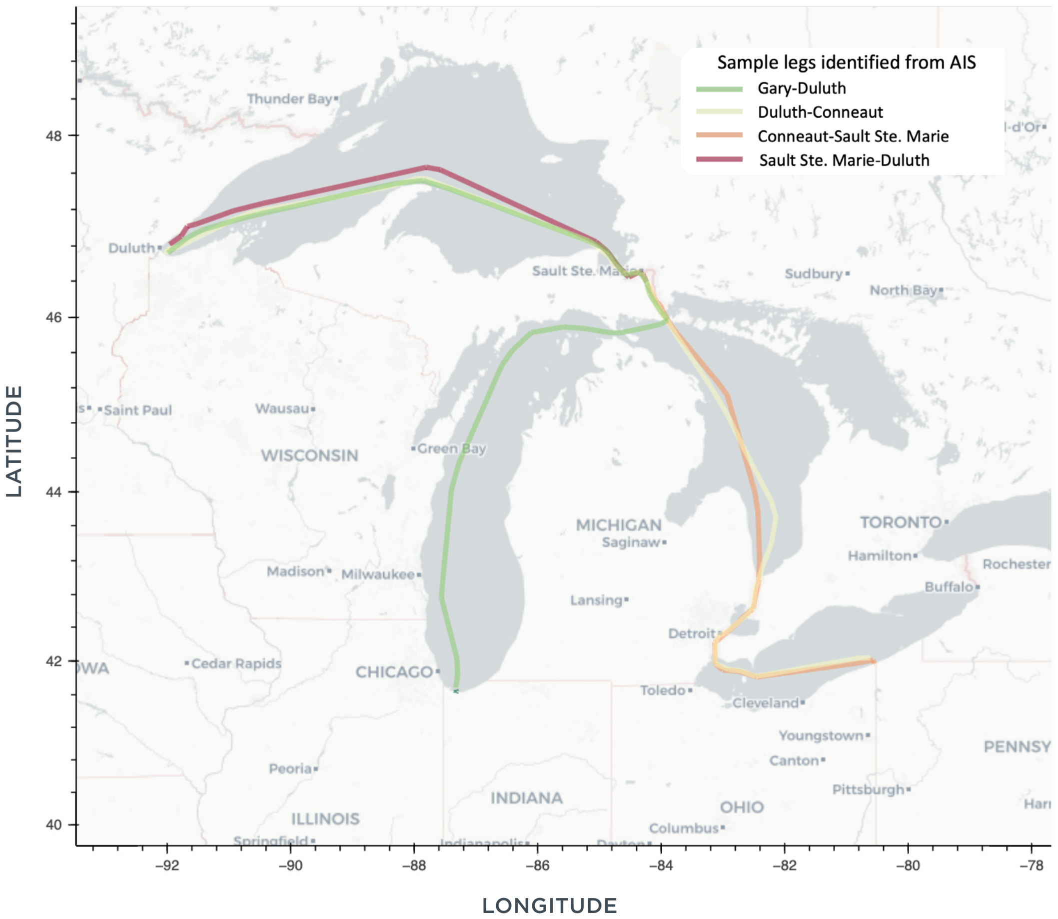


Figure 4. Identified leg samples of bulk carrier *American Mariner* in 2021.

Baseline energy demand

The energy demand of each leg was derived from SAVE, with both energy output demand from the engine and the energy input demand based on the fuel consumption.

The feasibility assessment method for hydrogen fuel cells was mostly aligned with previous ICCT research (Mao et al., 2020). In that work, it was found that the limitation of deploying LH_2 fuel cells is the lower volumetric energy density of LH_2. In this study the volume demand to cover legs using LH_2 $V_{LH_2\ need_i}$, calculated by Equation 3, was compared to available volume space on the ship $V_{LH_2\ capacity_i}$, calculated by Equation 4, to decide the feasibility.

Equation 3

$$V_{LH_2\ need_i} = \sum_{j=1}^{n} \frac{F_{required_{ij}} \times D_{fuel} \times EIR_j}{D_{LH_2} \times \eta_{kWh_{toMJ}}} \times fuel\ margin$$

where:

$V_{LH_2\ need_i}$	LH_2 fuel system volume needed to cover the energy demand of leg *i*, in m^3
$F_{required_{ij}}$	Fuel consumption of fossil fuel of AIS signal *j* in leg *i*, in kg
D_{fuel}	Energy density of the baseline fuel, 40 MJ/kg for HFO, 42.7 MJ/kg for MGO, 50 MJ/kg for LNG.
EIR_j	Energy intensity ratio of AIS signal *j*, estimated by American Bureau of Shipping

D_{LH_2}	Volumetric density of LH_2 fuel system, 1332 kWh/m^3
$\eta_{kWh_{toMJ}}$	Ratio from kWh to MJ, 3.6
fuel margin	Ships usually carry more fuel than needed onboard, and a assume fuel margin of 1.2 was assumed

Equation 4

$$V_{LH_2\ capacity_i} = 5 \times V_{e_i} - 2 \times V_{FC_i} + V_{f_i}$$

where:

$V_{LH_2\ capacity_i}$	available volume space on the ship *i*, in m^3
V_{e_i}	volume of existing engine on the ship *i*, in m^3
V_{FC_i}	volume of fuel cell system needed to provide same output power as existing engine, in m^3
V_{f_i}	volume of existing fuel tank on the ship *i*, in m^3

The volume of the existing fuel tank (V_{f_i}) is available in the ship registry information dataset from IHS. The engine volume (V_{e_i}) and fuel cell system volume (V_{FC_i}) are estimated using same method as used in Minnehan & Pratt (2017), based on statistical relationships between engine size and power.

The fuel system volume needed ($V_{LH_2\ need_i}$) and volume available ($V_{LH_2\ capacity_i}$) of each leg of each ship were compared, and if $V_{LH_2\ capacity_i}$ was greater, the ship has enough volume to store the required LH_2, and that leg was considered attained. If all legs of a ship were attained, hydrogen was assumed to be applicable for that ship.

Previous research on battery-electric ferries found that the mass of battery system was the limiting factor of deploying battery-electric options (Mao et al., 2021). In this case, the available battery energy (AE_{max}) converted from available mass (AE_{max}) as the battery size of the ship was used. Because the berthing time for ships was limited by its schedule, there would also be cases when the battery could not be fully charged while berthing at a port. Therefore, the charging power and charging time were taken into consideration, with an iteratively calculation of each ship from its first leg to the last leg. The feasibility is estimated using Equations 5 and 6:

Equation 5

$$BE_{demand_i} = \sum_{j=1}^{n} \frac{F_{required_{ij}} \times D_{fuel} \times EIR_j}{\delta_{discharge} \times \eta_{kWh_{toMJ}}}$$

where:

BE_{demand_i}	battery energy demand to cover leg *i*, in kWh
$\delta_{discharge}$	depth of discharge, 0.75

The other parameters are same as Equation 3

Equation 6

$$AE_i = AE_{i-1} - BE_{demand_{i-1}} + CP \times t$$

where:

AE_i available battery energy on the ship when starts leg i, in kWh

CP charging power, in kW/hour

t charging time, in hours

The battery capacity required for voyage was estimated using the same method as in Mao et al (2021). It was assumed that a ship would start with a fully charged battery with energy as AE_{max}, which would be iteratively discharged and charged during each leg, with the calculation above. A leg was considered attained when the AE_i was greater than BE_{demand_i}, and when all of legs of a ship were attained, the ship would be considered attained. For charging power, it was assumed that 1 MW was a commercially available choice in the baseline (2021) assessment. We also ran the analysis assuming 3 MW and 5 MW recharging infrastructure were available.

To allow comparison with other variables, the leg fuel attainment rate (see below) was converted to a five-point scale, as shown in Table 16.

Table 16. Five-point scale for assessing applicability

Capability rank	Designation	Leg fuel attainment ratio (LFAR)
1	Very poor	<10%
2	Poor	10% to 30%
3	Fair	30% to 50%
4	Good	50% to 70%
5	Very good	>70%

A fuel weighted average was used to assess the overall applicability of the fuel across bulk carriers, tugs, and chemical tankers.[17] In the baseline assessment, a charging rate of 3 MW was used to develop the five-point scale for electric ships; for 2030, a base charging rate of 5 MW was used. For 2040 and 2050, the unlimited charging (battery swapping) charging rate was used to assign the five-point scale. Ultimately, the applicability of electric ships ranged from 1 to 4 depending on the scenario year. Liquid hydrogen, one of the least energy dense fuels available, scored a five when used with a fuel cell. All other fuels with a higher volumetric energy density than hydrogen were assigned a score of 5.

Compatibility methods

The American Bureau of Shipping (ABS) developed five major metrics to assess the compatibility of each fuel pathway: combustion compatibility and flammability limits, fuel supply systems, fuel storage systems, safety systems, and bunkering systems. Each fuel was rated from 1 to 5 rating for each category, and a total compatibility

---

[17] These ship types accounted for 75% of fuel use in the GL-SLS region in 2019. Ship types found in the GL-SLS region but predominately operated outside of it were excluded from the applicability analysis. For example, container ships were excluded because only 26 legs could be identified from container ships fully within GL-SLS region, and this sample size was not big enough for any feasibility analysis. Oil tankers were also excluded, as only 4 oil tankers could be found that mainly operated within the GL-SLS region (with criteria of over 50% of fuel consumption occurred within GL-SLS), which is a relatively small sample set to discuss anything about the feasibility.

rating was established as a simple average of the five categorical ratings. The 1-5 ratings were based on the scale shown in Table 17. The baseline for comparison was a traditional MGO internal combustion engine with industry standard fuel supply, fuel storage, safety, and bunkering systems. The review did not account for compatibility advantages that are associated with a specific vessel type; for example, using LNG on an LNG tanker would result in a higher compatibility rating than if it were being used on a container ship with a diesel engine.

Table 17. Criteria for developing the compatibility metric

Value	Description
1	Total modification/redesign needed
2	Major modification/redesign needed
3	Moderate modification/redesign needed
4	Minor modification/redesign needed
5	No modification/redesign needed

ABS relied on its technical and safety expertise, along with the ABS alternative fuel whitepapers,[18] to support the assignment of a compatibility rating for each fuel.

The team also leveraged public data on alternative fuels to further support the analysis, which included information from Makoś et al (2019) and Foretich et al (2021)

For the compatibility projections, the team considered advantages associated with expansion in the availability of alternative fuels and technologies, hence the increase in compatibility values over time.

Feedstock availability methods

Each marine alternative fuel was scored based on theoretical resource potential from an assessment of the underlying availability of regional resources to produce that fuel. Each fuel pathway was rated on a scale of 1 to 5, with a score of 5 signifying sufficient abundance to meet 100% of the Great Lakes region's maritime shipping needs, and 1 signifying that the pathway could supply less than 20% of the sector's fuel demand. This assessment was strictly based on an evaluation of the theoretical abundance of fuel feedstocks, without considering cost constraints or technological readiness, which were evaluated separately. For each pathway, the assessment of feedstock availability was modified based on the existence of competing uses for that material. If a feedstock is already used in transport, it received a -1 to its rating to account for cross-sectoral competition. For example, soy biodiesel is already used in significant volumes but is largely utilized in the road sector.

To quantify availability relative to the fuel demand for the region's maritime sector, the 2021 fuel demand for the Great Lakes fleet was first assessed using the SAVE model. This is shown in Table 18, and converted from tonnes of each fuel type into raw energy needs in PJ, based on fuel properties collected from the GREET model (M. Wang et al., 2021). The 2021 energy demand totaled approximately 17.9 PJ. Of that amount,

---

[18] The ABS Sustainability Whitepapers used for the review included the following: Ammonia as Marine Fuel (American Bureau of Shipping, 2020b), Biofuels as Marine Fuel (American Bureau of Shipping, 2021b), Hydrogen as Marine Fuel (American Bureau of Shipping, 2021c), LNG as Marine Fuel (American Bureau of Shipping, 2022), and Methanol as Marine Fuel (American Bureau of Shipping, 2021d).

14,103 tonnes of biodiesel was used in 2021 (Yousef El Bagoury, CSL Group, personal communication, December 2022).

Table 18. Total Great Lakes fuel demand, 2021

Unit	Distillate	Residual	LNG	Biodiesel	Total
Tonnes	336,222	69,097	6,207	14,103	425,629
Petajoules	14.4	2.7	0.3	0.5	17.9

For fossil fuel-derived pathways, specifically hydrogen and methanol made from fossil natural gas, it was assumed that the supply of feedstock was sufficiently elastic to support this sector's needs, and therefore receive a score of 5. Existing natural gas production in the United States in 2022 was approximately 35.8 trillion cubic feet, corresponding to approximately 38,000 PJ of energy, dwarfing the scale of energy demand for the Great Lakes fleet (U.S. Energy Information Administration, 2022). Electricity-based pathways, including e-fuels and electrolysis-derived hydrogen, were treated similarly to fossil fuels as fully elastic. Therefore, these pathways all received a score of 5.

Though renewable electricity is available in principle in quantities that greatly exceed the needs of the Great Lakes fleet, a penalty was incorporated to account for the difficulty of supplying the electricity to the ships and competition with other sectors using that energy, which necessitates safeguards such as additionality and temporal matching of renewable electricity to its end users (Malins, 2019). This reduced the scores of pathways using dedicated renewable energy by 1. A penalty of 1 was also assigned to pathways using DAC, such that an e-fuel pathway using both dedicated, renewable electricity and DAC would have a score of 3, whereas a pathway using grid-average electricity would have a score of 5.

In the assessment of biomass-based pathways, the availability of feedstocks was evaluated based on regional feedstock availability. For soybean oil, the study drew upon USDA state-level data to determine the existing production of soy oil in the Great Lakes region (U.S. Energy Information Administration, 2023b). The total annual soy production in this region is approximately 1.9 billion bushels, or approximately 52 million tonnes (USDA National Agricultural Statistics Service, 2022). Based on a soy biodiesel yield of approximately 1.5 gallons to bushel in GREET, this equates to approximately 368 PJ of potential, greatly exceeding the Great Lakes Fleet energy demand and thus qualifying for a score of 5. However, this feedstock is already largely utilized for food consumption, road sector biofuel, and exports. Although it is possible to increase soy production to meet additional demand or reduce exports of soybeans to crush additional soy domestically, this distorts international vegetable oil markets and can generate unintended indirect emissions (O'Malley et al., 2022). Due to the difficulties associated with increasing soy biodiesel production and the degree of competition with the road sector, its rating is therefore decreased by 1.

For used cooking oil availability, regional level data is lacking so the assessment was based on nationwide potential through 2030 and adjust based on the population of the Great Lakes region (Zhou et al., 2020). Based on current trends, approximately 246 million gallons of biodiesel-equivalent would be available nationwide from used cooking oil in 2030; this was adjusted to 67 million gallons based on the Great Lakes region share of population. This amounts to approximately 8 PJ of supply. Because cooking oil is already widely used due to high incentives in West Coast low-carbon fuel standards, with any additional collection likely to be used for compliance there, the score was adjusted down by 1 to a score of 1/5 on availability (O'Malley et al., 2022).

For landfill gas, data were used from EPA's landfill methane outreach program (LMOP) project database, which provides the location and flow rate of landfill methane projects and potential new candidate projects in the United States (U.S. EPA, 2016a). Narrowing down projects just to those that provide renewable natural gas (RNG) injected into pipelines for use in transportation in the Great Lakes region produced an estimate of approximately 32 PJ of availability based on 2022 production, substantially more than the Great Lakes fleet energy usage. This potential could be even higher if existing projects that convert landfill gas to electricity were to divert from electricity production to upgrade their gas for grid injection, as well as if candidate landfills were to install landfill gas collection equipment.

An estimate of the potential availability of corn stover and miscanthus-derived biofuel feedstocks was based on an availability assessment in the Department of Energy's Billion Ton Study (Langholtz et al., 2016). To estimate supply, the availability based on the study's mid-range scenario of $60/ton roadside feedstock costs was narrowed down and the analysis was constrained to the Great Lakes region. After narrowing the geographic scope, an estimate of the availability of approximately 51 million tonnes of corn stover and 6 million tonnes of miscanthus was arrived at. Based on fuel conversion yields from GREET, there was an estimated availability of approximately 440 PJ and 53 PJ of middle distillates from each feedstock, respectively (M. Wang et al., 2022). As both values are significantly higher than 2021 Great Lakes fleet energy demand and neither feedstock has existing competing uses, both of these pathways have an availability score of 5.

Risk assessment methods

Each of the 31 fuel variants plus the primary power options within the study were assessed. ABS estimated risks taking into account five dimensions: personnel hazards, vessel hazards, environmental hazards, applicable regulations, and training requirements, as adopted from Alternative Low Emission Fuel for the Maritime Industry (Shipowners P&I Club et al., 2022). The results for fuel pathways generated a scale of 1 to 4, with fuels demonstrating the highest risk (e.g., ammonia toxicity and hydrogen flammability) scoring a 1 and fuels with lowest risk (drop-in diesel replacements) scoring a 4. Power risks were then overlaid with fuel risks by adding either a 1 (lower risk, incumbent propulsion technology like an ICE) or 0 (higher risk, emerging propulsion technology like fuel cell) to create a final 1 to 5 score (Table 19). This approach was adopted based on the understanding that fuel type, not propulsion type, is likely to drive risk profiles.

Table 19. Numerical scale for fuel and power option risks

Rating	Numerical Value
Very Poor	1
Poor	2
Moderate	3
Good	4
Very Good	5

This average was then extrapolated to 2030, 2040 and 2050 based on best available data from industry outlooks and projections, in addition to the qualitative judgment of experienced engineers. Though the projections, particularly long-term projections, cannot be perfectly accurate, ABS made every effort to mitigate assumptions. That said, breakthrough innovations might come in at any time and change the face of the industry. Hence, radical shifts in technology could not be incorporated or estimated.

Technological maturity methods

Technology readiness levels (TRL) are measurement benchmarks used to assess the maturity level of a particular technology. Usually there are nine TRLs with TRL 1 being the lowest and TRL 9 being the highest. However, for consistency of rating and ranking in this project, TRL levels were converted to technological maturity levels on a scale of 1–5 for fuel and power options (Table 20).

Table 20. Numerical scale for technological maturity

Technological maturity level	Typical technology readiness level	Explanation
1	TRL 1–2	Basic technology research and research to prove feasibility
2	TRL 3–4	Technology development
3	TRL 5–6	Technology demonstration
4	TRL 7–8	Technology/system testing for operations
5	TRL 9	Proven technology

ABS conducted a detailed analysis wherein specific projects were identified to understand technological maturity. Joint development projects, joint industry projects, new construction projects, modification projects, and new technology qualification projects from all parts of the world were included within the analysis (Basso et al., 2022; ETIP Bioenergy, n.d.-a, n.d.-b; Foretich et al., 2021; FuelCellsWorks, 2022; IEA, 2023; IMO, 2023b; International Chamber of Shipping, 2021; Law et al., 2021; Lloyd's Register, 2020; Recharge News, 2022; Verbeek et al., 2020).

Based on the projects available, these TRL levels were identified and translated to technological maturity levels on a 1–5 scale for both power options and fuels. ABS used qualitative analysis based on available research to identify the TRLs where no projects were available or identified during the analysis. The final numbers were then verified by another experienced engineer to normalize any anomalies present within the analysis and rating. Individual technological maturity scales for fuel and power options and a simple average were calculated for relevant fuel and power option combinations.

These were then extrapolated to 2030, 2040 and 2050 based on best available data from industry outlooks and projections and the qualitative judgment of experienced engineers. Although the projections, particularly long-term projections, cannot be perfectly accurate, every effort was made to mitigate assumptions. As in the case of the risk assessment ratings, radical shifts in technology could not be incorporated or estimated and, as such, is a limitation of the projections.

RESULTS

PROFILING THE GREAT LAKES SHIPPING INDUSTRY

KEY FINDINGS

- Bulk carriers were the most important ship type in the GL-SLS in 2021, contributing more than half of tonnage, fuel use, CO_2 emitted, and air pollution. Service tugs were the second most important ship type, accounting for about 30% of activity hours and one-eighth of fuel use and CO_2 emissions.
- Fuel use in GL-SLS shipping stood at 510,000 tonnes in 2021, dominated by distillate fuel (401,000 tonnes), with residual fuel (87,000 tonnes), used in combination with scrubbers, being an important source of energy for bulk carriers in particular. Limited amounts of biofuel use (about 14,000 tonnes) was reported in 2021, whereas LNG use was negligible (8,000 tonnes).
- Most larger vessels (e.g., bulk carriers, tankers, and containers) operated slow speed diesel engines for main propulsion. Smaller vessels, notably port tugs, ferries, fishing vessels, and service vessels, used high speed diesel engines.
- Ships operating in the GL-SLS region emitted about 1.5 and 1.6 million tonnes of CO_2 in 2020 and 2021, respectively, which is a slight decrease from 2019. Ships flagged to the United States and Canada were responsible for three quarters of those emissions, or equivalent to annual emissions from about 250,000 U.S. passenger vehicles. At-berth emissions, which could be reduced in the future using on-shore power, represented 15% of CO_2 emissions.
- Within the U.S.-flagged fleet, bulk carriers were the dominant source of CO_2 (67%), followed by tugs (25%). The Canadian flagged fleet was more diverse, with bulk carriers accounting for about half of CO_2, but chemical tankers (16%), ferry ro-pax, and tugs (7% each) were also important sources.

The profile results of the GL-SLS in 2021 are summarized in the following tables. Results for U.S.- and Canadian-flagged vessels in the SL-SLS in 2021 are provided in Appendix B.

Table 21 summarizes average, total, maximum, and minimum tonnage (dwt and gt) by ship type for vessels that operated in the GL-SLS system in 2021. Results for the 1100 ships captured in the inventory are arranged in order of decreasing contribution to overall tonnage. As seen in the table, bulk carriers were the most important ship type, contributing more than half of both dwt and gt. Tankers (chemical and oil) were the second largest ship type, followed by container ships and general cargo ships. Service tugs were also important in terms of number of vessels (fourth most prevalent),[19] although their average size (only about 100 dwt and 400 gt) was small compared to other ship types.

---

[19] Includes tug-barge combinations.

Table 21. 2021 GL-SLS fleet ship size per ship type

Ship type	Number of vessels	Deadweight tonnage (dwt)				Gross tonnage (gt)			
		Total	Average	Maximum	Minimum	Total	Average	Maximum	Minimum
Bulk carrier	420	20,230,000	48,200	182,588	968	11,780,000	28,000	95,086	415
Chemical tanker	185	6,220,000	33,600	74,999	1,231	3,800,000	20,600	43,693	749
Oil tanker	60	5,570,000	92,900	159,186	6,265	3,070,000	51,200	83,480	6,105
Container	62	3,150,000	50,800	85,786	12,193	2,650,000	42,800	75,061	9,909
General cargo	141	2,100,000	14,900	42,497	0	1,510,000	10,700	28,239	109
Ro-ro	4	38,500	9,620	19,460	0	57,800	14,500	26,786	192
Ferry-ropax	26	21,300	820	3,058	92	73,500	2,800	15,901	291
Service-other	36	20,700	580	3,048	0	42,100	1,200	6,098	0
Service-tug	136	12,000	90	1,050	0	56,000	400	1,578	88
Yacht	4	11,100	2,780	10,907	0	9,300	2,300	7,191	220
Cruise	3	9,500	3,170	9,500	0	136,900	45,600	121,878	5,402
Ferry-pax only	20	3,100	160	1,697	0	10,900	500	2,112	110
Offshore	3	2,200	750	1,200	436	1,200	400	673	131
Miscellaneous-fishing	21	500	20	180	0	3,400	200	399	19
Miscellaneous-other	2	0	0	0	0	0	0	0	0
Entire fleet	**1,123**	**37,390,000**	**33,300**	**182,588**	**0**	**23,210,000**	**20,700**	**121,878**	**0**

Figure 5 provides a breakdown of tonnage by flag state for both total gt (bars, left scale) and the average per ship (dot, right scale). More variation is seen between flag states for total tonnage than for average tonnage, which varies between 25,000 and 50,000 gt per vessel with the exception of U.S. and Canada vessels, which are smaller than 10,000 gt on average. The larger average size of foreign-flagged vessels reflects that the larger oceangoing vessels that operate in the SLS waterway are typically flagged to foreign states. The Marshall Islands, Liberia, Panama, Malta, and Hong Kong, China were the most prevalent flag states.

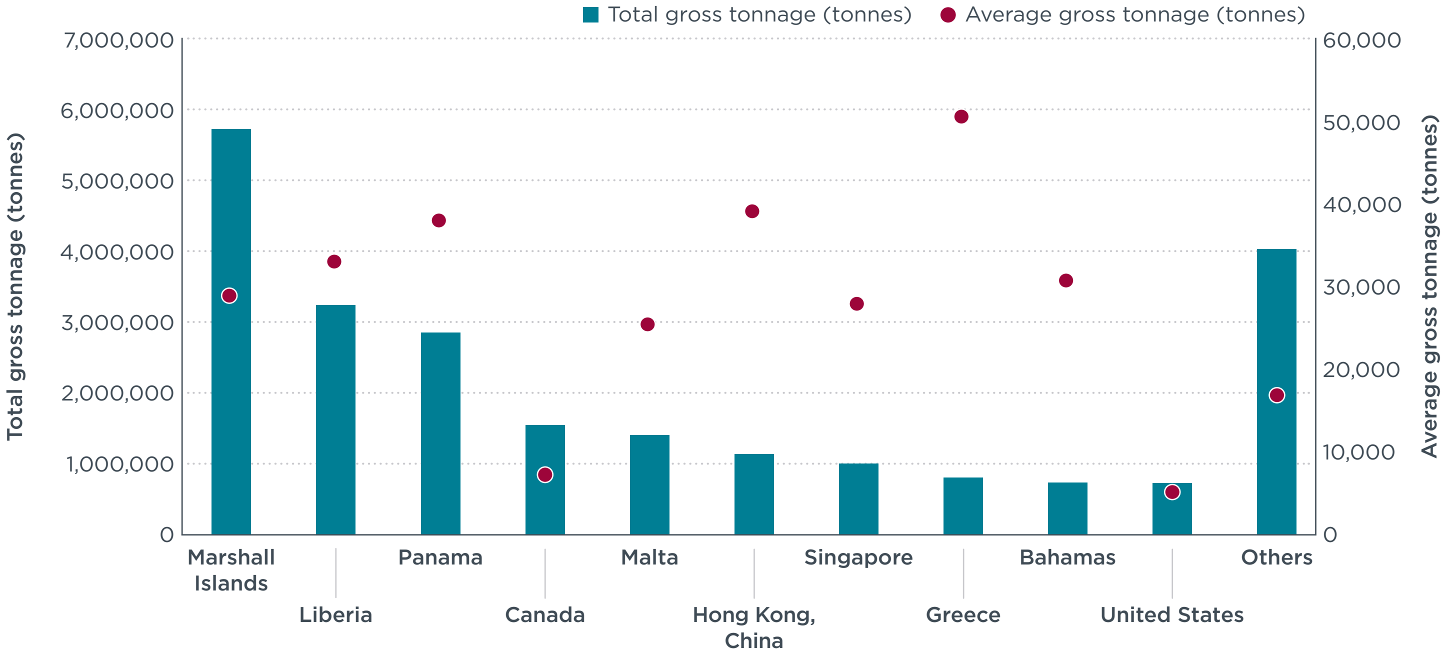


Figure 5. Gross tonnage by flag state in the GL-SLS region in 2021

Figure 6 shows the distribution of ship age in the GL-SRL region in 2021. As seen in the figure, average ship age varies between 15 and 45 years from most ship types, and a maximum age between 20 and 95 years. The largest vessels by total and average gt (bulk carriers, tankers, and container ships) tend to be somewhat newer, with an average age below 20 years, while smaller vessels trend somewhat older with typically more than 20 years in service.

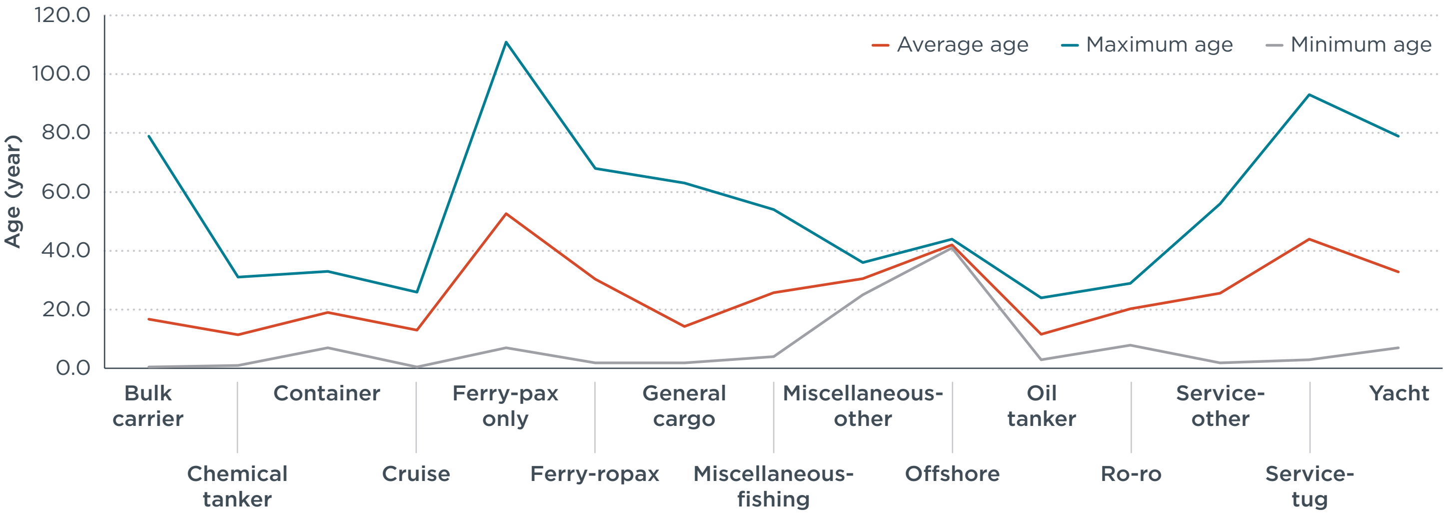


Figure 6. Age by ship type in the GL-SLS region in 2021

Figure 7 plots similar information for draught for ships operating the GL-SLS region in 2021. Average draft hovers around 12 meters for larger ship types like bulk carriers, tankers, and container ships, and at 15m+ for the maximum for those ship types. Average draughts are smaller than 8m for those ship types that are designed for near-port operations, including ferries, general cargo, service vessels, and tugs.

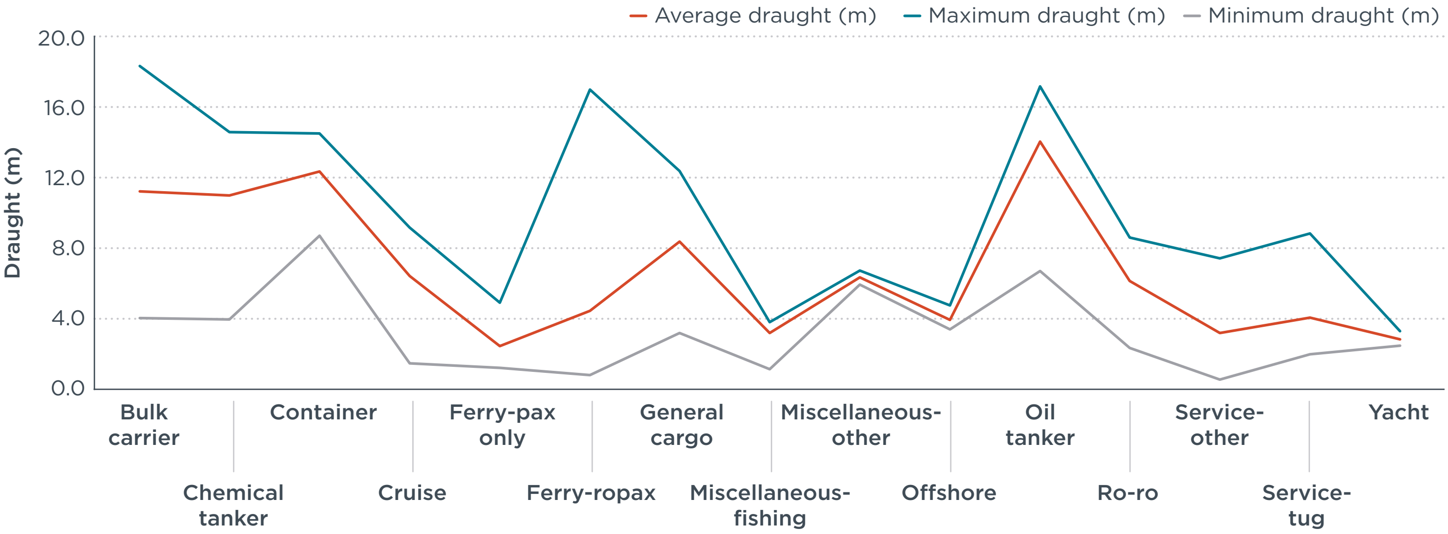


Figure 7. Representative draughts per ship type in the GL-SLS region in 2021

Table 22 provides a summary of main engine ship power by ship type for the GL-SLS region in 2021. As shown, main engine power trends generally with tonnage, with the exception of service tugs which have disproportionally large engines in order to push or tug larger ships. The largest contributor to main engine power were bulk carriers, which accounted for a collective 3400 MW of installed power. This was followed by tankers (chemical and oil, 2100 MW), then container ships (2000 MW), followed distantly by general cargo ships (about 800 MW) and service tugs (300 MW). Average power was the largest for the one cruise ship operating in the GL-SLS region (67 MW), following by container ships (34 MW), oil tankers (12 MW), bulk carriers (8 MW), and chemical tankers (7 MW).

Table 22. Propulsion power by ship type in the GL-SLS region in 2021

Ship type	Total power (kW)	Average power (kW)	Maximum power (kW)	Minimum power (kW)
Bulk carrier	3,408,162	8,115	22,890	412
Chemical tanker	1,364,116	7,374	13,560	662
Container	2,066,741	33,335	68,520	9,000
Cruise	73,493	24,498	67,200	2,493
Ferry-pax only	31,127	1,556	7,015	257
Ferry-ropax	101,042	3,886	20,880	905
General cargo	792,259	5,619	9,960	749
Miscellaneous-fishing	13,891	661	1,492	232
Miscellaneous-other	34,521	17,261	30,700	3,821
Offshore	4,848	1,616	2,206	760
Oil tanker	735,263	12,254	18,624	3,500
Ro-ro	37,651	9,413	16,800	851
Service-other	135,404	3,761	13,020	253
Service-tug	356,554	2,622	10,914	294
Yacht	7,417	1,854	2,648	7

Figure 8 breaks down engine type by ship type in the GL-SLS region in 2021. As shown, most larger vessel types (bulk carriers, tankers, and containers) operated slow speed diesel engines for main propulsion. Smaller vessels, notably port tugs but ferries, fishing vessels, and service vessels, are dependent on diesel high-speed engines. Medium-speed diesel engines are prevalent for a single ship type (general cargo ships), and LNG use in the GL-SLS region is minimal.

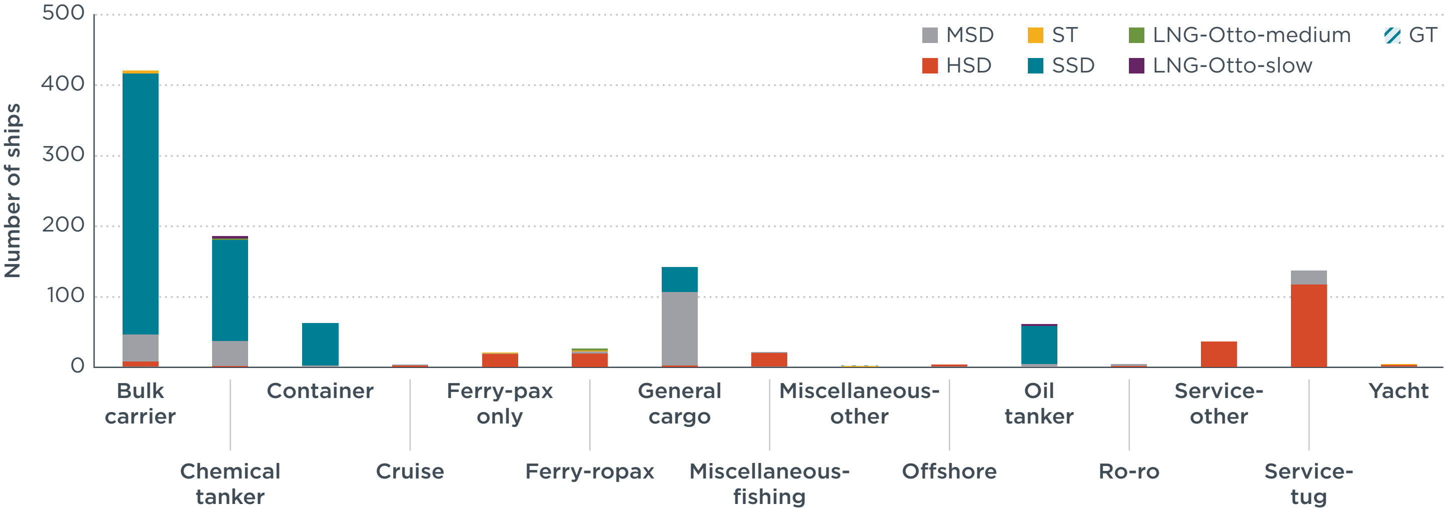


Figure 8. Main engine type by ship type in the GL-SLS region in 2021

Our inventory work also identified a number of ships using exhaust gas aftertreatment uptake, namely exhaust gas scrubbers (Figure 9). Overall, scrubber penetration was around 10% in 2021 in the GL-SLS, concentrated in the largest ships. Among the major ship types, container ships had the largest share with scrubbers (20%), followed by oil tankers, general cargo, bulk carriers, and then chemical tankers, respectively. Roll on roll off ferries (RoRos) have the highest share of scrubbers but make up a minimal share of the total fleet (only four ships).

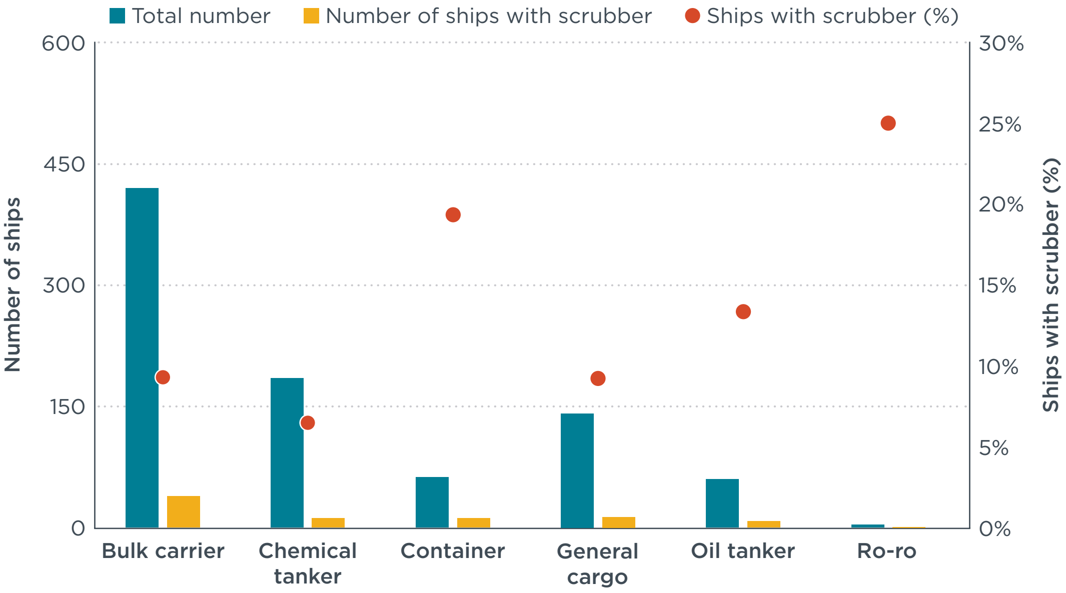


Figure 9. Exhaust gas aftertreatment status by ship type in the GL-SLS region in 2021

The inventory showed large variation in the total operating hours by ship type, with bulk carriers being responsible for 35% of all hours operated in the GL-SLS in 2021 (Figure 10), followed closely by service tugs (about 750,000 hours). Among the various operating phases, at-anchor is the most prevalent operating condition, followed by at-berth and cruise. Maneuvering at slower speeds, defined as operating between 3 and 5 nautical miles per hour, is the least common operating phase. Tankers have a relatively larger proportion of their hours at anchor or at berth, and a smaller proportion at cruise, relative to other ship types. Average hours per ship by operating phase and ship type is likewise shown in Table 23.

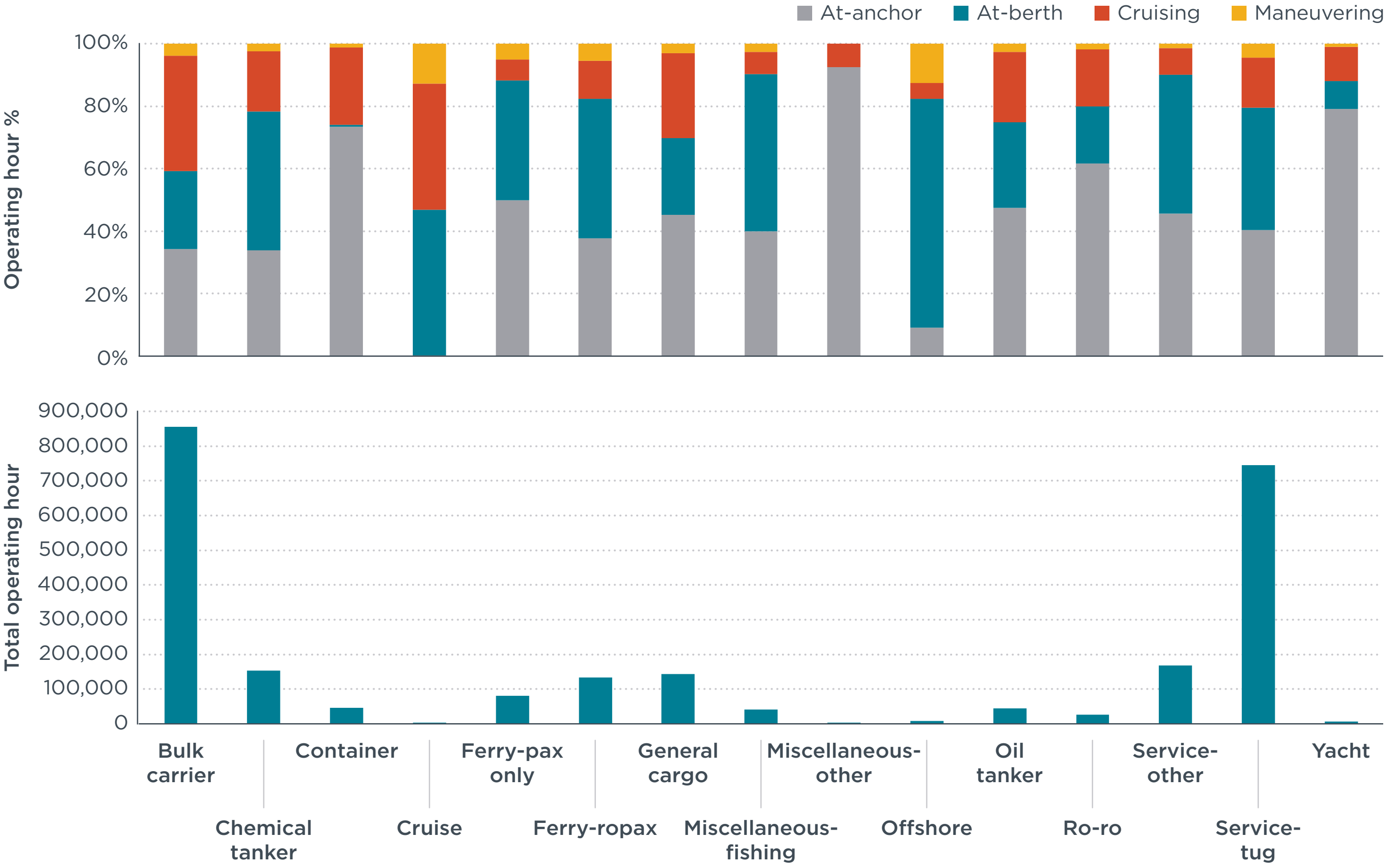


Figure 10. Operating hours by ship type and phase in the GL-SLS region in 2021

Table 23. Operating hours by phase and ship type in the GL-SLS region in 2021

Ship type	Number of vessels	Average operating hours				Total operating hours			
		At-anchor	At-berth	Cruising	Maneuvering	At-anchor	At-berth	Cruising	Maneuvering
Bulk carrier	420	697	509	749	78	292,746	213,954	314,741	32,662
Chemical tanker	185	277	365	158	20	51,235	67,530	29,155	3,702
Container	62	532	4	178	9	32,991	275	11,027	568
Cruise	3	1	168	145	46	3	505	436	138
Ferry-pax only	20	1,957	1,513	260	199	39,148	30,250	5,203	3,977
Ferry-ropax	26	1,926	2,277	619	277	50,063	59,198	16,094	7,202
General cargo	141	454	248	273	30	63,961	34,943	38,500	4,196
Miscellaneous-fishing	21	746	938	129	50	15,665	19,690	2,716	1,042
Miscellaneous-other	2	612	0	50	0	1,224	0	100	0
Offshore	3	219	1,753	122	302	656	5,259	367	906
Oil tanker	60	346	198	164	19	20,747	11,890	9,842	1,132
Ro-ro	4	3,807	1,130	1,131	107	15,228	4,521	4,524	426
Service-other	36	2,116	2,066	402	60	76,177	74,385	14,469	2,163
Service-tug	136	2,209	2,143	873	243	300,357	291,407	118,686	33,081
Yacht	4	990	114	137	11	3,959	455	549	45

Fuel consumption by ship type is shown in Figure 11. Total fuel consumption in the GL-SLS in 2021 was 510,000 tonnes, with 401,000 tonnes from distillate fuel, 87,000 tonnes from residual fuel used in combination with sulfur scrubbers, 14,000 tonnes of biodiesel, and 8,000 tonnes of LNG. Fuel consumption is dominated by bulk carriers, followed by tugs, chemical tankers, general cargo ships, and container ships. Considering the different fuel types, fuel use was dominated by distillate, with residual fuels making up a substantial share of fuel use for bulk carriers only. Biodiesel use was reported to be 14,103 tonnes, as reported by the Canadian Steamship Lines (Yousef El Bagoury, CSL Group, personal communication, December 2022).

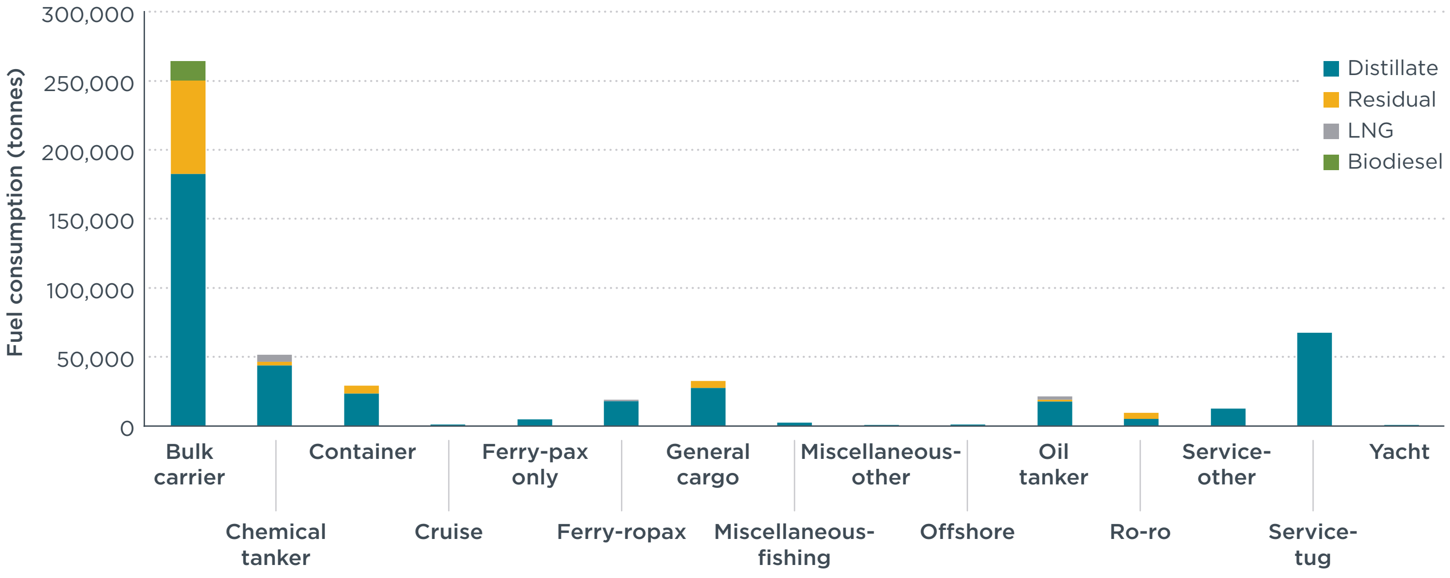


Figure 11. Fuel consumption by ship type in the GL-SLS region in 2021

Estimates of air pollution by ship type in the GL-SLS region in 2021 are shown in Table 24. As can be seen, the entire fleet emitted about 1.6 million tonnes of CO_2 in 2021. Bulk carriers emitted about half of that, followed by tugs (190,000 tonnes), chemical tankers (160,000 tonnes) and general cargo ships (102,000 tonnes). Bulk carriers were the primary driver of air pollution as well, generally accounting for about half of emissions of NO_x, SO_x, and $PM_{2.5}$. Owing to the limited use of LNG in the region, methane emissions were relatively low at a little over 100 tonnes in 2021, driven largely by chemical tankers (42% of the total). Most (92%) of the particulate matter emitted from GL ships was fine particulate matter ($PM_{2.5}$) linked to black carbon and sulfates emitted during fuel combustion.

Table 24. GHG and air pollution by ship type in the GL-SLS region in 2021

Ship type	Tonnes emitted									
	CO_2	CH_4	N_2O	BC	SO_x	PM_{10}	$PM_{2.5}$	NO_x	CO	VOCs
Bulk carrier	800,466	12	48	99	301	260	239	16,681	644	631
Chemical tanker	160,851	42	12	14	63	38	35	1,900	105	85
Container	91,287	2	7	9	37	31	29	1,957	82	89
Cruise	1,364	<1	<1	<1	1	<1	<1	14	1	1
Ferry-pax only	13,162	<1	1	1	6	3	3	182	9	8
Ferry-ropax	58,420	20	5	5	23	12	11	567	35	27
General cargo	102,082	2	8	14	42	36	33	1,962	86	77
Miscellaneous-fishing	5,507	<1	1	1	2	2	1	106	5	4
Miscellaneous-other	757	<1	<1	<1	<1	<1	<1	4	<1	<1
Offshore	1,602	<1	<1	<1	1	<1	<1	27	1	1
Oil tanker	65,353	23	4	5	25	14	13	694	45	35
Ro-ro	29,232	<1	3	5	11	11	10	453	21	19
Service-other	38,714	1	4	4	17	11	10	734	34	29
Service-tug	189,184	3	12	22	81	51	47	3,739	160	146
Yacht	597	<1	<1	<1	<1	<1	<1	11	1	1
Entire fleet	**1,558,577**	**105**	**105**	**178**	**610**	**470**	**432**	**29,031**	**1,230**	**1,152**

Figure 12 shows the breakdown of fuel consumption by operating phase and fuel type. Cruise operations was the most important use of all fuel types in the GL-SLS region in 2021, accounting for about 250,000 tonnes of distillate fuel use and about 70,000 tonnes of residual fuel use. Auxiliary engines and boilers in operation at anchor and at berth were also important; each phase of operation consumed about 70,000 tonnes of fuel that year. Maneuvering, a slow speed and low fuel consumption phase of operation, was the least important source of fuel use.

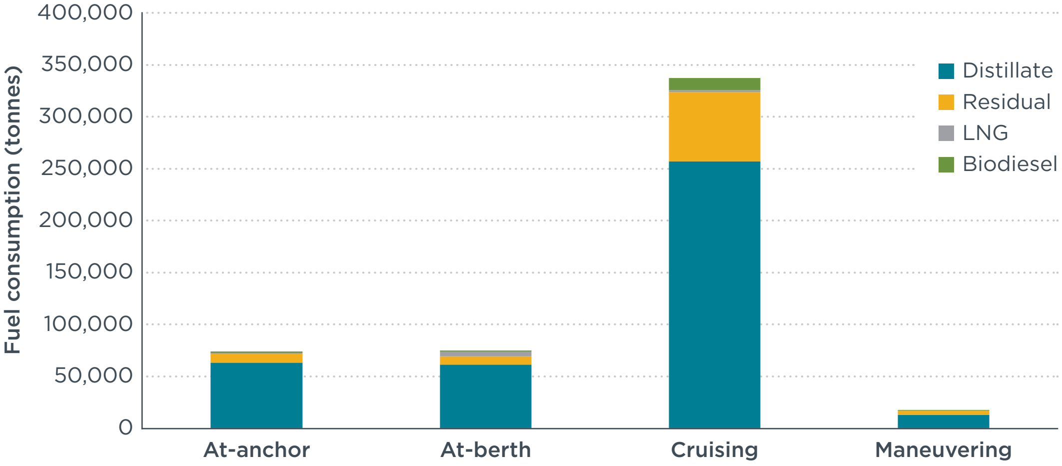


Figure 12. Fuel consumption by operating phase in the GL-SLS region in 2021

Table 25 shows the breakdown of emissions by operating phase in the GL-SLS region in 2021. Most GHGs and air pollutants were emitted by ships while they were sailing (i.e., at-cruise phase). Ships in the cruising phase were responsible for two-thirds of CO_2 emitted, about three-quarters (73%) of particulate matter, and 80% of NO_x emissions. At-berth emissions, which could eventually be reduced using OPS, represented approximately 15% of CO_2 emissions, plus 10% of $PM_{2.5}$ and 7% of NO_x emissions. Ships at anchor contributed 15% of CO_2,12% of $PM_{2.5}$, and 9% of NO_x emissions. Maneuvering was only a marginal contributor to emissions, generally contributing 5% or less of GHG and air pollution. Relatively more black carbon (9% of the total) was emitted during maneuvering owing to incomplete combustion conditions at lower engine loads, which correspond to slower ship speeds.

Figure 13 shows CO_2 emissions by flag state and ship type in the GL-SLS region in 2021. As shown, Canadian and U.S.-flagged vessels were responsible for approximately equal shares of CO_2 emitted in 2021, at 38% and 37%, respectively. Other ships were responsible for the remaining one-quarter of CO_2 emitted. For U.S.-flagged ships, bulk carriers were the dominant source of CO_2 (67%), followed by tugs (25% of emissions). The Canadian flagged fleet was more diverse, which was reflected in the CO_2 inventory. Bulk carriers still accounted for about half of CO_2 emissions, but chemical tankers (16%), ferry ro-pax, and tugs (7% each) were also important sources. Other ship types, including oil tankers and general cargo ships, were responsible for the remaining 20% of emissions.

Table 25. Air emissions by operating phase in the GL-SLS region in 2021

	Tonnes emitted									
Operating phase	**CO_2**	**CH_4**	**N_2O**	**BC**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**	**NO_x**	**CO**	**VOCs**
At-anchor	228,840	22	33	19	92	56	51	2,718	142	98
At-berth	230,256	21	11	17	102	49	45	1,919	112	78
Cruising	1,046,666	57	53	125	385	342	314	23,312	916	903
Maneuvering	52,814	5	7	16	30	24	22	1,082	59	72
Total	**1,558,577**	**105**	**105**	**178**	**610**	**470**	**432**	**29,031**	**1,230**	**1,152**

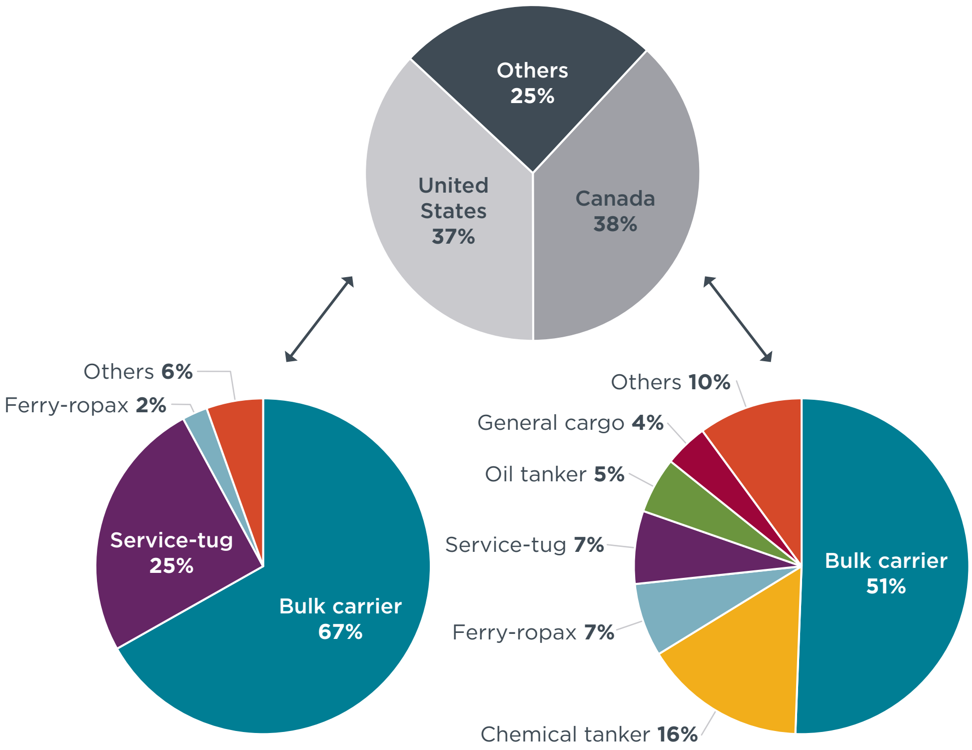


Figure 13. CO_2 emissions by flag state and ship type in the GL-SLS region in 2021

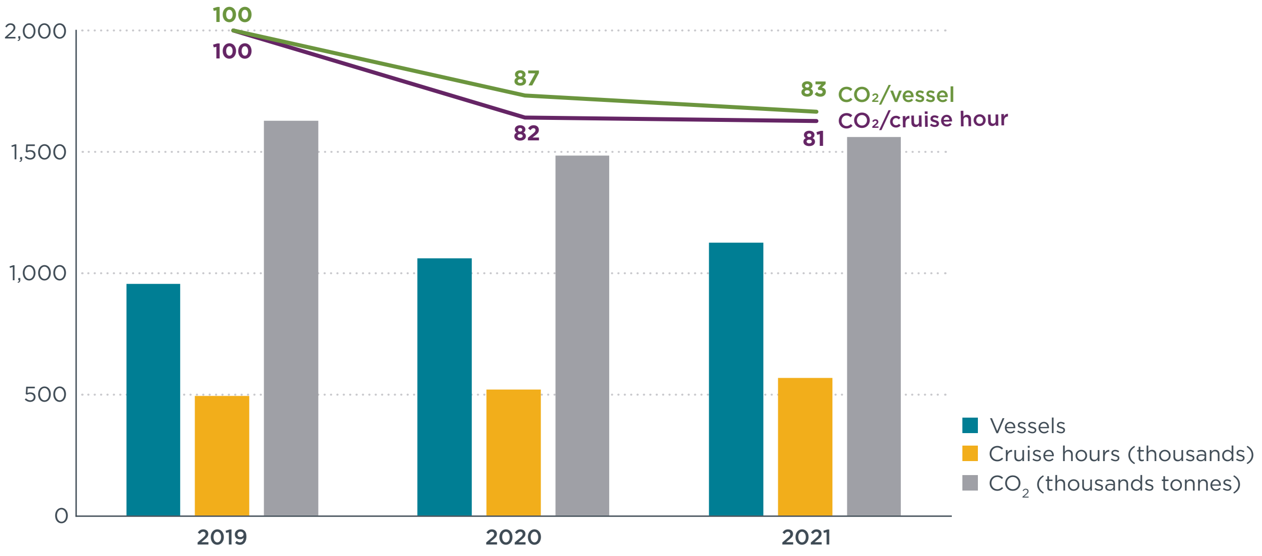
Trends in emissions and activity over time

Overall, it is estimated that ships operating in the GL-SLS region emitted about 1.5 and 1.6 million tonnes of CO_2 in 2020 and 2021, respectively, which is a slight decrease from 2019 values. Ships flagged to the United States and Canada were responsible for three quarters of those emissions, or 1.17 Mt of CO_2 in 2021 (Figure 13). This is equivalent to emissions from about 250,000 U.S. passenger vehicles.[20]

Figure 14 summarizes of key trends from 2019 to 2022, which as noted above are influenced by a change in modeling methods. Relative to 2019, the 2021 inventory included about 170 (18%) more vessels and about 80,000 (15%) more cruise hours in the GL-SLS region. However, estimated CO_2 emissions were flat because modeled CO_2 per emissions per ship and CO_2 per cruise hour fell 19% and 17%, respectively. It is difficult to attribute any change in emissions to external drivers, such as the impact of COVID 19, given the changes in modeling methods summarized above. Results for 2020 and 2021 are directly comparable, however.

---

[20] Assuming a typical passenger vehicle emits 4.6 tonnes of CO_2 annually, according to the U.S. EPA: https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle



Note: Trends between 2019 and other years are uncertain due to modeling improvements for 2020+; however, 2020 and 2021 can be directly compared. CO_2/vessel and CO_2/cruise hour is an index where then values in 2019 are set to 100.

Figure 14. GL-SLS vessels, cruise hours, and CO_2 emissions from 2019 to 2021

PROFILING GREAT LAKES PORT INFRASTRUCTURE AND BUNKERING OPERATIONS

KEY FINDINGS

- Among the ports surveyed, Chicago provided the widest array of fuel types, including propane, gasoline, and diesel fuel. The Port of Duluth provides a diesel capacity of 560,000 gallons, which is more than 20-times greater than the next-highest port, Erie (24,000 gallons).
- Trucks are the most common way fuels are replenished at the ports, with tankers used to replenish bunker oil and sometimes diesel and gasoline.
- Seven regional ports (Chicago, Cleveland, Duluth, Erie, Milwaukee, Montréal, and Québec) reported some form of electrical connections at the port, but only four have onshore power supply: Chicago, Duluth, and Milwaukee have low-voltage connections and Montréal has high-voltage connections.
- All ports expressed willingness to engage further in alternative fuels or shore power.

The results of the infrastructure survey are summarized here. The alternative fuel or technology capabilities for each port covered in the survey can be seen in Figure 15. Seven of the ten ports had some form of electrical connections at the port but only four have onshore power supply (OPS): Chicago, Duluth, and Milwaukee have low-voltage connections and Montréal has high-voltage connections The only other available alternative fuel was LNG, available in Québec. Chicago and Cleveland have natural gas supplied to the port for purposes such as heating, but it is not provided as a ship fuel.

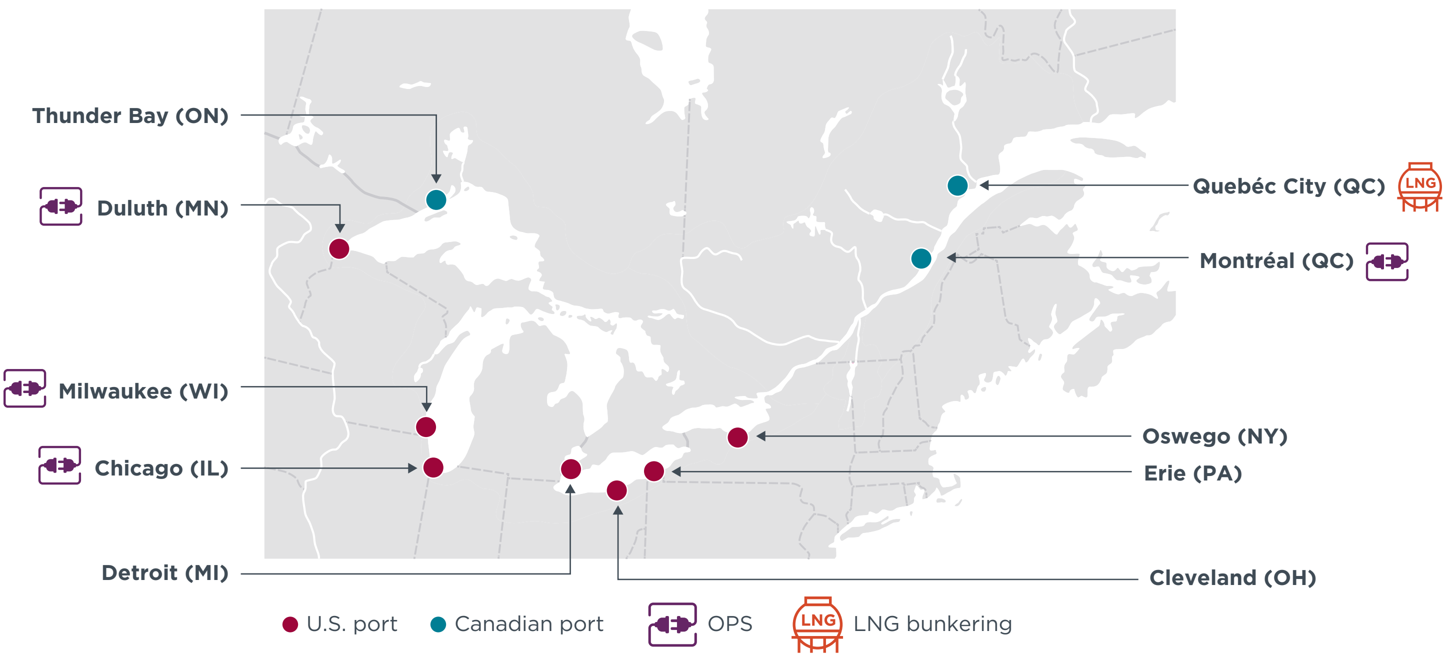


Figure 15. Port locations and key characteristics

Figure 16 shows the size and yearly tonnage of each of the 10 ports. The largest surveyed port was Montréal, at more than 11 square kilometers, and the smallest was Erie. Regionally, port authorities often act as landlords, which explains why not all port area is controlled by the port authority. Figure 16 also provides additional details for each port relating to the ability to support alternative fuel and power options in the Great Lakes region.

Chicago-USA

- # of terminals: 3
- Tonnage/year: 2.7 million tonnes
- Land area: 7.28 km^2
- % controlled by PA: 100%
- Land available for re-use: 0.20 km^2
- length of berths (PA*): 3,658 m
- length of berths (Overall**): 3,658 m

Cleveland-USA

- # of terminals: 21
- Tonnage/year: 12.2 million tonnes
- Land area: 1.62 km^2
- % controlled by PA: 30%
- Land available for re-use: <5%
- length of berths (PA): 2,286 m
- length of berths (Overall): Unknown

Detroit-USA

- # of terminals: 20-30
- Tonnage/year: 11.8-13.6 million tonnes
- Land area: 4.05 km^2
- % controlled by PA: ~3.5%
- Land available for re-use: 30%
- length of berths (PA): 610 m
- length of berths (Overall): 3,048 m

Duluth-USA

- # of terminals: 20
- Tonnage/year: 31.7 million tonnes
- Land area: Unknown
- % controlled by PA: 10%
- Land available for re-use: 0.14 km^2
- length of berths (PA): 2,200 m
- length of berths (Overall): 10,735 m

Erie-USA

- # of terminals: 2
- Tonnage/year: 907,000 tonnes
- Land area: 0.069 km^2
- % controlled by PA: 100%
- Land available for re-use: 0%
- length of berths (PA): 732 m
- length of berths (Overall): 732 m

Milwaukee-USA

- # of terminals: 27
- Tonnage/year: 2.3 million tonnes
- Land area: 2.02 km^2
- % controlled by PA: 93%
- Land available for re-use: Unknown
- length of berths (PA): 4,877 m
- length of berths (Overall): 5,883 m

Montréal-CAN

- # of terminals: 22
- Tonnage/year: 34 million tonnes
- % controlled by PA: Almost all
- Land available for re-use: Unknown
- length of berths (PA): 21,000 m
- # of berths (Overall): 21,000 m

Oswego-USA

- # of terminals: 2
- Tonnage/year: 450k-680k tonnes
- Land area: 0.38 km^2
- % controlled by PA: 100%
- Land available for re-use: 15%
- length of berths (PA): 1,067 m
- length of berths (Overall): 1,067 m

Québec-CAN

- # of terminals: 14
- Tonnage/year: 25.4 million tonnes
- Land area: 2.2 km^2
- % controlled by PA: 35%
- Land available for re-use: Unknown
- length of berths (PA): 7,200 m
- length of berths (Overall): Unknown

Thunder Bay-CAN

- # of terminals: 14
  Tonnage/year: 9 million tonnes
- Land area: Unknown
- % controlled by PA: 1.21 km^2
- Land available for re-use: 0.36 km^2
- length of berths (PA): 1,250 m
- length of berths (Overall): 4,000 m

*PA: Port Authority controlled area

**Overall: Entire Port area

Figure 16. Detailed port characteristics.

Figure 17 through Figure 20 provide detailed information on storage capacities and replenishment mechanisms for each port. Figure 17 shows the current fuel capacities by port. With the exception of Québec, the chart shows storage tanks controlled by the port authority, because the "overall" fuel capacity of tanks were identical to those controlled by the port authority. In Québec, there are more than 60 tanks with a combined capacity of 3 million barrels (126 million gallons) for bunker, diesel, gasoline, jet fuel, other refined petroleum products, and chemicals. Chicago has the widest array of fuel types, with propane, gasoline, and diesel fuel. Detroit, Milwaukee, Oswego, Québec, and Thunder Bay do not report any fuel capacity controlled by the port authority. In the Port of Duluth, diesel capacity is 560,000 gallons, which is more than 20-times greater than the next highest port, Erie, which stores 24,000 gallons.

Figure 18 displays the number of storage tanks by port. Québec and Detroit have the most storage tanks, but they are both categorized as "other," representing a variety of fuels. With the exception of Québec and Detroit, the chart shows storage tanks controlled by the port authority, because the "overall" number of tanks were identical. The most common tank type was for diesel fuel. In Québec, terminal operators have over 60 tanks with different specs, but they were not clearly categorized in the survey. In Detroit, there were 73 tanks but the details of what they hold were unknown and hence they were categorized as "other."

Figure 19 displays the replenishment mechanism for each fuel type, aggregated across all ports interviewed. Trucks are the most common replenishment type, with tankers being the second most common. There was only one instance of trains being used for fuel replenishment. Bunker oil is only delivered by tanker. Diesel and gasoline are mainly delivered by truck, but each also had one instance of delivery by tanker. Propane is delivered by truck.

Figure 20 shows the electrical connections at the ports. Chicago, Duluth, and Milwaukee have low-voltage OPS available at the dock. Montréal has high-voltage OPS used for wintering and cruise ships. Cleveland, Oswego, and Québec have electrical connections at the port, but they are not available at the dock.

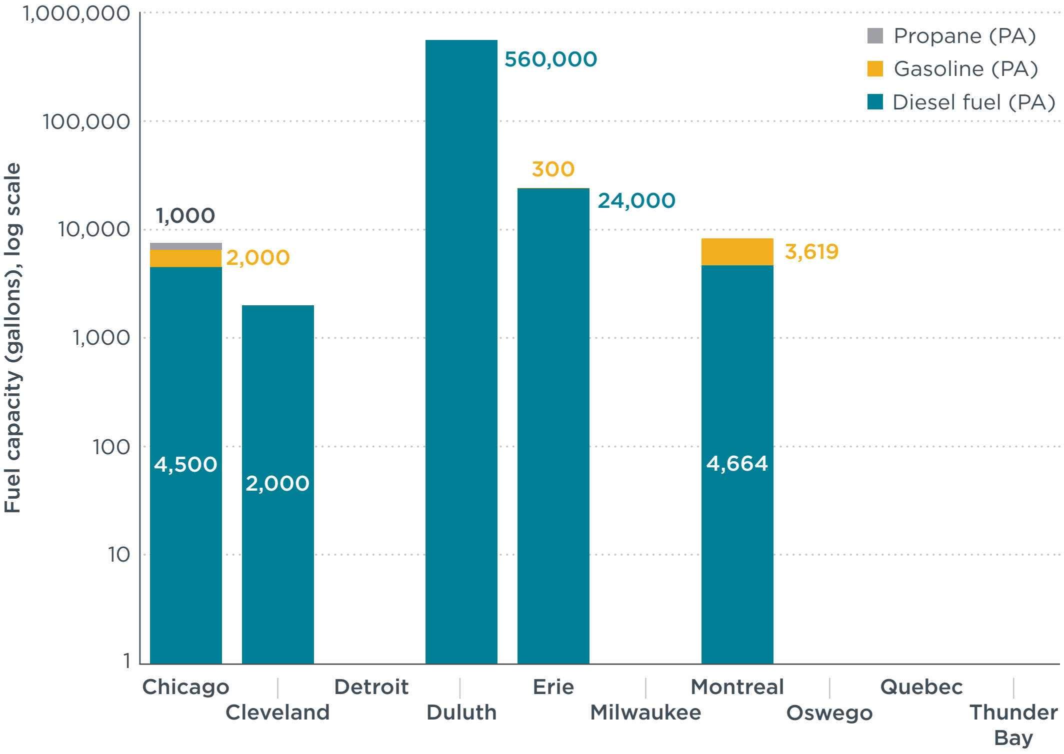


Figure 17. Fuel capacity

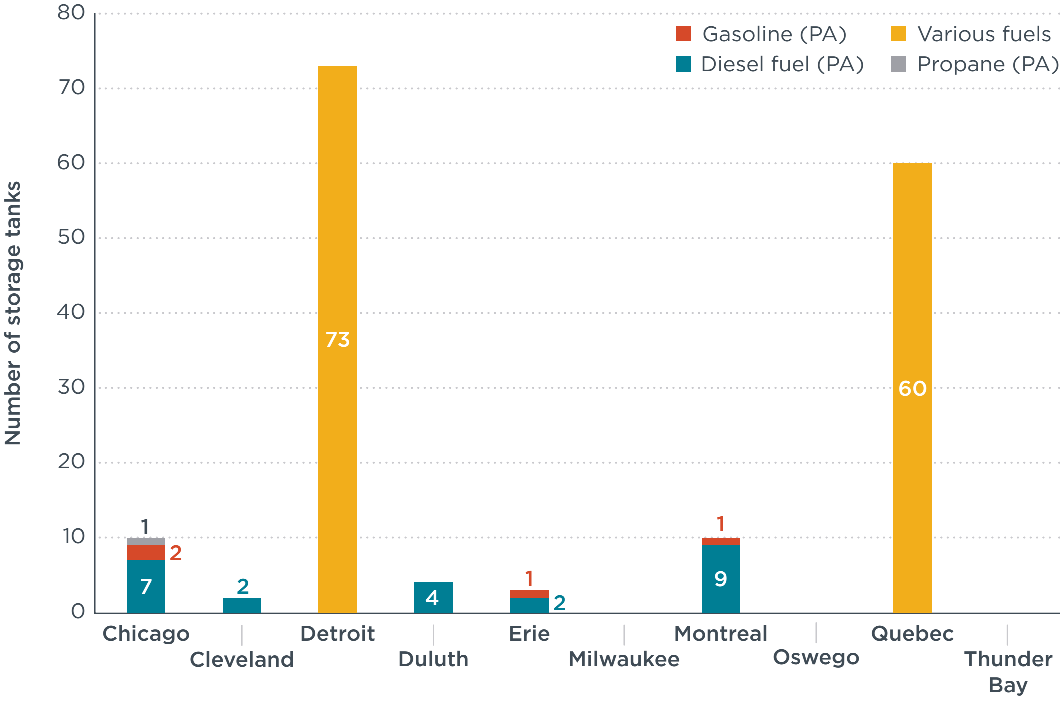


Figure 18. Number of storage tanks

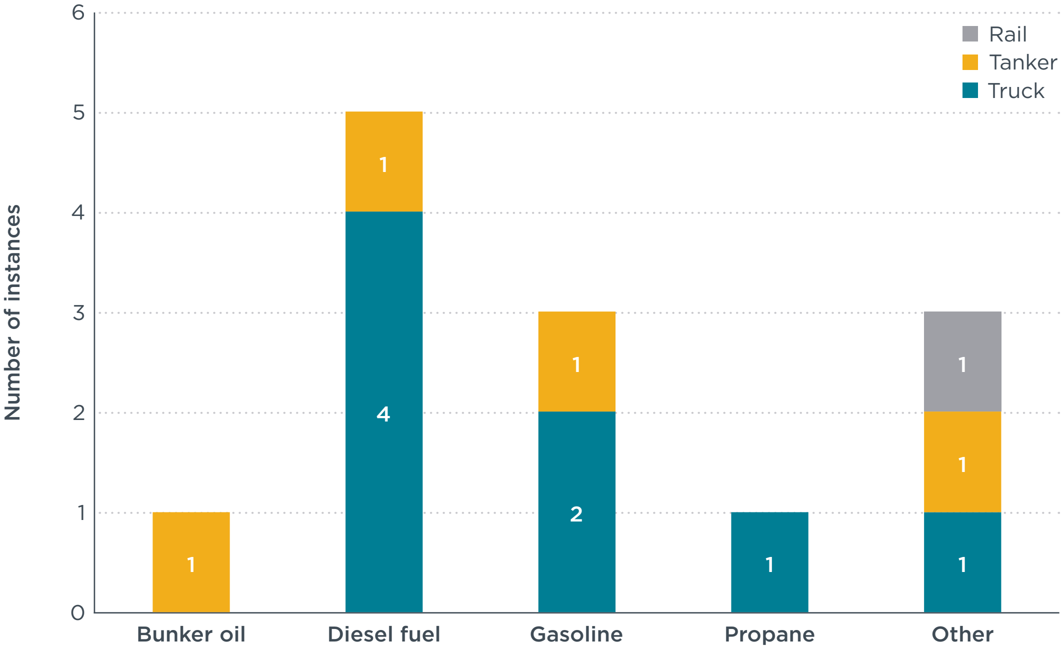


Figure 19. Fuel replenishment mechanisms

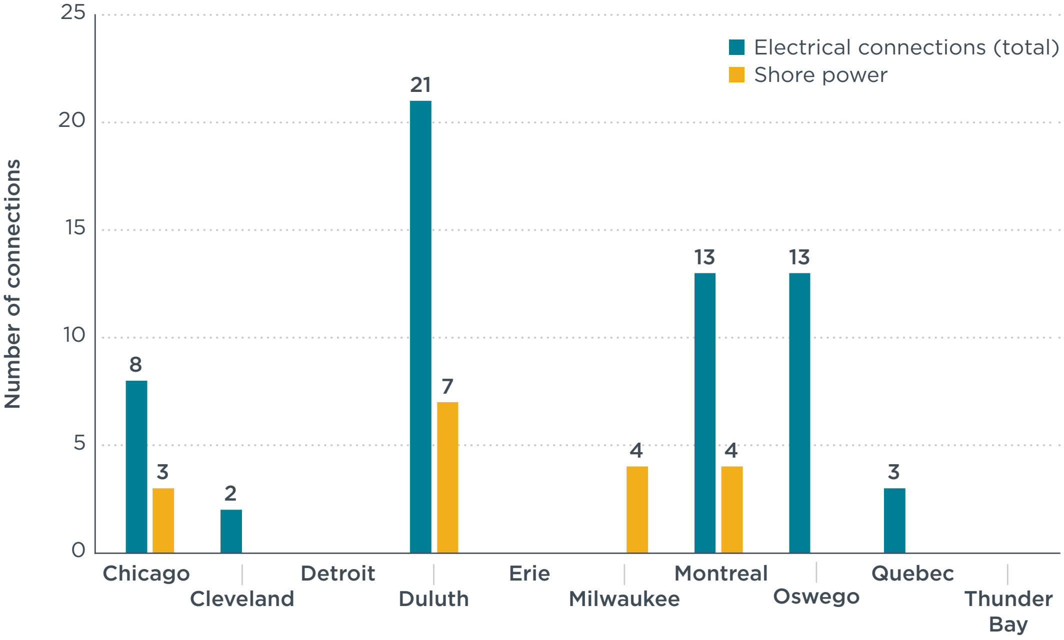


Figure 20. Total port electrical and shore power connections

Table 26 shows shore power capabilities and specifications by port. Seven of the ports surveyed included electrical connections at the port, but only four have shore power capabilities. All OPS connections are low voltage, with the exception of Montréal, which has high voltage connections for cruise ships and wintering operations.[21] Accordingly, additional investments would be needed to develop high-voltage systems suitable for large commercial ships in other ports. Considering the current capabilities for OPS across various ports, the voltage, phase, frequency, and current specifications differ among the surveyed locations. Notably, Duluth stands out with a variable current range of 400-600A, while Montréal and Québec each provide 600-volt AC for vessels.

Table 26. Current possibilities for onshore power supply

	Port						
Parameter	**Chicago**	**Cleveland**	**Duluth**	**Erie**	**Milwaukee**	**Montréal***	**Québec**
Existing OPS?	Yes	No	Yes	No	Yes	Yes	No
Voltage (V, AC)	480	480	480	480	460	600*	600
Phase	3-phase						
Frequency (Hz)	60						
Current (A)	Unknown	Unknown	400-600	200	400	Unknown	Unknown

**Note:* Port of Montréal has DC infrastructure of 15 MVA for cold ironing.

Chicago: Chicago's port authority expresses openness to the adoption of alternative fuels in the future, signaling a willingness to explore innovative solutions for maritime energy. The port was also designated as a potential site to house windfarms and hydrogen in the future.

---

[21] According to IEEE 80005-1, Utility connections in port – Part 1: High voltage shore connection (HVSC) systems, high voltage is nominal voltage in range above 1,000 V AC and up to and including 15 kV AC. Low voltage is nominal voltage up to and including 1,000 V AC.

Cleveland: Cleveland's port authority is actively pursuing electrification plans with the assistance of a recently announced Port Infrastructure Development Program (PIDP) grant. The "Electrification and Warehouse A Modernization" project aims to lay the groundwork for the eventual switch away from diesel-powered equipment. Specific elements include conducting electrification and clean air master planning studies and making necessary power upgrades to support low or zero-emission fleets. Cleveland is also actively involved with the American Association of Port Authorities and its alternative energy-focused POWERS program.

Detroit: The Detroit Wayne County Port Authority recently received a $1 million grant to develop a decarbonization plan. Alongside this plan, the port is investigating the cost, specifications, and funding sources for the installation of shore power at its cruise ship dock. It will also be working with its private terminal operators to support their efforts to install shore power and other alternative fuels. Additionally, the port authority is taking other steps towards sustainability by leveraging federal funding to install solar panels and a hydrokinetic energy harvester at its office location and cruise ship dock. It also joined the MachH2 planning group, which has submitted a concept paper to the U.S. DOE to develop hydrogen fuel production, distribution, and utilization at the port.

Duluth: Duluth's port authority demonstrates a proactive approach to staying informed about alternative fuel options for maritime shipping, with an emphasis on monitoring developments in steamship lines, Great Lakes shipping, coastal ports, and green shipping corridors. The port currently provides shore power and is exploring the impact of cold temperatures on energy provision in order to identify electrification and microgrid opportunities. Duluth will most likely start by converting some of its yard equipment to electric vehicles. The port also remains engaged in conversations surrounding hydrogen hubs, including both the Heartland Hydrogen Hub and Midwest Hydrogen Hubs.

Erie: Erie's port authority noted a desire to see the established success of these technologies before implementing them at their port.

Milwaukee: Milwaukee's port authority has implemented the StewardSHIP initiative, providing financial incentives to shipping lines incorporating sustainability practices. The port currently has limited shore power available, but electrification and other alternative fuels will be taken into consideration as technology develops, and the process of planning and designing future infrastructure is underway.

Montréal: The Port of Montréal is implementing a comprehensive decarbonization strategy. They emphasize a technologically neutral approach, prioritizing solutions that result in significant greenhouse gas emission reductions. The port facilitates access to alternative fuels for various stakeholders, such as ship owners, terminal operators, and trucking companies. The port currently provides shore power connections for wintering and cruising ships, and plans to expand such solutions across different terminals. They collaborate closely with terminal operators to transition port equipment to electricity and are exploring LNG options for vessels. The port is also involved in a collaborative effort with the port of Antwerp to establish a transatlantic green corridor, aiming to have commercial ships exclusively using alternative fuels.

Oswego: In addition to considering federal grants for dock electrification, Oswego's port authority is exploring the possibility of a solar farm on port property and is considering renewable energy sources.

Québec: Québec's port authority is actively exploring different opportunities for alternative fuels, including electrification and hydrogen for various vehicles. LNG is already offered at the dock for ships. Québec is prioritizing establishing high-voltage shore power connections for cruise ships to improve air quality and is discussing providing low-voltage connections for some commercial ships. Québec noted the need for long-term transition planning to supply alternative fuels at the port.

Thunder Bay: Thunder Bay's port authority is considering the conversion of a hydraulic port mobile harbor crane to biofuel, showcasing an interest in alternative fuels for equipment. It is also looking into electrification of conveyor equipment for use in bulk handling operations.

BASELINE ASSESSMENT OF ALTERNATIVE ENERGY OPTIONS

KEY FINDINGS

- When produced from waste biomass or 100% renewable electricity, alternative marine fuels can provide deep reduction in life-cycle GHGs. In contrast, high ILUC emissions lead to limited decarbonization benefits from crop-based biofuels, whereas fuels generated from grid electricity or fossil energy can have more than double the carbon intensity of baseline fossil fuels.
- Alternative marine fuels cost more than conventional marine fuels, with the exception of "gray" fuels derived from fossil fuels, which have high life-cycle GHG emissions.
- The lower energy density of alternative marine fuels should not be a major barrier to adoption in the GL-SLS. The one exception is battery-electric ships, which would not be widely applicable today due to battery energy density and charging constraints.
- Most fuels investigated are sufficiently scalable to meet the energy needs of GL-SLS shipping. A notable exception is renewable diesel produced from used cooking oil, which is already in high demand in other transport modes.
- Two advanced biofuels—methanol produced from corn stover, and bio-LNG derived from landfill gas—scored well on the baseline assessment and should be carefully considered by policymakers for support. However, any LNG should be encouraged to be used in low-methane-slip engines to maximize emissions reductions.

Emissions results

Figure 21, Figure 22, and Figure 23 show the life-cycle GHG emissions of alternative fuels analyzed in this study compared to MGO. Figure 21 presents bio- and fossil-based fuels. When produced from waste biomass, such as corn stover, biofuels can provide deep decarbonization. In contrast, high ILUC emissions lead to limited decarbonization benefits from crop-based biofuels. The GHG emissions from alternative fuels produced from fossil sources, such as natural gas, can be even higher than emissions from using MGO.

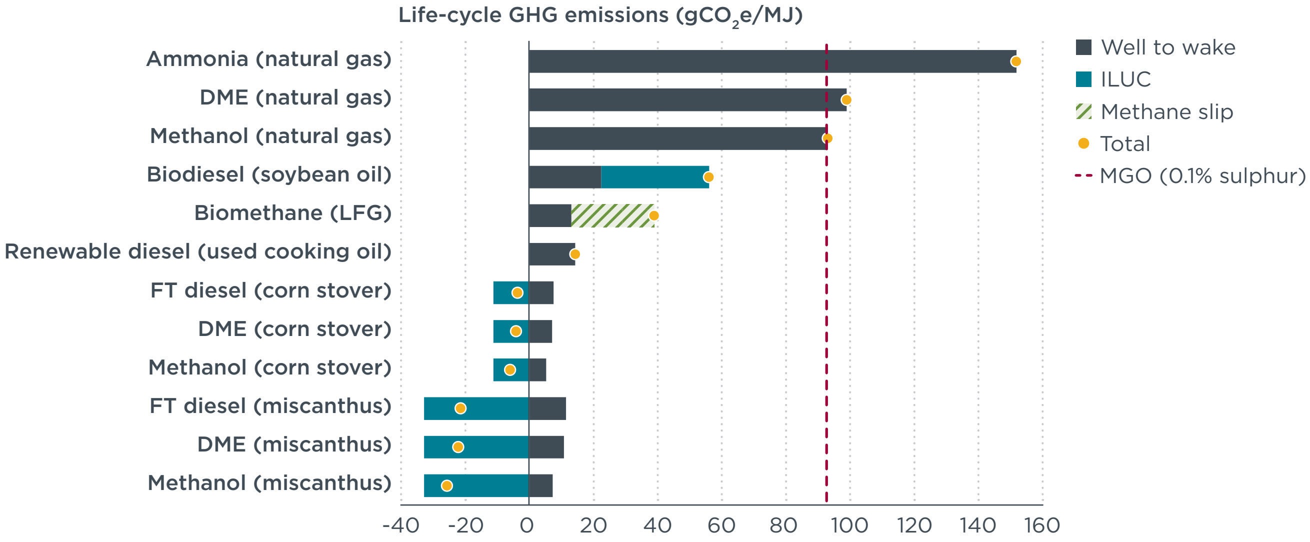


Figure 21. Life-cycle emissions of bio-based and fossil-based fuels, 100-year GWP

Figure 22 shows the carbon intensity of liquid hydrogen and electricity, accounting for the higher vessel efficiency when fuel cells or batteries are used (yellow circles) or not (the bars). For liquid hydrogen, only when using 100% additional renewable electricity, where the life-cycle emissions are essentially zero, can liquid hydrogen have better climate performance than MGO. When renewable electricity additionality is not met, the climate impacts of electrolyzing hydrogen would be the same as using grid electricity, which can be more than double the carbon intensity of MGO. The low carbon capture rate at hydrogen plants due to current industrial practices limits the decarbonization potential of blue hydrogen. For electricity, even after considering the cleaner grid mix in the future and the higher efficiency of electric vessels, the life-cycle GHG emission from using grid electricity is only half that of MGO.

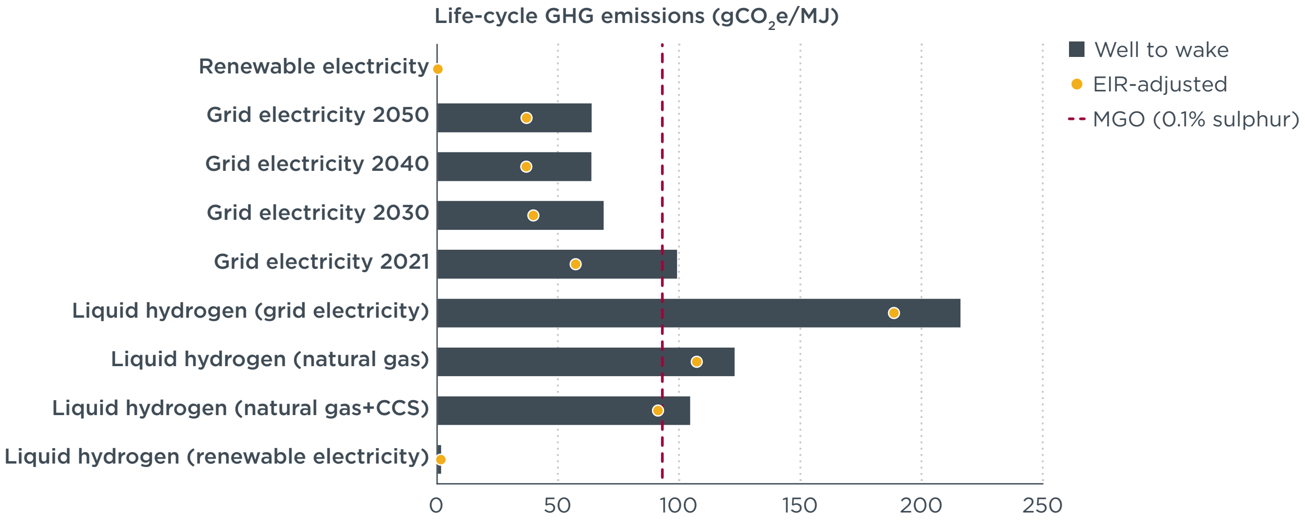


Figure 22. Life-cycle emissions of hydrogen and electricity, 100-year GWP

Figure 23 indicates the life-cycle emissions from electrolysis-based fuels. As with electrolysis hydrogen, renewable additionality is the key to their decarbonization potentials. When additionality is not met, all these fuels fail to provide any climate benefits.

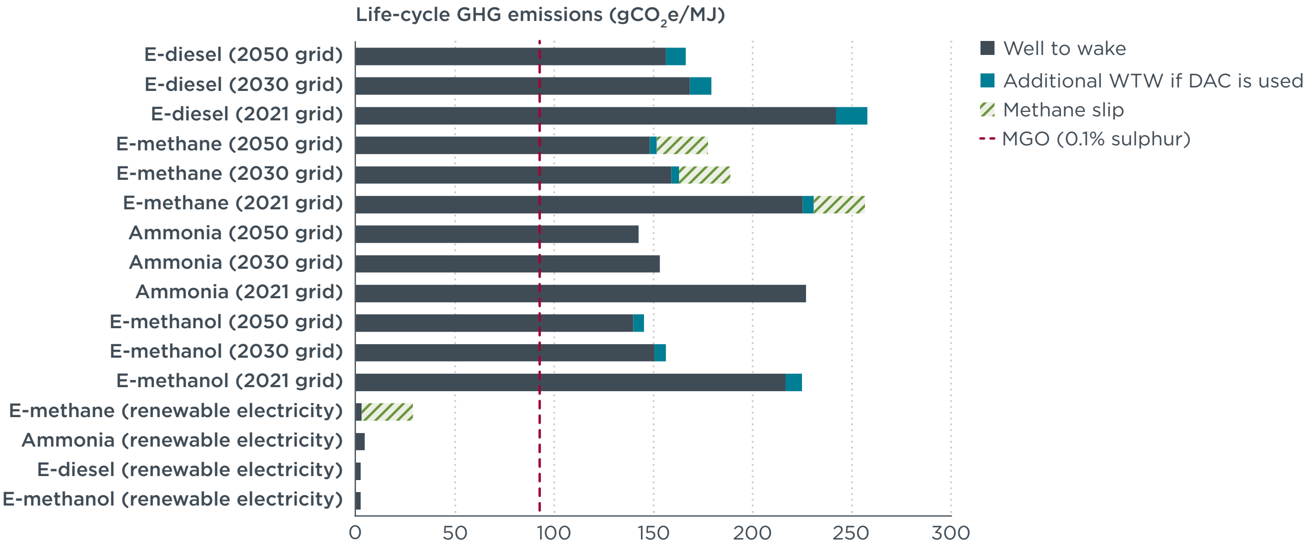


Figure 23. Life-cycle emissions of e-fuels, 100-year GWP

Table 27 shows the five-point scale used to develop an emissions score for comparison with other qualitative metrics.

Table 27. Five-point scale for emissions metric

Scale	Descriptor	GWP$_{100}$ reduction relative to MGO
1	Very poor	<20%
2	Poor	20 to 39%
3	Fair	40 to 59%
4	Good	60 to 79%
5	Very good	80%+

Table 28 shows the full results of the life cycle assessment, including the g CO$_2$e/MJ, the reduction from the MGO baseline, and the emissions score applied. For the reduction, a negative number indicates a fuel that is more carbon intensive than MGO after adjusting for EIRs for the primary propulsion option.

Table 28. Life-cycle emissions for fuel pathways with primary propulsion option

Pathway	Primary propulsion option	Life cycle emissions (g CO$_2$e/MJ)[a]	% reduction from MGO[b]	Emissions score
Biodiesel (soybean oil)	**ICE**	56	40%	3
Renewable diesel (used cooking oil)		14.3	85%	5
FT diesel (miscanthus)		-21.5	123%	5
FT diesel (corn stover)		-3.7	104%	5
DME (miscanthus)		-22.2	124%	5
DME (corn stover)		-4.1	104%	5
DME (natural gas)		98.9	-7%	1
Methanol (miscanthus)		-25.7	128%	5
Methanol (corn stover)		-6.0	106%	5
Methanol (natural gas)		93.0	0%	1
Liquid hydrogen (natural gas)	**Fuel cell**	113.3	-22%	1
Liquid hydrogen (natural gas and CCS)		96.3	-4%	1
Liquid hydrogen (grid electricity)		199.5	-115%	1
Liquid hydrogen (renewable electricity)		1.3	99%	5
Ammonia (natural gas)	**ICE**	151.8	-64%	1
Ammonia (grid electricity)		226.8	-145%	1
Ammonia (renewable electricity)		4.3	95%	5
E-diesel (renewable electricity and point CO$_2$)		2.3	97%	5
E-diesel (renewable electricity and DAC)		2.33	97%	5
E-diesel (grid electricity and point CO$_2$)		241.9	-161%	1
E-diesel (grid electricity and DAC)		257.7	-178%	1
E-methanol (renewable electricity and point CO$_2$)		2.3	98%	5
E-methanol (renewable electricity and DAC)		2.30	98%	5
E-methanol (grid electricity and point CO$_2$)		216.4	-134%	1
E-methanol (grid electricity and DAC)		224.9	-143%	1
Biomethane (LFG)[c]		27.7	70%	4
E-methane (renewable electricity and point CO$_2$)		17.5	81%	5
E-methane (renewable electricity and DAC)		17.5	81%	5
E-methane (grid electricity and point CO$_2$)		239.8	-159%	1
E-methane (grid electricity and DAC)		245.4	-165%	1
2021 Grid electricity	**Battery electric**	54.8	41%	3
100% renewable electricity		0	100%	5

[a] EIR adjusted for primary power option

[b] 0.1% sulfur MGO; 92.6 g CO$_2$e/MJ

[c] Methane fuel emissions are reported based on using them in low-pressure fuel injection dual fuel (LPDF) 2-stroke engines; the full range of emissions varies based on methane slip, which varies by engine technology, as shown in Figure 21 and Figure 23.

Total cost of ownership

Table 29 summarizes the results of the baseline TCO analysis. It shows the cost of the MGO baseline ($0.018/dwt-nm) and the relative performance of the other pathways when paired with their main propulsion options. TCO scores ranging from 1 (worst, 300%+ the MGO baseline, red) up to 5 (best, less than 150% of the MGO baseline, in blue) are also shown.

Table 29. Total cost of ownership results, baseline

Fuel pathway	Primary propulsion option	TCO (2021$/dwt-nm)	Score
MGO baseline	**ICE**	**$0.018**	**—**
Biodiesel (soybean oil)	**ICE**	$0.037	**3**
Renewable diesel (used cooking oil)		$0.035	**3**
b-FT diesel (miscanthus)		$0.066	**1**
b-FT diesel (corn stover)		$0.069	**1**
e-FT diesel (ethanol CO_2 and grid power)		$0.081	**1**
e-FT diesel (DAC and grid power)		$0.106	**1**
e-FT diesel (ethanol CO_2 and renewable power)		$0.090	**1**
e-FT diesel (DAC and renewable power)		$0.116	**1**
f-LH2 (gray)	**Fuel cell**	$0.066	**1**
f-LH2 (blue)		$0.072	**1**
e-LH2 (grid)		$0.080	**1**
e-LH2 (green)		$0.084	**1**
f-NH3 (gray)	**ICE**	$0.030	**4**
e-NH3 (grid)		$0.066	**1**
e-NH3 (green)		$0.072	**1**
f-MeOH (gray)		$0.016	**5**
e-MeOH (ethanol CO_2 and grid power)		$0.065	**1**
e-MeOH (DAC and grid power)		$0.089	**1**
e-MeOH (ethanol CO_2 + renewable power)		$0.072	**1**
e-MeOH (DAC and renewable power)		$0.096	**1**
b-MeOH (miscanthus)		$0.040	**3**
b-MeOH (corn stover)		$0.040	**3**
b-DME (miscanthus)		$0.046	**2**
b-DME (corn stover)		$0.046	**2**
f-DME (natural gas)		$0.022	**5**
b-LNG (landfill gas)		$0.029	**4**
e-LNG (ethanol CO_2 and grid power)		$0.067	**1**
e-LNG (DAC and grid power)		$0.082	**1**
e-LNG (ethanol CO_2 and renewable power)		$0.074	**1**
e-LNG (DAC and renewable power)		$0.089	**1**
Grid electricity (current)	**Battery electric**	$0.058	**1**
100% renewable electricity		$0.064	**1**

To put these figures into perspective, bulk carriers in the Great Lakes region provided an estimated 85 billion dwt-nm of transport activity in 2021. With a baseline TCO of $0.0015 per dwt-nm for bulk carriers, it equates to about $130 million in operating costs. In contrast, fueling the entire bulk carrier fleet using a fuel and power option designated as “fair” in cost terms, such as ICE powered by methanol derived from miscanthus at $0.0034 per dwt-nm, would roughly double that cost to $290 million annually. A fuel and power option with “poor” economics like ICE e-LNG derived from DAC and renewable power, at $0.0079 per dwt-nm, would cost about $670 million annually.

As shown, most synthetic fuels were estimated to carry a substantial cost premium of more than 3 times the MGO baseline. DME and methanol derived from cellulosic feedstocks (miscanthus and corn stover) had somewhat better cost performance, with methanol having somewhat better economics than DME. Biodiesel and renewable diesel had fair economic performance at less than twice the cost of the MGO baseline. The best economic performance was provided by “gray” synthetic fuels derived from fossil fuels; note that those fuels also had the worst life-cycle emissions performance and were worse than MGO. Bio-LNG from landfill gas showed both good economic and emissions performance when used in a low-methane-slip engine, but it had only fair compatibility and feedstock availability (see below).

Applicability analysis

Bulk carriers, chemical tankers, and tugs are the biggest fuel consumers and emission contributors in GL-SLS region, accounting for 75% of the total fuel consumption. Here the focus is on these three types of ships and estimate their feasibility to deploy LH_2 fuel cell and battery electric propulsion options. Table 30 shows the leg attainment rate (LAR)[22] of bulk carriers, chemical tankers, and tugs on legs completely within the GL-SLS region if powered by LH_2 fuel cell or battery.[23] At the leg level, the LH_2 fuel cell demonstrated high applicability for all three ship types at over 98%. The battery electric power option looked reasonably applicable, especially for the tugs.

Table 30. Leg attainment rate of key ship operations within the GL-SLS region in 2021

Ship class	Number of legs	Average leg length (km)	Leg attainment rate			
			LH_2 fuel cell	Battery electric at charging rate		
				1 MW	3 MW	5 MW
Bulk carrier	9764	608	99.9%	49.0%	52.8%	54.5%
Chemical tanker	1073	334	99.9%	63.4%	67.8%	71.2%
Tug	9226	210	98.1%	75.6%	77.2%	77.7%

Fuel consumption will vary by leg length, with longer legs that are more difficult to attain typically consuming more fuel. Thus, the LAR alone cannot perfectly measure the applicability of a given fuel or power option. Therefore, the leg fuel consumption attainment rate (LFAR), which equals the fuel consumption of attained legs divided by fuel consumption of all legs (Table 31), was also calculated. As expected, LFAR is lower than LAR for battery-electric option, which reflects that the longer legs that consume more fuel are hard to attain. As measured using LFAR perspective, battery-electric ships would not be generally applicable to GLSLS shipping in 2021.

---

[22] As described in the Methods section, LAR only measures the share of legs that can be attained by a given fuel and power combination, without consideration of how much fuel is used on that leg. LFAR, in contrast, accounts for the fact that the longest legs that will be most difficult to attain will also consume the most fuel. For that reason, LFAR is used as a metric to measure applicability.

[23] LAR here only represents the activity inside the GL-SLS, which means only legs falling completely within the GL-SLS region. Legs which fall partially outside of that region were excluded because hydrogen and/or electric infrastructure may not be guaranteed, especially on deep sea routes.

Table 31. Leg fuel consumption attainment rate of key ship operations in GL-SLS in 2021

Ship class	Number of legs	Average leg length (km)	Leg fuel consumption attainment rate			
			LH_2 fuel cell	Battery electric at charging rate		
				1 MW	3 MW	5 MW
Bulk carrier	9764	608	98.6%	17.9%	19.8%	20.8%
Chemical tanker	1073	334	97.2%	31.8%	36.5%	40.3%
Tug	9226	210	76.9%	17.4%	18.7%	19.5%

Table 32 summarizes the resulting applicability scores for battery electric and hydrogen fuel cell ships. Given the relatively short average voyage length in the GL-SLS region, the lower energy density of alternative marine fuels should not be a major barrier to regional adoption. LH_2 fuel cell ships achieve very good applicability to the GL fleet, while electric ships are judged to provide poor (2) to good (4) applicability, depending on the analysis year. Because other fuel types provide higher energy density than liquid hydrogen, all other fuel pathways were assigned an applicability score of 5 in the analysis.

Table 32. Applicability score for battery electric and LH_2 fuel cell ships, 2021 to 2050.

Fuel and power option	Charging scenario (MW)	Year			
		2021	2030	2040	2050
Battery electric	1 MW	2	2	3	3
	3 MW	2	3	3	3
	5 MW	2	3	3	4
	Battery swapping	–	3	4	4
LH_2 fuel cell		5			

QUALITATIVE ANALYSIS

The compiled results of the qualitative analysis are shown in Table 33. A wide range of current compatibility scores were assessed, ranging from complete compatibility (biodiesel, renewable diesel, FT diesel, and DME), to medium compatibility (methanol and LNG) to low compatibility (liquid hydrogen and electricity). Many fuels ranked well in terms of feedstock availability owing to the relatively modest energy demands of GL shipping. Alternative fuels generated from common residues (corn stover), industrial gases (ethanol CO_2), fossil fuels, and grid electricity received the highest ranking on feedstock availability. Synthetic fuels derived from 100% renewable electricity and those sourcing carbon from DAC had moderate feedstock availability rankings. Used cooking oil, which is already in high demand in other transport sectors, is ranked with the lowest feedstock availability.

On technological maturity, bio- and renewable diesel, fossil-fuel derived synthetic fuels, landfill gas, and grid electricity rank as the highest in terms of technological maturity. FT fuels, e-LH_2 and e-ammonia, synthetic fuels with carbon sourced from biomass, and 100% renewable electricity ranked as moderately mature. Less mature fuels included biological FT fuels and synthetic fuels relying upon DAC. In terms of risks, biodiesel, renewable diesel, and FT diesel were associated with low risks. Methanol and LNG had moderately positive risk profiles, while DME, ammonia, and hydrogen were viewed as having average to poor risk performance.

Table 33. Qualitative variable summary by fuel option, 2021

Fuel pathway	Primary propulsion option	Variable			
		Compatibility	Feedstock availability	Technological maturity	Risks
Biodiesel (soybean oil)	ICE	5	4	5	5
Renewable diesel (used cooking oil)		5	1	5	5
b-FT diesel (miscanthus)		5	4	3	5
b-FT diesel (corn stover)		5	5	3	5
e-FT diesel (ethanol CO_2 and grid power)		5	5	4	5
e-FT diesel (DAC CO_2 and grid power)		5	4	3	5
e-FT diesel (DAC CO_2 and renewable power)		5	3	3	5
e-FT diesel (ethanol CO_2 and renewable power)		5	4	4	5
f-LH_2 (gray)	Fuel cell	1	5	5	2
f-LH_2 (blue)		1	5	4	2
e-LH_2 (grid)		1	5	4	2
e-LH_2 (green)		1	4	4	2
f-NH_3 (gray)	ICE	1	5	5	3
e-NH_3 (grid)		1	5	5	3
e-NH_3 (green)		1	4	4	3
f-MeOH		3	5	5	4
e-MeOH (ethanol CO_2 and grid power)		3	5	4	4
e-MeOH (DAC and grid power)		3	4	3	4
e-MeOH (DAC and renewable power)		3	3	3	4
e-MeOH (ethanol CO_2 and renewable power)		3	4	4	4
b-MeOH (miscanthus)		3	4	3	4
b-MeOH (corn stover)		3	5	3	4
b-DME (miscanthus)		5	4	3	3
b-DME (corn stover)		5	5	3	3
f-DME		5	5	5	3
b-LNG (landfill gas)		3	3	5	4
e-LNG (ethanol CO_2 and grid electricity)		3	5	4	4
e-LNG (DAC and grid electricity)		3	4	3	4
e-LNG (DAC and renewable power)		3	3	3	4
e-LNG (ethanol CO_2 and renewable power)		3	4	4	4
Grid electricity (current)	Battery electric	1	5	5	3
100% renewable electricity		1	4	4	3

Figure 24 provides a radar chart summarizing the outcomes of the baseline assessment. Results are shown for the drop-in diesel replacements (top left), ammonia and hydrogen pathways (top right), methanol and LNG (left and right in the middle row, respectively), DME (bottom left) and direct electrification (bottom right). Biodiesel, renewable diesel, and FT diesel showed significant diversity in the results, with both emission performance and feedstock availability varying from very poor to very good depending on feedstock. In contrast, risks, compatibility, and applicability were very good for these drop-in fuels. Cost performance ranged from very poor (e-fuels) to fair (biodiesel and renewable diesel), while technological maturity ranged from fair to good.

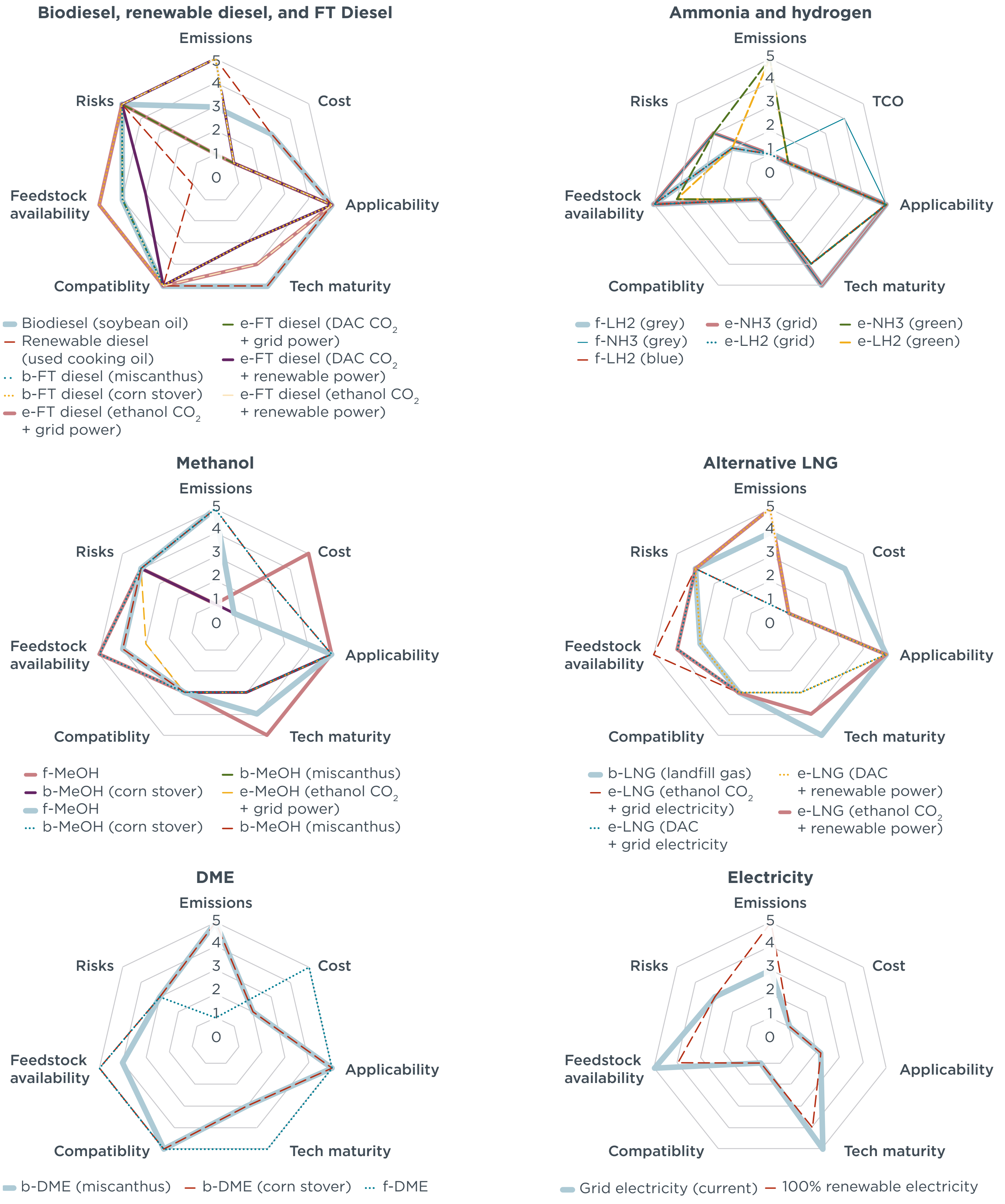


Figure 24. Radar charts for fuel and power options, baseline assessment

For ammonia and hydrogen, neither of which contain carbon but require substantial energy for production, the baseline assessment was sensitive to the input energy source. Emissions performance was either very good or very poor, depending on whether renewable electricity or fossil fuel was used for production. Conversely, cost varied from very poor to good, respectively. All fuels assessed were scalable (good or very good on feedstock availability) and present some safety concerns (poor to fair on risks), but ranked good to very good on technological maturity.

Methanol demonstrated commonality across several indicators, including risks (good), compatibility (fair), and applicability (very good). Both feedstock and technology maturity were fair to very good, whereas cost and emissions varied widely and were generally either very poor or very good depending on the feedstock and process energy used. One fuel, methanol produced from corn stover, provided the best overall performance, receiving a fair or better score all indicators and very good for three (emissions, feedstock availability, and applicability).

On alternative LNG, substantial commonality can be seen across fuels. Fossil LNG is an established fuel in international shipping, with few safety concerns, widespread applicability, and fair to very good technological maturity. Compatibility is fair due to the commercial availability of dual-fuel engines. However, the cost of producing alternative LNG is currently very high, and emissions reductions can only be ensured if a fuel is produced by additional renewable power and when used in a low-methane-slip engine. A notable exception here is bio-LNG derived from landfill gas, which receives good or very good scores on most metrics.

Like other fuels, there is a clear distinction between DME derived from biological feedstocks and DME produced using natural gas. DME derived from both miscanthus and corn stover rank very good on emissions, applicability, and compatibility, fair on risks and technological maturity, but poor on cost. Fossil derived DME excels in most categories but is very poor on emissions and fair on risks.

The final radar chart, for electricity (bottom right), provides a baseline negative assessment for direct electrification. Battery electric ships powered by either grid electricity or 100% renewable power struggle in terms of cost, applicability, and compatibility. Shifting from grid electricity to renewable electricity reduces the feedstock availability and technological maturity scores somewhat but improves the emissions performance from fair to very good. Note, however, that direct electrification of tugs was more promising, with better leg attainment rates for tugs compared to bulk carriers and chemical tankers, even at relatively low battery electric charging rates.

PROJECTION OF ALTERNATIVE FUELS AND POWER OPTIONS

KEY FINDINGS

- Fuel and power options with poor emissions performance continue to emit more on a life-cycle basis than the MGO baseline through 2050, whereas fuels derived from biomass residues and renewable power provide the largest lifecycle emission reductions.
- The economics of most alternative fuel and power options improve significantly through 2050, although they are expected to remain more costly than fossil fuels. Fossil-fuel derived alternative marine fuels continue to have the lowest TCO through 2050, but as previously noted demonstrate the worst emissions performance on a life-cycle basis.

- The compatibility of future fuel and power options should improve over time as ships, their fuel systems, and fueling infrastructure evolve to service alternatives to MGO and HFO. The compatibility of hydrogen improves from very poor to fair, while ammonia and electricity improve from very poor to good by 2050.
- The remaining four variables—applicability, feedstock availability, technological maturity, and risks—are broadly consistent with the conclusion that a variety of fuel and power options will be suitable for GL shipping.

Following this baseline assessment, the results were projected out to 2030, 2040, and 2050. Scores on two variables—emissions and applicability—are largely stable over the period studied. Fuel and power options with poor emissions performance continue to emit more on a life-cycle basis than the MGO baseline through 2050, while fuels derived from biomass residues and renewable power provide the largest life-cycle emission reductions. Minor reductions in the GHG intensity of grid-derived synthetic fuels are seen as the power sector adopts increasing shares of renewable energy, but overall, those fuels remain GHG intensive. As noted in the discussion of applicability, most fuels assessed are widely applicable to GL shipping, with the exception of electricity. However, the applicability of battery-electric ships improves from poor to fair in 2030 and to good in 2050 as battery energy density improves and charging rates increase (see Table 32).

In contrast, the economics of most alternative fuel and power options improve noticeably over the study period (see Appendix D), although they remain more costly than current fuels. The TCO of most synthetic fuels improves from very poor (300%+ the MGO baseline) to fair (200%+ the MGO baseline), with the exception of DAC-derived fuels and FT diesel, which continue to struggle from poor economics. The TCO of battery electric ships improves somewhat from very poor to fair for grid-derived electricity. Bio-derived feedstocks demonstrate the best economics of alternative fuels, achieving good to very good economic performance by 2050. Fossil-fuel derived alternative marine fuels continue to have the lowest TCO through 2050, but as previously noted demonstrate the worst emissions performance on a life-cycle basis.

Compatibility scores likewise improve over time as ships, their fuel systems, and fueling infrastructure evolve to service alternatives to MGO and HFO. The compatibility of hydrogen improves from very poor to fair, while ammonia and electricity improve from very poor to good from the baseline assessment to 2050. E-fuels improve from fair to very good, and LNG improves from fair to good. Other drop-in fuels remain very good throughout the entire period (see Table 34).

The remaining four variables—applicability (Table 32), feedstock availability (Table 35), technological maturity (Table 36), and risks (Table 37)—are also consistent with the conclusion that a variety of fuel and power options will be suitable for GL shipping. Feedstock availability is anticipated to be very good in 2050 for all fuels, with the exception of miscanthus-derived fuels (good), landfill gas (fair), and UCO (very poor). All fuel and power combination pathways are expected to achieve good or very good tech maturity scores in 2040 as demonstration projects mature and ship owners, operators, and crew gain more familiarity with the options. Finally, risks are expected to be mostly addressed by 2030, with most fuels achieving the best risk score in 2050.

Table 34. Compatibility scores by fuel, 2021 to 2050

Fuel pathway	Primary propulsion option	Variable			
		2021	2030	2040	2050
Biodiesel (soybean oil)	**ICE**	5	5	5	5
Renewable diesel (used cooking oil)		5	5	5	5
b-FT diesel (miscanthus)		5	5	5	5
b-FT diesel (corn stover)		5	5	5	5
e-FT diesel (ethanol CO_2 and grid power)		5	5	5	5
e-FT diesel (DAC CO_2 and grid power)		5	5	5	5
e-FT diesel (DAC CO_2 and renewable power)		5	5	5	5
e-FT diesel (ethanol CO_2 and renewable power)		5	5	5	5
f-LH_2 (gray)	**Fuel cell**	1	1	2	3
f-LH_2 (blue)		1	1	2	3
e-LH_2 (grid)		1	1	2	3
e-LH_2 (green)		1	1	2	3
f-NH_3 (gray)		1	2	3	4
e-NH_3 (grid)		1	2	3	4
e-NH_3 (green)		1	2	3	4
f-MeOH	**ICE**	3	3	4	5
e-MeOH (ethanol CO_2 and grid power)		3	3	4	5
e-MeOH (DAC and grid power)		3	3	4	5
e-MeOH (DAC and renewable power)		3	3	4	5
e-MeOH (ethanol CO_2 and renewable power)		3	3	4	5
b-MeOH (miscanthus)		3	3	4	5
b-MeOH (corn stover)		3	3	4	5
b-DME (miscanthus)		5	5	5	5
b-DME (corn stover)		5	5	5	5
f-DME		5	5	5	5
b-LNG (landfill gas)		3	3	4	4
e-LNG (ethanol CO_2 and grid electricity)		3	3	4	4
e-LNG (DAC and grid electricity		3	3	4	4
e-LNG (DAC and renewable power)		3	3	4	4
e-LNG (ethanol CO_2 and renewable power)		3	3	4	4
Grid electricity_current	**Battery electric**	1	2	3	4
100% renewable electricity		1	2	3	4

Table 35. Feedstock availability scores by fuel, 2021 to 2050

Fuel pathway	Primary propulsion option	Variable			
		2021	2030	2040	2050
Biodiesel (soybean oil)	ICE	4	4	4	4
Renewable diesel (used cooking oil)		1	1	1	1
b-FT diesel (miscanthus)		4	4	4	4
b-FT diesel (corn stover)		5	5	5	5
e-FT diesel (ethanol CO_2 and grid power)		5	5	5	5
e-FT diesel (DAC CO_2 and grid power)		4	4	5	5
e-FT diesel (DAC CO_2 and renewable power)		3	3	4	5
e-FT diesel (ethanol CO_2 and renewable power)		4	4	5	5
f-LH_2 (gray)	Fuel cell	5	5	5	5
f-LH_2 (blue)		5	5	5	5
e-LH_2 (grid)		5	5	5	5
e-LH_2 (green)		4	4	4	5
f-NH_3 (gray)		5	5	5	5
e-NH_3 (grid)		5	5	5	5
e-NH_3 (green)		4	4	4	5
f-MeOH	ICE	5	5	5	5
e-MeOH (ethanol CO_2 and grid power)		5	5	5	5
e-MeOH (DAC and grid power)		4	4	5	5
e-MeOH (DAC and renewable power)		3	3	4	5
e-MeOH (ethanol CO_2 and renewable power)		4	4	5	5
b-MeOH (miscanthus)		4	4	4	4
b-MeOH (corn stover)		5	5	5	5
b-DME (miscanthus)		4	4	4	4
b-DME (corn stover)		5	5	5	5
f-DME		5	5	5	5
b-LNG (landfill gas)		3	3	3	3
e-LNG (ethanol CO_2 and grid electricity)		5	5	5	5
e-LNG (DAC and grid electricity		4	4	5	5
e-LNG (DAC and renewable power)		3	3	4	5
e-LNG (ethanol CO_2 and renewable power)		4	4	5	5
Grid electricity_current	Battery electric	5	5	5	5
100% renewable electricity		4	4	4	5

Table 36. Technological maturity scores by fuel and main power option, 2021 to 2050

Fuel pathway	Primary propulsion option	Variable			
		2021	2030	2040	2050
Biodiesel (soybean oil)	ICE	5	5	5	5
Renewable diesel (used cooking oil)		5	5	5	5
b-FT diesel (miscanthus)		3	4	4	4
b-FT diesel (corn stover)		3	4	4	4
e-FT diesel (ethanol CO_2 and grid power)		4	4	4	4
e-FT diesel (DAC CO_2 and grid power)		3	4	4	4
e-FT diesel (DAC CO_2 and renewable power)		3	4	4	4
e-FT Diesel (ethanol CO_2 and renewable power)		4	4	4	4
f-LH_2 (gray)	Fuel cell	5	5	5	5
f-LH_2 (blue)		4	4	4	5
e-LH_2 (grid)		4	4	4	5
e-LH_2 (green)		4	4	4	4
f-NH_3 (gray)		5	5	5	5
e-NH_3 (grid)		5	5	5	5
e-NH_3 (green)		4	4	4	5
f-MeOH	ICE	5	5	5	5
e-MeOH (ethanol CO_2 and grid power)		4	4	4	5
e-MeOH (DAC and grid power)		3	4	4	4
e-MeOH (DAC and renewable power)		3	3	4	4
e-MeOH (ethanol CO_2 and renewable power)		4	4	4	4
b-MeOH (miscanthus)		3	4	4	4
b-MeOH (corn stover)		3	4	4	4
b-DME (miscanthus)		3	4	4	4
b-DME (corn stover)		3	4	4	4
f-DME		5	5	5	5
b-LNG (landfill gas)		5	5	5	5
e-LNG (ethanol CO_2 and grid electricity)		4	4	4	4
e-LNG (DAC and grid electricity		3	4	4	4
e-LNG (DAC and renewable power)		3	4	4	4
e-LNG (ethanol CO_2 and renewable power)		4	4	4	4
Grid electricity_current	Battery electric	5	5	5	5
100% renewable electricity		4	4	5	5

Table 37. Risk scores by fuel and main power option, 2021 to 2050

Fuel pathway	Primary propulsion option	Variable			
		2021	2030	2040	2050
Biodiesel (soybean oil)	ICE	5	5	5	5
Renewable diesel (used cooking oil)		5	5	5	5
b-FT diesel (miscanthus)		5	5	5	5
b-FT diesel (corn stover)		5	5	5	5
e-FT diesel (ethanol CO_2 and grid power)		5	5	5	5
e-FT diesel (DAC CO_2 and grid power)		5	5	5	5
e-FT diesel (DAC CO_2 and renewable power)		5	5	5	5
e-FT diesel (ethanol CO_2 and renewable power)		5	5	5	5
f-LH_2 (gray)	Fuel cell	2	4	4	5
f-LH_2 (blue)		2	4	4	5
e-LH_2 (grid)		2	4	4	5
e-LH_2 (green)		2	4	4	5
f-NH_3 (gray)	ICE	3	4	4	5
e-NH_3 (grid)		3	4	4	5
e-NH_3 (green)		3	4	4	5
f-MeOH		4	5	5	5
e-MeOH (ethanol CO_2 and grid power)		4	5	5	5
e-MeOH (DAC and grid power)		4	5	5	5
e-MeOH (DAC and renewable power)		4	5	5	5
e-MeOH (ethanol CO_2 and renewable power)		4	5	5	5
b-MeOH (miscanthus)		4	5	5	5
b-MeOH (corn stover)		4	5	5	5
b-DME (miscanthus)		3	3	3	3
b-DME (corn stover)		3	3	3	3
f-DME		3	3	3	3
b-LNG (landfill gas)		4	4	4	4
e-LNG (ethanol CO_2 and grid electricity)		4	4	4	4
e-LNG (DAC and grid electricity		4	4	4	4
e-LNG (DAC and renewable power)		4	4	4	4
e-LNG (ethanol CO_2 and renewable power)		4	4	4	4
Grid electricity_current	Battery electric	3	5	5	5
100% renewable electricity		3	4	4	5

REGULATORY ASSESSMENT AND ANALYSIS

KEY FINDINGS

- The regulatory framework for most alternative fuel and power options for shipping is incomplete. International regulations are under development; flag states including the United States and Canada should continue participating in their development to prepare for developing interpretations and modified versions based on national circumstances.
- The Great Lakes region is an emission control area and subject to special emission requirements for NO_x and SO_x. All fuels investigated should be able to comply with the SO_x regulations because they contain little or no sulfur. There should be no challenges complying with NO_x regulations, provided exhaust aftertreatment technologies such as SCR remain appliable to new fuels.
- Engines intended to be installed onboard U.S. flagged vessels must comply with the emission requirements laid down in 40 CFR Part 1042 and 40 CFR Part 1043 and in addition to NO_x, limit hydrocarbons (HC), PM and carbon monoxide (CO). All fuels investigated should be able to comply with those requirements.
- Future regulations are expected to limit WTW GHG emissions. Regulation of WTW nitrous oxide (N_2O) and methane (CH_4) could potentially impact the uptake of ammonia and LNG, respectively.
- The regulatory framework for LNG is the most mature of those for alternative fuels but its applicability to the GL-SLS fleet depends on addressing release of CH_4 throughout its production cycle, including methane slip from marine engines.

INTRODUCTION

Transboundary GL-SLS management

The Great Lakes waterway is subject to unique management due to the transboundary nature of the Great Lakes between Canada and the United States. This binational waterway is co-governed and co-administered by the Canadian and U.S. governments. The International Joint Commission (IJC) is an independent binational organization established by both governments to jointly manage and protect lakes and river systems along the U.S./Canadian border. Most shared duties and responsibilities are outlined in the Boundary Waters Treaty, which was signed by Canada and the United States in 1909 (Clear Seas, 2023; International Joint Commission, 2016).

The International Joint Commission has two main responsibilities (International Joint Commission, 2023):

1. Approving projects that affect water levels and flows across the boundary
2. Investigating transboundary issues and recommending solutions

The activities of International Joint Commission include:

1. Regulating shared water uses
2. Improving water quality
3. Improving air quality
4. Investigating issues and recommending solutions

Administration of the GL/SLS is shared by two entities—Great Lakes St. Lawrence Seaway Development Corporation in the United States, a federal agency within the U.S. Department of Transportation, and the St. Lawrence Seaway Management Corporation in Canada, a not-for-profit corporation (Great Lakes St. Lawrence Seaway System, 2023).

Great Lakes St. Lawrence Seaway Development Corporation operates and maintains the St. Lawrence Seaway between the Port of Montréal and Lake Erie within the territorial limits of the United States. The St. Lawrence Seaway Management Corporation is a not-for-profit corporation responsible for the safe and efficient movement of marine traffic through the Canadian Seaway facilities, which consists of 13 of the 15 locks between Montréal and Lake Erie.

The two Seaway entities coordinate operational activities particularly with respect to rules and regulations, overall day-to-day operations, traffic management, navigation aids, safety, environmental programs, operating dates, and trade development programs.

Shipping vessels on the GL-SLS system belong to one of three categories:

1. U.S.-flag operators, whose vessels are documented under U.S. law and primarily serve U.S. ports,
2. Canadian-flag operators, whose vessels are documented under Canadian law and carry both domestic and binational commerce, and
3. Foreign-flag operators, whose vessels operate between Great Lake ports and overseas destinations.

Regulations for future energy options in the GL-SLS region

As this study is primarily focusing on future energy options in the GL-SLS region, this section discusses those energy options in detail. The future energy options have been categorized into nine fuel specific sections: diesel, biofuels, synthetic fuels, hydrogen, ammonia, methanol, dimethyl ether, liquefied natural gas, and electricity. This categorization was done to group the full list of fuels and match them with Table 2.

Note that diesel regulations are of special interest to the GL-SLS as the region falls under an emission control area (ECA). The Great Lakes region is also subject to special provisions for control of NO_x, SO_x, and PM emissions from marine engines and vessels (40 CFR Part 1043.95). Hence, diesel is also discussed in detail.

The future energy options have generally been categorized as requirements for the United States, Canada, IMO, IACS/Class Society regulations and regulatory analysis. Most flag states including the United States and Canada are already participating in the international rule development process for these future energy fuels and are learning from each other as regulations develop. A table showing a summary of regulations for future energy options in GL-SLS is listed in Table 38.

Table 38. Summary of regulations for future energy options in GL-SLS

Fuel type	Impact area	U.S. regulations (EPA and GL applicability)	Canadian regulations (Transport Canada/ Provincial Regulations)	IMO regulations	IACS/Class regulations (based on the selected Class Society)
Diesel/ marine fuel oil	All emissions	40 CFR 1043 and 1042	Canada Shipping Act Vessel Pollution and Dangerous Chemicals Regulations	IMO MARPOL Annex VI	
	NO_x and HC	40 CFR 1043.95 - Great Lakes provisions 40 CFR 1042.101 (Tier 1 and 2) 40 CFR 1042.104 (Tier 3) 40 CFR 1043.60	Vessel Pollution and Dangerous Chemicals Regulations (Subsection 110.3(4)) Canada Declaration on Zero Emission Shipping by 2050 North American Emission Control Area (NA-ECA).	NO_x Technical Code	
	SO_x and fuel sulfur limits		Regulations Amending the Vessel Pollution and Dangerous Chemicals Regulations Canadian North America ECA	Revised MARPOL Annex VI – Resolution MEPC.176(58) Regulation 14 of MARPOL Annex VI, Emission Control Areas (ECA)	
	Particulate matter (PM)			1042.101, Table 1 and Table 2 Indirectly Regulated b Regulation 14 to Annex VI for Sulfates	
	CO			IMO MARPOL Annex VI	
	GHG emissions		Vessel Pollution and Dangerous Chemicals Regulations	IMO MARPOL Annex VI- MEPC 80 Updates Energy Efficiency Design Index (EEDI) reporting Energy Efficiency Existing Ship Index (EEXI) Carbon Intensity Indicator (CII)	
Biofuels	Fuel standard			MARPOL Annex VI- ISO Standard 8217	
	SO_x			IMO MARPOL Annex VI	
	Safety standard			IMO International Safety Management Code (ISM)	
	NO_x			MEPC.1/Circ.795/Rev.6. NO_x Technical Code	
Synthetic fuel	Fuel standard			ISO 8217:2017	
	Safety standard			IMO CCC sub-committee [under development]	
Hydrogen (liquefied)	Safety standard			CCC 8/3, Annex 9	Class specific requirements
Ammonia	Safety standard			SOLAS Chapter II-2 Regulation 4.2.1 IGF Code[24] IGC Code, Chapter 17 IBC Code	Class specific requirements
	Alternative design			Part A, 2.3 of the IGF Code SOLAS regulation II-1/55 MSC.1/Circ.1212 SOLAS Chapters II-1 and III (2006) Flag Administration Approval IMO GISIS database IMO MSC.1/Circ.1455	Class specific requirements
Methanol	Safety standard			IMO MSC.1/Circ.1621	Class specific requirements IACS Recommendation No.146
	Flag administration			IGF Code, Risk Assessment (HAZID, HAZOP, FMEA) Case-by-case basis	
Dimethyl ether	Fuel standard			DME can be blended with MGO or MGO with minimal engine modifications at low blends	
	Safety standard			Regulatory requirements may closely align with those of biofuels at low blends.	
Natural gas (liquefied)	Safety standard	USCG safety alerts and bulletins specific to liquefied gas as fuel	TC Requirements for Vessels Using Natural Gas as Fuel	IGF Code, Part A-1 SOLAS Part G Chapter II-1	IACS UR G IACS UI GF Class specific requirements
	Alternative design			IGF Code, Section 2.3 SOLAS Regulation II-1/55	Class specific requirements
	Exhaust emissions			IMO LCA guidelines [under development, available in draft format]	
Electricity	Regulatory requirements			Case-by-case basis	Class specific requirements Novel technologies

---

[24] More information at https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx

Overview of regulatory analysis by fuels

Existing international and domestic regulations provide opportunities for and barriers to the use of credible alternative fuel and powering options for Great Lakes shipping. Under each fuel type, there is discussion of how the use of the fuel in different powering options will address the regulatory requirements for air pollution and GHGs. When discussing WTW GHG emissions, the main source is an analysis of GREET (Argonne National Laboratory, 2022), except where indicated.

A note on GHG regulations: The IMO currently limits the tank-to-wake (TTW) CO_2 intensity of ships under the Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing ship Index (EEXI), and it ranks the operational CO_2 intensity of ships under the carbon intensity indicator (CII). The IMO is currently developing LCA guidelines to allow the organization to incorporate non-CO_2 GHGs, such as CH_4 and N_2O, into its regulations. One regulation that is being developed is a GHG fuel standard, which will set limits on the allowable WTW CO_2e intensity of marine fuels. The GHG fuel standard is scheduled to be developed between now and 2025, with a potential entry into force in 2027.

The content of this section is summarized in Table 39.

Table 39. Summary of expected environmental performance by fuel compared with marine gas oil

Fuel	Air pollution				GHGs	
	SO_x	NO_x	CO	PM	TTW	WTW
Diesel alternatives (bio and renewable)	+	o	o	+	o	+ (soy bio) ++ (UCO renewable)
Synthetic FT diesel	+	o	o	+	o	++ (miscanthus/ corn stover gasification) -- (captured CO_2 and grid elec.) ++ (captured CO_2 and renew. elec.)
Hydrogen	++	++ FC o ICE	++	++	++	++ renewable electricity - SMR of natural gas o SMR of natural gas with CCS -- grid electricity
Ammonia	++	++ FC o ICE	++ FC + ICE	++ FC + ICE	++ FC + ICE (N_2O?)	++ renewable electricity -- SMR of natural gas -- grid electricity
Methanol	++	++ FC o ICE	++ FC + ICE	++	++ FC o ICE	++ DAC and renewable electricity ++ (miscanthus/corn stover gasification) o SMR of natural gas -- ethanol CO_2 & grid elec. -- DAC CO_2 & grid elec.
Dimethyl ether	++	++ FC o ICE	++ FC + ICE	++FC + ICE	++ FC o ICE	o SMR of natural gas ++ (miscanthus/corn stover gasification)
LNG	++	++ FC + LPDF o HPDF	-	++	++ FC + HPDF - LPDF	-- ethanol CO_2 and grid electricity -- DAC CO_2 and grid electricity ++ DAC and renewable electricity (and LPDF 4-stroke) + landfill gas (LPDF) ++ landfill gas (HPDF)
Electricity	++	++	++	++	++	+ grid electricity ++ renew. elec.
++ much better than MGO				FC: fuel cell		
+ better than MGO				ICE: internal combustion engine		
o same as MGO				LPDF: low-pressure dual-fuel ICE		
- worse than MGO				HPDF: high-pressure, dual-fuel ICE		
-- much worse than MGO						

DETAILED ASSESSMENT AND ANALYSIS OF SPECIFIC FUELS

DIESEL

United States regulations

U.S. Environmental Protection Agency and Clean Air Act

The U.S. Environmental Protection Agency (EPA) and U.S. Coast Guard are authorized to administer MARPOL Annex VI by the Act to Prevent Pollution from Ships.

U.S. flagged vessels are subject to engine requirements under the Clean Air Act. The U.S. EPA categorizes marine engines as follows under Clean Air Act regulations in 40 CFR part 1042:

» Category 1: Displacement <7.0 liter/cylinder

» Category 2: Displacement from 7.0 and above but <30 liter/cylinder

» Category 3: Displacement ≥30 liter/cylinder

Engines intended to be installed onboard U.S. flagged vessels must comply with the emission requirements laid down in 40 CFR Part 1042 and 40 CFR Part 1043 and in addition to NO_x, limit hydrocarbons (HC), PM, and carbon monoxide (CO). Category 1 and 2 engines must comply with the emission tiers in accordance with Tables 1, 2, 3, 4 of 40 CFR Part 1042.101. Category 3 engines must comply with Table 1 of 40 CFR Part 1042.104, which is equivalent to the IMO NO_x emission levels, except that the CFR also sets a HC limit of 2.0 g/kWh and a CO limit of 5.0 g/kWh under Tier 2/II and Tier 3/III.

Table 2 of Part 1043.60 specifically covers the fuel oil sulfur limits in accordance with the requirements of Regulation 14 of MARPOL Annex VI. The NO_x emission limits in Regulation 13 of MARPOL Annex VI are applicable to U.S. flagged ships trading in international waters and foreign flag ships while operating in the U.S. ECA areas. The EPA has four NO_x emission tiers written in Arabic numerals (e.g., Tier 1, 2, 3 & 4) compared to IMO MARPOL, which has three NO_x emission tiers written in Roman numerals (e.g., Tier I, II & III).

Engines on U.S. flagged vessels that do not operate in waters subject to the jurisdiction of another country may comply with the EPA's domestic emission standards in lieu of compliance with Annex VI.

Great Lakes provisions

The provisions of 40 CFR 1043.95 apply to vessels operating exclusively in the Great Lakes. The list of exemptions and the subject conditions are listed within this regulation. Serious economic hardship and sulfur limits are also addressed in this regulation.

USCG Work Instruction: Exercise of Enforcement Discretion with regard to MARPOL Annex VI Regulation 13.5.1.2

On October 17, 2018, the United States Coast Guard (USCG) released a Work Instruction (WI) to clarify how it will enforce Regulation 13.5.1.2 of Annex VI due to the unavailability of Tier III engines of the size required to comply with this regulation. The USCG will defer enforcement of this regulation on qualified vessels and engines. In lieu of meeting MARPOL Annex VI Tier III performance standards, engines with rating of 130 kW to 600 kW installed on vessels with keel laying date on or after January 1, 2016, may instead be accepted by the U.S. government provided they meet the Clean Air Act Tier 3 requirements under 40 CFR part 1042.

Such certified engines are available and will be accepted in the short term if available engines of the required size certified to meet MARPOL Annex VI Tier III are demonstrated to be unsuitable. This work instruction is applicable to U.S.-flagged and foreign-flagged vessels.

EPA guidance

EPA also provides guidance for compliance issues for the North American and U.S. Caribbean Sea ECA. Please refer to the following web pages for the relevant EPA policy and guidance documents.[25]

- Guidance Documents related to Anne VI Standards for Marine Diesel Engines and Fuel
- Certification for Marine Compression-Ignition (CI) Engines
- EPA Emission Standards for Nonroad Engines and Vehicles

Canadian regulations

A Canadian ship operating exclusively in Canadian waters or fishing zones must meet applicable requirements of the Canadian Oil Pollution Prevention Regulations, including carrying a Canadian Oil Pollution Prevention (COPP) Certificate. The COPP Certificate indicates compliance with applicable provisions of Canadian regulations. The COPP does not indicate that a ship complies with applicable requirements of MARPOL 73/78 Annex I.

A Canadian ship operating internationally must comply with the requirements of both the Canadian regulations and MARPOL 73/78 Annex I and must carry an International Oil Pollution Prevention (IOPP) Certificate certifying compliance with applicable requirements of Annex I. Convention ships are not required to carry a COPP Certificate if the vessel is in compliance with the international regulations and the MARPOL certificate is valid.

Canadian vessels operating in the Canadian waters of the Great Lakes and the St. Lawrence River west of Anticosti Island are to be equipped with 5 parts per million oily bilge alarms. These alarms shall comply with TP 12301: Standard for 5 ppm Bilge Alarms for Canadian Inland Waters.

IMO regulations

The primary international regulatory mechanism for controlling air pollution from ships is IMO MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships (American Bureau of Shipping, 2023a). MARPOL Annex VI was adopted by the Protocol of 1997 to MARPOL and entered into force on 19 May 2005; the conference also adopted the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines (American Bureau of Shipping, 2020a).

Regulations 13 (NO_x) and 14 (SO_x) of MARPOL Annex VI contain provisions for countries to apply to the IMO for designation of emission control areas (ECAs) to further reduce harmful emissions from ships operating in their coastal waters. IMO approved two ECAs relevant to the United States including the North American ECA

---

[25] Relevant documents can be found at: https://iaspub.epa.gov/otaqpub/; https://www.epa.gov/regulations-emissions-vehicles-and-engines/guidance-documents-related-annex-vi-standards-marine; https://www.epa.gov/ve-certification/certification-marine-compression-ignition-ci-engines; and https://www.epa.gov/emission-standards-reference-guide/epa-emission-standards-nonroad-engines-and-vehicles (for further information on EPA emission standards for nonroad engines and vehicles).

and U.S. Caribbean Sea ECA (Figure 25). These later ECAs include NO_x Tier III emission restrictions in addition to the SO_x emissions restrictions. The NO_x Tier III emissions restrictions were enforced from January 1, 2016, in these two ECAs. It should be noted that MARPOL Annex VI does not specifically limit PM, but PM is reduced by regulating the sulfate portion of PM formation through the fuel sulfur content requirements of Regulation 14 to Annex VI.

Figure 25. The North American ECA– © ABS (American Bureau of Shipping, 2023a)

Beginning January 1, 2015, ships that operate in an ECA are required to use ultra-low sulfur oil (e.g., ULSFO-DM or ULSFO-RM) fuel with a sulfur content no greater than 0.10%. Alternatively, ships can use higher sulfur HFO if they use an approved EGCS, also known as a scrubber.

IMO regulations do not apply to the entire GL-SLS, which is divided into two parts: the freshwater Great Lakes and the partially saltwater St. Lawrence River, which constitutes an IMO emission control area downriver from Montréal. All ships navigating this ECA must comply with the stricter NO_x emission standards and the IMO-imposed 0.1% cap on fuel SO_x content. This situation is unique because the Great Lakes constitute an inland waterway system divided by the Canada-U.S. border, with differing Canadian and U.S. regulations and initiatives (IMAR & GSGP, 2022).

IACS/Class regulations

Typically, IACS and Class regulations for diesel are similar to IMO requirements but these vary by Class Society. Since the scope of the study is not to delve into each class society regulations, it is expected that vessels when classed under a class society adhere to those requirements.

Regulatory analysis

In the diesel category, diesel is used as the baseline and is expected to meet all regulations within the current regulatory framework.

Air pollution: Any of these fuels will be able to comply with existing international and domestic air pollution regulations.

GHGs: These fuels are the baseline for GHGs on a TTW basis.

BIOFUELS

Biofuel is derived from biomass which includes cooking oils, fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE), straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), glycerol, and other biomass-to-liquid type products (American Bureau of Shipping, 2021b; European Maritime Safety Agency, 2023a). Some biofuels are functionally equivalent to petroleum fuels and therefore compatible with existing equipment without system modifications are known as drop-in biofuels.

United States regulations

There are no specific U.S. regulations in the Great Lakes regions for biofuels. However, as renewable diesel regulations exist and are applicable in the California region, these may be referenced. The U.S. Coast Guard does not allow fuel oil with a flashpoint of less than 60 °C (140 °F) to be used in marine vessels; This needs to be closely considered when using renewable diesel.

Canadian regulations

There are no specifically identified Canadian regulations for biofuel use in the GL-SLS region.

IMO regulations

Liquid biofuels, or biofuel blends, intended to replace conventional residual or distillate fuel oils are to meet the SOLAS requirement for a flashpoint of no less than 60 °C. The IMO *International Safety Management Code* (ISM Code) (IMO, 2018) provides an international standard for the safe management and operation of ships and to prevent pollution. With respect to biofuels, the fuel supplier's fuel specifications, Bunker Delivery Note (BDN), MSDS sheets, equipment manufacturer's recommendations, and industry stakeholder guidelines provide the basis for operators to undertake their ISM Code obligations. While there are some risks to equipment and operation with certain biofuels, the drop-in nature and similarity to conventional residual or distillate fuels makes application relatively simple:

- Operation on distillate biofuels containing up to 7% FAME: The grades detailed by ISO 8217:2017 are permitted and would not require NO_x recertification or any onboard NO_x emissions measurements to be undertaken for engines already certified to Regulation 13.
- For blends between 7% and 30% (inclusive) biofuel: An assessment of NO_x impacts is not required under the provisions of MEPC.1/Circ.795/Rev.6.
- For blends of more than 30% biofuel: If biofuel can be burned without changes to the NO_x critical components or settings, an assessment of NO_x impacts is not required.

Most marine 2-stroke slow speed engines and larger 4-stroke medium speed engines, which are designed for a broad range of distillate and residual marine fuels, can already accommodate a wide variation in fuel quality and have the span of NO_x performance criteria associated with the engines' adjustable features defined in the NO_x Technical File. These engines are likely able to burn biofuels without any changes to the NO_x critical components or settings.

For biofuel blends of 30% by volume or more where the engines' NO_x critical components, settings, or operating values in the approved Technical File need to change to use that fuel, NO_x emissions verification will be required to maintain the ship's IAPP certificate. The emissions can be measured by an onboard simplified measurement method in accordance with 6.3 of the NO_x Technical Code 2008,[26] the direct measurement and monitoring method in accordance with 6.4 of the NO_x Technical Code 2008, or by reference to relevant testbed testing. For the purposes of demonstrating compliance and as applicable to possible deviations when undertaking measurements on board, an allowance of 10% of the applicable limit may be accepted.

As part of the increased interest in the use of alternative fuels that reduce air pollutants and GHGs, MARPOL Annex VI has dealt with the use of biofuels through fuel oil quality standards while the ISO standard 8217 "Petroleum products — Fuels (class F) — Specifications of marine fuels" was modified in 2017 to widen tolerances for the use of biofuels in existing and new fuel oil grades.[27] In particular, biofuels are considered in the marine industry for their renewable qualities and reduced emissions from engines, primarily reduced SO_x, as evidenced by a 2020 International Council on Clean Transportation paper (Zhou et al., 2020). ISO 8217 states that FAME blend stock for DF grades is to meet the quality and testing specifications of either EN 14214 or ASTM D6751.

IACS/Class regulations

There are no specifically identified IACS/Class regulations for biofuel use in the GL-SLS region.

Regulatory analysis

In the biodiesel category, biodiesel made from soybean oil and renewable diesel made from UCO are considered. These fuels can be used in internal combustion engines.

Air pollution: Either of these fuels will be able to comply with existing international and domestic air pollution regulations. Because they are made from bio feedstocks, they will have lower sulfur content compared with diesel made from fossil fuels. That will make it easier for them to comply with fuel sulfur regulations than it will be for their fossil fuel counterparts. These fuels will also emit less particulate matter than fossil diesel fuel because burning them will emit fewer sulfate particles. For NO_x and THC, as well as CO, these fuels are not expected to face any additional challenges compared to their fossil fuel counterparts.

GHGs: These fuels will emit the same GHGs on a TTW basis as their fossil fuel counterparts and therefore will be controlled under existing international regulations that limit or rank the CO_2 intensity of ships, such as the EEDI, EEXI, and CII; however, on a WTW basis, their emissions will be much lower. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas soy-based biodiesel, which has been demonstrated on Great Lakes cargo vessels[28] is 56 gCO_2e/MJ (accounting for ILUC) and UCO-based renewable diesel is 14.3 gCO_2e/MJ. Using these fuels will enable the continued use of drop-in diesel fuel until GHG regulations become stringent enough that the WTW GHG intensity of soy-based biodiesel is disqualified. However, soy-based biodiesel could

---

[26] Text available at https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.177(58).pdf

[27] See https://www.iso.org/standard/64247.html

[28] CSL ships have run 75,000 hours on B100 soy-based biodiesel as of 2023: https://green-marine.org/stayinformed/news/csl-achieves-milestones-in-decarbonization-efforts/

still be blended into lower WTW GHG fuels, such as UCO renewable diesel. Eventually, even 100% UCO-based renewable diesel will not qualify if regulations require a 100% reduction in WTW GHG emissions from the fossil fuel baseline. For now, the most stringent WTW GHG intensity regulation is the FuelEU Maritime regulation, which would be applicable to ships sailing between the Great Lakes and the European Union.

SYNTHETIC FUELS

United States regulations

There are no specifically identified United States regulations for synthetic fuel use in the GL-SLS region.

Canadian regulations

There are no specifically identified Canadian regulations for synthetic fuel use in the GL-SLS region.

IMO regulations

Acceptance of lower flash points for fuel oils is an item of debate to IMO. Currently, the IMO has asked the Sub-Committee on Carriage of Cargoes and Containers (CCC) to consider how best to proceed with developing draft amendments to the International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels (IGF Code) that will address new safety provisions for ships using low-flashpoint oil fuels. There is recognition of the need for IMO requirements for such fuels, and it has been suggested that these provisions should cover an increased range of oil-based fossil fuels, liquid biofuels, synthetic fuels—and any mixture thereof—with flashpoints under 60 ˚C. However, this issue has yet to be finalized.

The IMO Data Collection System (DCS) requires ships with a size of 5,000 gt or more to report their fuel oil consumption, by fuel oil type, to their administration on an annual basis (Resolution MEPC.278(70)). The DCS does not currently explicitly require ships to report the nature of the fuel. For example, when using methanol, there is no requirement to report whether the fuel is fossil, biological, or synthetic.

IACS/Class regulations

There are no specifically identified IACS/Class regulations for synthetic fuel use in the GL-SLS region.

Regulatory analysis

In the synthetic diesel category, we assess bio FT diesel made from miscanthus or corn stover and e-FT diesel made from ethanol CO_2 and grid electricity; DAC CO_2 and grid electricity; and DAC CO_2 and renewable electricity. These fuels can be used in internal combustion engines.

Air pollution: Any of these fuels will be able to comply with existing international and domestic air pollution regulations. They will have lower sulfur content compared with diesel made from fossil fuels, making it easier to comply with fuel sulfur regulations than their fossil fuel counterparts. These fuels will also emit less PM than fossil diesel fuel because burning them will emit fewer sulfate particles. For NO_x and THC, as well as CO, these fuels are not expected to face any additional challenges compared to their fossil fuel counterparts.

GHGs: These fuels will emit the same GHGs on a TTW basis as their fossil fuel counterparts and therefore will be controlled under existing international regulations that limit or rank the CO_2 intensity of ships, such as the EEDI, EEXI, and CII; however, on a WTW basis, their emissions will be much lower, and even negative in some cases. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas bio FT diesel made from gasifying miscanthus or corn stover are -21.5 and -3.7 gCO_2e/MJ, respectively. For e-FT diesel made from ethanol CO_2 and grid electricity its WTW GHG intensity is 242 gCO_2e/MJ, primarily reflecting the GHG intensity of the grid electricity. This is followed by DAC CO_2 and grid electricity at 256 gCO_2e/MJ, again reflecting the GHG intensity of the grid electricity used to capture the CO_2, electrolyze water into hydrogen, and synthesize the fuel.

Finally, e-FT diesel made using DAC CO_2 and renewable electricity has WTW GHG emissions of just 2.3 gCO_2e/MJ. The fuels made from grid electricity will not be able to be used to meet WTW GHG regulations, given that they exceed the GHG intensity by more than two-and-a-half times. Using DAC and renewable electricity instead of grid electricity results in nearly zero WTW GHG emissions, making this a better pathway to use e-FT synthetic diesel for GHG compliance. Fuels made by gasifying miscanthus or corn stover have negative emissions, meaning they will comply with even the most stringent GHG regulations; they can also be blended into other fuels to help achieve GHG reduction requirements.

HYDROGEN (LIQUEFIED)

United States regulations

There are no specifically identified United States regulations for hydrogen fuel use in the GL-SLS region. Some relevant regulations for general hydrogen use are listed in Table 40.

Table 40. United States regulations on general use of hydrogen

United States
• NFPA 2 Hydrogen Technologies Code. Edition 2 • NIST Handbook 130, The U.S. National Work Group (USNWG) • U.S. 40 CFR Ch. I Subchapter J Part 370 Hazardous Chemical Release Reporting: Community Right-To-Know • U.S. 29 CFR Ch. XVII Part 1910 Subpart H: Occupational Safety and Health Standards: 103 Hydrogen • ASME B31.12-2019 Hydrogen Piping and Pipelines • ASME BPVC Section VIII Rules for Construction of Pressure Vessels. Division 1, Division 2-Alternative Rules and Division 3-Alternative Rules for Construction of High-Pressure Vessels • CGA S-1.1 Pressure Relief Device Standards – Part 1 – Cylinders for Compressed Gases & S-1.2 Pressure Relief Device Standards – Part 2 – Portable Containers for Compressed Gasses • CGA H-3: Standard for Cryogenic Hydrogen Storage • CGA G-5.4 Standard for Hydrogen Piping Systems at User Locations. • CGA G-5.5 Hydrogen Vent Systems

Canada regulations

There are no specifically identified Canadian regulations for hydrogen fuel use in the GL-SLS region.

IMO regulations

The regulatory landscape for liquefied hydrogen for use in marine vessels is currently in development at the IIMO. The CCC 8/3 document, "Report of the Correspondence Group on LPG, Hydrogen, low-flashpoint oil fuels and amendments to the IGF Code" provides insight that the development of guidelines for the safety of ships using hydrogen as fuel are under development (IMO, 2022). These hydrogen fuel guidelines are expected to follow the IGF Code structure and it was generally agreed that these guidelines should not be in conflict with the Guidelines for the safety of ships using fuel cell power installations (MSC.1/Circ.1647).[29]

Annex 9 of the CCC 8/3 document, "Draft Interim Guidelines for the safety of ships using Hydrogen as Fuel," acts as a precursor to understand the upcoming regulation. However, this draft version should not be construed as final or used to build hydrogen fueled vessels because it may undergo significant changes before it is eventually published.

Until the guidelines are finalized, the following standards, requirements, and guidelines act as bridges for those seeking to implement hydrogen as fuel on their vessels through the alternative design process and risk assessment philosophy of the IGF Code.[30] The MSC.1/Circ.1455, Guidelines for the Approval of Alternatives and Equivalents as Provided in Various IMO Instruments (2013) and MSC.1/Circ.1212, Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III (2006) are to be considered for equivalent arrangements. The Interim Recommendations for the carriage of liquefied hydrogen in bulk (MSC.420(97)) can also be referenced though are not directly applicable.

Hydrogen as fuel is expected to gain traction in the future due to an outcome of the MPEC 80 (Resolution MEPC.377(80)), the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, which increases the levels of ambition compared to the Initial 2018 Strategy (American Bureau of Shipping, 2021c; IMO, 2023c).

The levels of ambition in the 2023 IMO GHG strategy are as follows:

1. Carbon intensity of the ship to decline through further improvement of the energy efficiency for new ships: to review with the aim of strengthening the energy efficiency design requirements for ships
2. Carbon intensity of international shipping to decline: to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008
3. Uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to increase: uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, and striving for 10%, of the energy used by international shipping by 2030

---

[29] Available at https://www.gard.no/Content/33841081/cache=20220807173450/MSC.1-Circ_1647.pdf

[30] EMSA Report, Potential of hydrogen as fuel for shipping, https://emsa.europa.eu/publications/reports/item/5062-potential-of-hydrogen-as-fuel-for-shipping.html

4. GHG emissions from international shipping to reach net zero: to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around, i.e., close to, 2050, considering different national circumstances while pursuing efforts toward phasing them out as called for in the Vision consistent with the long-term temperature goal set out in Article 2 of the Paris Agreement.

In addition, there are two “indicative checkpoints” in the 2023 IMO GHG Strategy:

1. To reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008
2. To reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008

IACS/Class regulations

Class societies have published requirements and regulations for the use of hydrogen. A summary of those and additional class supporting documents is listed in Table 41.

Table 41. Class Society regulations and supporting documents

Class fuides and guidelines	Supporting class documents
• ABS Requirements for Hydrogen Fueled Vessels. • ABS Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels. • ABS Guide for Fuel Cell Power Systems for Marine and Offshore Applications. • Lloyd’s Register (LR) Classification of Ships Using Gases or Other Low-Flashpoint Fuels • Bureau Veritas (BV) Ships Using Fuel Cells. Rule Note NR 547 R01. • Det Norske Veritas (DNV) Handbook for hydrogen-fuelled shipping. • Korean Register (KR) Guidelines for Selection of Metallic Materials of Containment Systems for Alternative Fuels for Ships. • NKK (Nippon Kaiji Kyokai – ClassNK) Guidelines for Liquefied Hydrogen Carriers.	• ABS Sustainability Whitepaper Hydrogen as Marine Fuel. • NKK (Nippon Kaiji Kyokai – ClassNK) Guidelines for Ships Using Alternative Fuels. • Bureau Veritas (BV) Gas-Fuelled Ships.

Regulatory analysis

In the hydrogen category, there is liquefied hydrogen made from both fossil and nature sources of hydrogen. For fossil sources, gray and blue hydrogen is made from steam methane reforming (SMR) of natural gas without (gray) and with (blue) carbon capture and storage (CCS). For nature sources, there is hydrogen produced through electrolysis of water using either grid electricity or renewable electricity. Hydrogen can be used in internal combustion engines or fuel cells.

Air pollution: When used in a fuel cell, hydrogen emits no TTW air pollution. When used in an internal combustion engine, hydrogen results in NO_x emissions. Engines will need to be certified to IMO Tier III limits for use in the North American Emission Control area, and will likely require exhaust gas aftertreatment, such as selective catalytic reduction (SCR).

GHGs: These fuels emit zero GHGs on a TTW basis, meaning they will comply with any existing GHG regulation that limits only TTW emissions; however, on a WTW basis, their emissions differ depending on the source of hydrogen. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas hydrogen made using natural gas SMR has a WTW GHG intensity of 122 gCO_2e/MJ without CCS (i.e., gray) and 104 gCO_2e/MJ with

CCS (i.e., blue, assuming 55% carbon capture). For hydrogen made by electrolyzing water using grid electricity, its WTW GHG intensity is 216 gCO_2e/MJ. For hydrogen made by electrolyzing water using 100% additional renewable electricity, its WTW GHG intensity is only 1.4 gCO_2e/MJ. Hydrogen produced from natural gas (even with CCS) or with grid electricity will have higher emissions than MGO. The only hydrogen pathway that emits less than MGO is green hydrogen made by electrolyzing water using renewable electricity that is generated additionally.

AMMONIA

In general, for use of ammonia on marine vessels, there is lack of robust regulation at national, regional, and international levels due to its sparse usage and the unavailability of commercial engines as of September 2023 (American Bureau of Shipping, 2020b; European Maritime Safety Agency, 2023b). The alternative design process allows for ammonia use with associated risk assessments and flag administration concurrence, but this has impeded the uptake of ammonia. That said, it is expected that once these issues are resolved, ammonia will be poised for a significant uptake.

United States regulations

There are no specifically identified United States regulations for ammonia fuel use in the GL-SLS region. Some relevant regulations for general ammonia use are listed in Table 42.

Table 42. United States regulations on general use of ammonia

International Organization for Standardization (ISO) standards covering ammonia	Other onboard ship regulations	Other land based regulations
• ISO 8217:2017 – Petroleum products – Fuels (class F) – Specifications of marine fuels • ISO 5771:2008 – Rubber hoses and hose assemblies for transferring anhydrous ammonia. • ISO 7103:1982 – Liquefied anhydrous ammonia for industrial use – Sampling – Taking a laboratory sample. • ISO 7105:1985 – Liquefied anhydrous ammonia for industrial use – Determination of water content – Karl Fischer method. • ISO 7106:1985 – Liquefied anhydrous ammonia for industrial use – Determination of oil content – Gravimetric and infra-red spectrometric methods. • ISO 6957:1988 – Copper alloys – Ammonia test for stress corrosion resistance. • ISO 17179:2016 – Stationary source emissions – Determination of the mass concentration of ammonia in flue gas – Performance characteristics of automated measuring systems. • ISO 21877:2019 - Stationary source emissions – Determination of the mass concentration of ammonia – Manual method.	• U.S. e-CFR 46 98.25 Shipping: Anhydrous Ammonia in Bulk. • U.S. e-CFR 46 151.50-32 Shipping – Barges Carrying Bulk Liquid Hazardous Material Cargoes: Ammonia, Anhydrous. • U.S. CFR § 130.230 – Protection from Refrigerants.	• U.S. 40 CFR Ch. I Subchapter J Part 372 – Toxic Chemical Release Reporting: Community Right-To-Know. • U.S. 33 U.S.C §1251 – Clean Water Act. • U.S. EPA 822-R-18-002 – Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater 2013. • ANSI K61.1-1999 / CGA G-2.1 – American National Standard Safety Requirements for the Storage and Handling of Anhydrous Ammonia. • ANSI/CGA G-2.1-2014 – Requirements for the design, construction, repair, arrangement, and operation of storage and handling systems for anhydrous ammonia, including refrigerated ammonia storage systems. • ASME B31.3-2020 Process Piping. • U.S. e-CFR 29 1910.111 Occupational Safety and Health Standards: Storage and handling of anhydrous ammonia.

Canadian regulations

There are no specifically identified Canadian regulations for ammonia fuel use in the GL-SLS region.

IMO regulations

The International Convention for the Safety of Life at Sea (SOLAS, 1974, as amended) is a foundational safety IMO document. That said, SOLAS has traditionally prohibited the use of conventional fuel oils with less than a 60 ˚C flashpoint, except for emergency generator use (where the flashpoint limit is 43 ˚C) and subject to additional requirements detailed under SOLAS Chapter II-2 Regulation 4.2.1. To accommodate the interest in using gaseous and liquid fuels with a flashpoint of less than 60 ˚C, the IMO adopted the IGF Code by including a new Part G to SOLAS II-1 in 2015.

The IGF Code is largely based on the *IMO's International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)* (IMO, n.d.), itself developed from the experience with carrying LNG in bulk on gas carriers over the past 60 years or so. The IGC Code does include dedicated requirements for the carriage of anhydrous ammonia. Note, the *International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code)* contains only the requirements for carriage of aqueous ammonia up to 28% in water (IMO, 2020). The main IGC Code requirements for carrying ammonia are detailed under Chapter 17, Special Requirements, which focuses on the problems with stress corrosion cracking of anhydrous ammonia in carbon manganese or nickel steels. There are other IGC Code requirements driven by the toxic and corrosive nature of the carriage of ammonia.

Historically, ammonia has been carried in IMO Type A or C tanks on gas carriers that may have been designed predominantly for carrying LPG, with the Type C tanks enabling carriage at fully pressurized conditions at the standard IMO upper ambient reference conditions of 45 °C air and 32 °C sea water or semi-refrigerated or semi-pressurized conditions. Because ammonia can be liquefied relatively easily at -33 °C (or 17-18 bar) it offers a range of design solutions.

In the longer term, it is understood that the IMO's intent is to amend the IGF Code to include detailed prescriptive requirements for all the gases and low-flashpoint fuels used by the marine industry. While experience develops with these fuels, interim guidelines such as MSC.1/Circ.1621 (2020) Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (IMO, 2020) are expected to be developed. Prior to the availability of these guidelines for other fuels, such as LPG, ammonia and hydrogen, the IGF Code can still be applied.

The basic philosophy of the IGF Code considers the goal-based approach (MSC.1/Circ.1394). Therefore, goals and functional requirements were specified for each section forming the basis for the design, construction, and operation. The current version of this code includes regulations to meet the functional requirements for natural gas fuel. Regulations for other low-flashpoint fuels will be added to this code as they are developed by the organization. In the meantime, for other low-flashpoint fuels, compliance with the functional requirements of this code must be demonstrated through alternative design.

Applications for gases or low-flashpoint fuels other than methane need to apply the provisions from Part A, 2.3 of the IGF Code for Alternative Design (Table 43).[31] SOLAS regulation II-1/55 requires an engineering analysis to be submitted to the flag administration, in accordance with the footnote to MSC.1/Circ.1212, Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III (2006). Once approved, the flag administration will need to communicate this information to the IMO's GISIS database. This process follows a risk-based approach for approval of the design to ensure the goals and functional requirements of the IGF Code have been met. The IMO's MSC.1/Circ.1455, Guidelines for the Approval of Alternatives and Equivalents as Provided in Various IMO Instruments (2013), could offer a more appropriate framework for approval, subject to agreement by the flag administration.

Table 43. Excerpts from IGF Code, Adoption of the International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels (MSC.391(95))

	2.3 Alternative design
2.3.1	This code contains functional requirements for all appliances and arrangements related to the usage of low-flashpoint fuels.
2.3.2	Fuels, appliances, and arrangements of low-flashpoint fuel systems may either: 1. deviate from those set out in this Code, or 2. be designed to use fuel not specifically addressed in this Code. Such fuels, appliances and arrangements can be used provided they meet the intent of the related goals and functional requirements and provide an equivalent level of safety of the relevant chapters.
2.3.3	The equivalence of the alternative design shall be demonstrated as specified in SOLAS regulation II-1/55 and approved by the Administration. However, the Administration shall not allow the application of operational methods or procedures as an alternative to a particular fitting, material, appliance, apparatus, item of equipment, or type thereof which is prescribed by this Code.
	4.2 Risk assessment
4.2.1	A risk assessment shall be conducted to ensure that risks are addressed related to the use of low-flashpoint fuels that affect persons onboard, the environment, the structural strength or the integrity of the ship. Consideration shall be given to the hazards associated with physical layout, operation, and maintenance, following any reasonably foreseeable failure.
4.2.3	The risks shall be analyzed using acceptable and recognized risk-analysis techniques, and loss of function, component damage, fire, explosion, and electric shock shall as a minimum be considered. The analysis shall ensure that risks are eliminated wherever possible. Risks which cannot be eliminated shall be mitigated as necessary. Details of risks, and the means by which they are mitigated, shall be documented to the satisfaction of the Administration.

Currently, ammonia is considered to fall under the MARPOL Annex VI definition of fuel oil, which includes "… any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship, including gas, distillate and residual fuels." Ammonia is sulfur free and therefore provides a way to comply with the requirements of MARPOL Annex VI Regulation 14. It is expected that the dual fuel ammonia engines will use sulfur-compliant pilot fuel and, depending on the engine technology, this may represent a significant proportion of the fuel consumed.

In summary, though there is a lack of regulation for the use of ammonia as a fuel at the national, regional, and international levels, there are established methods for approving ship designs using the risk-based alternative design approval process. Furthermore,

---

[31] For more information: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/gas-and-low-flashpoint-fuels-advisory.pdf

classification societies have introduced tentative rules and guidelines to facilitate the adoption of ammonia-fueled ships.

IACS/Class regulations

Class societies have published requirements and regulations for the use of ammonia. A summary of relevant IACS ammonia documents, class society regulations and additional class supporting documents is listed in Table 44.

Table 44. IACS ammonia relevant documents, Class Society regulations and Class supporting documents

International Association of Classification Societies	Class guidelines	Class supporting documents
• IACS Recommendation No.33. – Guidelines for the Construction of Pressure Vessel Type Tanks Intended for the Transportation of Anhydrous Ammonia at Ambient Temperatures – Deleted in March 2021 after incorporation into IGC Code. • IACS Unified Requirement M57 - Use of ammonia as a refrigerant – not updated since 1993. • IACS Unified Requirement M78 – Safety of Internal Combustion Engines Supplied with Low-Pressure Gas • IACS "GF" Unified Interpretations of the IGF Code – GF1 through GF 18 • IACS Recommendation No. 142 – LNG Bunkering Guidelines • IACS Recommendation No. 146 – Risk assessment as required by the IGF Code • IACS recommendation No. 148 – Survey of liquefied gas fuel containment systems • All IACS publications are publicly available on their website: https://www.iacs.org.uk/publications/	• American Bureau of Shipping (ABS). ABS Guide for Ammonia Fueled Vessels. Published • Bureau Veritas (BV). Ammonia-fuelled Ships – Tentative Rules. Rule Note NR 671 DT R00 E • Det Norske Veritas (DNV). Rules for Ammonia in Part 6 Chapter 2 Section 14 • Korean Register (KR). Guidelines for Ships Using Ammonia as Fuels • NKK (Nippon Kaiji Kyokai – ClassNK). Guidelines for Ships Using Alternative Fuels (Edition 1.1) (Methyl / Ethyl Alcohol / LPG / Ammonia)	• ABS Sustainability Whitepaper on Ammonia as Marine Fuel • DNV Ammonia as a marine fuel white paper • DNV (on behalf of the Green Shipping Programme and with input from the Norwegian Maritime Authority and other partners) Ammonia as a Marine Fuel Safety Handbook. • KR Whitepaper on Forecasting the Alternative Marine Fuel: Ammonia • Lloyd's Register. Ammonia Detection Limits Discussion Paper

Regulatory analysis

In the ammonia category, there is ammonia made from both fossil and nature sources of hydrogen. For fossil sources, there is gray ammonia made from SMR of natural gas. For nature sources, there is ammonia made using hydrogen produced by electrolysis of water using either grid electricity or renewable electricity. Ammonia can be used in internal combustion engines or fuel cells.

Air pollution: When used in a fuel cell, ammonia emits no TTW air pollution. When used in an internal combustion engine, ammonia will result in NO_x emissions, as well as PM and CO emissions. Engines will need to be certified to IMO Tier III limits for use in the North American Emission Control area, and will likely require exhaust gas aftertreatment, such as selective catalytic reduction (SCR) or exhaust gas recirculation. There may be tradeoffs between reducing NO_x emissions and producing additional nitrous oxide (N_2O) GHG emissions when using SCR (Cames et al., 2021). This implies that ammonia will face additional regulatory challenges if emission limits are set for N_2O on a TTW basis. PM and CO emissions are expected to be lower than conventional fuels, according to GREET (Argonne National Laboratory, 2022).

GHGs: When used in a fuel cell, ammonia will emit zero GHGs on a TTW basis and therefore will be able to comply with existing international regulations that limit or rank the CO_2 intensity of ships, such as the EEDI, EEXI, and CII. When used in an internal combustion engine, ammonia emits N_2O; how much N_2O is not yet fully understood, because ammonia marine engines are still being developed and tested. When regulations control non-CO_2 GHGs, the amount of N_2O emissions will be factored in, and ammonia will need to comply with those regulations. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas ammonia made using natural gas SMR has a WTW GHG intensity of 152 gCO_2e/MJ with most of the emissions associated with CO_2 and methane. For ammonia made by electrolyzing water using grid electricity, its WTW GHG intensity is 227 gCO_2e/MJ, with most of the emissions associated with upstream emissions from the grid electricity. For ammonia made by electrolyzing water using renewable electricity, its WTW GHG intensity is only 4.6 gCO_2e/MJ. The only ammonia pathway that emits less than MGO is green ammonia made by electrolyzing water using renewable electricity, but it is unknown how much N_2O will be produced by ammonia-fueled marine engines, which could further increase WTW emissions.

METHANOL

United States regulations

There are no specifically identified United States regulations for methanol fuel use in the GL-SLS region.

Canadian regulations

There are no specifically identified Canadian regulations for methanol fuel use in the GL-SLS region.

IMO regulations

The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) provides the standard for ships operating on gas or low-flash point liquids as fuels (American Bureau of Shipping, 2021d). The code provides mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuel to minimize the risks associated with the the fuels involved (IMO, n.d.).

The IMO Maritime Safety Committee (MSC) has also adopted MSC.1/Circ.1621, the *Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as fuel* (IMO, 2020). The purpose of these Interim Guidelines is to provide an international standard for ships using methyl/ethyl alcohol as fuel. The Interim Guidelines provide provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using methyl/ethyl alcohol as fuel to minimize risks.

Because the IGF Code was developed on a prescriptive basis for the use of natural gas, there are additional steps to be undertaken when burning other low-flashpoint fuels. This involves a risk assessment process. Risk assessments and engineering analyses are required to varying extents for the use of low-flashpoint fuels on marine vessels. The IGF Code includes such requirements, but the extent and process to be followed is to be agreed upon with the flag administration in each case. Where required, risks are to be analyzed using acceptable and recognized risk analysis techniques, eliminate the risks where possible, mitigate those risks that cannot be eliminated, and document the process.

Furthermore, to support the uptake of methanol and ethanol as marine fuels, at the 99th session of the IMO MSC meeting, the IMO invited the ISO to develop standards for methyl/ethyl alcohol as a fuel and methyl/ethyl alcohol fuel couplings. The ISO/CD 6583 specification of methanol as a fuel for marine applications standard is currently under development.

IACS/Class regulations

Class societies including ABS, LR and DNV have published requirements and regulations for the use of methanol. These are the *ABS Requirements for Methanol and Ethanol Fueled Vessels*, *LR Rules for the Classification of Methanol Fuelled Ships*, and *DNV Part 6 Additional Class Notations, Section 6 - Low-flashpoint liquid-fuelled engines – LFL Fuelled*. The IACS *Recommendation No.146 Risk Assessment as Required by the IGF Code* can also be applied to methanol.

Regulatory analysis

Methanol for fueling vessels is made from fossil, nature, and biogenic sources. Fossil source-derived methanol includes gray methanol made from SMR of natural gas. Nature sources for methanol include methanol made using CO_2 from ethanol or DAC and hydrogen produced by electrolysis of water using either grid electricity or renewable electricity. For biogenic sources, there is gasification of miscanthus, or corn stover. Methanol can be used in internal combustion engines or fuel cells.

Air pollution: When used in a fuel cell, methanol emits no TTW air pollution. When used in an internal combustion engine, methanol will result in NO_x, CO, and PM emissions, as well as some SO_x emissions, primarily from the diesel pilot fuel used to initiate the combustion process. Engines will need to be certified to IMO Tier III limits for use in the North American Emission Control area, requiring exhaust gas aftertreatment. Emissions of CO are expected to be low (Faber et al., 2020), and should not be a barrier to regulatory compliance. PM emissions will be very low, stemming mainly from pilot fuel combustion.

GHGs: When used in a fuel cell, methanol emits zero GHGs on a TTW basis and therefore will be able to comply with existing international regulations that limit or rank the CO_2 intensity of ships, such as the EEDI, EEXI, and CII. When used in an internal combustion engine, methanol will emit CO_2 and to a much lower extent CH_4 and N_2O; the CO_2 emission intensity of ships using these fuels will be controlled by the EEDI and EEXI and ranked by the CII. The methane and nitrous oxide emissions will be negligible; it is the carbon dioxide that will be the primary GHG emitted from using the fuel in an engine. The WTW emissions will depend on the methanol feedstock. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas methanol made using natural gas SMR has a WTW GHG intensity of 93.0 gCO_2e/MJ (essentially the same as MGO). For methanol made from ethanol CO_2 and hydrogen from electrolyzing water using grid electricity, its WTW GHG intensity is 216 gCO_2e/MJ. For methanol made using DAC CO_2 and hydrogen from electrolyzing water using grid electricity, its WTW GHG intensity is 225 gCO_2e/MJ. For methanol made using DAC CO_2 and hydrogen from electrolyzing water using renewable electricity, its WTW GHG intensity is only 2.8 gCO_2e/MJ. For bio-methanol, gasification of miscanthus results in WTW GHG emissions of 7.2 gCO_2e/MJ, whereas gasification of corn stover yields 5.2 gCO_2e/MJ. The pathways that emit less WTW GHG than MGO are “green” methanol, including methanol made with DAC CO_2 and hydrogen from electrolyzing water using renewable electricity and methanol made from gasifying miscanthus or corn stover.

DIMETHYL ETHER

Regulatory requirements for DME closely align with those of biofuels. DME has a low flash point, presenting challenges for safe handling. DME has a high cetane number but exhibits a lower boiling point and lower energy density compared to conventional diesel, with 29 MJ/kg LCV versus diesel's 43 MJ/kg. DME features a straightforward chemical structure and a high oxygen content. A significant advantage of DME lies in its minimal generation of particulate matter, NO_x, and CO during combustion (IEA Bioenergy, 2018). Additionally, DME is miscible with water, allowing for blending with water. However, a drawback of DME usage is its potential to dry out engine components like injectors, possibly leading to seizures. To mitigate this, measures such as sealing oil or friction coatings may be required.

Despite a well-established production pathway and favorable CO_2 reduction characteristics, DME has not gained significant traction in the maritime industry. DME can be blended with diesel only at very low blending ratios (5-10%). Consequently, its potential for CO_2 reduction is restricted. At higher blending ratios, DME requires specialized gas storage and fuel handling systems, along with specific safety protocols. Consequently, it fails to meet the criteria of a drop-in fuel for traditional fuel oil installations.

In newbuilds, it faces competition from other alternative fuels like methanol, which have already seen the development of ship installations with lower overall installation costs than DME. The limited prevalence of LPG-powered ships further constrains the prospects for DME adoption.

United States regulations

There are no specifically identified United States regulations for dimethyl ether fuel use in the GL-SLS region.

Canadian regulations

There are no specifically identified Canadian regulations for dimethyl ether fuel use in the GL-SLS region.

IMO regulations

There are no specifically identified IMO Regulations for dimethyl ether fuel use in the GL-SLS region.

IACS/Class regulations

There are no specifically identified IACS/Class Regulations for dimethyl ether fuel use in the GL-SLS region.

Regulatory analysis of dimethyl ether

In the dimethyl ether (DME) category, there is bio-DME made from gasifying miscanthus or corn stover. DME can be used in internal combustion engines or fuel cells.

Air pollution: When used in a fuel cell, DME emits no TTW air pollution. When used in an internal combustion engine, DME will result in NO_x, CO, THC, and PM emissions, but no SO_x. Engines will need to be certified to IMO Tier III limits for use in the North American Emission Control area, requiring exhaust gas aftertreatment. Emissions of other pollutants are expected to be low and able to comply with existing regulations. For example, a DME-fueled research truck had emissions lower than those expected from a Euro V-compliant truck (Szybist et al., 2014).

GHGs: When used in a fuel cell, DME emits zero GHGs on a TTW basis and therefore will be able to comply with existing international regulations that limit or rank the CO_2 intensity of ships, such as the EEDI, EEXI, and CII. When used in an internal combustion engine, DME will emit CO_2 and to a much lower extent CH_4 and N_2O. The methane and nitrous oxide emissions will be negligible; it is the carbon dioxide that will be the primary GHG emitted from using the fuel in an engine. The CO_2 emissions intensity of ships using these fuels will be controlled by the EEDI and EEXI and ranked by the CII. The WTW emissions will depend on the feedstock. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas DME made from gasification of miscanthus results in WTW GHG emissions of 10.7 gCO_2e/MJ, whereas gasification of corn stover yields 7.1 gCO_2e/MJ.

NATURAL GAS (LIQUEFIED)

Liquefied natural gas (LNG) is a relatively mature fuel, consisting primarily of methane (American Bureau of Shipping, 2022). Its carbon-to-hydrogen ratio offers a reduction in CO^2 emissions of up to 20% compared to baseline heavy fuel oil, but methane slip, which varies by engine technology, means that it may emit more GHGs than conventional fuels.

Regulatory and classification requirements are in place for the use of natural gas fuel in marine applications. The specific gas fueled ship (GFS) arrangements depend on the fuel containment, the fuel gas supply system (FGSS), and selected prime mover technologies. The link between fuel storage, fuel preparation and gas consumer is much more interdependent as compared to conventional fuels. Critical equipment and system design decisions cannot be made in isolation.

United States regulations

LNG is the most mature alternate fuel with wide adoption. The United States Coast Guard has issued policy letters specific to liquefied gas as fuel:[32]

- CG-MMC Policy Letter 01-21, (2021) Change-1 Guidance for Obtaining Endorsements for Basic and Advanced Endorsement for Low Flashpoint Fuels (IGF Code)
- CG-MMC Policy Letter 01-21, (2021) Guidance for Obtaining Endorsements for Basic and Advanced Endorsement for Low Flashpoint Fuels (IGF Code)
- CG-MMC Policy Letter 02-19, (2019) Training of Personnel on Vessels Using Low Flashpoint Fuels
- CG-ENG Policy Letter 01-12, Change-1 (2017) Equivalency Determination - Design Criteria for Natural Gas Fuel Systems
- CG-ENG Policy Letter 02-15 (2015) Design Standards for U.S. Barges Intended to Carry Liquefied Natural Gas in Bulk
- CG-521 Policy Letter 01-12 (2012) Equivalency Determination - Design Criteria for Natural Gas Fuel Systems

The USCG has also released additional guidance specific to liquefied gas a fuel and this includes:

- Liquefied Natural Gas [as fuel] Design Considerations

---

[32] Liquefied Gas Carrier National Center of Expertise, Safety Alerts and Bulletins Specific to Liquefied Gas as Fuel, https://www.dco.uscg.mil/lgcncoe/fuel/alerts-policy-regs/

- Alternate Compliance Program (ACP) Tactics, Techniques, and Procedures (TTP)
- IMO Resolution MSC.285(86) (2009) Interim Guidelines on Safety for Natural Gas-Fueled Engine Installations in Ships (2009)
- USCG Marine Safety Manual, Vol. II Material Inspection Section D, Chapter 6, Procedures Applicable to Foreign Tank Vessels

Canadian regulations

Transport Canada Requirements for Vessels Using Natural Gas as Fuel policy came into effect on July 28, 2017.[33] This policy will expire upon the coming into force of the Vessel Construction and Equipment Regulations, which is expected with the Marine Safety and Security initiatives planned for April 2023 – April 2025.[34]

IMO regulations

The IMO's IGF Code applies to ships to which the SOLAS Part G Chapter II-1 applies and contains only detailed prescriptive requirements for LNG under Part A-1 of the code. The IGF Code and class require specific areas of ship design to be risk assessed.

Other low-flashpoint fuels may also be used as marine fuels on ships falling under the scope of the IGF Code, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety. This equivalency is to be demonstrated by applying the alternative design risk assessment process and SOLAS novel concepts approval procedure of SOLAS regulation II-1/55, and as required by 2.3 of the IGF Code.

The following basic operations and routing items are to be considered for a risk assessment:

- Type of vessel and associated cargo operations (e.g., offshore support vessel, tug, container carrier, bulk carrier)
- Expected trade route (including roundtrip or one way)
- Location of vessel bunkering, including frequency, bunker providers, and bunkering duration
- Bunker tank sizes required (vessel bunker tank sizes have increased considerably, and thus bunker tank sizes require careful planning for cargo transfer operations as the operation might take weeks in port)
- Vessel build location and maintenance/repair locations, which might influence scheduled and unscheduled delays (choice of fuel between locations may also affect OPEX planning)

These basic considerations can affect choices and selections for a vessel and may enter into determining engine choice, gas fuel handling system, and amount of redundancy needed. Specific areas of ship design to be risk assessed are shown in Table 45 below.

---

[33] See Transport Canada, Marine Safety Management System, https://tc.canada.ca/sites/default/files/migrated/policy_requirements_for_vessels_using_natural_gas_as_fuel.pdf

[34] More information can be found at https://tc.canada.ca/en/corporate-services/acts-regulations/forward-regulatory-plan/marine-initiatives-planned#vessel-constr-equip-reg

Table 45. Risk assessment

Ship design risk assessment sections
Capacity of drip trays
Separation of spaces by airlocks
Containment system – integration to overall design
Design load for membrane tanks – accidental scenarios
Closed or semi-enclosed bunkering stations
Alternative ventilation capacity for tank connection spaces
Ventilation system for bunkering station not on open deck
Gas detectors for ventilation inlets
Novel containment systems – alternative design factor
Novel containment systems – accidental scenarios

Contingency planning is necessary to account for unexpected vessel repairs (emergency drydocking, hull inspection, engine repair, major damage) to accommodate tank emptying, gas freeing, and subsequent return to service. Extensive prior planning for integration of LNG fuel, methods and procedures with crews, fuel suppliers, transporters, port authorities, and regulators is necessary.

In addition to the design of the vessel, the operations associated with bunkering the vessel may need to be further assessed for risk based on the specific operation concept and the stakeholders. Handling risk is a shared responsibility among all stakeholders. Typically, the shipowner or operator will take the lead in developing risk and safety studies as they are in control of the vessel operations and procedures, with the added expectation of operation-specific knowledge combined with access to LNG safety and technical expertise from the earlier concept development phase.

Once the initial studies have been completed, ship operators must ensure that the resulting mitigations and safety measures that reduce the risk of LNG fuel and bunkering operations into the acceptable range are fully implemented within their safety management system process, communicated to crew and other stakeholders, and consistently implemented. A key element of consistent implementation to reduce risk to as low as reasonably practical level relies on the capability of persons in charge of bunkering to recognize on-scene, site, and condition-specific risks to the LNG fuel vessel or bunkering operation and take effective measures to eliminate or reduce it, including canceling, postponing, or halting the operation.

Training is required for crew, shore staff, and commercial teams, including charterers on LNG fueled vessels. The *International Convention on Standards of Training and Certification of Watchkeeping for Seafarers* (STCW) Part A, Chapter V, Section A-V/3 lists the mandatory minimum requirements for the training and qualification of masters, officers, ratings, and other personnel on ships subject to the IGF Code.

Methane slip refers to the unburned methane present in engine exhaust emissions. Options to address methane slip include direct methane emission controls or indirect means by regulating carbon dioxide equivalent emissions or emissions intensity, such as through a GHG fuel standard, or by incorporating methane slip into existing IMO regulations such as the EEDI, EEXI, and CII. The IMO is already incorporating methane slip into its LCA Guidelines, which are set to be finalized in 2024, which will enable the IMO to include methane and other non-CO_2 GHGs into its regulatory framework.

IACS/Class regulations

Most class societies have published extensive requirements on LNG. These rules have even been standardized across IACS.[35]

Regulatory analysis

In the LNG category, there is LNG made from nature and from biogenic sources. Nature sources for LNG include methanol made using CO_2 from ethanol or DAC and hydrogen produced by electrolysis of water using either grid electricity or renewable electricity. For biogenic sources, LNG can be made from landfill gas using anaerobic digestion and upgrading and purification of biogas. LNG can be used in internal combustion engines or fuel cells.

Air pollution: When used in a fuel cell, LNG emits no TTW air pollution. When used in an internal combustion engine, LNG will result in NO_x, HC, CO, and PM emissions, as well as some SO_x emissions, primarily from the diesel pilot fuel used to initiate the combustion process. Engines will need to be certified to IMO Tier III limits for use in the North American Emission Control area, requiring exhaust gas aftertreatment for HPDF or the use of LPDF. Emissions of CO are higher than conventional fuels but should not be a barrier to regulatory compliance. PM and SO_x emissions will be very low, stemming mainly from pilot fuel combustion. EPA has Tier 4 HC limits for marine engines for model years 2014and beyond (implementation dates vary based on engine power and displacement), but they only apply to category 1 and 2 engines >600 kW (EPA, 2008). Category 1 and 2 engines have per-cylinder displacements <30 L. There are no HC limits for the largest marine engines (category 3; >30 liters per cylinder). The smallest LPDF LNG engines have per-cylinder displacements of less than 30 liters per cylinder; for example, Wartsila's 6L20DF engine, which is an LPDF 4-stroke engine, has per-cylinder displacements of 8.8 liters per cylinder. However, the HC limits are calculated as non-methane hydrocarbons (NMHC) when natural gas is used as a fuel, meaning the HC limits do not limit the use of LNG as a marine fuel.

GHGs: When used in a fuel cell, LNG emits zero GHGs on a TTW basis and will comply with any GHG regulation that limits only TTW emissions. When used in an internal combustion engine, LNG will emit CO_2, CH_4 and, to a much lower extent, N_2O. The CO_2 emissions intensity of ships using these fuels will be controlled by the EEDI and EEXI and ranked by the CII. The nitrous oxide emissions will be negligible, but the methane emissions can be substantial. This implies that LNG will face additional regulatory challenges if emission limits are set for CH_4 on a TTW basis.

TTW methane emissions vary depending on the engine type, with LPDF 4-stroke engines having the highest "methane slip" (unburned methane emissions) and HPDF 2-stroke engines having the lowest. Methane slip assumptions are based on Comer and Osipova (2021), which are consistent with those in the Fourth IMO GHG Study (Faber et al., 2020). The WTW emissions will depend on the methane feedstock and the engine technology. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ. For LNG made from ethanol CO_2 and hydrogen from electrolyzing water using grid electricity, its WTW GHG intensity is 251 gCO_2e/MJ when used in an LPDF 4-stroke engine, 240 gCO_2e/MJ when used in an LPDF 2-stroke engine, and 226 gCO_2e/MJ when used in an HPDF 2-stroke engine, with 225 gCO_2e/MJ from upstream (WTT) emissions in all cases.

---

[35] A list of all IACS Unified Interpretations for Gas Fueled Vessels can be accessed at https://iacs.org.uk/resolutions/unified-interpretations/ui-gf. The IACS Unified Requirements concerning Gas Tankers can be found at https://iacs.org.uk/resolutions/unified-requirements/ur-g.

For LNG made using DAC CO_2 and hydrogen from electrolyzing water using grid electricity, its WTW GHG intensity is 257 gCO_2e/MJ when used in an LPDF 4-stroke engine, 245 gCO_2e/MJ when used in an LPDF 2-stroke engine, and 232 gCO_2e/MJ when used in an HPDF 2-stroke engine, with 231 gCO_2e/MJ from upstream (WTT) emissions in all cases. For LNG made using DAC CO_2 and hydrogen from electrolyzing water using renewable electricity, its WTW GHG intensity is 28.7 gCO_2e/MJ when used in an LPDF 4-stroke engine, 17.5 gCO_2e/MJ when used in an LPDF 2-stroke engine, and 3.7 gCO_2e/MJ when used in an HPDF 2-stroke engine, with 2.8 gCO_2e/MJ from upstream (WTT) emissions in all cases. For bio-LNG from landfill gas, its WTW GHG intensity is 38.9 gCO_2e/MJ when used in an LPDF 4-stroke engine, 27.7 gCO_2e/MJ when used in an LPDF 2-stroke engine, and 14.0 gCO_2e/MJ when used in an HPDF 2-stroke engine, with 13.0 gCO_2e/MJ from upstream (WTT) emissions in all cases. The pathways that emit less WTW GHG than MGO are LNG made with DAC CO_2 and hydrogen from electrolyzing water using renewable electricity and LNG made from landfill gas.

ELECTRICITY

Electricity can be used for propulsion and its use for primary propulsion is slowly increasing. Though this type of propulsion is not new, it has only gained popularity in recent years.[36] Longer ranges, compactness, reliability, and lower cost have all played a role in pushing this technology forward. Hybrid electric power systems can play a role in meeting regulatory and operational demands of vessels.

United States regulations

The United States Coast Guard, CG-ENG Policy Letter 02-19, details the Design Guidance for Lithium-Ion Battery Installations Onboard Commercial Vessels.

Though lithium-ion batteries are the most favored option for battery technology, there are a myriad of solutions such as metal-air batteries, redox flow batteries, ammonia batteries and solid-state batteries which are trying to make inroads into shipping. All of these types of emerging battery technologies come with advantages and disadvantages and can be useful on a case-by-case basis (American Bureau of Shipping, 2021a).

Other flag administrations also have analogous battery requirements including United Kingdom Maritime & Coastguard Agency, Guidance MGN 550, *Design, installation, operation of lithium-ion batteries* and Norwegian Maritime Authority, RSV 12 – 2016, *Guidelines for chemical energy storage – maritime battery systems*. These other flag requirements are only provided for reference.

The other use of electricity is in the realm of port electrification for onshore power supply (shore power). Here power from the grid is provided to vessels at berth so diesel emissions are reduced when vessels are at berth. This is becoming increasingly important as communities living closer to the ports demand clean air surrounding the ports. However, the United States does not address other forms of electrification including shore power and fuel cells.

The U.S. EPA report *Shore Power Technology Assessment at U.S. Ports - 2022 Update* (U.S. Environmental Protection Agency, 2022), characterizes the technical and operational aspects of shore power systems in the United States and demonstrates

---

[36] D. Paul, "A History of Electric Ship Propulsion Systems [History]," in *IEEE Industry Applications Magazine*, vol. 26, no. 6, pp. 9-19, Nov.-Dec. 2020, Abstract, https://doi.org/10.1109/MIAS.2020.3014837.

an approach for comparing shore power and vessel emissions while at berth. This reference is provided for informational purposes only.[37]

Canadian regulations

There are no specifically identified Canadian regulations for electrification use in the GL-SLS region.

IMO regulations

IMO MSC.1/Circ.1675 - *Interim Guidelines on Safe Operation of Onshore Power Supply (OPS) Service in Port For Ships Engaged On International Voyages* (IMO, 2023a), was developed with a view to promoting safe operation of OPS service in port on ships. These interim guidelines have been developed to facilitate both ship- and shore-side application.

IACS/Class regulations

IACS Unified Requirements concerning electric installations can be found publicly online.[38] A list of Class rules and guides related to electrification is listed in Table 46.

Table 46. Class Rules and guides for electrification

Class Rules	Class Guides
• ABS Guide for Hybrid Electric Power Systems for Marine and Offshore Applications (Hybrid IEPS) • Lloyd's Register Rules and Regulations for the Classification of Ships (Hybrid Power/ (+)) • Bureau Veritas Rules for the Classification of Steel Ships (Electric Hybrid, Hybrid Mechanical Propulsion) • China Classification Society Rules for Classification of Sea-Going Steel Ships (Hybrid)	• ABS Guide for Use of Lithium-ion Batteries in the Marine and Offshore Industries (ESS-LiBATTERY) • Lloyd's Register Guidance Note on Large Battery Installations • BV Rules for the Classification of Steel Ships (Battery System) • DNV Rules for Classification of Ships (Battery (Power), Battery (Safety)) • Korean Register Guidance for Large Battery Systems on Board of Ships (Battery) • China Classification Society (Battery Power)

Regulatory analysis

In the electricity category, there is grid electricity for four years (2023, 2030, 2040, and 2050) and a scenario with 100% renewable electricity. Electricity can be used to power batteries for hybrid powered ships and for battery-electric ships.

Air pollution: Electricity used in batteries results in no TTW air pollution.

GHGs: Electricity used in batteries emits zero GHGs on a TTW basis and will comply with any GHG regulation that limits TTW emissions. On a WTW basis, the emissions depend on the grid's fuel mix. MGO has a WTW GHG intensity of 92.6 gCO_2e/MJ, whereas the 2023 grid is estimated to emit 98.7 gCO_2e/MJ, which would be 54.8 gCO_2e/MJ adjusting for the superior energy efficiency of batteries compared to internal combustion engines using the EIR. By 2030, that is expected to fall to 68.4 gCO_2e/MJ (38 gCO_2e/MJ EIR-adjusted). By 2040 and 2050, the expectation is that will fall to approximately 63 gCO_2e/MJ (35 gCO_2e/MJ EIR-adjusted). With 100% additional renewable electricity, WTW emissions are 0 gCO_2e/MJ.

---

[37] IEC/IEEE 80005-1:2019 - *Utility connections in port — Part 1: High voltage shore connection (HVSC) systems — General requirements* describes high-voltage shore connection systems, onboard the ship and on shore, to supply the ship with electrical power from shore.

[38] See https://iacs.org.uk/resolutions/unified-requirements/ur-e.

CONCLUSIONS AND POLICY RECOMMENDATIONS

CONCLUSIONS

- All fuel options analyzed except fully battery electric cargo ships could be broadly applicable to GL-SLS shipping; battery-electric tugs and hybrid battery power for cargo ships is applicable. Thus, U.S. and Canadian policymakers will need to carefully track technology trends and international policymaking before prioritizing any particular fuel or power option.
- There is generally a tradeoff between the emissions performance, technological maturity, and cost of alternative marine fuel and power options. Because the fuel pathways that provide the largest life-cycle emission reductions also tend to be the most expensive and least technologically mature, they may require targeted policy support to succeed.
- All major alternative fuel pathways identified will be more expensive than fossil fuels for the foreseeable future, although that price premium is expected to fall over time. To drive down costs, governments should consider implementing policies including incentives, carbon pricing, and legally binding mandates.
- There was a wide variation in the emissions performance of synthetic e-fuels, hydrogen, and electricity depending on the energy source. Measures will be needed to ensure the additionality of renewable energy supply for alternative marine fuels in the GL-SLS region.
- In the short term (through 2030), ports and governments can explore expanding OPS to mitigate harbor craft and at-berth ship emissions. In the medium term (through 2040), methanol, ammonia, and liquid hydrogen are all potential fuels for use in GL-SLS shipping, but production capacity and bunkering infrastructure will need to expand to meet this demand. In the long term (through 2050), meeting both domestic and international climate targets will require the complete replacement of fossil fuels in GL-SLS shipping.
- To track technological progress and to make informed policy decisions, governments and ports should work to collect better primary data on GL-SLS vessels. This includes port-to-port collaboration to collect data from common voyages and developing a central public fuel consumption and emissions database similar to the EU MRV system.
- Additional research is recommended to further refine the understanding of potential fuel and power options for GL-SLS shipping. This includes assessments of regional e-fuel and synthetic fuel production, detailed port surveys regarding the potential for specific bunkering infrastructure, such as for ammonia and hydrogen, regulations to ensure the safe transport of higher risk fuels, and consideration of how cargo being transported today might support the creation of alternative marine fuels at regional ports.

This work has provided an initial assessment of alternative fuel and power options that may be suitable for GL-SLS maritime shipping today and through 2050. It included a survey of current ship activity, fuel use, and emissions, along with a compilation of data on port infrastructure to support fueling. The baseline assessment of fuel and power options concluded that all fuel options analyzed except battery electric ships could be broadly applicable to GL-SLS shipping. Thus, U.S. and Canadian policymakers will need to carefully monitor technology trends and international policymaking before prioritizing any particular fuel or power option.

This report concludes that there is generally a tradeoff between emissions performance, technological maturity, and cost. The least expensive alternative fuel and power options investigated were generated from fossil fuel feedstocks, which are technologically mature pathways but which have higher life-cycle GHG emissions than MGO. In contrast, alternative fuels with the lowest life-cycle emissions tend to be more costly and less technologically mature, suggesting the need for policy support.

When projected out to 2050, the assessment framework developed in this report confirms that a variety of fuel and power options will be suitable for GL-SLS shipping. Scores on two variables—emissions and applicability—remained largely stable over time. Fuel and power options with poor emissions performance continue to emit more on a life-cycle basis than the MGO baseline through 2050, whereas fuels derived from biomass residues and renewable power provide the largest life-cycle emission reductions. The economics of most alternative fuel and power options improve significantly through 2050, although they are expected to remain more costly than fossil fuels. The compatibility of future fuel and power options should improve over time as ships, their fuel systems, and fueling infrastructure evolve to service alternatives to MGO and HFO.

Assessment of international and domestic regulations highlighted that the regulatory framework for most alternative fuel and power options for shipping is incomplete. All fuels investigated should be able to comply with national and regional SO_x regulations because they contain little or no sulfur, whereas engines that consume the various fuels considered should also be able to meet limits on NO_x, HC, PM and CO. Future regulations of WTW GHG emissions, particularly N_2O and CH_4, could potentially affect the uptake of ammonia and LNG, respectively. Some alternative fuels, such as hydrogen and ammonia, have additional safety concerns compared to conventional marine fuels, including risk of explosion for hydrogen and acute toxicity for ammonia. These risks will need to be managed through regulatory compliance and enforcement if they are to be used in GL-SLS shipping.

POLICY RECOMMENDATIONS

Based on these findings, a preliminary list of policy recommendations to support the uptake of alternative fuel and power options in GL-SLS shipping has been compiled. The considerations have been broken down into the short, medium, and long-term as applicable. More general recommendations are also provided.

In the *short term* (until 2030), ports and governments can explore expanding OPS to mitigate at-berth emissions given the current strengths of the region. Ports like Chicago, Cleveland, and Duluth with existing OPS capabilities should continue to invest in enhancing their shore power infrastructure. Other ports should also consider OPS infrastructure and learn from those who have already installed it. Because existing OPS is low-voltage (except for the Port of Montréal, where high voltage shore power is available for wintering and cruising ships) and suitable only for small vessels such as tugs, expanding OPS to include high-voltage options that could be used for larger cargo ships would help eliminate at-berth emissions until cleaner fuel options become widely available.[39]

---

[39] For example, the Québec Port Authority is currently conducting a feasibility study for shore power provision for cruise ships. Additional collaboration with other ports to explore similar projects could reduce greenhouse gas emissions from cruise ship operations in a cost effective manner because the ships are already equipped with this technology because of the regulations requiring it on the U.S. West Coast.

Biofuels may also be an important short-term alternative fuel for shipping. Ports could provide biofuel infrastructure by converting typical MGO bunker tanks to biofuel tanks that can store 100% biofuel or biofuel blends. A blended solution will lower uptake costs and will cause less disruption to the current MGO supply chain. As noted previously, the viability of the use of biofuels in GL-SLS shipping depends on their life-cycle emissions, including potential ILUC emissions.

In the *medium term* (until 2040), methanol, the current fuel of choice for alternative fuel newbuild orders, is likely to be a key alternative fuel in GL-SLS shipping. Although somewhat behind methanol in terms of deployment, ammonia and hydrogen may also be midterm options. But capacity and infrastructure will need to expand to meet any future demand, and dedicated port fuel supply and storage capacity will be required. Establishing a periodic reassessment of the alternative fuel uptake and the likely future demand for these fuels will inform where investments should be directed in the medium to long term. The viability of each fuel will depend on its well-to-wake emissions, which vary based on how the fuels are produced. Fuels offering deep life-cycle emission reductions will be needed to meet the ambitious climate goals highlighted for the region. Moreover, the transport of dangerous goods, like ammonia, raises its own set of regulatory and safety considerations.

Because hydrogen will be a feedstock for all synthetic alternative fuels, GL-SLS ports may consider building hydrogen and hydrogen-derivative storage infrastructure into their midterm plans. The development of port infrastructure can support export markets for ammonia and hydrogen as a marine fuel. For example, the recent agreement between Canada and Germany may provide synergies for the use of those fuels in ships.

Over the *long term* (to 2050), both national and international climate targets imply the complete replacement of fossil fuels in GL-SLS shipping. Additional policies will be needed to promote the universal repowering of vessels in the region or the replacement of older vessels with newbuilds powered by alternative fuels. These targets may range from incentives to performance standards, like a drastically strengthened CII and EEXI, to regional zero-emission vessel mandates. Short- and midterm measures are also desirable to help mature the technologies needed to support this transition.

This work also identified more general recommendations. To validate and supplement AIS-based inventories, ports should consider collaborating to maintain up-to-date data on port calls, deadweight tonnage, and infrastructure capabilities to track progress and make informed policy decisions. Governments could encourage ships to report total annual fuel consumption and annual in-port fuel consumption to a central public database similar to the European Union's EU MRV to enable assessment of where OPS could be most effective at reducing emissions. Greater collaboration among GL-SLS ports is encouraged in order to share best practices, experiences, and insights related to decarbonization efforts and alternative fuels. Finally, options should be explored to diversify refueling options for alternative marine fuels. Given that trucking is the most common replenishment method, ports might explore opportunities to diversify replenishment mechanisms, such as increasing the use of tankers or exploring the feasibility of using trains where applicable.

A key finding of this work is that all major fuel pathways identified will be more expensive than fossil fuels for the foreseeable future, although that price premium is expected to fall over time. To drive those costs down further, governments could consider implementing policies, including incentives, carbon pricing, and legally binding mandates. Financial incentives such as tax credits could be used to bring down the cost of alternative marine fuels and to improve their commercial prospects. An example of relevant incentives in the United States is the variety of Inflation Reduction Act tax credits for renewable electricity, carbon capture and storage, and hydrogen production.

On their own, however, tax credits can be limited in their impact and highly subject to political uncertainty, particularly for fuel pathways with long and uncertain commercialization timelines. A 10-year credit, such as the 45V credit implemented for hydrogen under the Inflation Reduction Act, would create greater policy certainty and enable more long-term investments. Because fuel pathways that provide the largest life-cycle emission reductions also tend to be the most expensive and least technologically mature, it may be necessary to introduce strict eligibility criteria for incentives to ensure that policy support goes specifically toward those fuels.

Blending mandates could be implemented through U.S. and Canadian federal legislation via a minimum energy or blend requirement on fuel consumed by ships flagged to those nations or sold at ports in the GL-SLS region. Policymakers could also consider adopting a low-carbon fuel standard modeled on California's approach, an accelerated greenhouse gas fuel standard, such as that being developed by IMO, or expanding Canada's Clean Fuel Standard to cover marine fuels. In lieu of a combined low carbon fuel standard that includes multiple sectors, a dedicated marine-only fuel standard could set a more direct signal rather than a system accepting cheaper, out of sector credits. Reaching higher volumes of advanced marine fuels will require investing in even more challenging pathways with higher costs and uncertain commercialization timelines. In the near term, these pathways' production costs will require special policy support to reach cost parity with conventional marine fuels, such as incentives to secure a price floor.

FUTURE WORK

This report provides an initial feasibility assessment of alternative fuel and power options for the Great Lakes region. Future work will be needed to refine and update these findings. This could include assessments of regional e-fuel and synthetic fuel production (e.g., taking advantage of low carbon electricity in Ontario to produce synthetic fuels), detailed port surveys regarding the potential for specific bunkering infrastructure (e.g., ammonia and hydrogen), replenishment mechanisms, and production locations. An investigation of regulations to ensure the safe transport of higher risk fuels should also be considered. Finally, consideration of how cargo being transported today might support the creation of alternative marine fuels at regional ports might also be investigated using a tool under development by GSGP.

Another potential area of future work could assess the costs and benefits of using wind-assisted propulsion on new and existing Great Lakes ships. That analysis could consider which wind-assisted propulsion technology is feasible for various ship types, sizes, and operations for the Great Lakes fleet. The environmental benefits of reduced air pollution and GHG emissions could be quantified, along with public health benefits, including avoided premature mortality, reduced rates of childhood asthma, and monetized health benefits.

This report generated a detailed profile of Great Lakes shipping using AIS-based methods. Additional public data, potentially collected under mandatory reporting requirements, could be used to further refine and validate those results. That data could include public, annual, and ship specific fuel consumption and activity data similar to that being collected in the EU. Ideally, fuel consumption would be reported by fuel type for each engine with an indicator for how the fuel was produced to enable a LCA. Annual engine load distribution data for main and auxiliary engines would enable more precise and accurate estimates of fuel consumption and emissions. These data would also allow researchers to better model the impacts of regulations that affect ship speed and engine power. Similarly, continuous emissions monitoring data for air and climate pollutants of major concern, notably SO_2, NO_x, PM, BC, CO, CO_2, CH_4, N_2O, and NH_3 (for ammonia engines) could be considered. Finally, data on shore power use per ship per year, or per berth as reported by individual ports would be valuable for tracking technology progress.

REFERENCES

Amaral, A. F., Previtali, D., Dell'Angelo, A., Bisotti, F., Pretoro, A. D., Andoglu, E. M., Colombo, S., & Manenti, F. (2019). Methanol production from biomass gasification: Techno-economic assessment of different feedstocks. *Chemical Engineering Transactions 74*(6), 1237–1242. https://doi.org/10.3303/CET1974207

American Bureau of Shipping. (2020a). *Advisory on NOx Tier III Compliance.* (2020). https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS-Advisory-on-NOx-Tier-III-Compliance-20068.pdf

American Bureau of Shipping. (2020b). *Sustainability Whitepaper: Ammonia as Marine Fuel*. https://absinfo.eagle.org/acton/attachment/16130/f-157fdb59-8b2c-4c12-a6c0-be887d7417ae/1/-/-/-/-/Ammonia_as_Marine_Fuel_Whitepaper_20188.pdf

American Bureau of Shipping. (2021a). *Emerging Battery Technologies in the Maritime Industry*. https://absinfo.eagle.org/acton/attachment/16130/f-17992c26-a01d-4201-8f34-a36284b19eef/1/-/-/-/-/battery-technology-whitepaper-21157.pdf

American Bureau of Shipping. (2021b). *Sustainability Whitepaper: Biofuels as Marine Fuel*. https://absinfo.eagle.org/acton/attachment/16130/f-614d1fcd-23a0-4dff-b56d-dc26fa4a2e53/1/-/-/-/-/biofuels-as-marine-fuel-whitepaper-21089.pdf

American Bureau of Shipping. (2021c). *Sustainability Whitepaper: Hydrogen as Marine Fuel*. https://absinfo.eagle.org/acton/attachment/16130/f-bd25832f-8a70-4cc9-b75f-3aadf5d5f259/1/-/-/-/-/hydrogen-as-marine-fuel-whitepaper-21111.pdf

American Bureau of Shipping. (2021d). *Sustainability Whitepaper: Methanol as Marine Fuel*. https://absinfo.eagle.org/acton/attachment/16130/f-550f9b97-e682-455a-af43-a3352bf061bf/1/-/-/-/-/Sustainability-Methanol-as-Marine-Fuel.pdf

American Bureau of Shipping. (2022). *Sustainability Whitepaper: LNG as Marine Fuel*. https://absinfo.eagle.org/acton/attachment/16130/f-72cc9ae6-41ce-42a9-b8f8-8cdea3578dac/1/-/-/-/-/Sustainability%20Whitepaper_LNG%20as%20Marine%20Fuel.pdf

American Bureau of Shipping. (2023a). *Marine Fuel Oil Advisory*. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/marine-fuel-oil-advisory.pdf

American Bureau of Shipping. (2023b). *Setting the Course to Low Carbon Shipping: Zero Carbon Outlook*. https://ww2.eagle.org/en/publication-flip/zero-carbon-outlook.html

Ammar, N. R., & Seddiek, I. S. (2021). Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: Case study passenger vessel. *Environmental Science and Pollution Research*, *28*(28), 37851–37866. https://doi.org/10.1007/s11356-021-13271-4

Andersson, K., & Salazar, C. M. (2015). *Methanol as a marine fuel*. FCBI Energy, Methanol Institute. http://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

Argonne National Laboratory. (2022). *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)* (Version 2022) [Computer software]. https://greet.es.anl.gov/index.php

Baldino, C., O'Malley, J., Searle, S., Zhou, Y., & Christensen, A. (2020). *Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050*. International Council on Clean Transportation. https://theicct.org/publication/hydrogen-for-heating-decarbonization-options-for-households-in-the-united-kingdom-in-2050/

Basma, H., Buysse, C., Zhou, Y., & Rodriguez, F. (2023). *Total cost of ownership of alternative powertrain technologies for class 8 long-haul trucks in the United States*. International Council on Clean Transportation. https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/

Basso, M. N., Abrahamoglu, S., Foseid, H., Spiewanowski, P., Winje, E., & Jakobsen, E. (2022). *Screening and Selection of Sustainable Zero-Carbon Fuels*. https://futurefuelsnordic.com/screening-and-selection-of-sustainable-zero-carbon-fuel/

Bennett, J., Mishra, P., Miller, E., Borlaug, B., Meintz, & Birky, A. (2022). *Estimating the breakeven cost of delivered electricity to charge class 8 electric tractors*. https://www.nrel.gov/docs/fy23osti/82092.pdf

Cames, M., Wissner, N., & Sutter, J. (2021). *Ammonia as a marine fuel*. Öko-Institut e.V. https://en.nabu.de/imperia/md/content/nabude/verkehr/210622-nabu-study-ammonia-marine-fuel.pdf

Carvalho, L., Furusjö, E., Kirtania, K., Wetterlund, E., Lundgren, J., Anheden, M., & Wolf, J. (2017). Techno-economic assessment of catalytic gasification of biomass powders for methanol production. *Bioresource Technology*, *237*, 167–177. https://doi.org/10.1016/j.biortech.2017.02.019

Clausen, L. R., Elmegaard, B., & Houbak, N. (2010). Technoeconomic analysis of a low CO_2 emission dimethyl ether (DME) plant based on gasification of torrefied biomass. *Energy*, *35*(12), 4831–4842. https://doi.org/10.1016/j.energy.2010.09.004

Clear Seas. (2023). *Marine shipping in the Great Lakes: What you need to know*. https://clearseas.org/en/blog/marine-shipping-in-the-great-lakes-what-you-need-to-know/

Comer, B., Georgeff, E., & Osipova, L. (2020). *Air emissions and water pollution discharges from ships with scrubbers*. International Council on Clean Transportation. https://theicct.org/publication/air-emissions-and-water-pollution-discharges-from-ships-with-scrubbers/

Comer, B., Olmer, N., Mao, X., Roy, B., & Rutherford, D. (2017). *Black carbon emissions and fuel use in global shipping, 2015*. International Council on Clean Transportation. https://theicct.org/publication/black-carbon-emissions-and-fuel-use-in-global-shipping-2015/

Comer, B., O'Malley, J., Osipova, L., & Pavlenko, N. (2022). *Comparing the future demand for, supply of, and life-cycle emissions from bio, synthetic, and fossil LNG marine fuels in the European Union*. International Council on Clean Transportation. https://theicct.org/publication/lng-marine-fuel-sep22/

Comer, B., & Osipova, L. (2021). *Update: Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*. International Council on Clean Transportation. https://theicct.org/publication/update-accounting-for-well-to-wake-carbon-dioxide-equivalent-emissions-in-maritime-transportation-climate-policies/

Conference of Great Lakes St. Lawrence Governors & Premiers (GSGP). (2022). *The Great Lakes St. Lawrence Circuit, Electrification Opportunities for the Regional Maritime System*. https://gsgp.org/media/x4rpsaqf/great-lakes-st-lawrence-circuit-one-pager.pdf

Congressional Research Service. (2019). *Shipping Under the Jones Act: Legislative and Regulatory Background*. https://crsreports.congress.gov/product/pdf/R/R45725

DNV. (2022). *Maritime forecast to 2050: Energy transition outlook 2022*. DNV. https://www.dnv.com/Publications/maritime-forecast-to-2050-2022-edition-235251

Elkafas, A. G., Rivarolo, M., Gadducci, E., Magistri, L., & Massardo, A. F. (2022). *Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives*. https://doi.org/10.3390/pr11010097

Elkafas, A., & Shouman, M. (2022). A Study of the Performance of Ship Diesel-Electric Propulsion Systems From an Environmental, Energy Efficiency, and Economic Perspective. *Marine Technology Society Journal*, *56*(1), 52–58. https://doi.org/10.4031/MTSJ.56.1.3

ETIP Bioenergy. (n.d.-a). *Demonstration of BioDME - Dimethyl ether as an advanced biofuel at industrial scale*. https://www.etipbioenergy.eu/value-chains/products-end-use/products/biodme

ETIP Bioenergy. (n.d.-b). *Report on Biomethanol Production and Use as Fuel*. https://www.etipbioenergy.eu/report-on-biomethanol-production-and-use-as-fuel

European Commission. (2021). *Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council*. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559

European Maritime Safety Agency. (2023a). *Update on Potential of Biofuels for Shipping*. https://www.emsa.europa.eu/publications/reports/item/4834-update-on-potential-of-biofuels-for-shipping.html

European Maritime Safety Agency. (2023b). *Potential of Ammonia as Fuel in Shipping*. https://www.emsa.europa.eu/publications/reports/item/4833-potential-of-ammonia-as-fuel-in-shipping.html

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., Schim van der Loeff, W., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J.-M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D., Liu, Y., … Yuan, H. (2020). *Fourth IMO greenhouse gas study*. International Maritime Organization. https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Foretich, A., Zaimes, G. G., Hawkins, T. R., & Newes, E. (2021). Challenges and opportunities for alternative fuels in the maritime sector. *Maritime Transport Research*, *2*, 100033. https://doi.org/10.1016/j.martra.2021.100033

Fornell, R., Berntsson, T., & Åsblad, A. (2013). Techno-economic analysis of a kraft pulp-mill-based biorefinery producing both ethanol and dimethyl ether. *Energy*, *50*, 83–92. https://doi.org/10.1016/j.energy.2012.11.041

FuelCellsWorks. (2022). *Nine Of The Largest Green Hydrogen Projects 2022*. https://fuelcellsworks.com/news/nine-of-the-largest-green-hydrogen-projects-2022/

Global Maritime Forum. (2021). *NoGAPS: Nordic Green Ammonia Powered Ship*. https://www.globalmaritimeforum.org/content/2021/06/The-Nordic-Green-Ammonia-Powered-Ship-_Project-Report.pdf

Glosten. (2016). *Ship Operations Cooperative Program, Energy Efficiency White Paper*. https://www.maritime.dot.gov/sites/marad.dot.gov/files/2020-12/15099.01_%20SOCP%20Marine%20Vessel%20Energy%20Efficiency_Rev-_signed.pdf

Graser, A. (2019). MovingPandas: Efficient Structures for Movement Data in Python. *GI_Forum*, *1*, 54–68. https://doi.org/10.1553/giscience2019_01_s54

Great Lakes St. Lawrence Seaway System. (2023). *Management of the Seaway*. https://greatlakes-seaway.com/en/about-us/

Haro, P., Ollero, P., Villanueva Perales, A. L., & Gómez-Barea, A. (2013). Thermochemical biorefinery based on dimethyl ether as intermediate: Technoeconomic assessment. *Applied Energy*, *102*, 950–961. https://doi.org/10.1016/j.apenergy.2012.09.051

Hydro Québec. (2021). Comparison of electricity prices in major North American cities. https://www.hydroquebec.com/data/documents-donnees/pdf/comparison-electricity-prices.pdf

IEA Bioenergy. (2018). *Biofuels for the marine shipping sector*. https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf

Independent Electricity System Operator. (2023). *Ontario's electricity grid*. https://www.ieso.ca/en/Learn/Ontario-Electricity-Grid/Supply-Mix-and-Generation

Innovation Maritime (IMAR) & GSGP. (2022). *Domestic Great Lakes & St. Lawrence Shipping Industry: Transition to Biofuels*. https://gsgp.org/media/vzxbk1ig/imar-gsgp-biofuels-report.pdf

Innovation Maritime (IMAR) & GSGP. (2023). *Domestic Great Lakes & St. Lawrence Shipping Industry: Transition to Biofuels – Transit Cost Analysis*. https://gsgp.org/media/pqvh34yd/imar-gsgp-biofuels-report-2023.pdf

Intergovernmental Panel on Climate Change [IPCC]. (2021). 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.)]. https://doi.org/10.1017/9781009157896

International Chamber of Shipping. (2021). *A Zero Emission Blueprint for Shipping*. https://www.ics-shipping.org/publication/a-zero-emission-blueprint-for-shipping/

International Civil Aviation Organization (ICAO). (2021). *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*. https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf

International Council on Clean Transportation (ICCT). (2011). *The Energy Efficiency Design Index (EEDI) for New Ships*. https://theicct.org/sites/default/files/publications/ICCTpolicyupdate15_EEDI_final.pdf

International Energy Agency (IEA). (2023). *ETP Clean Energy Technology Guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

International Energy Agency. (2023). *Energy Technology Perspectives 2023*. IEA. https://www.iea.org/reports/energy-technology-perspectives-2023

International Joint Commission. (2016). *The Boundary Waters Treaty of 1909*. https://www.ijc.org/sites/default/files/2018-07/Boundary%20Water-ENGFR.pdf

International Joint Commission. (2023). *Role of the IJC*. https://ijc.org/en/who/role

International Maritime Organization (IMO). (n.d.). *International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)*. Retrieved September 30, 2023, from https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx

International Maritime Organization (IMO). (2010). *The International Convention on Standards of Training and Certification of Watchkeeping for Seafarers* (STCW). https://www.imo.org/en/OurWork/HumanElement/Pages/STCW-Convention.aspx

International Maritime Organization (IMO). (2016). *International Code for the Construction and Equipment of Ships carrying Gases in Bulk (IGC Code), 2016 edition*. https://www.imo.org/en/ourwork/safety/pages/igc-code.aspx

International Maritime Organization (IMO). (2018). *International Safety Management Code (ISM Code)*. https://www.imo.org/en/ourwork/humanelement/pages/ISMCode.aspx

International Maritime Organization (IMO). (2020). *International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC)*. https://www.imo.org/en/OurWork/Environment/Pages/IBCCode.aspx#:~:text=The%20IBC%20Code%20provides%20an,noxious%20liquid%20chemicals%20in%20bulk

International Maritime Organization (IMO). (2020). *The Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as fuel*. https://www.register-iri.com/wp-content/uploads/MSC.1-Circ.1621.pdf

International Maritime Organization (IMO). (2022). *Report of the Correspondence Group on LPG, Hydrogen, low-flashpoint oil fuels and amendments to the IGF Code*. https://docs.imo.org/Shared/Download.aspx?did=137187

International Maritime Organization (IMO). (2023a). *Interim guidelines on safe operation of onshore power supply (OPS) service in port for ships engaged on international voyages*. https://www.mardep.gov.hk/en/msnote/pdf/msin2361anx1.pdf

International Maritime Organization (IMO). (2023b). *Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels*. https://wwwcdn.imo.org/localresources/en/MediaCentre/WhatsNew/Documents/MEPC80.INF10.pdf

International Maritime Organization (IMO). (2023c). *Revised GHG reduction strategy for global shipping adopted*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx

International Renewable Energy Agency (IRENA). (2019). *Navigating the way to a renewable future: Solutions to decarbonise shipping*. IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf?rev=2263292d8ec54b5eb676c7b3c545da97

International Renewable Energy Agency (IRENA). (2021). *Innovation Outlook: Renewable Methanol*. https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

Jeong, B., Wang, H., Oguz, E., & Zhou, P. (2018). An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. *Journal of Cleaner Production*, *187*, 111–130. https://doi.org/10.1016/j.jclepro.2018.03.184

Johnson, K., Miller, W., Durbin, T., Jiang, Y., Yang, J., Karavalakis, G., & Cocker, D. (2017). *Black carbon measurement methods and emission factors from ships*. International Council on Clean Transportation. https://theicct.org/publication/black-carbon-measurement-methods-and-emission-factors-from-ships/

Langholtz, M. H., Stokes, B. J., & Eaton, L. M. (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks* (DOE/EE-1440, ORNL/TM-2016/160, 1271651). https://doi.org/10.2172/1271651

Law, L. C., Foscoli, B., Mastorakos, E., & Evans, S. (2021). A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. *Energies*, *14*(24), Article 24. https://doi.org/10.3390/en14248502

Lloyd's Register. (2020). *Techno-economic assessment of zero-carbon fuels*. https://www.lr.org/en/knowledge/research-reports/techno-economic-assessment-of-zero-carbon-fuels/

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021). Calculate Total Cost of Ownership (TCO) for decarbonization of vessels. https://www.zerocarbonshipping.com/publications/calculate-total-cost-of-ownership-tco-for-decarbonization-of-vessels/

Makoś, P., Słupek, E., Sobczak, J., Zabrocki, D., Hupka, J., & Rogala, A. (2019). Dimethyl ether (DME) as potential environmental friendly fuel. *E3S Web of Conferences*, *116*, 00048. https://doi.org/10.1051/e3sconf/201911600048

Malins, C. (2019). *What does it mean to be a renewable electron?* International Council on Clean Transportation. https://theicct.org/publication/what-does-it-mean-to-be-a-renewable-electron/

Mao, X., Georgeff, E., Rutherford, D., & Osipova, L. (2021). *Repowering Chinese coastal ferries with battery-electric technology*. The International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/06/chinese-coastal-ferries-electric-apr2021.pdf

Mao, X., Rutherford, D., Osipova, L., & Comer, B. (2020). *Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?* The International Council on Clean Transportation. https://theicct.org/publication/refueling-assessment-of-a-zero-emission-container-corridor-between-china-and-the-united-states-could-hydrogen-replace-fossil-fuels/

Martin Associates. (2023). *Economic Impacts of Maritime Shipping in the Great Lakes-ST. Lawrence Region*. https://www.greatlakesports.org/wp-content/uploads/2023/07/AGLPA_EconomicStudyDocument_EN_13juillet_v2.pdf

Meng, Z., & Comer, B. (2022). *Great Lakes-St. Lawrence Seaway ship emissions inventory, 2019*. International Council on Clean Transportation. https://theicct.org/publication/ships-great-lakes-emissions-mar22/

Minnehan, J. J., & Pratt, J. W. (2017). *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels* (SAND--2017-12665, 1410178; p. SAND--2017-12665, 1410178). Sandia National Laboratories. https://doi.org/10.2172/1410178

Minnesota Power. (2022). *Minnesota power electric rate book*. https://minnesotapower.blob.core.windows.net/content/Content/Documents/CustomerService/mp-ratebook.pdf

Mrzljak, V., Žarković, B., & Prpić-Oršić, J. (2017). Marine Slow Speed Two-Stroke Diesel Engine – Numerical Analysis of Efficiencies and Important Operating Parameters. *Machines. Technologies. Materials.*, *11*(10), 481–484.

Nelissen, D., Faber, J., van der Veen, R., van Grinsven, A., Shanthi, H., & van den Toorn, E. (2020). *Availability and costs of liquefied bio- and synthetic methane: The maritime shipping perspective*. CE Delft. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190236_Availability_and_costs_of_liquefied_bio-_and_synthetic_methane_Def.pdf

Neste. (2023). *Biodiesel prices (SME & FAME)*. Neste Worldwide. https://www.neste.com/investors/market-data/biodiesel-prices

Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). *Greenhouse gas emissions from global shipping, 2013–2015: Detailed methodology*. https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

O'Malley, J., Pavlenko, N., Searle, S., & Martin, J. (2022). *Setting a lipids fuel cap under the California Low Carbon Fuel Standard*. International Council on Clean Transportation. https://theicct.org/publication/lipids-cap-ca-lcfs-aug22/

Overview of the Great Lakes/St. Lawrence Seaway System. (2019). Great Lakes-St. Lawrence Seaway Development Corporation. https://greatlakes-seaway.com/wp-content/uploads/2019/10/overview_brochure-1.pdf

Parbowo, H. S., Ardy, A., & Susanto, H. (2019). Techno-economic analysis of Dimethyl Ether production using Oil Palm Empty Fruit Bunches as feedstock – a case study for Riau. *IOP Conference Series: Materials Science and Engineering*, *543*(1), 012060. https://doi.org/10.1088/1757-899X/543/1/012060

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel*. International Council on Clean Transportation. https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/

Pavlenko, N., Searle, S., & Christensen, A. (2019). *The cost of supporting alternative jet fuels in the European Union*. International Council on Clean Transportation. https://theicct.org/publication/the-cost-of-supporting-alternative-jet-fuels-in-the-european-union/

Recharge News. (2022). *Why multi-million-dollar blue hydrogen investments might fast end up as "stranded assets."* Recharge | Latest Renewable Energy News. https://www.rechargenews.com/energy-transition/why-multi-million-dollar-blue-hydrogen-investments-might-fast-end-up-as-stranded-assets/2-1-1146527

Ricks, W., Xu, Q., & Jenkins, J. D. (2023). Minimizing emissions from grid-based hydrogen production in the United States. *Environmental Research Letters*, *18*(1), 014025. https://doi.org/10.1088/1748-9326/acacb5

Shipowners P&I Club, UCL, & UMAS. (2022). *Alternative Low Emission Fuel for the Maritime Industry*. https://shp-13383-s3.s3.eu-west-2.amazonaws.com/media/8216/8630/7488/Alternative-Low-Emission-Fuels-2022.pdf

Sofiev, M., Winebrake, J. J., Johansson, L., Carr, E. W., Prank, M., Soares, J., Vira, J., Kouznetsov, R., Jalkanen, J.-P., & Corbett, J. J. (2018). Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nature Communications*, *9*(1), 406. https://doi.org/10.1038/s41467-017-02774-9

SOLAS. (1974, as amended) *International Convention for the Safety of Life at Sea*. https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

Szybist, J. P., McLaughlin, S., & Iyer, S. (2014). *Emissions and Performance Benchmarking of a Prototype Dimethyl Ether-Fueled Heavy-Duty Truck*. https://afdc.energy.gov/files/u/publication/ornl_dme_tm-2014-59.pdf

The White House. (2021). *National Climate Task Force*. The White House. https://www.whitehouse.gov/climate/

TNO. (2020). *Power-2-fuel cost analysis*. TNO. https://smartport.nl/wp-content/uploads/2020/09/Cost-Analysis-Power-2-Fuel_def_2020.pdf

U.S. Department of State. (2022). *Special Presidential Envoy for Climate John Kerry "Implementation Plus: Global Climate Action in 2022."* https://www.state.gov/special-presidential-envoy-for-climate-john-kerry-implementation-plus-global-climate-action-in-2022/

U.S. Energy Information Administration. (2022). *Annual Energy Outlook 2022*. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=62-AEO2022&cases=ref2022&sid=&sourcekey=0

U.S. Energy Information Administration. (2023a). *EIA Annual Energy Outlook 2023*. https://www.eia.gov/outlooks/aeo/

U.S. Energy Information Administration. (2023b). *State Energy Data System (SEDS): 2021*. https://www.eia.gov/state/seds/seds-data-fuel-prev.php

U.S. Environmental Protection Agency (EPA). (2008). *Control of Emissions of Air Pollution From Locomotive Engines and Marine Compression-Ignition Engines Less Than 30 Liters per Cylinder*. https://www.govinfo.gov/content/pkg/FR-2008-06-30/pdf/R8-7999.pdf

U.S. Environmental Protection Agency (EPA). (2016a). *LMOP Landfill and Project Database* [Overviews and Factsheets]. https://www.epa.gov/lmop/lmop-landfill-and-project-database

U.S. Environmental Protection Agency (EPA). (2016b). *Lifecycle Greenhouse Gas Emissions for Select Pathways*. https://www.epa.gov/sites/default/files/2016-07/documents/select-ghg-results-table-v1.pdf

U.S. Environmental Protection Agency (EPA). (2022). *Shore Power Technology Assessment at U.S. Ports 2022 Update* [Reports and Assessments]. https://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports

U.S. Environmental Protection Agency. (EPA). (2023). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

U.S. Office of Energy Efficiency & Renewable Energy. (2023). *Hydrogen and Fuel Cell Technologies Office*. Energy.Gov. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office

USDA National Agricultural Statistics Service. (2022). *Crop Production 2021 Summary*. https://downloads.usda.library.cornell.edu/usda-esmis/files/k3569432s/sn00c1252/g158cj98r/cropan22.pdf

Verbeek, R., 't Hart, P., Pruyn, J. F. J., & Bergsma, J. (2020). *Assessment of alternative fuels for seagoing vessels using Heavy Fuel Oil*. https://repository.tudelft.nl/islandora/object/uuid%3A531f5251-4841-4109-9e06-4338b78fdf70

Wang, M., Amgad, E., Lee, U., Adarsh, B., Sudhanya, B., Benavides, Pahola, Bobba, Pallavi, Burnham, Andrew, Cai, Hao, Gracida, Ulises, Hawkins, Troy, Iyer, Rakesh, Kelly, Jarod, Kim, Taemin, Kingsbury, Kathryn, Kwon, Hoyoung, Li, Yuan, Liu, Xinyu, Lu, Zifeng, … Zang, Guiyan. (2021). *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2021 Excel)* [Computer software]. Argonne National Laboratory (ANL), Argonne, IL (United States). https://doi.org/10.11578/GREET-EXCEL-2021/DC.20210902.1

Wang, M., Elgowainy, A., Lee, U., Baek, K. H., Bafana, A., Benavides, P. T., Burnham, A., Cai, H., Cappello, V., Chen, P., Gan, Y., Gracida-Alvarez, U. R., Hawkins, T. R., Iyer, R. K., Kelly, J. C., Kim, T., Kumar, S., Kwon, H., Lee, K., … Zaimes, G. (2022). *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 Excel). [Computer software]*. https://doi.org/10.11578/GREET-Excel-2022/dc.20220908.1

Wang, Y., & Wright, L. A. (2021). *A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation*. https://www.mdpi.com/2673-4060/2/4/29

Zhang, Z., Delcroix, B., Rezazgui, O., & Mangin, P. (2021). Simulation and techno-economic assessment of bio-methanol production from pine biomass, biochar and pyrolysis oil. *Sustainable Energy Technologies and Assessments*, *44*, 101002. https://doi.org/10.1016/j.seta.2021.101002

Zhou, Y., Baldino, C., & Searle, S. (2020). *Potential biomass-based diesel production in the United States by 2032*. International Council on Clean Transportation. https://theicct.org/publication/potential-biomass-based-diesel-production-in-the-united-states-by-2032/

Zhou, Y. Pavlenko, N., Rutherford, D., Osipova, L, & Comer, B. (2020). *The potential of liquid* biofuels in reducing ship emissions. International Council on Clean Transportation. https://theicct.org/publication/the-potential-of-liquid-biofuels-in-reducing-ship-emissions/

Zhou, Y & Searle, S. (2022). *Cost of renewable hydrogen produced onsite at hydrogen refueling stations in Europe*. International Council on Clean Transportation. https://theicct.org/publication/fuels-eu-onsite-hydro-cost-feb22/

Zhou, Y., Searle, S., & Pavlenko, N. (2022). *Current and future cost of e-kerosene in the United States and Europe*. International Council on Clean Transportation. https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/

Zhou, Y., Swidler, D., Searle, S., & Baldino, C. (2021). *Life-cycle greenhouse gas emissions of biomethane and hydrogen pathways in the European Union*. International Council on Clean Transportation. https://theicct.org/publication/life-cycle-greenhouse-gas-emissions-of-biomethane-and-hydrogen-pathways-in-the-european-union/

APPENDIX A: PROJECT PARTNERS

The ICCT[40] was established as an independent, nonprofit organization in 2005 to provide first-rate, unbiased technical and scientific analysis to environmental regulators. Over the course of the last decade, the ICCT has steadily acquired the technical skills and expertise in regulatory development on motor vehicle emission standards, energy efficiency, CO_2 and greenhouse gas emission standards, fuel standards, and life-cycle analysis, and computing and other technical skills. The ICCT has five offices in Washington D.C., San Francisco, Berlin, Beijing, and São Paulo, as well as full-time consultants in India, Indonesia, Mexico, and Vietnam numbering about 120 in total.

ICCT's marine program works to further policies that address the air quality and climate impacts of shipping at the international, regional, national, and local (port) levels. ICCT's marine program is recognized as a world leader in providing policy-relevant technical analyses to regulators, as evidenced by its ongoing participation as technical advisors to United States and Brazil delegations to the International Maritime Organization and our service on the European Commission's European Sustainable Shipping Forum. ICCT researchers led the development of the emissions inventory methodology for the Fourth IMO Greenhouse Gas Study (Faber et al., 2020). The Fourth IMO GHG study uses ICCT emission factors for black carbon (Comer et al., 2017), which were informed by a 2016-2017 MARAD META project (Johnson et al., 2017), as well as methane, the emission factors for which we developed in ICCT's 2020 LNG study (Pavlenko et al., 2020).

The American Bureau of Shipping[41] is a completely unique organization in the United States, serving as an important partner with industry and government (as designated in both the U.S. Code and the Code of Federal Regulations). As a marine classification society, ABS is not only a Recognized Standards Organization (RSO) for the maritime industry, but also engages in both engineering and field survey verification of maritime assets to assess their initial and ongoing compliance with applicable requirements from ABS and government authorities such as the U.S. Coast Guard. Additionally, ABS publishes a wide range of guides, guidance notes, and advisories for the maritime industry on high priority topics and challenges.

ABS includes a team of more than 100 research scientists and engineers with varied backgrounds who work with government agencies and industry partners to investigate key issues, develop innovative technology solutions, and transfer technology to the industry. ABS offerings related to sustainability include its simulation-based Energy Efficiency Evaluation (EEE) Service, which allows shipowners and shipyards to compare different propulsion systems and test the performance impact of adding different technologies for new build vessels. ABS has also developed a variety of information technology tools to support sustainable shipping. For example, the ABS Environmental Monitor is the maritime industry's most comprehensive digital sustainability solution to help shipowners achieve their sustainability goals by leveraging multiple data sources, including vessel routing, waste stream, operations, and emissions data, to provide transparent reporting and management.

The Conference of Great Lakes St. Lawrence Governors & Premiers (GSGP, https://gsgp.org) unites the chief executives from Illinois, Indiana, Michigan, Minnesota, New

---

[40] The ICCT, https://theicct.org.

[41] ABS, www.eagle.org.

York, Ohio, Ontario, Pennsylvania, Québec, and Wisconsin. The governors and premiers work as equal partners to grow the region's $6 trillion economy and protect the world's largest system of surface fresh water. The objective of GSGP's maritime work portfolio is to double trade on the Great Lakes and St. Lawrence River by showcasing the economic and environmental advantages of shipping on the region's maritime system. GSGP's recent maritime projects include commissioning yearly emission reports for vessels operating on regional waterways, evaluating the viability of biofuels use in the system, developing potential regional uses for maritime electrification applications for new technologies at the new Soo Locks, developing sustainable fisheries, and developing partnerships for the deployment of smart ships. Regionally, nationally, and internationally, GSGP regularly partners with public and private entities to accomplish high-impact and high-visibility projects in the maritime space.

APPENDIX B: SHIPPING INDUSTRY PROFILE FOR UNITED STATES AND CANADIAN-FLAGGED VESSELS IN THE GL-SLS

Table B1. 2021 United States and Canadian flagged vessels in the GL-SLS—Ship size (dwt) and gt per ship type

Ship type	Number of vessels	Deadweight tonnage (dwt)				Gross tonnage (gt)			
		Total	Average	Maximum	Minimum	Total	Average	Maximum	Minimum
Bulk carrier	81	2,840,000	35,100	93,641	968	1,660,000	20,500	36,360	415
General cargo	18	290,000	16,300	37,515	1,231	200,000	11,200	23,552	749
Chemical tanker	4	180,000	45,300	74,940	14,719	110,000	27,200	42,810	11,285
Container	8	70,000	9,100	16,736	0	50,000	6,100	11,953	109
Oil tanker	3	30,000	8,400	19,460	0	30,000	11,500	26,786	192
Service-other	26	21,300	820	3,058	92	73,500	2,800	15,901	291
Yacht	35	20,400	580	3,048	0	40,300	1,200	6,098	0
Cruise	1	14,700	14,750	14,747	14,747	14,600	14,600	14,639	14,639
Service-tug	2	10,900	5,450	10,907	0	7,400	3,700	7,191	220
Ferry-ropax	133	10,700	80	923	0	52,900	400	1,578	88
Offshore	2	1,600	820	1,200	436	600	300	425	131
Miscellaneous-fishing	18	1,400	80	935	0	8,900	500	2,112	110
Ferry-pax only	19	400	20	180	0	3,300	200	399	28
Miscellaneous-other	2	0	0	0	0	15,000	7,500	9,590	5,402
Ro-ro	1	0	0	0	0	0	0	0	0
Entire fleet	**353**	**3,500,000**	**9,900**	**93,641**	**0**	**2,270,000**	**6400**	**42,810**	**0**

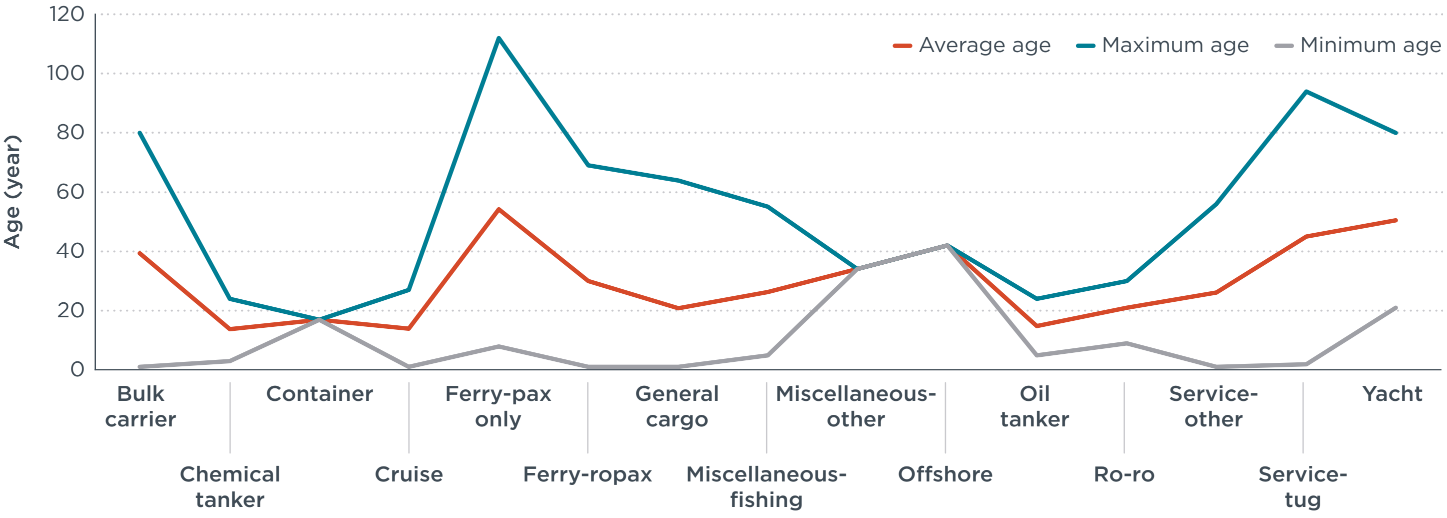


Figure B1. Age by United States and Canadian-flagged ship type in the GL-SLS in 2021

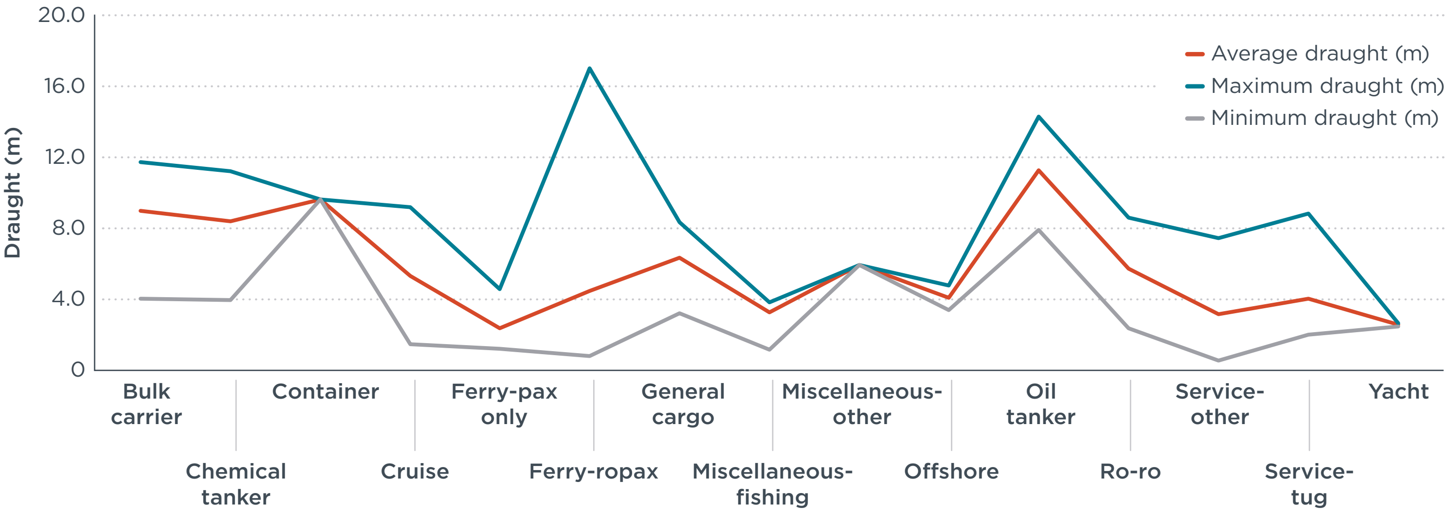


Figure B2. Representative draughts by United States and Canadian-flagged ship type in the GL-SLS in 2021

Table B2. Propulsion power by United States and Canadian-flagged ship type in the GL-SLS in 2021

Ship type	Total power (kW)	Average power (kW)	Maximum power (kW)	Minimum power (kW)
Bulk carrier	605,201	7,472	22,890	412
Chemical tanker	98,877	5,493	9,619	662
Container	11,120	11,120	11,120	11,120
Cruise	6,293	3,147	3,800	2,493
Ferry-pax only	23,031	1,279	7,015	257
Ferry-ropax	101,042	3,886	20,880	905
General cargo	23,630	2,954	4,440	749
Miscellaneous-fishing	12,822	675	1,492	295
Miscellaneous-other	3,821	3,821	3,821	3,821
Offshore	2,642	1,321	1,882	760
Oil tanker	36,140	9,035	13,650	4,800
Ro-ro	25,051	8,350	16,800	851
Service-other	125,404	3,583	13,020	253
Service-tug	342,094	2,572	10,914	294
Yacht	2,421	1,211	1,958	463

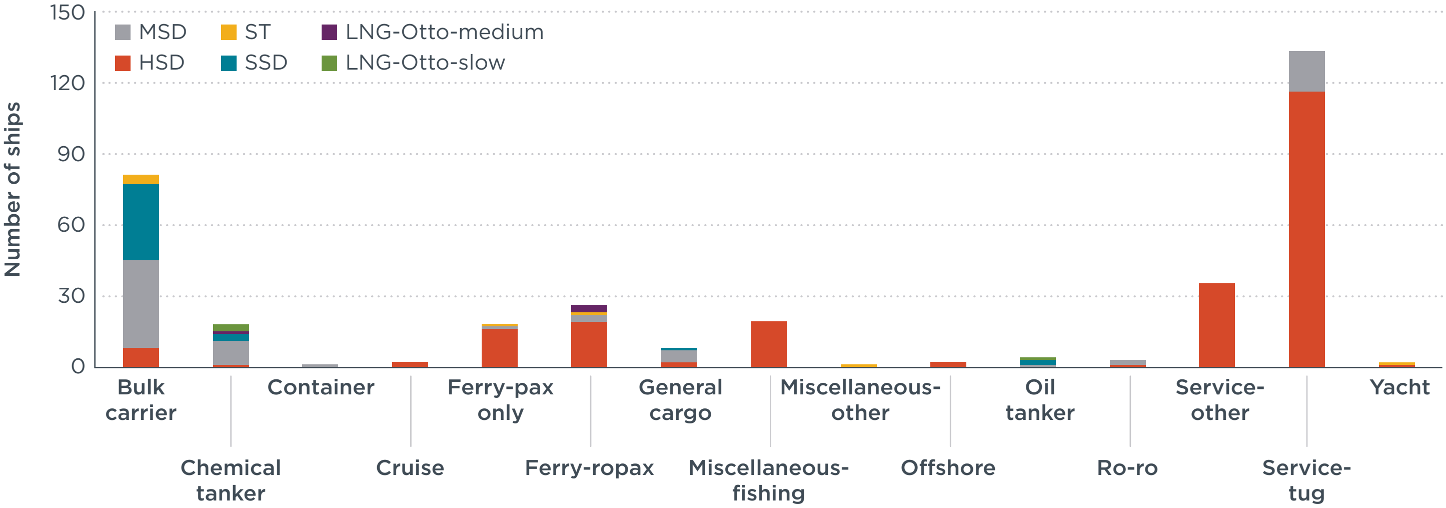


Figure B3. Main engine type by United States and Canadian-flagged ship type in the GL-SLS in 2021

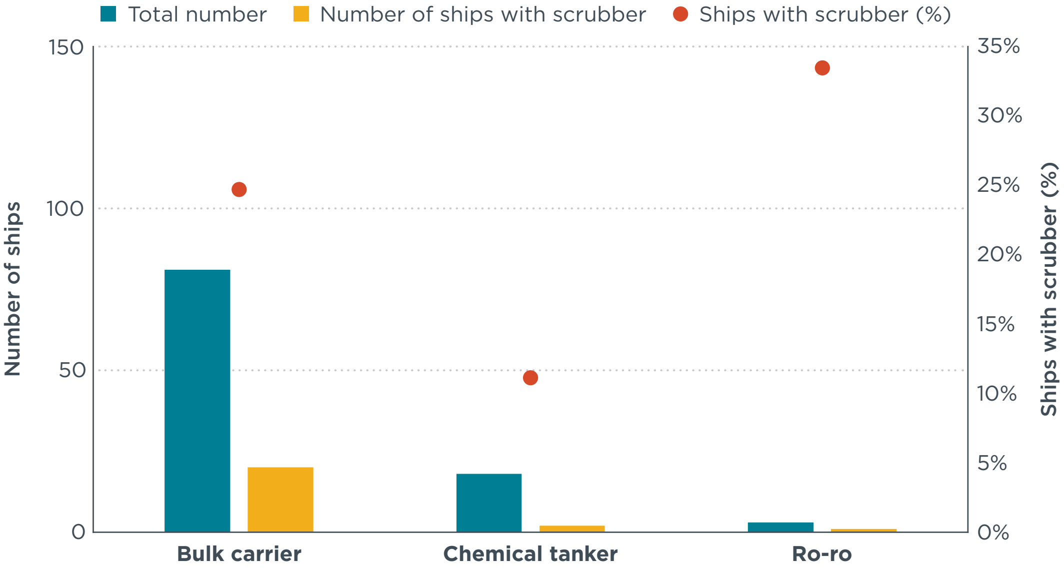


Figure B4. Exhaust gas aftertreatment status by United States and Canadian-flagged ship type in the GL-SLS in 2021

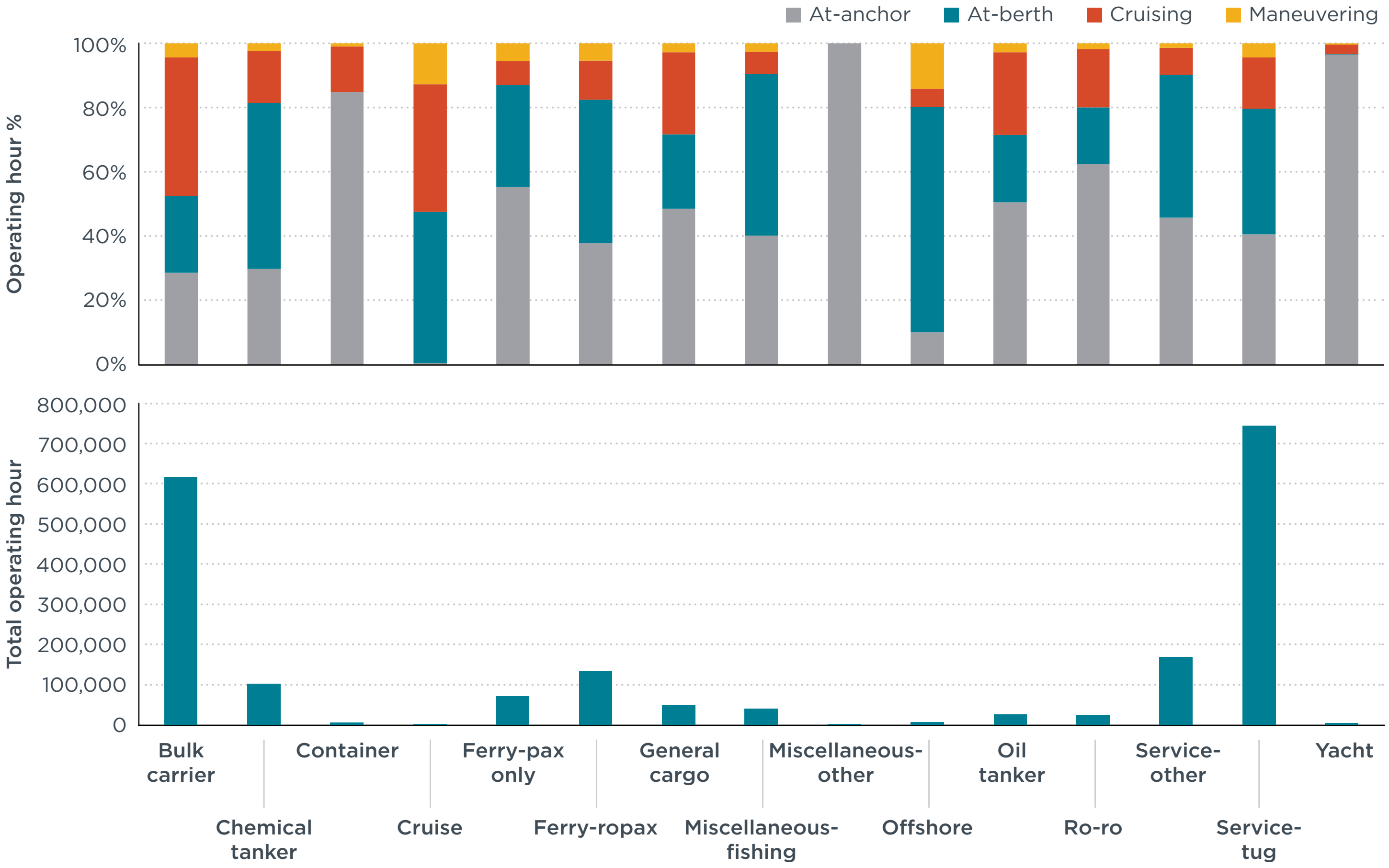


Figure B5. Operating hours by Unites States and Canadian-flagged ship type and phase in the GL-SLS in 2021

Table B3. Operating hours by United States and Canadian-flagged ship type and phase in the GL-SLS region in 2021

Ship type	Number of vessels	Average operating hours				Total operating hours			
		At-anchor	At-berth	Cruising	Maneuvering	At-anchor	At-berth	Cruising	Maneuvering
Bulk carrier	81	2,165	1,817	3,278	337	175,348	147,182	265,481	27,332
Chemical tanker	18	1,673	2,917	911	131	30,105	52,499	16,394	2,362
Container	1	4,454	0	749	49	4,454	0	749	49
Cruise	2	2	253	213	69	3	505	425	137
Ferry-pax only	18	2,157	1,237	288	219	38,820	22,264	5,192	3,948
Ferry-ropax	26	1,926	2,277	619	277	50,063	59,198	16,094	7,202
General cargo	8	2,943	1,410	1,540	175	23,541	11,279	12,318	1,401
Miscellaneous-fishing	19	824	1,036	140	55	15,665	19,690	2,669	1,037
Miscellaneous-other	1	1,224	0	0	0	1,224	0	0	0
Offshore	2	317	2,261	184	453	633	4,521	367	906
Oil tanker	4	3,200	1,336	1,633	176	12,800	5,345	6,532	702
Ro-ro	3	5,074	1,434	1,487	141	15,222	4,301	4,462	422
Service-other	35	2,176	2,125	406	62	76,177	74,385	14,206	2,159
Service-tug	133	2,258	2,184	891	249	300,300	290,515	118,555	33,072
Yacht	2	1,717	4	53	8	3,433	8	106	15

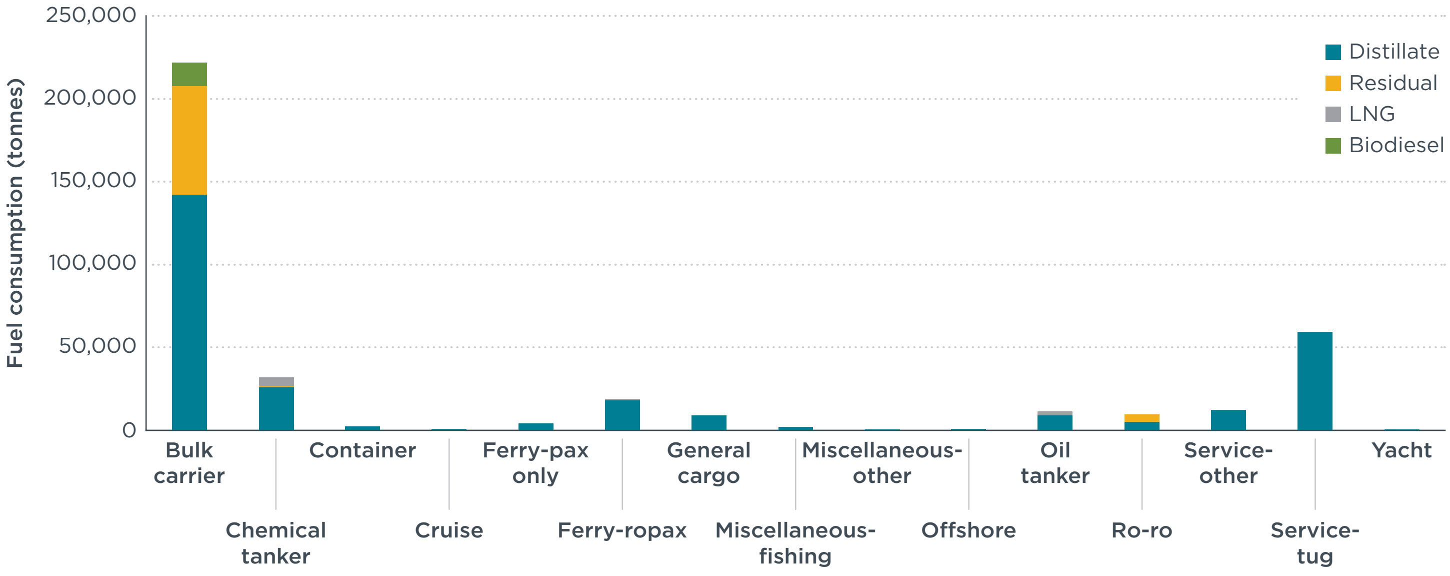


Figure B6. Fuel consumption by United States and Canadian-flagged ship type in the GL-SLS in 2021

Table B4. GHG and air pollution by United States and Canadian-flagged ship type in the GL-SLS in 2021

Ship type	Tonnes emitted									
	CO_2	CH_4	N_2O	BC	SO_x	PM_{10}	$PM_{2.5}$	NO_x	CO	VOCs
Bulk carrier	664,034	10	37	89	261	214	197	13,537	525	506
Chemical tanker	98,483	39	7	9	42	20	19	965	63	47
Container	6,354	<1	1	1	3	2	2	110	5	4
Cruise	1,176	<1	<1	<1	1	<1	<1	10	1	1
Ferry-pax only	12,081	<1	1	1	5	3	3	164	8	7
Ferry-ropax	58,420	20	5	5	24	12	11	567	35	27
General cargo	26,845	<1	2	4	16	10	9	540	23	21
Miscellaneous-fishing	5,498	<1	1	1	2	2	1	106	5	4
Miscellaneous-other	326	<1	<1	<1	<1	<1	<1	1	<1	<1
Offshore	1,438	<1	<1	<1	1	<1	<1	24	1	1
Oil tanker	34,025	22	2	2	13	7	7	426	29	22
Ro-ro	28,750	<1	3	5	11	10	10	444	21	19
Service-other	38,368	1	4	4	16	11	10	725	34	28
Service-tug	189,025	3	12	22	81	51	47	3,737	159	146
Yacht	280	<1	<1	<1	<1	<1	<1	6	<1	<1
Entire fleet	**1,165,103**	**96**	**75**	**142**	**476**	**342**	**315**	**21,362**	**910**	**832**

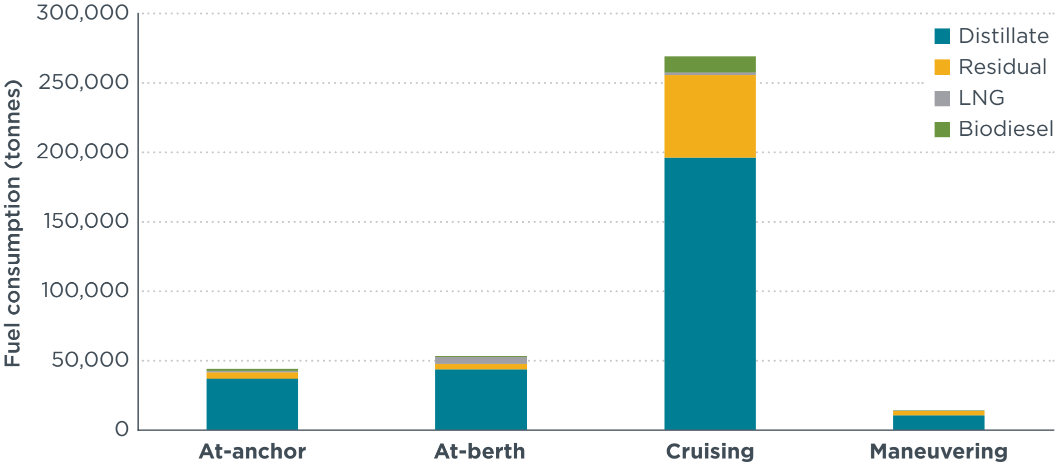


Figure B7. Fuel consumption by operating phase for United States and Canadian-flagged ships in the GL-SLS in 2021

Table B5. Air pollution by operating phase from United States and Canadian-flagged ships in the GL-SLS in 2021

Operating phase	Tonnes emitted									
	CO_2	CH_4	N_2O	BC	SO_x	PM_{10}	$PM_{2.5}$	NO_x	CO	VOCs
At-anchor	134,094	21	21	11	57	32	29	1,618	86	59
At-berth	161,163	20	8	11	69	32	29	1,384	82	57
Cruising	827,407	51	40	105	325	261	240	17,515	695	660
Maneuvering	42,440	4	6	14	24	18	16	846	47	56
Total	**1,165,103**	**96**	**75**	**142**	**476**	**342**	**315**	**21,362**	**910**	**832**

APPENDIX C: FULL LIFE-CYCLE ASSESSMENT RESULTS

Table C1. Life-cycle assessment results using the GREET model, 100-year GWP, 2021

Fuel pathway	gCO_2e/MJ fuel					% reduction from MGO[b]
	Well-to-wake	ILUC	Methane slip[a]	Total	EIR-adjusted	
Biodiesel (soybean oil)	22.4	33.6	0.0	56	56	40%
Renewable diesel (used cooking oil)	14.3	0.0	0.0	14.3	14.3	85%
FT diesel (miscanthus)	11.4	-32.9	0.0	-21.5	-21.5	123%
FT diesel (corn stover)	7.5	-11.2	0.0	-3.7	-3.7	104%
DME (miscanthus)	10.7	-32.9	0.0	-22.2	-22.2	124%
DME (corn stover)	7.1	-11.2	0.0	-4.1	-4.1	104%
DME (natural gas)	98.9	0.0	0.0	98.9	98.9	-7%
Methanol (miscanthus)	7.2	-32.9	0.0	-25.7	-25.7	128%
Methanol (corn stover)	5.2	-11.2	0.0	-6.0	-6.0	106%
Methanol (natural gas)	93.0	0.0	0.0	93.0	93.0	0%
Liquid hydrogen (natural gas)	122.4	0.0	0.0	122.4	106.8	-22%
Liquid hydrogen (natural gas and CCS)	104.1	0.0	0.0	104.1	90.8	-4%
Liquid hydrogen (grid electricity)	215.5	0.0	0.0	215.5	188.1	-115%
Liquid hydrogen (renewable electricity)	1.4	0.0	0.0	1.4	1.2	99%
Ammonia (natural gas)	151.8	0.0	0.0	151.8	151.8	-64%
Ammonia (grid electricity)	226.8	0.0	0.0	226.8	226.8	-145%
Ammonia (renewable electricity)	4.3	0.0	0.0	4.3	4.3	95%
E-diesel (renewable electricity and point CO_2)	2.33	0.0	0.0	2.3	2.3	97%
E-diesel (renewable electricity and DAC)	2.33	0.0	0.0	2.33	2.3	97%
E-diesel (grid electricity and point CO_2)	241.9	0.0	0.0	241.9	241.9	-161%
E-diesel (grid electricity and DAC)	257.7	0.0	0.0	257.7	257.7	-178%
E-methanol (renewable electricity and point CO_2)	2.30	0.0	0.0	2.3	2.3	98%
E-methanol (renewable electricity and DAC)	2.30	0.0	0.0	2.30	2.3	98%
E-methanol (grid electricity and point CO_2)	216.4	0.0	0.0	216.4	216.4	-134%
E-methanol (grid electricity and DAC)	224.9	0.0	0.0	224.9	224.9	-143%
Biomethane (LFG)	13.0	0.0	14.7	27.7	27.7	70%
E-methane (renewable electricity and point CO_2)	2.8	0.0	14.7	17.5	17.5	81%
E-methane (renewable electricity and DAC)	2.8	0.0	14.7	17.5	17.5	81%
E-methane (grid electricity and point CO_2)	225.1	0.0	14.7	239.8	239.8	-159%
E-methane (grid electricity and DAC)	230.7	0.0	14.7	245.4	245.4	-165%
Grid electricity_current	98.7	0.0	0.0	98.7	56.9	41%
100% renewable electricity	0	0	0	0	0	100%

[a]assuming LPDF 2-stroke engines; [b]relative to 0.1% MGO; 92.6 g CO_2e/MJ.

Table C2. Life-cycle assessment results using the GREET model, 20 year GWP

Fuel pathway	gCO_2e/MJ fuel					% reduction from MGO[b]
	Well-to-wake	ILUC	Methane slip[a]	Total	EIR-adjusted	
Biodiesel (soybean oil)	24.2	33.6	0.0	57.8	57.8	41%
Renewable diesel (used cooking oil)	16.3	0.0	0.0	16.3	16.3	83%
FT renewable diesel (miscanthus)	12.6	-32.9	0.0	-20.3	-20.3	121%
FT renewable diesel (corn stover)	8.7	-11.2	0.0	-2.5	-2.5	103%
DME (miscanthus)	14.3	-32.9	0.0	-18.6	-18.6	119%
DME (corn stover)	10.7	-11.2	0.0	-0.5	-0.5	101%
DME (natural gas)	112.5	0.0	0.0	112.5	112.5	-15%
Methanol (miscanthus)	37.6	-32.9	0.0	4.7	4.7	95%
Methanol (corn stover)	35.1	-11.2	0.0	23.9	23.9	76%
Methanol (natural gas)	103.4	0.0	0.0	103.4	103.4	-5%
Liquid hydrogen (natural gas)	139.9	0.0	0.0	139.9	160.4	-64%
Liquid hydrogen (natural gas and CCS)	126.3	0.0	0.0	126.3	144.8	-48%
Liquid hydrogen (grid electricity)	238.2	0.0	0.0	238.2	272.9	-178%
Liquid hydrogen (renewable electricity)	42.0	0.0	0.0	42.0	48.1	51%
Ammonia (natural gas)	210.9	0.0	0.0	210.9	210.9	-115%
Ammonia (grid electricity)	250.5	0.0	0.0	250.5	250.5	-156%
Ammonia (renewable electricity)	4.6	0.0	0.0	4.6	4.6	95%
E-diesel (renewable electricity)	2.4	0.0	0.0	2.4	2.4	98%
E-diesel (renewable electricity and DAC)	2.40	0.00	0.00	2.40	2.40	0.98
E-diesel (grid electricity and point CO_2)	267.3	0.0	0.0	267.3	267.3	-173%
E-diesel (grid electricity and DAC)	284.7	0.0	0.0	284.7	284.7	-190%
E-methanol (renewable electricity)	2.4	0.0	0.0	2.4	2.4	98%
E-methanol (renewable electricity and DAC)	2.41	0.00	0.00	2.41	2.41	0.98
E-methanol (grid electricity and point CO_2)	239.1	0.0	0.0	239.1	239.1	-144%
E-methanol (grid electricity and DAC)	248.4	0.0	0.0	248.4	248.4	-154%
Biomethane (LFG)	33.5	0.0	40.6	74.2	74.2	24%
E-methane (renewable electricity)	7.4	0.0	40.6	48.0	48.0	51%
E-methane (renewable electricity and DAC)	7.4	0.0	40.6	48.0	48.0	0.5
E-methane (grid electricity and point CO_2)	231.4	0.0	40.6	272.1	272.1	-178%
E-methane (grid electricity and DAC)	237	0.0	40.6	277.7	277.7	-183%
Grid electricity_current	109.1	0.0	0	109.1	189.2	-93%
100% renewable electricity	0	0.0	0	0	0	100%

[a]assuming LPDF 2-stroke engines; [b]relative to 0.1% MGO; 98.0 g CO_2e/MJ.

APPENDIX D: FUEL COST PROJECTIONS TO 2030, 2040, AND 2050

Table D1. Fuel cost assumptions for 2030, 2021$/MJ

Fuel pathway	Cost (2021$/MJ)		
	Fuel production	Fueling cost[a]	At-the-pump cost
Biodiesel (soybean oil)	$0.0331	$0.0002	$0.0332
Renewable diesel (used cooking oil)	$0.0314	$0.0002	$0.0315
FT diesel (miscanthus)	$0.0630	$0.0002	$0.0632
FT diesel (corn stover)	$0.0662	$0.0002	$0.0663
DME (miscanthus)	$0.0336	$0.0069	$0.0405
DME (corn stover)	$0.0336	$0.0069	$0.0405
DME (natural gas)	$0.0102	$0.0069	$0.0171
Methanol (miscanthus)	$0.0328	$0.0019	$0.0347
Methanol (corn stover)	$0.0328	$0.0019	$0.0347
Methanol (natural gas)	$0.0094	$0.0019	$0.0113
Liquid hydrogen (natural gas)	$0.0194	$0.0269	$0.0463
Liquid hydrogen (natural gas and CCS)	$0.0260	$0.0269	$0.0529
Liquid hydrogen (grid electricity)	$0.0305	$0.0269	$0.0574
Liquid hydrogen (renewable electricity)	$0.0301	$0.0269	$0.0570
Ammonia (natural gas)	$0.0230	$0.0032	$0.0262
Ammonia (grid electricity)	$0.0540	$0.0032	$0.0572
Ammonia (renewable electricity)	$0.0537	$0.0032	$0.0569
E-diesel (renewable electricity and point CO_2)	$0.0724	$0.0002	$0.0726
E-diesel (renewable electricity and DAC)	$0.0935	$0.0002	$0.0937
E-diesel (grid electricity and point CO_2)	$0.0732	$0.0002	$0.0734
E-diesel (grid electricity and DAC)	$0.0943	$0.0002	$0.0944
E-methanol (renewable electricity and point CO_2)	$0.0543	$0.0019	$0.0562
E-methanol (renewable electricity and DAC)	$0.0746	$0.0019	$0.0765
E-methanol (grid electricity and point CO_2)	$0.0549	$0.0019	$0.0568
E-methanol (grid electricity and DAC)	$0.0752	$0.0019	$0.0771
Biomethane (LFG)	$0.0167	$0.0069	$0.0236
E-methane (renewable electricity and point CO_2)	$0.0505	$0.0069	$0.0575
E-methane (renewable electricity and DAC)	$0.0631	$0.0069	$0.0700
E-methane (grid electricity and point CO_2)	$0.0511	$0.0069	$0.0580
E-methane (grid electricity and DAC)	$0.0636	$0.0069	$0.0705
Grid electricity	$0.0099	$0.0371	$0.0470
Renewable electricity and grid fee	$0.0204	$0.0371	$0.0575

[a] Includes liquefaction costs.

Table D2. Fuel cost assumptions for 2040, 2021$/MJ

Fuel pathway	Cost (2021$/MJ)		
	Fuel production	Fueling cost[a]	At-the-pump cost
Biodiesel (soybean oil)	$0.0331	$0.0002	$0.0332
Renewable diesel (used cooking oil)	$0.0314	$0.0002	$0.0315
FT diesel (miscanthus)	$0.0630	$0.0002	$0.0632
FT diesel (corn stover)	$0.0662	$0.0002	$0.0663
DME (miscanthus)	$0.0336	$0.0069	$0.0405
DME (corn stover)	$0.0336	$0.0069	$0.0405
DME (natural gas)	$0.0103	$0.0069	$0.0173
Methanol (miscanthus)	$0.0328	$0.0019	$0.0347
Methanol (corn stover)	$0.0328	$0.0019	$0.0347
Methanol (natural gas)	$0.0095	$0.0019	$0.0114
Liquid hydrogen (natural gas)	$0.0196	$0.0257	$0.0453
Liquid hydrogen (natural gas+CCS)	$0.0262	$0.0257	$0.0519
Liquid hydrogen (grid electricity)	$0.0264	$0.0257	$0.0521
Liquid hydrogen (renewable electricity)	$0.0238	$0.0257	$0.0495
Ammonia (natural gas)	$0.0232	$0.0032	$0.0264
Ammonia (grid electricity)	$0.0491	$0.0032	$0.0524
Ammonia (renewable electricity)	$0.0462	$0.0032	$0.0494
E-diesel (renewable electricity and point CO_2)	$0.0582	$0.0002	$0.0583
E-diesel (renewable electricity and DAC)	$0.0743	$0.0002	$0.0745
E-diesel (grid electricity and point CO_2)	$0.0629	$0.0002	$0.0631
E-diesel (grid electricity and DAC)	$0.0790	$0.0002	$0.0792
E-methanol (renewable electricity and point CO_2)	$0.0449	$0.0019	$0.0468
E-methanol (renewable electricity and DAC)	$0.0604	$0.0019	$0.0624
E-methanol (grid electricity and point CO_2)	$0.0484	$0.0019	$0.0503
E-methanol (grid electricity and DAC)	$0.0639	$0.0019	$0.0658
Biomethane (LFG)	$0.0167	$0.0069	$0.0236
E-methane (renewable electricity and point CO_2)	$0.0424	$0.0069	$0.0493
E-methane (renewable electricity and DAC)	$0.0520	$0.0069	$0.0589
E-methane (grid electricity and point CO_2)	$0.0458	$0.0069	$0.0527
E-methane (grid electricity and DAC)	$0.0554	$0.0069	$0.0623
Grid electricity	$0.0099	$0.0371	$0.0470
Renewable electricity and grid fee	$0.0201	$0.0371	$0.0572

[a] Includes liquefaction costs.

Table D3. Fuel cost assumptions for 2050, 2021$/MJ

Fuel pathway	Cost (2021$/MJ)		
	Fuel production	Fueling cost[a]	At-the-pump cost
Biodiesel (soybean oil)	$0.0331	$0.0002	$0.0332
Renewable diesel (used cooking oil)	$0.0314	$0.0002	$0.0315
FT diesel (miscanthus)	$0.0630	$0.0002	$0.0632
FT diesel (corn stover)	$0.0662	$0.0002	$0.0663
DME (miscanthus)	$0.0336	$0.0069	$0.0405
DME (corn stover)	$0.0336	$0.0069	$0.0405
DME (natural gas)	$0.0104	$0.0069	$0.0173
Methanol (miscanthus)	$0.0328	$0.0019	$0.0347
Methanol (corn stover)	$0.0328	$0.0019	$0.0347
Methanol (natural gas)	$0.0096	$0.0019	$0.0115
Liquid hydrogen (natural gas)	$0.0198	$0.0244	$0.0442
Liquid hydrogen (natural gas and CCS)	$0.0264	$0.0244	$0.0508
Liquid hydrogen (grid electricity)	$0.0230	$0.0244	$0.0475
Liquid hydrogen (renewable electricity)	$0.0191	$0.0244	$0.0435
Ammonia (natural gas)	$0.0234	$0.0032	$0.0266
Ammonia (grid electricity)	$0.0451	$0.0032	$0.0483
Ammonia (renewable electricity)	$0.0404	$0.0032	$0.0436
E-diesel (renewable electricity and point CO_2)	$0.0465	$0.0002	$0.0467
E-diesel (renewable electricity and DAC)	$0.0578	$0.0002	$0.0579
E-diesel (grid electricity and point CO_2)	$0.0533	$0.0002	$0.0535
E-diesel (grid electricity and DAC)	$0.0646	$0.0002	$0.0648
E-methanol (renewable electricity and point CO_2)	$0.0373	$0.0019	$0.0392
E-methanol (renewable electricity and DAC)	$0.0482	$0.0019	$0.0501
E-methanol (grid electricity and point CO_2)	$0.0423	$0.0019	$0.0442
E-methanol (grid electricity and DAC)	$0.0532	$0.0019	$0.0551
Biomethane (LFG)	$0.0167	$0.0069	$0.0236
E-methane (renewable electricity and point CO_2)	$0.0362	$0.0069	$0.0431
E-methane (renewable electricity and DAC)	$0.0429	$0.0069	$0.0499
E-methane (grid electricity and point CO_2)	$0.0414	$0.0069	$0.0483
E-methane (grid electricity and DAC)	$0.0481	$0.0069	$0.0550
Grid electricity	$0.0099	$0.0371	$0.0470
Renewable electricity and grid fee	$0.0191	$0.0371	$0.0562

[a] Includes liquefaction costs.

APPENDIX E: PORT AUTHORITY SURVEY – PORT INFRASTRUCTURE AND BUNKERING OPERATIONS

OVERVIEW

The Great Lakes St. Lawrence Governors & Premiers are working with the International Council on Clean Transportation and the American Bureau of Shipping on a U.S. Maritime Administration-funded project to assess future alternative fuel and power options that could be used to reduce air pollution and greenhouse gas (GHG) emissions from Great Lakes shipping.

As part of this project, we are sending the following survey to regional **Port Authorities** in the Great Lakes region in order to better understand their port infrastructure with an emphasis on current fueling infrastructure and electrification. This information will be **aggregated** and will help the project team to develop a profile of Great Lakes-St. Lawrence ports and identify potential alternative fuel and power options for regional shipping.

INSTRUCTIONS

As the Port Authority, please answer the following questions to the best of your ability. If additional clarification or comments are needed, please type additional information in the space provided for the question.

For assistance, feel free to contact John Schmidt – jschmidt@gsgp.org

Some questions will ask about the “overall port,” meaning the Port Authority, other parts of the port area, and privately operated terminals. Other questions will ask only about the Port Authority itself. We recognize that the Port Authority may not be able to fully answer questions about property not owned by the Port Authority, but please try to answer relevant questions where possible and to the best of your ability.

SURVEY QUESTIONS

1. Name of Port:

2. Port size:

	Size
How many terminals are there in the overall port?	
What is the tonnage volume for the overall port? (example: X tons per year)	
What is the total land area of the overall port? (example: acres / km^2)	
Of the overall port area, how much is owned or controlled by the Port Authority? (example: X%)	
Of the overall port area controlled by the Port Authority, how much is available for re-use for infrastructure required for electrification and/or alternative fuels? (example: X%)	
How many berths are there on Port Authority-owned property? (example: feet / meters)	
How many berths are there at the overall port? (example: feet / meters)	

3. Fuel available:

		Bunker Oil	Diesel Fuel	Gasoline	Propane	Coal	Other (Please specify)
What is the storage capacity on... (Please specify units)	Port Authority-owned property?						
	Overall port area?						
How many tanks are included in storage capacity of the...	Port Authority-owned property?						
	Overall port area?						
How is the on-site supply replenished for the... (example: rail car, truck, ship, etc.)	Port Authority?						
	Overall port area?						
What is the storage capacity at the dock for... (i.e. close enough to the dock to be able to be transferred to a boat / ship)	Port Authority-owned property?						
	Overall port area?						
Who is the current fuel supplier for the...	Port Authority-owned property?						
	Overall port area?						

Of the fuel capacity in the overall port, is there fuel available for uses other than ship propulsion? **(i.e. gasoline, home heating fuel, power generation, etc.)**	

4. Natural gas infrastructure:

		On Property	At Dock
What is the line size at… **(Pipe Diameter, please specify units)**	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		
What is the line pressure at… **(Please specify units)**	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		
Other known measures of capacity at… **(if you are aware of any other measures of, or have access to further information and data sources for, Natural Gas capacity, please add here)**	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		

5. Electricity infrastructure:

		Total Port	At Dock
How many points of connection are there with the utility grid at…	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		
What is the total capacity for… **(example: kW or KVA)**	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		
How much of the total capacity is being used at…	**Port Authority-owned property?**		
	Other parts of the port area or private terminals?		
Who is the electrical utility supplier for…	**The Port Authority?**		
	Other parts of the port area or private terminals?		

6. Other electricity sources:

		Solar Panels	Wind Turbines	Backup Generator
What is the power available on site for... (Please specify kW or KVA)	The Port Authority?			
	Other parts of the port area or private terminals?			

7. What are your plans or thoughts on alternative fuel use at your Port Authority facilities?

8. Please describe any plans for shore power, electrification, or alternative fuel use you may have.

(Alternate fuels might include fossil LNG, bio-LNG, synthetic LNG, biodiesel, renewable diesel, methanol, ethanol, dimethyl ether, bio-oils, biocrudes, hydrogen, and ammonia. Electrification options might include hybridization, fuel cells and battery electric ships, onboard renewable power, and shore power)

9. Is your port engaged in any current or upcoming projects, collaborations, or consortiums that are looking into alternative fuels and alternate power generation options? Please specify.

10. Contact information of the submitter:

Name:

Designation:

Email:

Phone #:

Thank you for your participation.

APPENDIX F: FULL TCO ANALYSIS THROUGH 2050

Table F1. Total cost of ownership results by fuel pathway and propulsion option, 2021 to 2050.

Pathway	Main propulsion option	TCO ($/dwt-nm by year)				5 point ranking by year			
		2021	2030	2040	2050	2021	2030	2040	2050
MGO baseline	**ICE**	**$0.018**	**$0.018**	**$0.020**	**$0.024**	—	—	—	—
Biodiesel (soybean oil)	**ICE**	$0.037	$0.037	$0.037	$0.037	3	3	4	4
Renewable diesel (used cooking oil)		$0.035	$0.035	$0.035	$0.035	3	3	4	5
b-FT diesel (miscanthus)		$0.066	$0.066	$0.066	$0.066	1	1	1	2
b-FT diesel (corn stover)		$0.069	$0.069	$0.069	$0.069	1	1	1	2
e-FT diesel (ethanol CO_2 and grid power)		$0.081	$0.079	$0.066	$0.056	1	1	1	3
e-FT diesel (DAC and grid power)		$0.106	$0.102	$0.081	$0.067	1	1	1	2
e-FT diesel (ethanol CO_2 and renewable power)		$0.090	$0.085	$0.061	$0.050	1	1	1	3
e-FT diesel (DAC and renewable power)		$0.116	$0.108	$0.077	$0.061	1	1	1	2
f-LH2 (gray)	**Fuel cell**	$0.066	$0.064	$0.057	$0.055	1	1	2	3
f-LH2 (blue)		$0.072	$0.070	$0.063	$0.061	1	1	1	2
e-LH2 (grid)		$0.080	$0.076	$0.063	$0.058	1	1	1	3
e-LH2 (green)		$0.084	$0.079	$0.061	$0.055	1	1	1	3
f-NH3 (gray)		$0.030	$0.031	$0.032	$0.032	4	3	4	5
e-NH3 (grid)	**ICE**	$0.066	$0.065	$0.057	$0.055	1	1	1	3
e-NH3 (green)		$0.072	$0.068	$0.054	$0.049	1	1	2	3
f-MeOH (gray)		$0.016	$0.017	$0.017	$0.017	5	5	5	5
e-MeOH (ethanol CO_2 and grid power)		$0.065	$0.064	$0.055	$0.049	1	1	2	3
e-MeOH (DAC and grid power)		$0.089	$0.086	$0.070	$0.059	1	1	1	2
e-MeOH (ethanol CO_2 and renewable power)		$0.072	$0.068	$0.051	$0.044	1	1	2	4
e-MeOH (DAC and renewable power)		$0.096	$0.090	$0.066	$0.055	1	1	1	3
b-MeOH (miscanthus)		$0.040	$0.040	$0.040	$0.040	3	2	3	4
b-MeOH (corn stover)		$0.040	$0.040	$0.040	$0.040	3	2	3	4
b-DME (miscanthus)		$0.046	$0.046	$0.046	$0.046	2	1	3	4
b-DME (corn stover)		$0.046	$0.046	$0.046	$0.046	2	1	3	4
f-DME (natural gas)		$0.022	$0.023	$0.023	$0.023	5	5	5	5
b-LNG (landfill gas)		$0.029	$0.029	$0.029	$0.029	4	4	5	5
e-LNG (ethanol CO_2 and grid power)		$0.067	$0.066	$0.057	$0.053	1	1	1	3
e-LNG (DAC and grid power)		$0.082	$0.079	$0.067	$0.060	1	1	1	2
e-LNG (ethanol CO_2 and renewable power)		$0.074	$0.069	$0.054	$0.048	1	1	2	3
e-LNG (DAC and renewable power)		$0.089	$0.083	$0.063	$0.055	1	1	1	3
Grid electricity_current	**Battery electric**	$0.058	$0.056	$0.056	$0.055	1	1	1	3
100% renewable electricity		$0.064	$0.063	$0.060	$0.056	1	1	1	2

www.theicct.org

communications@theicct.org

@theicct

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

BEIJING | BERLIN | NEW DELHI | SAN FRANCISCO | SÃO PAULO | WASHINGTON DC