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**Advancing Low- and
Zero-Emission
Marine Vessel
Technology Options
Workshop**

January 9, 2022

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TRANSPORTATION RESEARCH CIRCULAR E-C279

Advancing Low- and Zero-Emission Marine Vessel Technology Options Workshop

January 9, 2022

John Reeves
Elliott Bay Design Group
Moderator

Transportation Research Board
500 Fifth Street, NW
Washington, D.C.
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Preface

Convened in person on January 9, 2022, the Advancing Low- and Zero-Emission Marine Vessel Technology Options Workshop brought together 19 participants to discuss challenges and strategies for identifying best practices and future research needed to further and simplify the implementation of low- and zero-emission technology in the maritime sector. The singular session, conducted in conjunction with the 2022 TRB Annual Meeting, included presentations by operator, industry, and regulatory subject matter experts followed by a group discussion session. The topic areas included planning and operations, fuels and supply chains, and vessel regulations and design.

This report details the workshop program and provides summaries of invited speaker presentations and audience discussion. The Summary outlines the overall key issues, with the final chapter presenting several areas for future research to overcome current technological and programmatic impediments to broader implementation of this critical technology. Biographies for the presenters is included in the appendices.

Special acknowledgments to the Transportation Research Board staff Scott Brotemarkle, Ferry Transportation Committee Chair Noel Comeaux, and Inland Water Transportation Committee Chair Erika Witzke for their support and organizational expertise. The workshop was also co-sponsored by the Ports and Channels and Intermodal Freight Transport Committees.

The views expressed in this summary are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the technical committee, the related Federal agencies, or the Transportation Research Board.

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Summary

PURPOSE

The maritime industry at large has recognized the imperative to reduce localized and global emission impacts on our environment. There are numerous avenues to reducing vessel emissions, with one being the implementation of low- and zero-emission propulsion technology on vessels. Different technology and energy approaches are being considered around the world, with varying levels of technical maturity and application. Each option comes with benefits and impacts which need to be considered; some impacts have hindered implementation depending on agency and vessel operating profiles and locations. The workshop reviewed vessel alternative propulsion developments to date and discussed areas for future study or attention by interested parties with the goal to facilitate increased adoption of applicable technologies.

PROCESS

The workshop was conducted in two parts, presentations followed by a group discussion. The first part entailed various industry subject matter experts representing federal and state agencies, energy system vendors, and a design agent presenting evaluations on the state of the technology and energy options. Discussions covered over-arching regulatory and operational requirements, specific technology benefits, and gap analyses where information or technical maturity are hindering broader application. After the presentations, the second part comprised of audience and presenters engaging in a discussion of questions and observations. Subsequent to the workshop, the presenter team assembled this e-circular as a final deliverable report for TRB and an industry reference that documents the information presented, discussions, and possible areas for future research and development.

KEY TAKEAWAYS

There is no single solution which will apply for every application. Each alternative energy solution has attributes that make it attractive for certain operations, and has issues to be addressed:

- Battery-powered vessels with on-shore charging and hybrid electric vessels are currently the most established options, with many ferry operators already acquiring electric vessels or making fleet conversions. As well as decarbonization benefits, life-cycle costs of electric powertrains are typically lower than conventional diesel-powered vessels. At this stage, the technology is best suited to short-range, low-speed, fixed-route applications, such as ferries where frequent turnarounds at terminals make shore charging feasible. But this is not an option for some marine applications, such as long-distance oceangoing vessels. Other considerations, including the high shore power demand for fast-charging units, need for longer turnarounds, and the significantly higher power demands of high-speed vessels may also be obstacles to widespread adoption.
- Hydrogen fuel cell technology has the potential to offer zero carbon emissions without the disadvantage of shore charging. It therefore has potential for a wider range of marine applications, including long-distance ocean shipping. The technology is still in development and

commercial adoption depends on the availability of a global supply chain and improvements in safe storage and handling. The reduced energy density of hydrogen compared to diesel fuel and restrictions on where fuels can be stored—gaseous fuels cannot be stored below passenger spaces—are also disadvantages. An increase in the production and distribution of green hydrogen is also needed to fully realize the benefits.

- Ammonia (and other liquid alternative fuels) are attractive for their similarity with conventional diesel operations and direct combustion in engines. They are also more conventionally available through established distribution networks overlapping with other industries. The other considerations are a lower energy density, by twice or more, and, like any alternative energy, the full benefits require the use of a green energy source.

FUTURE EFFORTS

There are several noteworthy areas of investment to enable accelerated adoption of alternative energy propulsion systems. Specific research needs identified as possible future Transportation Research Board activities are outlined in the final section of this report, and are summarized in the following high-level categories:

- Improving the understanding and reducing the impacts of alternative fuels on operations and human factors;
- Advancing the development of regulatory frameworks;
- Improving the production and distribution supply chains for alternative fuels;
- Improving efficiency and reducing the weight of reduced emission systems; and
- Increasing the energy density of alternative energy storage mediums such as fuels and batteries.

Opening Session

WELCOME AND INTRODUCTION

The workshop was kicked off by John Reeves with a brief welcome and overview on the purpose. As a society, there is immense desire for “greener” marine operations both locally and across the supply chain. The industry is willing, but there are many impediments to wider adoption of greener infrastructure and fuels, especially on the accelerated timeline to meet global goals for reduction of 2008 greenhouse gas (GHG) emissions: 40% of CO₂ by 2030 and 50% of total GHG and 70% of CO₂ by 2050. The primary source of vessel emissions is the propulsion system and the diesel fuel which provides the energy, so operating on alternative fuels and energy sources will yield the most significant emissions savings.

Reducing the use of diesel as a fuel is often a complicated process with many stakeholders that include

- Governments, municipalities, and classification societies, which regulate the design and operation of the vessels to ensure public safety and efficient commerce;
- Private and public operators delivering critical services including transportation, logistics, resource development, etc.; and
- Shipyards, design agents, and vendors, which build the vessels to be operated and provide for their operational needs.

For each of these groups, and with variability by location and even the alternative being pursued, there are different and sometimes conflicting barriers to implement of low- and zero-emission marine vessel technology. This is the purpose of the workshop: to investigate those barriers, discuss lessons learned, educate interested parties on the many facets of the issues, and identify areas for further research and activity to accelerate the implementation of the technologies.

The workshop was conducted by first discussing the current state of low- and zero-emission marine vessel technologies. Presentations were made from representatives of each of the primary stakeholder groups to address the topics of vessel design and regulations, fuels and supply chains, and planning and operations. Each presentation is included in Appendix B for reference. At the conclusion of the presentations, the attendees participated in a group discussion question and answer session. Participants were also advised that the presentations and discussions would be assembled into a Transportation Research Board E-Circular for documentation and future reference by both attendees and non-attendees.

Planning and Operations

MARAD SUPPORT FOR ZERO EMISSIONS IN THE MARITIME INDUSTRY

DANIEL YUSKA, *U.S. Maritime Administration*

The maritime transportation sector is very broad, encompassing several components such as vessels, ports, and terminals. Within each of those broad components there is variability between oceangoing vessels, workboats, and terminal and port operations. Decarbonizing the sector as a whole requires understanding these nuances to determine what vessel fuels, technologies, and practices will be most applicable. At this point, there is no single fuel or technology that can be applied equally to all aspects of the sector to achieve decarbonization—what works for harborcraft may be less applicable for oceangoing vessels.

There are several fuels and technologies that are actively being discussed to lead the sector towards decarbonization goals. However, there is a significant amount of research and demonstration that is still needed to determine ease of use, effectiveness in reducing GHG, and availability. In addition to research, there are infrastructure and supply needs for fuels and technologies as well as costs and worker safety.

The U.S. Department of Transportation Maritime Administration's (MARAD's) Maritime Environmental and Technical Assistance (META) program has been at the research and development forefront for over 10 years, evaluating, studying, and demonstrating fuels and technologies that can lead to sector criteria pollutant and GHG emissions reductions. META actively collaborates with other government agencies, industry, and academia to carry out this necessary work. Results from projects and studies are made publicly available through the META webpage (<https://www.maritime.dot.gov/innovation/meta/maritime-environmental-and-technical-assistance-meta-program>) and often result in peer-reviewed journal articles, with the primary objective of informing the industry as to “what works” as well as informing broader U.S. government policy decisions.

To date, the META program has investigated various alternative fuels such as hydrogen, natural gas, methanol, and biofuels; new technologies that include battery/electric operations, exhaust gas cleaning, fuel cells, hybrid vessel applications, and microgrids; and energy efficiency applications such as optimal vessel designs, waste heat recovery, power management systems, and vessel routing. To complement that work, META has also produced industry guides and supported multimodal emissions reductions calculators and routing optimizations tools.

Finally, aside from research, development, and demonstration efforts, MARAD is actively engaged with other U.S. government agencies on domestic and international collaborations focused on decarbonization. MARAD partners with the U.S. Department of Energy on the Zero Emission Shipping Mission; with the State Department and other agencies on green corridor efforts; and is a member of the technology-focused Joint Development Program led by Det Norske Veritas.

While there are many efforts underway to move maritime transportation towards overall decarbonization, it is important to recognize the nuances of the various sector components and

that the best path forward will require active engagement of both the public and private sector. That engagement also needs to include a broader conversation around spurring U.S. innovation and manufacturing as well as workforce development and training.

OWNER–OPERATOR PERSPECTIVE IN LOW AND ZERO EMISSIONS THROUGH ELECTRIFICATION

MATTHEW VON RUDEN, *Washington State Department of Transportation, Ferries Division*

As owner–operators seek to lower their GHG emissions and minimize life-cycle cost, it may be tempting to leap to a particular technology such as clean hydrogen, renewable diesel, liquified natural gas (LNG), all electric, or hybrid diesel-battery electric. Washington State Ferries (WSF) advises to assess the full range of alternatives and develop a feasibility analysis that considers the circumstances and operational profile for a given application. In the case of WSF, who had previously considered LNG and biodiesel, hybrid diesel-battery solution was the leading candidate due to the ample supply of renewable electricity in the Pacific Northwest, the relatively mature state of the marine battery technology, and the modest distances of the majority of its ferry routes. A hybrid approach was needed to maintain service resilience, as the system frequently moves vessels from route to route and will need to continue service in the event of a grid disruption.

An implementation plan to assess the state of technology, determine the system requirements, and map out investment strategies will help lay a roadmap for the transition and document the benefits realized over time by these investments. WSF published its System Electrification Plan to chart their transition over a 20-year horizon. This document was effective in communicating the plan, building support for the transition, and ultimately securing funding.

With so many organizations seeking to electrify their assets, it is important to engage the servicing public or private utilities early. This has enabled WSF to understand the relative costs for different electrification design decisions, and to identify shared goals and partnering opportunities from other organizations. Most importantly it allows for utilities to understand requirements as early as possible, so that they can incorporate these potential new loads into their long-range planning efforts.

With the current state of marine battery technology, there are plenty of suppliers to choose from. Competition will help the owner identify the best solution for their application and obtain the most favorable pricing.

The marine classification societies have been a key enabler in furthering hybrid technology throughout the world. They have drawn from other industries and recent maritime experience to develop rules for marine battery installations. In addition, they have type-approval programs that include extensive design standards and equipment testing to expedite design approval and minimize risk to the prospective buyer. The classification societies can also assist with design review in advance of submittal to the U.S. Coast Guard (USCG) and consultant services to inform the design.

In advance of final rules for marine battery installations, the USCG has issued Policy Letter 02-19 to provide design guidance. Owners should review this document in advance of any design effort.

Finally, owner–operators constrained by cost can take comfort in the broad array of grant funding available. The substantial reduction on both local pollutants and greenhouse gas emissions makes any new build or conversion very competitive in state and federal grant competitions. MARAD, the Federal Transit Administration, the Federal Highway Administration, and the Environmental Protection Agency all offer grant funding to support marine electrification.

Fuels and Supply Chains

LOW AND ZERO EMISSIONS WITH AMMONIA

PETER BRYN, *Volta Hydrogen*

Volta Hydrogen believes strongly in the prospects for green ammonia as the marine fuel of the future, particularly aimed toward oceangoing cargo vessels. Volta has also included its references for the reader to review the sources Volta believes are most helpful in analyzing these solutions, and is available to contact for more information.

Volta did not set out to be an ammonia producer. Instead, Volta analyzed the different zero-emission fuel pathways and concluded that while no fuel being discussed matches the ease of very low sulfur fuel oil (VLSFO), ammonia offered fewer compromises and greatest overall value among zero-emission fuels well-to-wake. These advantages yield the most price-efficient solution when compared under the following criteria:

- **Well (production):** Ammonia has no practical limits to production. The major challenge for renewable “green” production is the land footprint required, with solar being the most intense and wind less so (and “pink,” i.e., generated from nuclear energy, ammonia minimal). Biological disruption can be minimized and deforestation avoided altogether by generating power in the world’s great deserts or offshore.
- **Distribution:** Ammonia is the second most-heavily traded fuel globally (Argus 2020), giving it a major distribution advantage over all others. This will prove valuable as production scales up and vessels can bunker both “green” and “gray,” i.e., fossil fuel sourced, molecules around the world until “green” molecules eventually dominate.
- **Onboard:** Ammonia’s greatest weaknesses are onboard the vessel itself. The safety and toxicity challenges of bunkering, storing, and transferring the fuel must be addressed, but many industry efforts are underway to manage these risks. Second, ammonia is roughly 3.6 times the volume and 2.2 times the mass of VLSFO (ABS 2021), making it both better and worse than the various competing fuels on each metric. This will result in ship owners enlarging the vessel, reducing cargo capacity, or bunkering more frequently.
- **Wake (consumption):** Ammonia’s conversion from fuel into turning the propeller can be achieved via internal combustion engine (ICE) with slow-speed diesels being developed by the world’s two large engine makers and both anticipated in 2024 (MAN Energy 2020; WinGD 2022; Wartsila 2020). The efficiency, pilot fuel requirements, potential fuel slip risks, and after-treatment needs of these engines are being assessed now. For electrified vessels (e.g., cruise, offshore), medium-speed diesels and solid oxide ammonia fuel cells (SOFC) are also being developed (<https://www.ammoniaenergy.org/topics/sofc/>). SOFC’s may avoid after-treatment and slip issues.

Ammonia is not perfect and competing fuels are superior by certain measures. But, Volta believes ammonia performs best across the entire value chain from well to wake, resulting in the most cost-competitive solution. Following is a brief assessment of the largest weaknesses that may drive up costs for each major competing fuel:

- Why not carbon-based (e.g., methanol)? Principally because price will always be higher (at scale) to produce and potentially more ecologically problematic than ammonia.
- Why not liquid H₂ (LH₂)? Principally because there is no existing global supply chain, extreme cryogenics are very expensive, and its volumetric density is over 25% greater than ammonia (ABS 2021, Section 5). Note that compressed hydrogen, though more energy efficient, is not considered as it has impractically high volume for oceangoing vessels.
- Why not liquid organic hydrogen carriers (LOHC)? Principally because there is currently no existing supply chain and the energy intensity is poorer than ammonia, making them more expensive. That said, this technology is evolving and may hold promise.
- Why not batteries? Principally because they are too heavy, large, and expensive for long-distance oceangoing vessels. Consider a tanker on a 2-week voyage averaging 10 MW requiring 3.4 GWh per voyage with an 80% depth of discharge (DoD) yields 4.2 GWh. The low C-rate optimized Corvus Blue Whale system would weight about 35,500 MT, require a volume of nearly 49,000 m³, and at \$500/kWh cost \$2.1 billion for the battery system alone. Further, they would be impractical to recharge as “bunkering” would place astronomically high shore-power demands on ports (on the order of hundreds of megawatts to gigawatts in some cases). Consider the following
 - a. The above mentioned tanker needing to bunker in 8 h = 2 weeks × (7 days/week) × [24 h/day] × [10 MW]/[12 h] = 420 MW or
 - b. A containership on a 2-week voyage averaging 50 MW needing to bunker in 12 h = 2 weeks × [7 days/week] × [24 h/day] × [50 MW]/[12 h] = 1,400 MW).
- Why not nuclear fission? Principally because of the real and perceived safety concerns. Technically, nuclear is a very capable technology and a possible pathway for ammonia production (aka “pink ammonia”). However, its direct use onboard 70,000 vessels globally calling on over 150 port state jurisdictions presents significant regulatory and social license hurdles. Further, the cost of fission has often proven to be more expensive than anticipated and it remains unclear where modern modular molten salt reactor costs will fall. Finally, these are very high-capital expenditure (CAPEX), very low-operational expenditure (OPEX) systems which create risk for ship owners over the vessel life by locking in a fixed high-cost structure and therefore eliminating cost-reduction measures (e.g., slow steaming, hot layup) often taken during market downturns.
- Why not nuclear fusion? Principally because it has not been proven to work yet. And though there are some very promising developments in this field and real reason for optimism, many of the technologies being envisaged would be too large to be practical for most ships. Finally, the systems have the same high-CAPEX/low-OPEX ownership model as with fission.

LOW AND ZERO EMISSIONS WITH HYBRID SYSTEMS

EDWARD SCHWARZ, *ABB Marine and Ports*

Summary

ABB has been an electrification and automation technology company for over a century. With about 147,000 employees across the globe and 24,000 in the United States, ABB specializes in power grids, advanced manufacturing technology, and electric transportation. This includes electric vehicle charging infrastructure as well as marine and port electrification and automation solutions. The marine industry is in the early stages of a transformation to low- and zero-

emissions technologies. While there is no one-size fits all approach to reducing marine emissions, ABB believes the future of marine vessels will be electric, digital, and connected.

With electric propulsion systems, marine vessels can get to zero emissions. Most alternative propulsion system arrangements are centered around an electric powertrain, including diesel or LNG electric hybrids ships, full battery-powered ships, and fuel-cell powered ships. Electric propulsion not only cuts emissions but also improve safety and reliability while reducing life-cycle costs. An electric based powertrain is also futureproof as new power sources are developed. Whether the power source is fuel cells, batteries, ammonia-fueled generators, or a wave energy harvesting system, electric powertrains can integrate them. This is especially important for Jones Act vessels which often undergo multiple repowers over their sometimes 50+ year lives.

1. It is critical to fit the right solution to the vessel. Vessel types are as varied as the missions they serve and cargoes they carry. Ferries, inland towboats, harbor tugs, offshore workboats, and oceangoing vessels all have different operational characteristics that require different low- or zero-emission technologies. Fortunately, there are several such technologies either available today or under development including diesel or LNG electric hybrids, biofuels, fuel cells, and batteries. Accordingly, policies should focus on setting emissions targets for the marine industry, allowing the industry to assemble the best technology solution for meeting emissions and operational goals, and providing support to the marine industry as they meet those targets.

2. Life-cycle costs of electric powertrains are typically lower than conventional diesel-powered vessels. Vessels with electric powertrains and direct current (DC) electrical systems typically cost less to operate over their lifetime due to higher energy efficiency, lower maintenance, and reduced fuel costs. However, their upfront capital costs tend to be higher. This challenge is similar to other recent energy technology breakthroughs, like wind and solar power and electric vehicles. However, through a myriad of research, development, and deployment policies and incentives, those upfront costs have come down considerably and have reached or are approaching cost parity. With appropriate support, the same will happen with zero-emission marine technologies.

3. Low- and zero-emission marine vessel technologies are in the early stages of adoption and need government and policy support. Today there are commercially available zero emission marine technologies for some segments, like ferries. However, they tend to be more expensive upfront to purchase, which can be a deterrent to ship owners and operators, even though they are cheaper to operate. For other segments like offshore workboats, and oceangoing vessels, cost-effective commercially available zero-emission solutions are still in their very early stages of development. To lower costs and reach a fully zero-emission vessel fleet, deployment of existing technology and development of new technology must be expedited. The industry would benefit from government investments in research, development, and deployment of zero emission marine technologies.

Reducing Marine Emissions

The marine industry is in the early stages of a transformation to low and zero emissions technologies. While ports have already begun moving toward electrification, which enables zero emission operations, the marine sector is just beginning. ABB provides ship and port electrification and automation technologies and solutions. From replacing diesel powered cranes at ports with electric solutions powered by microgrids, to fully electrifying marine vessel propulsion systems, and everything in between, ABB believes the future of the maritime industry will be electric, digital, and connected. These technologies are used in ports across the United States, from Charleston, South Carolina, to Long Beach, California. And the USCG has deployed one of ABB's advanced diesel–electric hybrid propulsion systems on the Great Lakes Icebreaker, the USCGC Mackinaw.

Global Adoption of Zero-Emissions Technology

Globally, the maritime industry remains dominated by diesel-power, but the beginnings of a significant shift in energy source is underway. The start of adoption of low to zero emission ship technology is shown in [Figure 1](#). While conventional power plants still dominate, a significant jump in both battery-powered and LNG ships is evident in [Figure 2](#).

By vessel type, certain technologies are emerging because they complement the vessel's operational profile. For example, ferries are great candidates for batteries because of their short-distance operation and predictable port calls, which allow for installation of shore chargers. Conversely, container ships travel long distances and have incredibly high power demands. Because battery and fuel cell technologies need more research and development to be able to meet oceangoing vessels' needs cost-effectively, these ship owners and operators have begun adopting LNG.



FIGURE 1 Alternative fuel by ship count (DNVGL 2018).

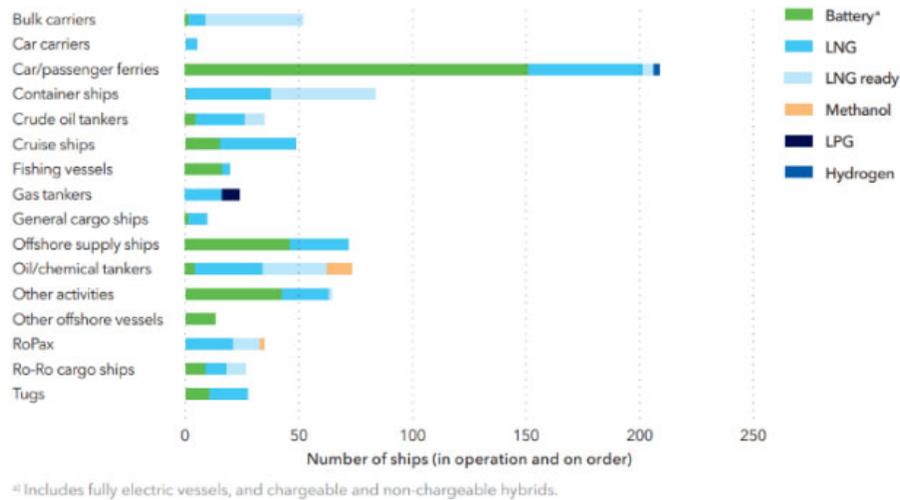


FIGURE 2 Alternative fuel by ship type (DNVGL 2018).

Fitting the Right Solution

Vessel designs vary significantly, based on the vessel’s application and purpose. The low- and zero-emission technologies that will be selected for a particular project will be dictated by the needs and operational profile of the vessel (Figure 3).

It is critical that ship owners and operators identify the proper solution for their vessel whether using a conventional diesel engine arrangement or some combination of low- or zero-emissions technologies. For example, a harbor tug which operates with a significant amount of idle time and short bursts of full power during operation has a very different operational profile than a Very Large Crude Carrier (VLCC) tanker which trades internationally on the spot market across oceans and can spend days at anchorage. Failing to consider the vessel’s operation may lead to a propulsion system that is less efficient and cost effective than the diesel mechanical baseline.

| Low Emissions | Net Zero Emissions |
|--|---|
| <ul style="list-style-type: none"> • Diesel-Electric • Diesel-Electric with Battery • Diesel-Electric with Battery and Shore Charging • Power Take In/Take Off (PTO/PTI) • LNG/dual-fueled engines • Biofuels (some) • Fuel Cell with Fossil-Derived Fuel | <ul style="list-style-type: none"> • Full Battery-Electric Propulsion and Shore Charging • Fuel Cell with Net-zero Fuel • Biofuels (some) • Ammonia |

FIGURE 3 Currently available low- and zero-emission technology options.

ABB is working with many Jones Act vessel owners, operators, and designers to seek the best solution for their operation. This ranges from ferries to fishing boats, harbor tugboats to dredgers, and passenger vessels to river towboats.

Across segments, some recurring challenges persist. First, while the total life-cycle cost of ownership of a vessel with electric propulsion is lower than a diesel-powered vessel, the upfront costs are often higher. Second, research, development, demonstration, and deployment investments are needed to bring down costs of these new systems and commercialize zero-emissions solutions for more challenging applications like high-speed catamarans and oceangoing cargo vessels.

U.S. New-Build Market

In the private sector, new-build construction in the United States is largely dominated by short-distance shipping (SDS) vessels, particularly tugs, towboats, and passenger vessels. By comparison, there is a small number of oceangoing vessels (OGV) (Figure 4).

There are some opportunities for Jones Act oceangoing vessels in the burgeoning offshore wind market, government fleet, offshore oil/gas activity, and larger cargo vessel markets. However, the bulk of this discussion will focus on the coastal and inland vessel markets, where most U.S. new-build construction is occurring.

Road and Passenger Ferries

Ferries have become one of the pioneering vessel types for zero-emission battery deployment (Figure 5) because they combine generally shorter routes with regular port visits. The shorter routes allow installation of battery packs that can fully power the vessels on their journeys while the predictable routes and turnaround times enable efficient deployment of shoreside charging infrastructure.

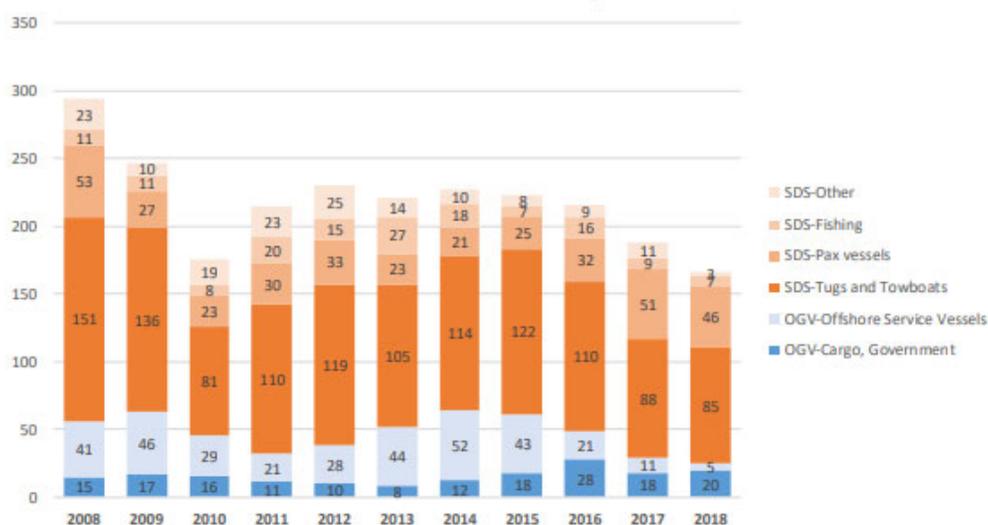


FIGURE 4 U.S. new-build vessel deliveries, by service type, 2008–2018 (Colton 2019).



| | |
|----------------------------------|--|
| Operational profile | Fixed route, limited distance, not overly weight sensitive, volume limited |
| Conventional solution | Diesel mechanical to propeller |
| Reduced emission solution | Diesel electric with battery with propulsion motor to propeller |
| Zero emissions solution | Battery-electric with propulsion motor to propeller |
| Common challenges | Charging infrastructure, utility demand charges |

FIGURE 5 Application of battery solution to ferries.

For these reasons, the ferry industry is among the first marine segments to adopt full battery-electric solutions. The first fully electric, battery-powered vessels to be built in the United States are the two new Maid of the Mist ferries (Figure 6) being powered by ABB. These Niagara Falls tour boats will be powered by a pair of battery packs with a total capacity of 316 kWh, split evenly between two catamaran hulls creating two independent power systems providing full redundancy.

The vessels will charge between every trip while passengers disembark and board. Shoreside charging will only take 7 min, allowing the batteries to power the electric propulsion motors capable of a total 400 kW (563 HP) output. This will all be controlled by ABB’s integrated Power and Energy Management System (PEMS), which will optimize the energy use onboard.



FIGURE 6 Maid of the Mist ferry.



FIGURE 7 ForSea ferry.

From small to large, most ferry boats and routes can be electrified. In 2018, two ForSea ferries (Figure 7), operating between Denmark and Sweden, became the largest battery-powered ferries, following an ABB-led conversion.

Economics play a large part in the push toward electrification. While zero-emission boats tend to have higher capital costs, operational costs are much lower than diesel-powered ships, making them more cost-effective over the lifetime of the vessel. Figure 8 is an example for an existing ferry opportunity where the battery electric option (Case E) is more expensive up front, but because it costs less to operate, the ship owner or operator ends up saving \$800,000 over the life the vessel. Just like with electric vehicles, increased deployments, financing support, as well as research and development can help lower the upfront capital cost of zero-emission options.

| 2.0 Results - Lifecycle Cost Calculation | | | | | | | |
|---|----------------------------|--------------------------|---------------------------------|---------------------------------|-----------------------------|----------------------------|--------|
| | (A) Diesel Mechanical (DM) | (B) Diesel Electric (DE) | (C) DE w/Battery for Peak Shave | (D) DE w/Battery & Shore Charge | (E) Battery Electric Vessel | (F) Shaft Generator Vessel | |
| CAPEX | \$0.66 | \$1.33 | \$1.46 | \$1.61 | \$1.50 | \$1.62 | \$M |
| AVG OPEX | \$0.31 | \$0.26 | \$0.24 | \$0.20 | \$0.17 | \$0.24 | \$M/yr |
| ANALYSIS 1: Payback Years | | | | | | | |
| Payback Years | -- | 11 | 12 | 9 | 6 | 13 | yrs |
| ANALYSIS 2: Internal Rate of Return | | | | | | | |
| Internal Rate of Return | -- | 8% | 7% | 11% | 19% | 6% | |
| ANALYSIS 3: Lifecycle Total Cost of Ownership | | | | | | | |
| Lifecycle Cost* | \$4.5 | \$4.5 | \$4.5 | \$4.2 | \$3.7 | \$4.6 | \$M |
| Lifecycle Savings | -- | \$0.0 | \$0.0 | \$0.3 | \$0.8 | -\$0.1 | \$M |

*25 year life, 7% discount rate

FIGURE 8 Example of project economics for ABB ferry project.

3.4 CO2 Emissions Summary

| | (A) Diesel Mechanical (DM) | (B) Diesel Electric (DE) | (C) DE w/Battery for Peak Shave | (D) DE w/Battery & Shore Charge | (E) Battery Electric Vessel | (F) Shaft Generator Vessel | |
|--|----------------------------|--------------------------|---------------------------------|---------------------------------|-----------------------------|----------------------------|-----------------------------|
| FUEL AND RUNNING HOURS | | | | | | | |
| Diesel Fuel consumed | 79,213 | 69,100 | 67,098 | 34,097 | 0 | 65,806 | gallons/yr |
| Electricity consumed | 0 | 0 | 0 | 497,636 | 1,039,034 | 0 | kWhe/yr |
| EMISSIONS TOTALS* | | | | | | | |
| Diesel Fuel CO ₂ emissions | 806,391 | 703,439 | 683,058 | 347,111 | 0 | 667,870 | kg CO ₂ /yr |
| Electricity CO ₂ emissions | 0 | 0 | 0 | 107,261 | 223,954 | 0 | kg CO ₂ /yr |
| TOTAL EMISSIONS | 806,391 | 703,439 | 683,058 | 454,372 | 223,954 | 667,870 | kg CO₂/yr |
| <small>*diesel emissions intensity per EPA; electric emissions intensity based on average for California</small> | | | | | | | |
| TOTAL REDUCTION | -- | 102,953 | 123,333 | 352,020 | 582,437 | 138,522 | kg CO₂/yr |

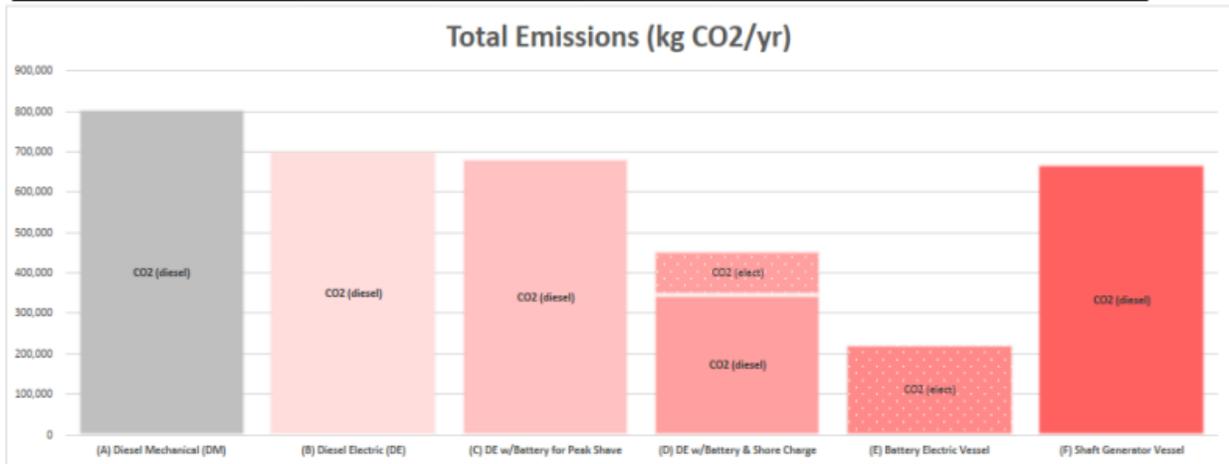


FIGURE 9 Example of project emissions estimate for ABB ferry project.

In addition to the cost savings of choosing a zero-emission solution, the CO₂ emissions reductions are stark, as shown in Figure 9. A significant reduction of CO₂ is shown in the battery electric option, which assumes an emissions profile in line with the energy generation mix of the power grid in California.

HYDROGEN FUEL CELL TECHNOLOGIES

JOE PRATT, *Zero Emission Industries*

Zero Emission Industries (ZEI) formerly Golden Gate Zero Emission Marine, is the team behind the Sea Change, the world’s first hydrogen fuel cell commercial ferry and the first hydrogen vessel in North America. ZEI’s technology is the only hydrogen and fuel cell system that has passed USCG regulatory approval, a process that takes more than 3 years. ZEI is now developing a next-generation marine powertrain system that is lighter, smaller, and less expensive than previous technology, and scalable for deployment on any vessel type. ZEI is led by Joe Pratt, who spent 8 years at the U.S. Department of Energy’s Sandia National Laboratories studying the viability of hydrogen fuel cells for the marine market and launched ZEI in 2018 to focus on providing zero-emission hydrogen fuel cell powertrains to vessel owners and shipyards.

TABLE 1 Comparison of Hydrogen Fuel Cells and Battery Energy Storage

| | Hydrogen Fuel Cell | Battery |
|----------------|---------------------------|---|
| Energy Costs | Decrease with scale | Increases with scale |
| Range | Long and high flexibility | Limited to locations with charging |
| Infrastructure | None required | Shore-based equipment at each charging dock |

Fuel Cells With Hydrogen

Fuel cells with hydrogen is currently the only available option for marine electrification of vessels with ranges that preclude the opportunity for shore charging. The fuel cells electrochemically convert the hydrogen to electrical energy with pure water as the only byproduct. A comparison of hydrogen fuel cells and battery energy storage is show in [Table 1](#).

As an example, a harbor tug that can run for 3 h on battery and needs to recharge twice per day could operate for 7 days on hydrogen.

Fuel

Hydrogen is similar to natural gas, but does not have carbon, which is what translates to clean emissions. Hydrogen does not collect if spilled or leaked, but instantly evaporates.

Hydrogen is also the building block of any other renewable fuel (renewable diesel, LNG, ammonia, methanol), but in each case has carbon, nitrogen, or oxygen added, making it more polluting or more toxic than hydrogen itself, with no technical advantages.

Fuel Cells

Fuel cells produce only energy and water, no hazardous substances. They also offer many other advantages:

- Reliable: solid state power decreases downtime;
- Modular: able to be located anywhere on the vessel, and distributed;
- Low maintenance: close to zero moving parts decreases maintenance needs;
- Scalable: from kW to multi-MW;
- Flexible: operates with same capabilities as a diesel boat and can be refueled just like diesel, no charging infrastructure needed; and
- Connected: enables predictive maintenance and autonomy.

Technology Summary

Hydrogen fuel cells give the best of both worlds: the clean and reliable part of a battery system, with the capability and flexibility of a diesel system. Fuel cells can be used in many vessel applications including:

- Ferries,
- Fishing vessels,
- Offshore supply vessels,

- Cargo vessels,
- Tankships,
- Yachts, and
- Tugs.

A study from Sandia National Laboratories (Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels 2017) showed that hydrogen fuel cells can power nearly all the vessels in the world's fleet without compromising their mission or cargo-carrying capacity.

Energy Independence

Marine vessels consume so much fuel that they can form the basis for establishment of an entire zero emission hydrogen-based energy system. The reliable, predictable consumption from the marine market enables construction of cost-effective hydrogen production plants and distribution networks that can be leveraged by other users. In the end, this provides a pathway for U.S. energy independence.

Vessel Regulations and Design

LOW AND ZERO EMISSIONS REGULATORY CONSIDERATIONS

BRADLEY PEIFER, *U.S. Coast Guard Marine Safety Center*

The USCG has several roles in ensuring the safe design and operation of commercial vessels using low- and zero-emission marine vessel technology. This presentation focuses on three specific aspects: regulatory design standards, plan review, and inspection. Additional concerns regarding mariner credentialing and training, along with waterways suitability are not addressed.

The first role involves the development of regulatory standards for designs involving low- or zero-emission vessel technology. This is handled by the Office of Design and Engineering Standards (CG-ENG). This office is also responsible for issuing vessel specific approvals for unique designs, or vessel technology not addressed in regulations. The next role involves plan review of the vessel's structure or systems against the requirements in the regulations or vessel-specific approval. This work is conducted by the Marine Safety Center (MSC) and involves detailed review of vessel drawings and calculations. The final role discussed during the presentation involves inspection of the construction and system installation onboard the vessel. This inspection work is conducted by the cognizant Officer in Charge, Marine Inspections (OCMI). During inspection, the OCMI may reach out to MSC or CG-ENG to provide technical advice or clarification on the design standard.

Currently, the USCG has guidance and experience for certain fuel types, such as biofuels, lithium-ion batteries, and LNG as fuel. For new low- and zero-emission fuel sources, considerable regulatory gaps remain. Until regulations or policy are developed for their fuel sources, the USCG works with a vessel designer to develop a design basis agreement (DBA). The vessel's DBA remains in place throughout the life of the vessel and provides an equivalent level of safety to what is specified by the regulations.

The first step in developing a DBA is to contact the MSC and request a concept review meeting. During the meeting, the vessel's design and associated standards should be presented. Additionally, the existing regulatory scheme should be discussed, identifying equipment or fuel sources that are not addressed in the regulations, and what proposed design standards will be at least as effective as specified in the inspection subchapter and provide an equivalent level of safety. MSC will forward the request to the CG-ENG who will finalize and approve the DBA. This approval may require further consultation with MSC or the cognizant OCMI.

VESSEL DESIGN IMPACTS

JOHN REEVES, *Elliott Bay Design Group*

Elliott Bay Design Group (EBDG) is an employee-owned naval architecture and marine engineering firm that supports owners, operators, and shipyards in the United States and abroad. EBDG combines naval architecture and marine engineering capabilities with analytical and design skills to deliver comprehensive solutions through a spectrum of services including development of new concepts, construction, and life-cycle sustainment. EBDG has built a 50+

person staff that provides complete design, engineering, and consulting services. Staffing includes team members with expertise in structures, mechanical systems, electrical power distribution, controls and instrumentation, and habitability outfit. Current and recent projects include a hydrogen fuel cell fast ferry feasibility study, multiple hybrid propulsion vehicle ferries, and an alternative fuel (methanol) tugboat.

Selection of low- and zero-emission vessel technology impacts not just design, but every aspect of a vessel operations. In fact, the design and operations are inextricably linked and create numerous trade-offs and compromises in design of a vessel. A holistic approach based on things like, capital cost, operating cost, supply chain availability, infrastructure requirements, emissions, fuel weight, etc., is required to determine the best fuel. The various energy sources: LNG, hydrogen, batteries, methanol, ammonia, and others that may be developed in the future, will also each affect those design decisions in different ways. The options are at different levels of maturity, with some just barely understood and some well-known. The regulations do exist for carriage of different fuels as cargo, and some are already used in other systems, i.e., ammonia in refrigeration. The design impacts can be categorized in three major groups: Arrangements, Supporting Systems, and Weight.

Arrangements

The arrangements are most significantly impacted by safety considerations. Different alternative fuels have different hazards which must be mitigated, such as increased flammability or toxicity. This manifests in changing hazardous zones, passenger and crew refuge areas, and egress routes, separating the people from the hazard as much as possible. Current restrictions on where fuels can be stored, i.e., not carrying gaseous fuels below passenger spaces, can also reduce the available deck areas and therefore the number of passengers allowed to be carried.

As a general rule, alternative energies do have a reduced-energy density, in some cases as much as 20%, which requires larger volumes and larger vessels unless the operation can be altered such as shorter-range requirements or more-frequent fueling operations. The system components are also typically heavier, reducing the deadweight capacity of the vessel, however as a benefit they can frequently be more distributed about the vessel, such as battery storage and electrical distribution systems.

Lastly, the machinery arrangements can be impacted by the presence of tonnage frames which reduce the admeasured tonnage of the vessel to meet some regulatory thresholds, but limit the utility of some spaces for larger machinery or maintenance access.

Supporting Systems

Each of the fuel and energy storage options requires differing supporting auxiliary systems. The most important are those supporting safety such as fire protection, which includes suppression systems such as water mist or chemical extinguishing agents and containment such as higher fire bulkhead ratings. These systems are also required for traditional diesel-fueled ships, but some higher-risk alternative fuels require additional spaces to be protected. Ventilation also contributes to safety by eliminating the fumes from both fuels themselves and also the residues from fires, i.e., energy storage system battery banks. Advanced monitoring systems are also typically required.

Gaseous fuels require one of two storage options to achieve sufficient on-board volumes for marine operations. The simpler of the two is high-pressure gas, where the fuel is stored already in the gaseous state needed for combustion, but at very high pressures in heavy cylinders. The alternative is storing in liquid form at cryogenic temperatures with systems to re-liquefy or capture and burn the boil-off gasses. Piping these fuels from storage to engines or fuel cells also requires double walled piping with monitoring systems for the annulus.

All-electric vessels, or those that are augmented by shore charging, required plugs or receptacles on the vessel to mate with the power supply ashore.

Weight

Regardless of the alternative fuel or energy system chosen, compared to conventional diesel power the vessel will be heavier to some measure. For those characteristics which increase the volume of fuel to be carried, the vessel will need to be larger or refueling conducted more frequently. Larger vessels will have more structure and have a larger displacement. Other systems require heavier components: high-pressure gas or cryogenic liquid systems, energy storage (batteries), electric motors, electric power conversion systems (generators, motors, fuel cells).

The additional vessel weight can be addressed by increasing length, beam, or draft, or some combination of all. These changes also increase the vessel resistance, and therefore increase power requirements, so a careful iterative process is required to identify the proper balance of alternative propulsion selection and vessel performance. Some examples compromise positions include reducing speed, passenger or cargo capacity, or endurance.

Outside of vessel service performance, the location of the weight can have an impact. While one benefit is the flexibility in arrangements, where heavy equipment is required to be placed outside, or particularly above, passenger spaces, there can be a negative impact on the vessel's stability characteristics. Conversely, if the weights can be placed low in the vessel, then a corresponding improvement in stability can be realized.

Implementation Steps

The previous discussion identified critical issues to be considered in designing a vessel with alternative propulsion, but the good news is that it can all be addressed. The imperative remains, and future technology improvements will continue to mitigate individual design and operation impacts. Alternative fuels can be selected for immediate emissions reduction impact, with the full benefit manifesting when the fuels themselves are also from green productions sources.

When starting a particular operation or developing a new vessel for an existing operation, first consider the energy availability and whether the shore-side infrastructure and supply chain exists (or can be developed) to provide the fuel in quantity and frequency needed. Do service operational profiles need to be adjusted? The crew will also experience a changing work environment in training required for new machinery, systems, or protocols.

As much as some options are currently in the early development phase, some technologies will become obsolete. This is the dilemma that most are wrestling with now. Vessels are significant capital assets, with life cycles spanning decades. Regulatory requirements are continually changing, and vessels are typically repowered at least once in their life. Any

vessel constructed in the near future will need to be designed with careful consideration to anticipated future power requirements and options. Generally, the current approach is to include space and weight margin in the design for the most likely alternative that a particular operation may find feasible in the future.

There will almost certainly be no single future alternative fuel solution. Each fuel option has its own merits which will apply differently to the myriad of vessel types, operational requirements, and regional regulations and energy availability. The educated operator is advised to follow a similar approach to this logic:

- Understand the options;
- Conduct alternatives analysis;
- Confirm the supply chain;
- Consider the long-term benefits of near-term investments;
- Account for intangible benefits;
- Select the most beneficial system; and
- “Future proof” the vessel for a desired system later.

Q&A Discussion

Following the presentations, the panelists fielded questions from the attendees on clarifications and other considerations. These questions (Q) and answers (A) are summarized below.

Q: The North Carolina Ferry System has noted there is a lot of work on building new vessels, with only an Alabama project known to be retrofitting an existing vessel. North Carolina is considering mid-life vessels and how to change over the propulsion system. Can alternative propulsion extend the life of a vessel?

A: The answer depends on the vessel and the extent of the modifications. For example, a diesel vessel could be converted to diesel electric, but if a singular large diesel engine is retained to operate a hybrid system then it would still be operating in an inefficient mode for some part of the operational profile. The Washington State ferries are converting some ferries to hybrid, but they are already diesel–electric and are able to replace a generator set by an energy storage system. Other vessels are not suitable for conversion and will run their service lives as originally designed. Volume and weight changes must also be considered as new energies are less energy dense. An existing vessel, designed around diesel, has a fixed volume available for tankage or limited capacity to absorb weight changes, so while conversion could be possible it would also require operational compromises.

Q: Protea (battery manufacturer) noted there are lots of potential resources and interest among the agencies within the U.S. DOT.

A: The Infrastructure Investment and Jobs Act does provide a significant amount of new funding and that has prompted a lot of interest. The different agencies have different timelines, but generally, for each funding opportunity, the responsible agency will publish a Notice of Funding Opportunity (NOFO) which will describe what funds are available, who is eligible, and what is required to compete for the funds.

Q: State DOTs have been testing alternative energy systems with busses, but not yet marine applications. What testing will be required for vessels?

A: Vessel testing has two components. The first is owner construction verification testing before the operator takes delivery of a vessel from the shipyard. The second, and overlapping, is USCG witnessing of certain safety and operational equipment testing to ensure the vessel and crew meets the regulatory requirements. For new and alternative fuels, the requirements are not finalized, there is not a definitive flow chart or process check-list.

Q: The New York City Ferries have been watching the progress of the Sea Change (first hydrogen fuel cell passenger ferry) and are aware of the different USCG Sectors having responsibility when construction and operation are in different regions. Will the local construction sector be able to sign off on the vessel?

A: In the case of this vessel, the sectors where the vessel is being built (Seattle) and where it will be operated (San Francisco) have been coordinating their efforts. Future projects will need to be addressed by the applicable sectors. The vessel crews will also need to be trained on any new or unique system requirements, and local regulations and ordinances must be considered (i.e., Sea Change will bunker hydrogen by truck in the early morning).

Q: Are there concerns about the specific location of power and the willingness of power companies to work through the process?

A: The utilities are very important stakeholders in considering an electric ferry operation. The power availability (and by extension alternative fuel supply chains) can sometimes be the harder issue than the vehicle or vessel. A key consideration is the volume of power, and any need for high power rapid charging or options to “trickle-charge” from the utility or charge during nonpeak hours. Early communications are important and negotiations could take longer than a year.

An option for building buy-in is to collaborate other users such that excess energy from a steady grid draw could be used for production of alternative fuels.

As a case study, Casco Bay Lines in Portland, Maine wanted to go all electric, which required a strong public relations program and collaboration with the utility to address their external pressures to lower emissions. Part of the solution was to place on-shore batteries to collect the power at nonpeak times, which then recharged the vessel overnight when it returned to the pier with depleted batteries. Another consideration is to have a standby vessel to help in peak use situations such as holiday weekends, so the electric vessel can be more modestly designed for standard use.

One approach is to start with an aspirational vessel, but scale the implementation of the infrastructure. Washington State Ferries is doing this in effect, recognizing the longer horizon to complete electrification infrastructure, they are still hybridizing vessels which will achieve some level of emissions reduction, with the full benefit realized when the dock charging is available.

Q: Is there concern that more nitrogen can be created in the combustion of ammonia?

A: After treatment will be needed for ammonia combustions systems to address certain emissions. This is being studied, as well as what happens when ammonia is used in a fuel cell. The ammonia solution is primarily being pursued for oceangoing cargo vessels, where passenger safety concerns are reduced.

Q: Is there a time scale for getting from where the industry is today to ultimate electric, fuel cell deployment?

A: The answer depends on the operation and where it is being implemented. It will happen when the economics make sense or there is regulatory push. For example, Chile is a good location because costs are very cheap. This may also be an export market, where the technologies are developed domestically and implemented globally, with the United States well positioned to develop their own renewables. International regulations, such as a pending bunker levy, will also have an impact. The California Air Resources Board has new regulations for zero-emission harbor craft. The Maritime Administration has a goal of 2050. Washington State Ferries, with gubernatorial and legislative leadership, has begun an electrification program, but the scope of vessel and infrastructure recapitalization will take decades to implement.

Q: What are the impacts of supply chains?

A: Supply of both materials and labor are impacting the implementation of alternative fuel systems. Materials and equipment are delayed, and costs are rising (with at least one new ferry project receiving no responses to a construction solicitation due in part to these issues). For example, a particular engine lead time was increase from 24 to 52 weeks.

In improvements, the increased availability and larger buying channels for electrification materials, i.e., energy storage, has resulted in some price reductions globally.

Q: What is the cost difference of building vessels with different technologies?

A: Typically, an alternative propulsion vessel can be expected to cost 25% to 30% more than a comparable conventionally powered vessel, depending on the systems being selected.

Q: Are there any studies out there that justify increased prices (25% to 30%) with decreased operating costs?

A: The exact balance is hard to say specifically. Each vessel is unique and requires a custom analysis for each system and operation to project exact construction and operating costs. Some factors to consider are: lower maintenance costs due to fewer operating parts for electric installations, higher reliabilities of electrical motors versus diesel engines, local fuel and energy costs, and economies of scale with a fleet of vessels.

Q: What are the new workforce requirements? Who should an interested operator talk to?

A: The training will depend on the specific system installed. Skillsets of the future will trend toward automation: electrical engineering, automation, diagnostics, and troubleshooting. Anticipate more remote work (less work on board), leveraging remote connectivity, Internet of Things, etc. The Maritime Administration is also focused on training the mariners of the future.

Q: What is the bottleneck to keep going? Policy would provide a way to prompt change.

A: From the Maritime Administration perspective, it may not just be policy. Across the sector, there are few incentives, and implementing low/zero emission technology likely brings significant new costs for the operator. It is in the national interest for manufacturing innovation to stay in the United States; however, the research, development, and testing has not been well funded. It is a complex issue, with indeterminate regulations that are more defined internationally than domestically.

This issue requires investment. Large industry entities such as Amazon, Tesla, and Uber are disruptors driving change. Generally the maritime industry is not a driver of change, but applies technology derived elsewhere.

Q: How does cold weather impact any of these technologies?

A: Some of the technologies are actually harder to operate in warmer climates, with significant cooling requirements. With respect to cold weather, the equipment does need to be winterized, or the local operating environment maintained by heating and cooling systems. There have been issues in cold weather operation, but those can be mitigated with defined operating conditions and proper design. The cooling needs could actually benefit operating in colder climates.

Future Research Needs

PLANNING AND OPERATIONS

Survey of Operators and Agencies

The workshop was beneficial, but only reflected the experiences of those able to attend in-person. It would be informative to conduct a survey of other operators (and transportation agencies where relevant) who have taken steps to evaluate and transition to low-emission propulsion. Both domestic and international experience will be helpful. While understanding that every operator has unique challenges, it would be helpful to know more about the following issues:

- The hurdles to adoption and if there are particular challenges which are specific to that operator (and why);
- The steps, if any, have been taken to overcome the hurdles;
- The further research and technology improvements would be most critical to increasing the chances of a successful transition;
- The regulatory or funding barriers; and
- The marine application(s) where the transition is most likely to be successful with the current technology.

Operational Considerations

The alternative fuels have some new and some well-understood safety implications, but they may not be well known in new vessel and service applications. For example, ammonia is commonly used in the fishing vessel industry, but relatively unknown in the passenger vessel industry. Information is needed on the various operational considerations for different fuels that can be used by operators evaluating the program and crew training implications of options.

This research topic is integrated with the design topics, as the changes in vessel design are also manifested in impacts on operations in the context of speed, performance, deadweight, endurance, etc. Different vessel types and services have different requirements in these areas, so further research would be helpful to clarify the relative impacts and their relative priorities in the different service profiles.

Vessel emissions reductions are just one aspect of a global initiative to reduce the pace and impact of climate change and improve the health of our populations. Ports are also implementing initiatives to reduce their environmental footprint, and collaboration with the ports in a regional approach can inform an operation's decisions, particularly as it relates to supply chain issues, and leverage the shoreside improvements.

Increasing the awareness and available tools for operators to monitor fuel consumption and emissions, and to optimize vessel operations in real time, will further improve the value in the alternative fuel capital investments and also reduce lifecycle costs as fuels and energy are a significant component of those expenses. For ferry operators, the constraint of longer terminal turnarounds for electric ferries could be ameliorated by more attention to continuous

improvement across operational processes. This includes innovative approaches to network design and scheduling, faster loading at intermediate stops, and artificial intelligence assisted docking.

Financial Implications

Application of any alternative fuel or energy system will increase the capital investment required for what are already expensive durable assets. To make better-informed business decisions and reduce overall risk, there needs to be an increased understanding and development of reference tools for capital investment strategies and available funding sources. Once costs are identified, a business plan needs visibility of options to strategically improve the financial viability of these high capital cost commercial assets such as incentives or other creative opportunities.

Operational tradeoffs are required to implement fuels with significantly reduced energy density. Research is needed to increase understanding of the balance in reducing fuel quantity or increasing bunkering operations to minimize the vessel size and therefore cost increase impacts.

FUELS AND SUPPLY CHAINS

There are several fuels and technologies that are actively being discussed to lead the sector towards decarbonization goals however there is a significant amount of research and demonstration that is still needed to determine ease of use, effectiveness in reducing GHGs, and availability. In addition to research, there are infrastructure and supply needs for fuels and technologies as well as costs and worker safety.

Alternative fuels have the capability of significantly reducing or eliminating point of source emissions, but the global improvements can only be achieved if the fuel production processes are themselves “green.” Continued research, technological development, and capital investment are required in the green manufacturing processes for them to be more efficient and available.

An operational impediment to implementation of alternative fuels is availability at the local point of use. Additional study, similar to MARAD’s current initiative evaluating Future Energy Options for Great Lakes Shipping, are required to identify and improving the distribution supply chains for alternative fuels, and to highlight the benefits of regional approaches.

One of the larger design impacts for alternative fuels is the significant weight of the equipment and systems for storage and transportation of the fuels. Advances in these technologies, or related new technologies to increase the fuel energy densities, would materially improve the feasibility for implementation in different service applications and reduce overall costs.

Advancing technology to use alternative fuels directly in internal combustion engines, reduce fuel slip, or improve overall system efficiencies.

Hydrogen fuel cells are mature technologies. Hydrogen storage systems at very small (kg to 10’s of kg) to small (100’s of kg to tons) quantities are also mature. What is needed is development of large (10’s of tons) and very large (100’s to 1,000’s of tons) marine transport-

ready LH₂ storage tanks to support high usage domestic vessels such as river push boats requiring hundreds of tons of onboard storage, all the way to LH₂ carrier ships transporting thousands of tons at a time. The United States has unique expertise in LH₂, with over 85% of all the world's LH₂ production since the 1960s due to the space program. This is a unique opportunity to take advantage of this expertise to create technologies that not only enable the achievement of an energy transition domestically but will be critically-needed all over the world. An example is the impact that Kawasaki has had in developing their 80-ton LH₂ storage tank currently onboard the Suiso Frontier. Because of that nationally-funded effort in Japan, they now hold the only key to transporting large amounts of LH₂. The United States could easily enact a similar program and leapfrog that development to produce something uniquely valuable.

VESSEL REGULATIONS AND DESIGN

While not research related, it would be helpful to have an established set of regulations for the safe use of alternative fuels onboard U.S.-flagged vessels, including education for regulatory stakeholders. Advancing the regulatory frameworks for alternative fuels would require a proactive industry to bring concepts and plans to the USCG for review, which would enable development. A better understanding of current and future regulatory requirements could help enable new vessels to be “future proofed” for yet undecided alternative fuel repower decisions.

The physical weight of emission propulsion systems and emission cleaning systems is an impediment, particularly for high speed or weight sensitive applications. Continued research and development could help improve the systems' efficiency, space requirements, and weight.

Carbon dioxide is the benchmark for GHG emissions, but there are no commercially available systems suitable for recovery of CO₂ in marine applications. Development of recovery systems for products of combustion, i.e. CO₂, would add another option beyond reducing fuel consumption or use of lower carbon content fuels.

Increased intergovernmental coordination on green corridors and collaboration—alignment of standards for construction and emissions would provide a more stable, and globally applicable, framework under which to make reliable business and operational decisions.

Safety, for both crews and the environment, is a paramount consideration. Work is needed to understand and improve the methods for addressing the increased (relative to diesel) safety risks of various options, and particularly as they apply differently to different vessel types, i.e., passenger vessels. These risks apply to both onboard systems and energy bunkering systems, from conventional tanker-hose arrangements to electrical rapid charging.

APPENDIX A

Speaker Biographies

PETER BRYN

Peter Bryn is the Director of Business Development for Volta Hydrogen (a DPP Company). Volta Hydrogen is a green ammonia producer focused on decarbonizing many hard-to-abate sectors, particularly agriculture, mining, marine, power production, and industrial heating. Prior to Volta, Peter was with ABB Marine & Ports designing battery and fuel cell electric propulsion systems for ships, and before that with ExxonMobil's marine company where he was involved in LNG as a marine fuel, vessel construction, commercial contracting, and offshore platform structural engineering. Peter has a BS in Naval Architecture/Marine Engineering from Webb Institute and an MS in Transportation from MIT.

BRADLEY PEIFER

Lieutenant Commander Peifer currently serves as the Machinery Branch Chief at the USCG Marine Safety Center. In this role, he serves as the Coast Guard's lead technical authority for machinery, piping, and fire suppression systems on U.S. flag commercial vessels and offshore energy facilities. Additionally, he serves as the Coast Guard's lead technical authority of pollution prevention system type approvals for 75,000 domestic and international vessels, including ballast water management systems, oily water separators, and sewage treatment devices. A 2008 graduate of the Coast Guard Academy, his first assignment was in a vessel engineering department. From 2010, he performed duties as a Marine Inspector, Port State Control Officer, Investigations Division Chief, Senior Investigating Officer, and Command Duty Officer. He holds a BS degree in Naval Architecture and Marine Engineering from the Coast Guard Academy and a MS degree from the University of California in Mechanical Engineering. His academic research focuses on frictional drag reduction on vessels to improve fuel efficiency and emission reductions. His research has been published in the *SNAME Journal of Ship Research* and the Symposium on Naval Hydrodynamics.

JOE PRATT

Joe Pratt is the CEO and CTO of Zero Emission Industries, formerly Golden Gate Zero Emission Marine. Pratt Holds a Ph.D. in Mechanical and Aerospace Engineering from the National Fuel Cell Research Center at the University of California Irvine. He started research in the hydrogen and fuel cell field in 1996, and worked for nearly 8 years at U.S. Department of Energy's Sandia National Laboratories where he founded and led Sandia's Zero Emission Maritime program and has been involved in collaborations with U.S. DOT/MARAD and regulatory development with the USCG since 2014. Pratt authored the landmark "SF-BREEZE" hydrogen ferry study in 2016 which arguably kicked-off the worldwide movement towards hydrogen-powered vessels. In 2018 he started the only company in the world dedicated to marine hydrogen fuel cell powertrains and has been featured in many media outlets and described as "one of the most knowledgeable individuals on applying hydrogen technology in the maritime world on the planet" and "the guru of hydrogen shipping."

JOHN REEVES

John D. Reeves joined EBDG in 2015 and serves as a Principal in Charge and is the Director of Business Development. A highly skilled engineering leader and mariner, he brings to his role extensive field experience gained through 23 years of operating and maintaining some of the most complex vessels in the USCG fleet. John's wide-ranging background includes 5 years as port engineer and manager of four industrial repair facilities, serving as an Associate Professor in Naval Architecture and Marine Engineering at the U.S. Coast Guard Academy, and more than a decade at-sea providing service on and maintenance of a variety of vessels, from salvage ships to the world's most powerful nonnuclear icebreaker. Operations included living marine resources and law enforcement, search and rescue, icebreaking, and high-latitude scientific research. John is a certified Project Management Professional, licensed Professional Engineer in four states, and a USCG licensed Master, Unlimited Tonnage, Oceans.

MATTHEW VON RUDEN

Matthew von Ruden is a maritime professional with 35 years' experience in the government and private sectors. A 1986 graduate of the U.S. Coast Guard Academy, von Ruden served 23 years in the USCG, including six assignments at sea, and retired at the rank of Captain in 2009. In the commercial sector, von Ruden worked in the chemical and shipbuilding industries in California, Washington, and British Columbia. He held the position of Associate Dean and Director of Seattle Maritime Academy at Seattle Central College before moving to Washington State DOT Ferries Division in 2015. Von Ruden's education includes a BS in Marine Engineering from the U.S. Coast Guard Academy, an MS in Marine Engineering and Naval Architecture and MS, Mechanical Engineering from Massachusetts Institute of Technology, and an MA, National Security and Strategic Studies from the U.S. Naval War College.

EDWARD SCHWARZ

Ed Schwarz is responsible for ABB's Marine and Ports Marine Systems business for in the Americas. With his experience in the marine propulsion market, Ed is helping to bring green technologies to help decarbonize vessels. His most proud project is the first all-electric zero-emission vessels for the Maid of the Mist Corp. Ed is a graduate of the U.S. Merchant Marine Academy, former MEBA Unlimited Chief Engineer and recipient of the 2020 Rear Admiral McCready Award.

DANIEL YUSKA

Daniel Yuska serves with the U.S. Maritime Administration as the Director of the Office of Environment and Innovation. As Director, Yuska oversees the META program and domestic and international maritime environmental policy. Prior to serving as the Director, Mr. Yuska served as Environmental Protection Specialist within the same office. Yuska helped to develop the META program and led environmental research and policy focused on vessel and port emissions reductions, energy efficiency, and alternative fuels and technologies. Prior to the development of the META program, Yuska spent several years leading Agency environmental planning efforts for major port and intermodal infrastructure projects. Yuska also has served as a member of the U.S. Delegation to the International Maritime Organization. Yuska holds an M.Sc. and B.Sc. in environmental and ecological science disciplines.

APPENDIX B

Presentations

MARAD SUPPORT FOR ZERO EMISSIONS IN THE MARITIME INDUSTRY



MARAD
U.S. MARITIME ADMINISTRATION

Unique Issues with Maritime Transportation

Maritime transportation/maritime sector is broad

- Oceangoing Vessels vs. inland vessels or harborcraft
- Multiple engines sizes
- Different operating/duty cycles
- Ports and terminals
 - Cargo handling equipment
 - Rail/trucks

What fuels are suitable

- MARAD has remained fuel neutral
- Exploring fuels based on vessel and engine types
- To get to "zero emissions", we need to define what constitutes "zero emissions"
 - Fuel lifecycle emission assessments

Challenges with various fuels

- Availability
- Safety
- Carriage vs cargo space
- Costs

2

MARAD
× ■ ■ ■ ■

Investigation into Alternative Fuels and Technologies

Maritime Environmental & Technical Assistance (META) Program

- Technology and innovation program that performs research, demonstration, data gathering
- Collaboration w/other government agencies, industry stakeholders, NGOs, academia
 - Federal partners include: DOE, USCG, EPA, Navy, NOAA, National Labs, DOT Modes
- Focus areas: criteria pollutant and GHG emissions reductions, alternative and renewable fuels, energy efficiency applications, green technologies (fuel cells, batteries), multimodal modeling
- Results: peer-reviewed articles, white papers, industry guidances
 - Informs regulatory/policy actions
 - Informs industry on "what works"
- <https://www.maritime.dot.gov/innovation/meta/maritime-environmental-and-technical-assistance-meta-program>

3

MARAD
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What We Have Investigated/Where We're Going

Alternative Fuels

- LNG
- Next generation alternative fuels from cleaner feedstocks
- H₂
- Methanol
- Ammonia – future work

Technologies

- Fuel cells/H₂
- Batteries
- Exhaust gas cleaning
- Land/shipboard carbon capture
- Port electrification
- Microgrids
- Hybrid systems

Energy Efficiency

- Reduce criteria pollutants as well as GHGs
- Hull design changes
- Mechanical systems
- Vessel routing

4

MARAD
X I O E

Challenges with Alt Fuels/Technologies

Shipboard Considerations

- Energy density
- Tank size vs cargo carried
- Safety!

Port considerations

- Availability
- Bunkering needs

Electrification as a sidebar

- Port authority/terminal operator/utility relationship
- Grid capability/multi-megawatt requirements
- Costs during peak hours

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MARAD
X I O E

MARAD/Broader U.S. Efforts

Domestic/Interagency Partnerships

- DOE/MARAD-led, Federal interagency maritime energy and decarbonization working group
- SES-level maritime decarbonization strategy group
 - MARAD/DOE/USCG

International Partnerships

- Mission Innovation – Shipping Mission
 - DOE-co lead/MARAD partner
 - Fuel focused
- Green corridor partnerships (Clydebank, QUAD)
- Battery Safety Joint Development Program (JDP)

Maritime Decarbonization Workshops

- Sponsored by Aspen Institute
- Domestic and International
- NGOs, USG, Industry

Multimodal Focus

- Maritime is a sector of surface transportation
- Ports can serve as critical multimodal hub for decarbonization and alternative fuel corridors
- Partnership with other DOT modes is critical

9

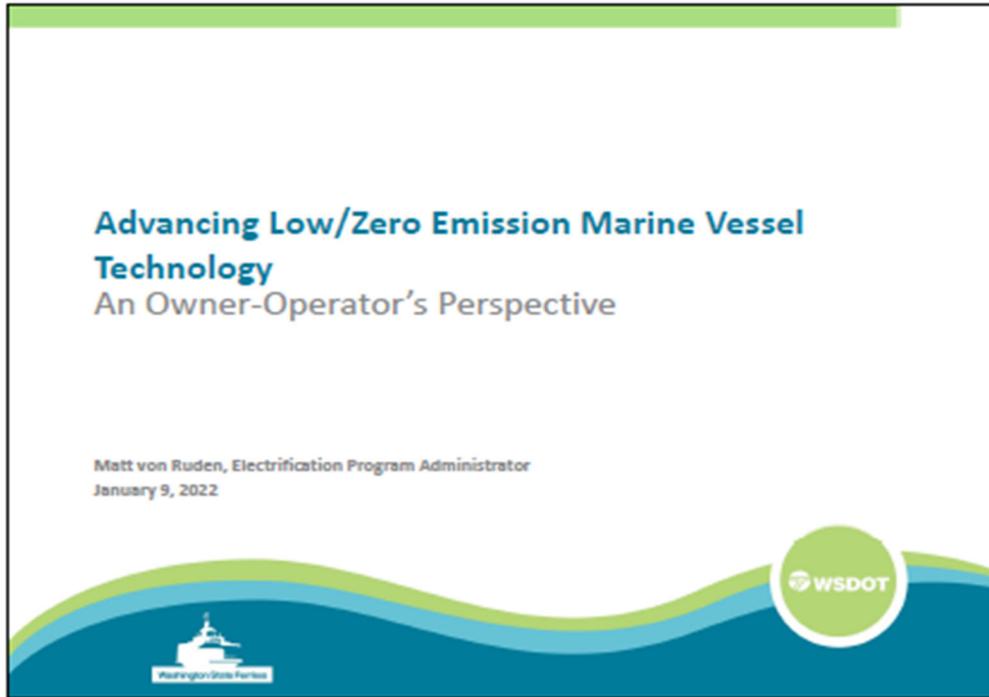


Questions

- Contact Information
 - Daniel Yuska
 - US Maritime Administration
 - Office of Environment
 - 202-366-0714
 - daniel.yuska@dot.gov

7

OWNER-OPERATOR PERSPECTIVE IN LOW AND ZERO EMISSIONS THROUGH ELECTRIFICATION



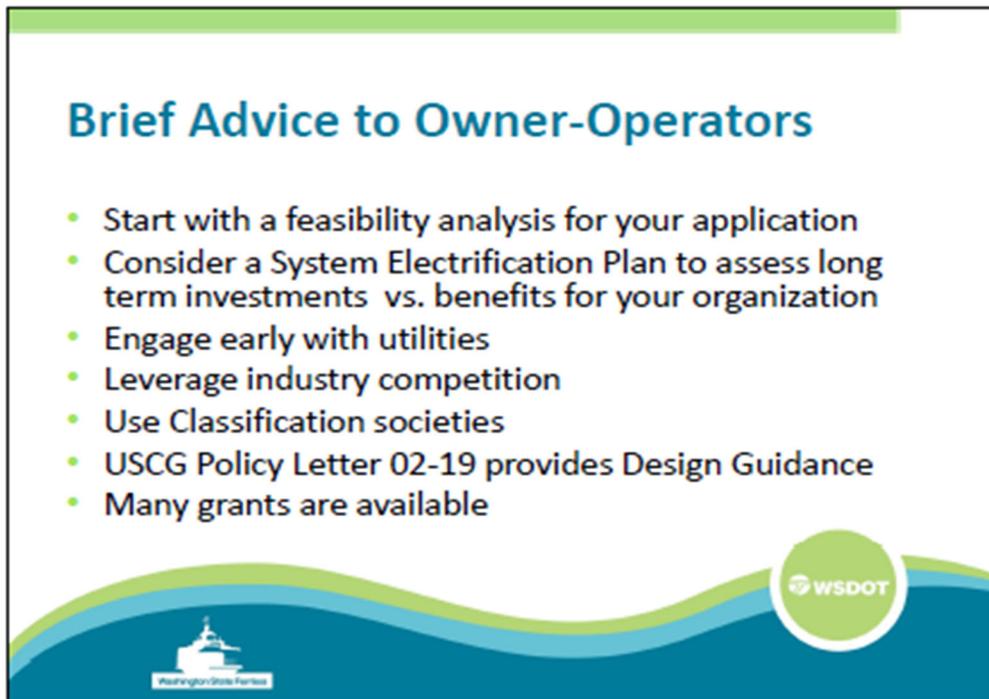
Advancing Low/Zero Emission Marine Vessel Technology
An Owner-Operator's Perspective

Matt von Ruden, Electrification Program Administrator
January 9, 2022

Washington State Ferries

WSDOT

This slide features a white background with a green horizontal bar at the top. The title is in blue and black text. Below the title, the speaker's name and date are listed. At the bottom, there is a decorative wave graphic in shades of blue and green, with the Washington State Ferries logo on the left and the WSDOT logo on the right.



Brief Advice to Owner-Operators

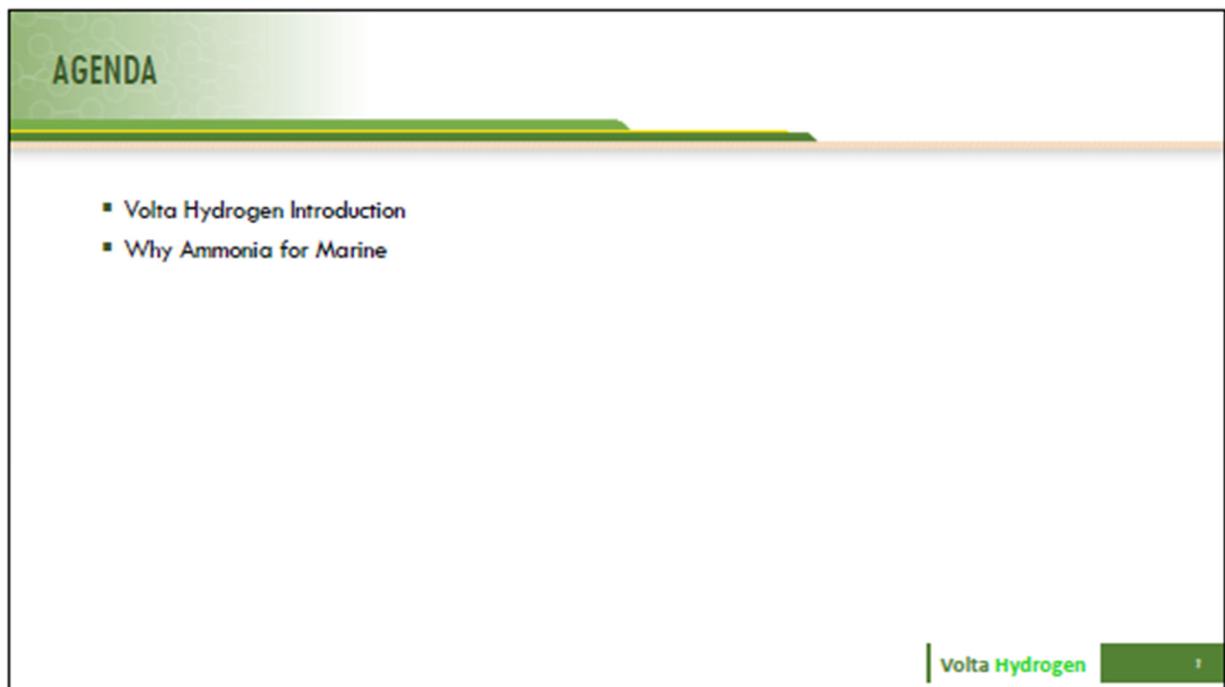
- Start with a feasibility analysis for your application
- Consider a System Electrification Plan to assess long term investments vs. benefits for your organization
- Engage early with utilities
- Leverage industry competition
- Use Classification societies
- USCG Policy Letter 02-19 provides Design Guidance
- Many grants are available

Washington State Ferries

WSDOT

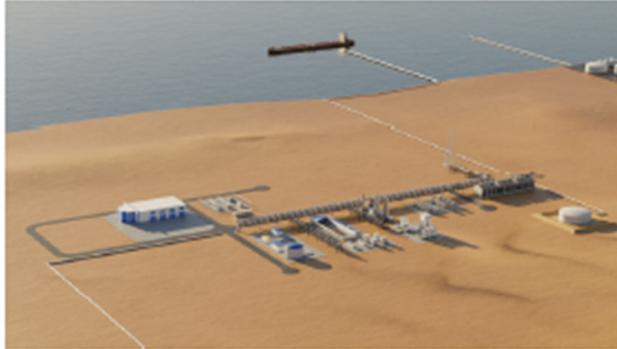
This slide features a white background with a green horizontal bar at the top. The title is in blue text. Below the title, there is a bulleted list of seven items. At the bottom, there is a decorative wave graphic in shades of blue and green, with the Washington State Ferries logo on the left and the WSDOT logo on the right.

LOW AND ZERO EMISSIONS WITH AMMONIA



VOLTA INTRODUCTION

- Overview
 - Green ammonia producer
 - Facility in northern Chile
 - Fluor providing EPC, entering FEED
- Goals to be among the...
 - ...largest producers in Chile
 - ...most cost-effective producers globally
- Background
 - Formed out of the expertise of Distributed Power Partners (DPP)
 - DPP is a US-based distributed renewable power developer with projects in Chile
 - Volta expected to launch in 2022



VOLTA PLAN | EXPANSION TO PHASES 1, 2, & 3

Phase 1

- Develop 300M MT/D facility (135MW)
- First delivery in 2026



Phase 2

- Expand facility to 1280M MT/D (580MW)
- First delivery in 2028



Phase 3

- Expand facility to 2500M MT/D (1GW)
- First delivery in 2030

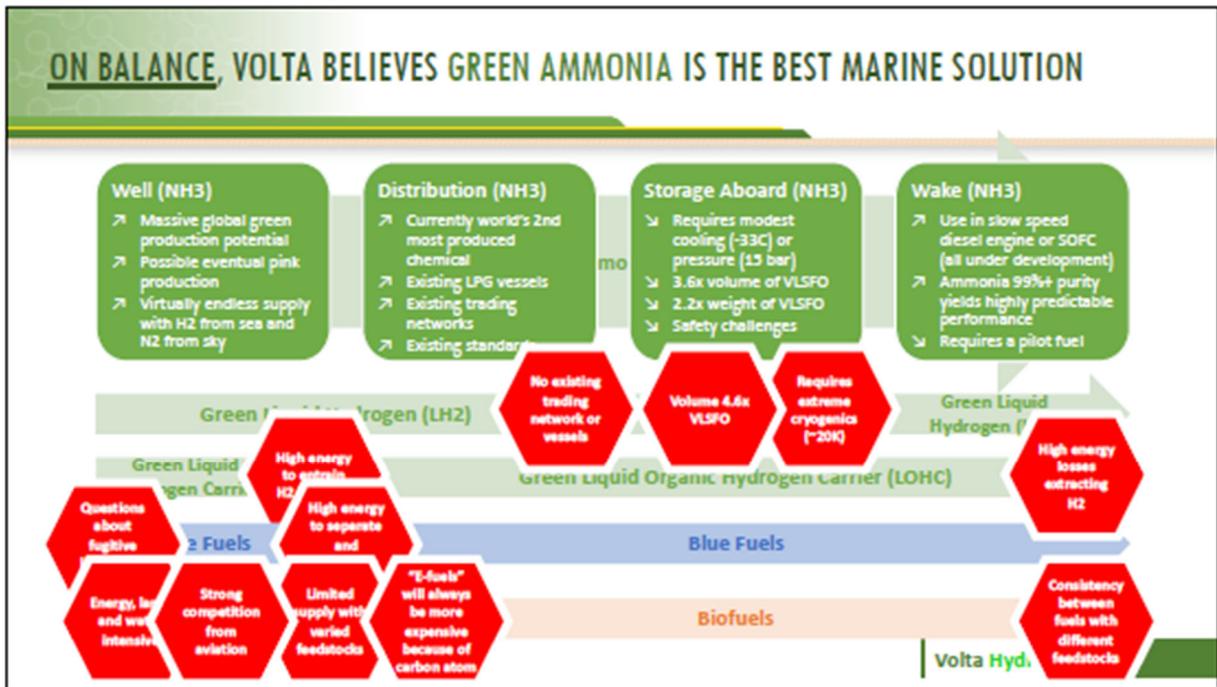


GREEN AMMONIA FOR MARINE

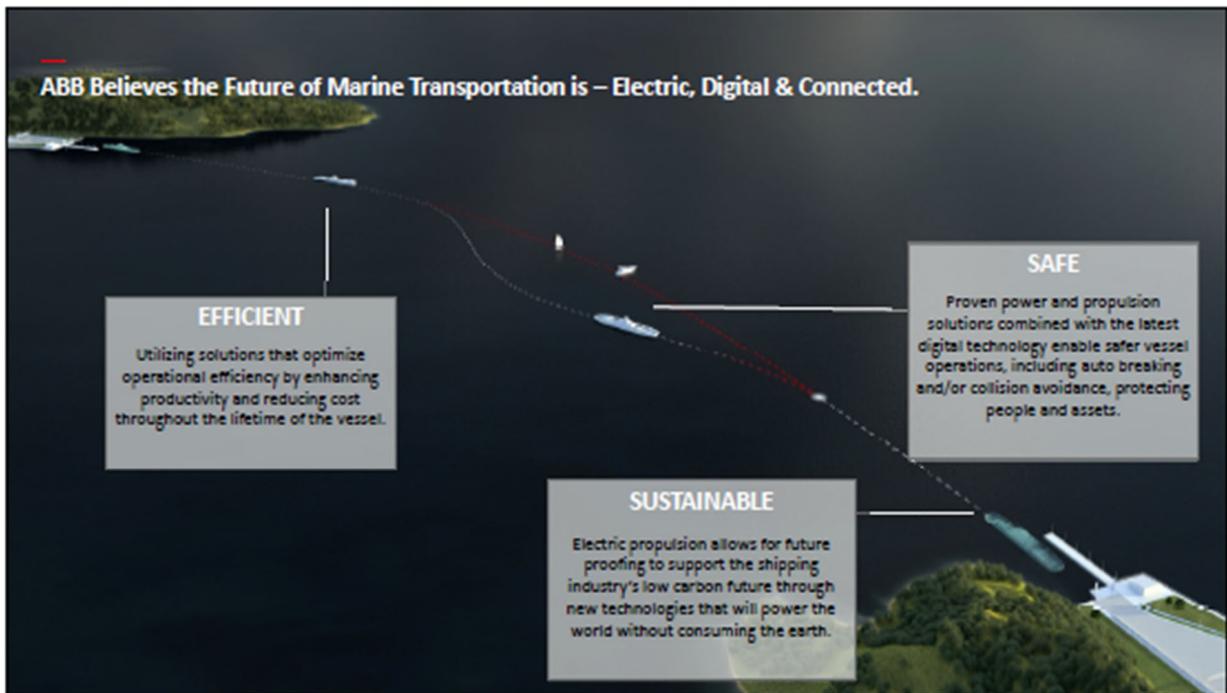
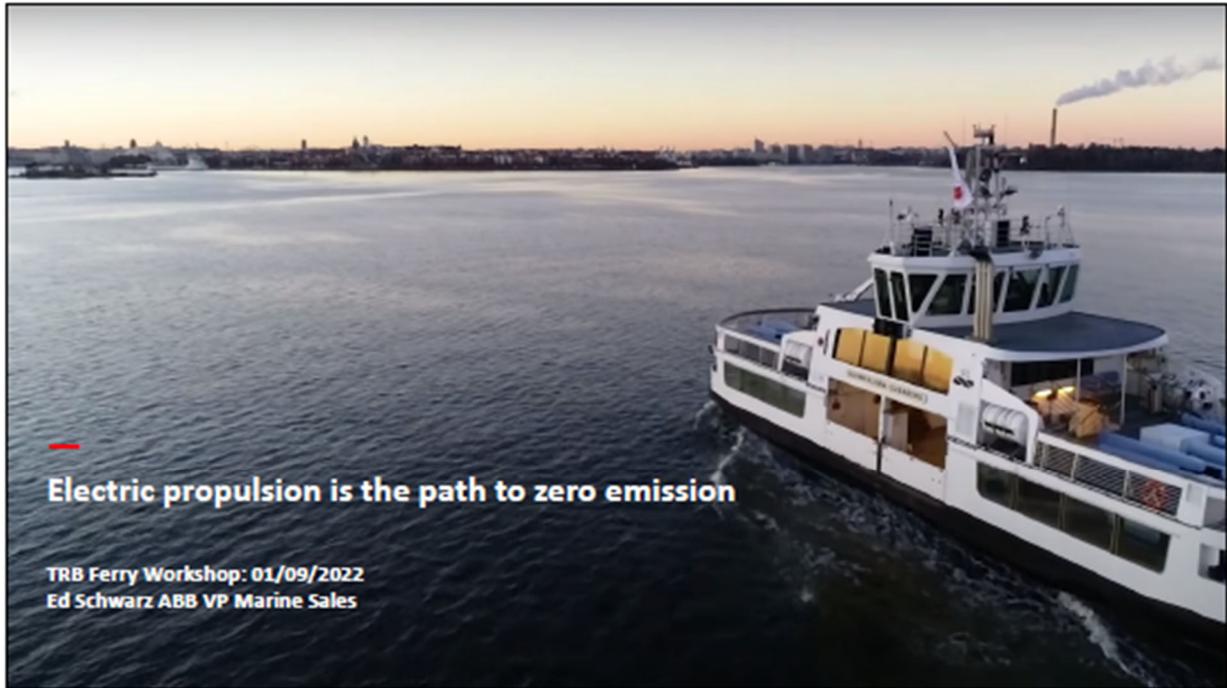
On balance, the best option

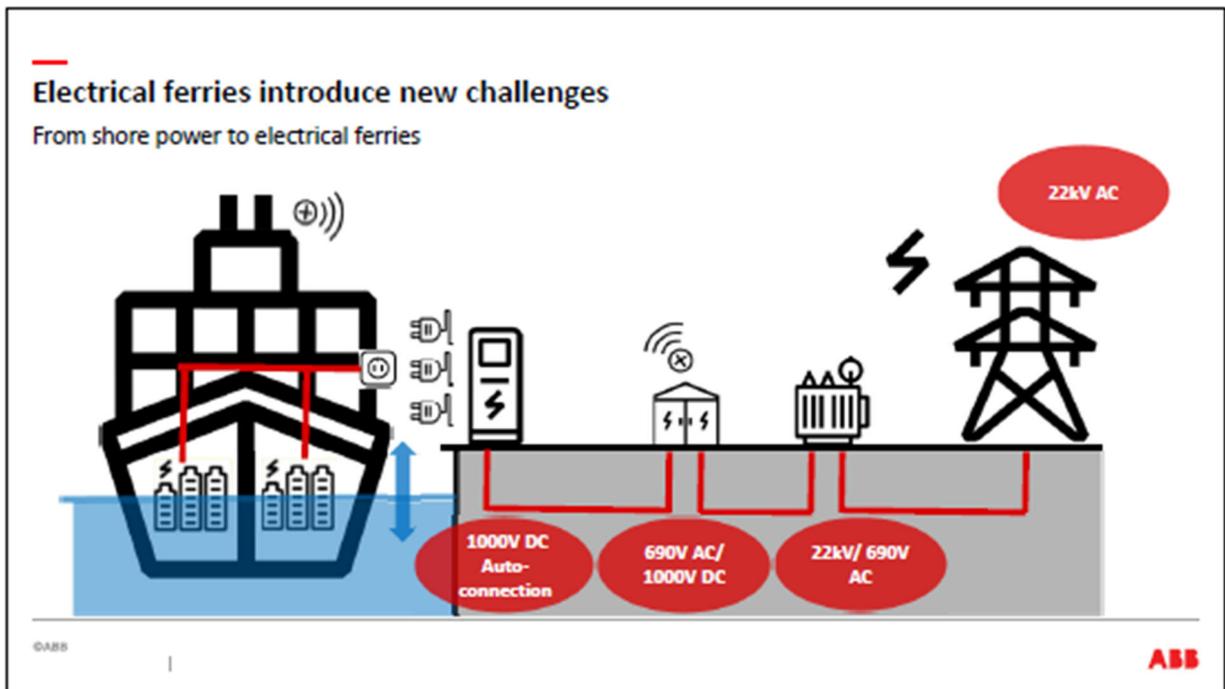
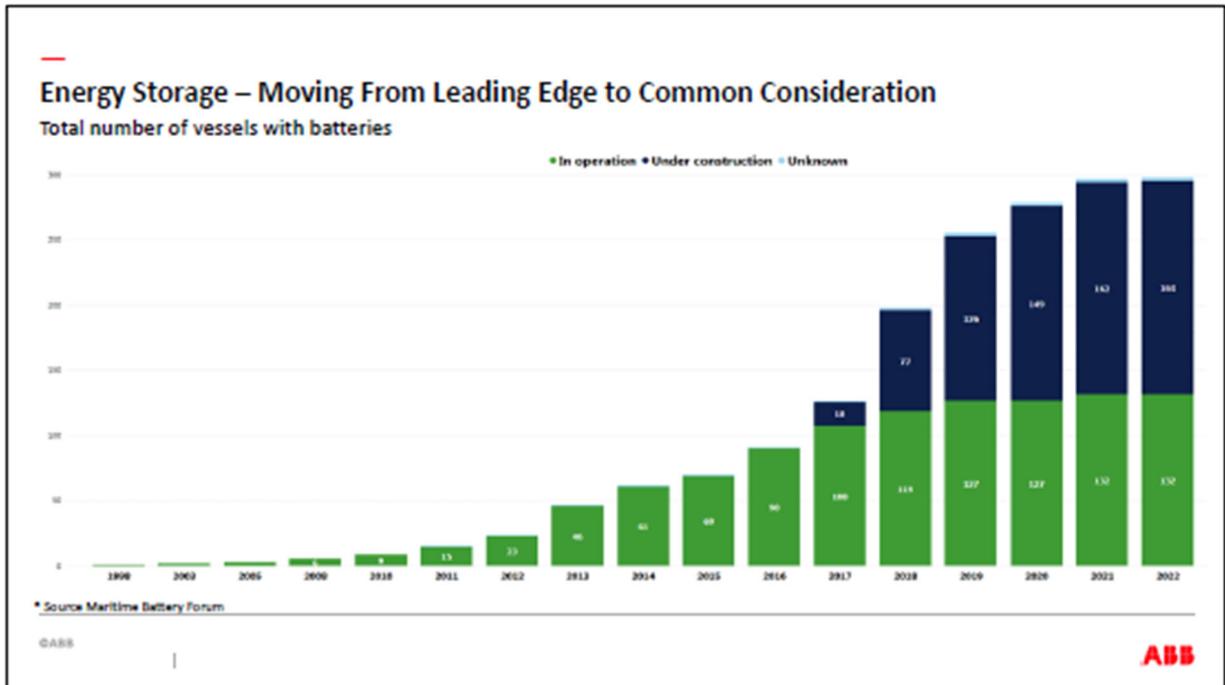
H
Hydrogen

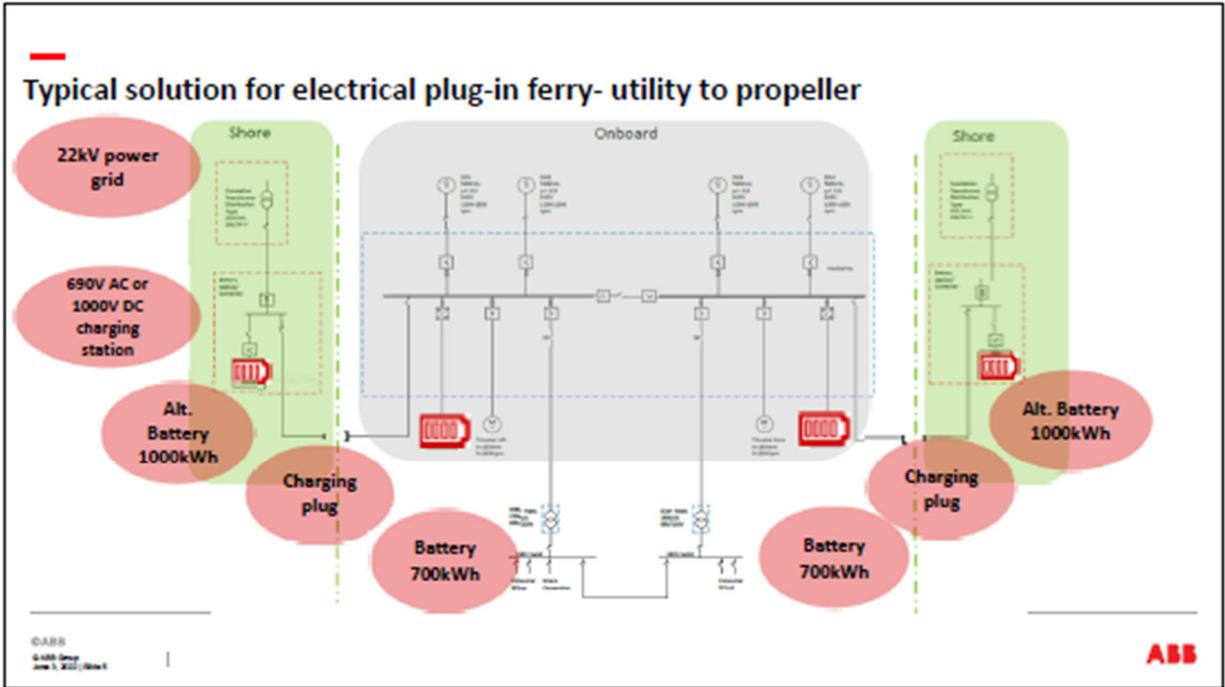
Volta Hydrogen



LOW AND ZERO EMISSIONS WITH HYBRID SYSTEMS







HYDROGEN FUEL CELL TECHNOLOGIES

Zero Emission Technologies in the Marine Industry: Hydrogen

Dr. Joseph Pratt, CEO & CTO



Workshop on Advancing Low- and Zero-Emission
Marine Vessel Technology Options

101st TRB Annual Meeting

January 9, 2022



Hydrogen is the only real option for marine electrification

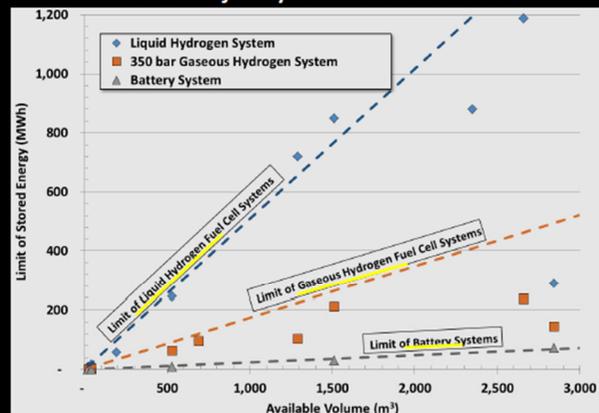
Hydrogen Fuel Cell

- Energy costs: Decrease with scale
- Usage: Long range, high flexibility
- Fueling method: Flexible, no infrastructure required

Battery

- Energy costs: Increases with scale (demand charges, infrastructure, grid upgrades)
- Usage: Limited to locations with charging, limited range
- Charging method: Shore based equipment needed at each charging dock

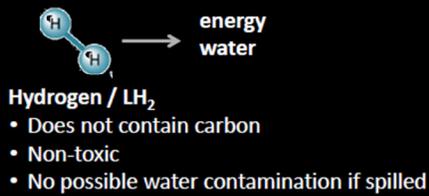
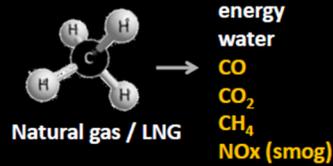
Batteries physically cannot work for the majority of marine vessels



Reference: *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*
(download from: maritime.sandia.gov)



Hydrogen is similar to natural gas, but does not contain carbon Fuel cells electrochemically convert hydrogen to power



3

The advantages of fuel cells goes far beyond environmental



Reliable

Fuel Cells are solid state, and the rest of the powertrain has few moving parts



Scalable

Power can be scaled up/down depending on vessel type and operating needs



Modular

No more "engine room", power train can be distributed across the vessel



Flexible

Maintain current operational flexibility



Low Maintenance

Reduce operation and maintenance cost by 20% to 50%



Connected

Remote monitoring and real time operational intelligence.



4

Technology Summary

| Diesel and LNG | Battery Electric | Fuel Cell <i>Best of Both</i> |
|---|---|---|
| <ul style="list-style-type: none"> ✓ Flexible ✗ Zero Emission ✗ Simple Maintenance | <ul style="list-style-type: none"> ✗ Flexible ✓ Zero Emission ✓ Simple Maintenance | <ul style="list-style-type: none"> ✓ Flexible ✓ Zero Emission ✓ Simple Maintenance |


5

Marine Applications of Hydrogen

Each of these vessels can be powered by fuel cells and hydrogen.

Hydrogen enables zero carbon and zero pollution operation.







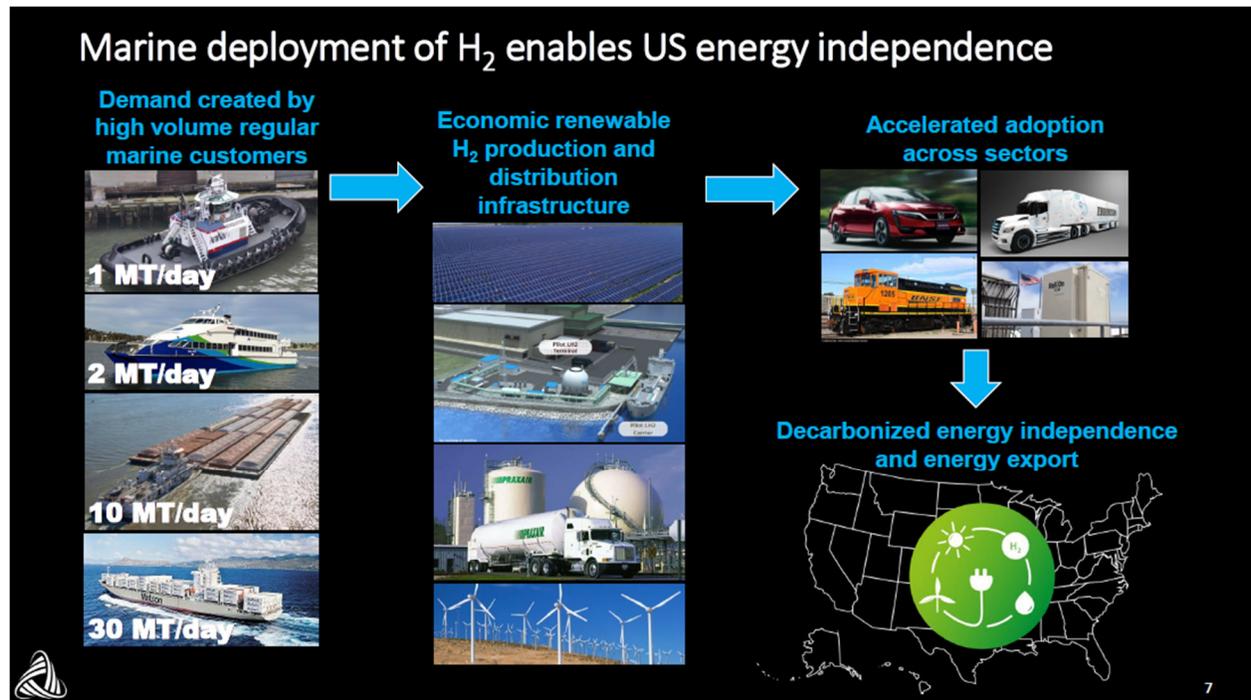






Reference: *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels* (download from: maritime.sandia.gov)





For further information please contact:
Dr. Joe Pratt
joe@zeroei.com
510-788-5101

ZERO EMISSION INDUSTRIES

Hydrogen Simplified.

8

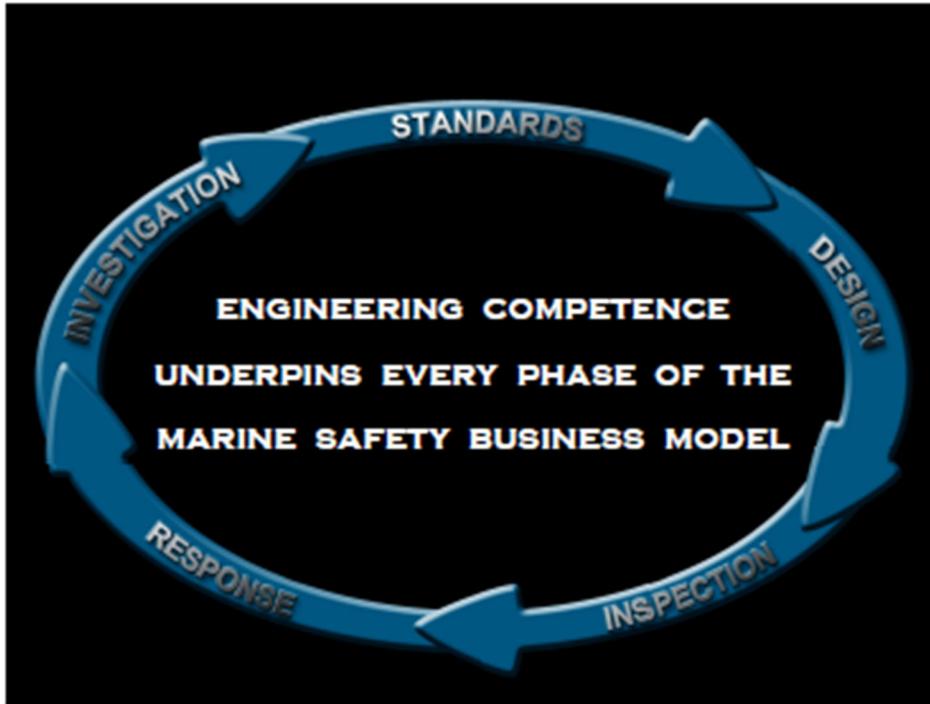
Low and Zero Emissions Regulatory Considerations



 *Bio* 

2008: B.S. in Naval Architecture, Marine Engineering, USCGA
2008 – 2010: Student Engineer, USCGC MELLON
2010 – 2013: Marine Inspections, MSU Port Arthur
2013 – 2016: Chief, Investigations, Sector Charleston
2016 – 2018: M.S in Mechanical Engineering, UC Berkeley
2018 – present: Machinery Branch Chief, MSC

The bio section is enclosed in a white box with a black border. It starts with a small USCGA logo on the left and another on the right, with the word "Bio" in italics between them. Below this, a list of career milestones is provided, including degrees, ship assignments, and roles in various sectors and centers.







Emerging energy sources

- USCG policy or general guidance exists
 1. Bio-fuels
 2. Lithium-ion batteries
 3. LNG as fuel
- Gaps in regulation, policy, or general guidance
 1. Ammonia
 2. Fuel cells
 3. Hydrogen
 4. Nuclear



VESSEL DESIGN IMPACTS

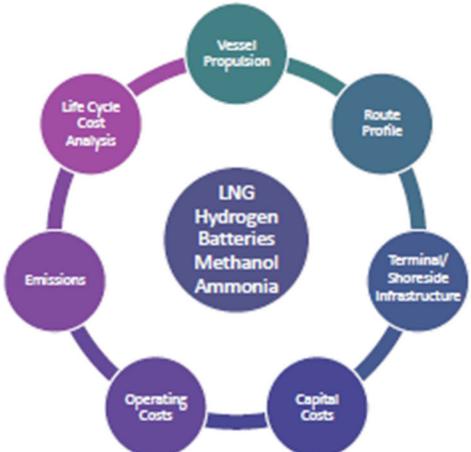
better to build · better to operate

Low/Zero Emission Vessel Technology: Impacts on Vessel Design

TRB Annual Meeting 2022, Workshop 1018
John Reeves, PE, PMP
Director of Business Development

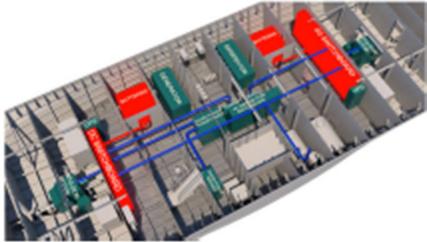
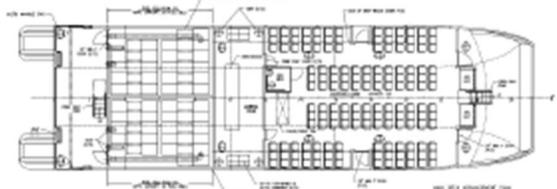


Does zero-emission technology impact vessel design?



YES! But how...?

- Arrangements
 - Machinery Arrangements
 - Egress routes
 - Refuge areas
 - Passenger capacity
- Supporting Systems
- Weight

TRB | Elliott Bay Design Group

YES! But how...?

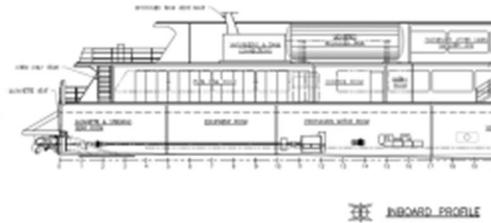
- Arrangements
- Supporting Systems
 - Ventilation and Cooling
 - Fire suppression
 - Gasification
 - Cryogenics
 - Piping systems
 - Charging systems
- Weight




TRB | Elliott Bay Design Group

YES! But how...?

- Arrangements
- Supporting Systems
- Weight
 - Speed
 - Passenger/Cargo Capacity
 - Stability



So, what do we need to do?

- Get educated on the options
- Conduct an alternatives analysis
- Confirm the supply chain
- Consider the long-term benefits of near-term investments
- Account for intangible benefits
- Select the most beneficial system
- "Future proof" the vessel for a desired system later



Questions/Follow-ups?

- John Reeves, PE, PMP
Director of Business Development
jreeves@ebdg.com
360-710-0389

www.ebdg.com



NATIONAL ACADEMIES

Sciences
Engineering
Medicine

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at www.nationalacademies.org.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to provide leadership in transportation improvements and innovation through trusted, timely, impartial, and evidence-based information exchange, research, and advice regarding all modes of transportation. The Board's varied activities annually engage about 8,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at www.TRB.org.



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Washington, DC 20001

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