Argonne NATIONAL LABORATORY

H2@PORTS WORKSHOP SUMMARY REPORT

September 10–12, 2019

Marines' Memorial Club & Hotel, San Francisco, CA

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

FCH FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

ANL-20/12

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H2@PORTS WORKSHOP SUMMARY REPORT

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September 10-12, 2019

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Abstract

This report serves as the proceedings of the H2@Ports Workshop held by the U.S. Department of Energy (DOE) Fuel Cell Technologies Office, the U.S. Department of Transportation (DOT) Maritime Administration (MARAD), and the European Union Fuel Cells and Hydrogen Joint Undertaking (FCH JU) on September 10-12, 2019 at the Marines' Memorial Club & Hotel in San Francisco, CA. The Workshop was held to identify opportunities, barriers to adoption, and research needs to accelerate technology development and industry commercialization of hydrogen and fuel cell systems in maritime applications. Experts and stakeholders from industry, government, and academia met to discuss the current state-of-the-art of hydrogen and fuel cell technologies and the requirements for using these technologies in port-side and ship-board maritime applications. This report summarizes the discussions and diverse opinions expressed at the Workshop.

Acknowledgements

We would like to acknowledge the U.S. Department of Energy Fuel Cell Technologies Office Director, Sunita Satyapal, the U.S. Department of Transportation (DOT) Maritime Administration (MARAD) Acting Associate Administrator for Environment and Compliance, Michael Carter, and the Fuel Cells and Hydrogen Joint Undertaking Head of Unit Operations, Mirela Atanasiu, for management and funding of the Workshop. Special thanks to Pete Devlin, Elizabeth Connelly, Shuk Han Chan, Geovanni Castano, and Lionel Boillot for their efforts planning and organizing the workshop.

We would like to thank Elaine Forbes, the Director of the Port of San Francisco, for delivering the opening remarks and Joseph Pratt, CEO of Golden Gate Zero Emission Marine, for the tour of their facilities and the Water-Go-Round.

The workshop organizers gratefully acknowledge those who presented talks at the workshop, including Rajesh Ahluwalia, Mirela Antanasiu, Gus Block, Lionel Boillot, Nico Bouwkamp, Per Brinchmann, Peter Brooks, Johan Burgren, Stefano Cantarut, Michael Carter, Renaud Cornu, Mercedes de Juan, Joerg Ferchau, Leslie Goodbody, Laurence Grand-Clément, Olav Hansen, Paul Helland, Leonard Klebanoff, Brian Lindgren, Alan Mace, Britney McCoy, Robert Missen, Steffen Møller-Holst, Koichi Nishifuji, Eiji Ohira, Bjoern Pistol, Joseph Pratt, Sunita Satyapal, Erik Schumacher, Ryan Sookhoo, Lindsay Steele, LCDR Frank Strom, Anthony Teo, Roel van de Pas, and Klaus Vänskä. Lastly, we would like to thank all the participants for the opinions and insights shared at the Workshop. Without these contributions the workshop would not have been a success.

Executive Summary

The H2@Ports Workshop was organized by the U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO) in collaboration with the U.S. Department of Transportation (DOT) Maritime Administration (MARAD) and the European Union Fuel Cells and Hydrogen Joint Undertaking (FCH JU). The Workshop was attended by over 100 participants, with representation from port authorities, ship system developers, power systems developers, vehicle and fuel cell manufacturers, academia, national laboratories, and government agencies. The objectives of the Workshop were to:

- Assess the state of the art for maritime applications using hydrogen fuel cells
- Discuss operational requirements and lessons learned from early fuel cell maritime projects
- Understand current technology gaps and identify collaborative R&D opportunities
- Identify regulatory challenges and needed safety codes and standards

The first day of the workshop focused on the perspectives of domestic and international government agencies, port authorities, and ship systems developers, who presented the first in a series of industry perspectives, highlighting technology status and development. The second day continued the series of industrial perspectives from the viewpoints of the power system developers and vehicle and fuel cell manufacturers for both port and marine applications. Additional sessions focused on regulations, codes, and standards and recent R&D activities in maritime applications. Topic sessions were followed by panel discussions on relative challenges and issues. The third day consisted of a tour of Golden Gate ZERO Emission Marine's *Water-Go-Round* passenger ferry.

A wide range of perspectives and potential applications were discussed during the workshop. This report captures the key themes discussed by the workshop participants and provides details on specific recommendations and collaborative opportunities. The report includes presentation overviews, panel discussion summaries, and a summary of major outcomes, recommendations, and envisioned pathways forward in the development and deployment of fuel cell and hydrogen maritime technology and international collaboration.

Participant feedback to identify the most pressing R&D needs to accelerate the development and deployment of hydrogen and fuel cell technologies in maritime applications is provided in Appendix A, the workshop agenda is provided in Appendix B, the speaker bios are provided in Appendix C, and a list of the workshop attendees is provided in Appendix D.

Presentation titles are hyperlinked to the slide presentations available on the U.S. Department of Energy H2@Ports Workshop website (https://www.energy.gov/eere/fuelcells/h2ports-workshop).

Current status/state of the art for hydrogen and fuel cells for maritime applications:

- Participants indicated that polymer electrolyte membrane fuel cells (PEMFC) are the most developed type of fuel cell for maritime applications. Opportunities exist for other fuel cell technologies, including high-temperature PEM fuel cells (HT-PEMFCs) and solid oxide fuel cells (SOFCs); however, additional R&D will be required for these fuel cell technologies to meet the demands and requirements for maritime applications.
- Hydrogen and fuel cells are more expensive than diesel fuel and diesel engines. Workshop participants considered reducing the cost of fuel cell systems to be less of a challenge than reducing the costs associated with the hydrogen fuel.

- Presenters discussed results and experiences from completed or on-going fuel cell demonstration projects. Port-side demonstration projects discussed included a reach stacker and yard tractor, Class 8 fuel cell trucks, a hybrid fuel cell top-loader for handling cargo, and a power unit for refrigerated cargo containers. Ship demonstration projects discussed included a sightseeing passenger ship, river push boat, and ferries.
- Workshop attendees indicated that storing enough hydrogen on board trans-oceanic cargo ships to meet demand while at sea may be impractical due to the lower volumetric energy density of hydrogen compared to marine fuel oil (MFO).
- The large footprint required for hydrogen storage at the port was identified as a critical issue given the value of port real estate. Sub-sea hydrogen storage was suggested as one option to free space in the port while providing an added safety benefit of reducing risk if there is a leak.
- Workshop participants indicated that safety is a major concern. The lack of codes and regulations for storage, handling, and use of hydrogen on board ships was identified as a major hurdle for ship designers. Risk management and liability remain important challenges.

Workshop participants identified the following needs for accelerating progress:

- Demonstrations are needed to help develop and validate technical targets for hydrogen and fuel cell systems to compete against diesel technologies for maritime applications, to benchmark the standards required for broad commercialization of hydrogen and fuel cell technologies, to develop the hydrogen infrastructure needed for maritime applications, and to fully address the regulatory challenges to ensure safety.
- Safety codes and regulations need to be standardized, and lessons learned from demonstration projects and from early adopters in other industries, such as automotive, buses, and stationary power, need to be shared and captured in the codes and regulations.
- For fuel cell systems, R&D is needed to improve durability, increase efficiency, and lower costs to compete against incumbent diesel technology.
- For hydrogen, R&D is needed to lower the cost of hydrogen production, delivery, and storage. The development of a hydrogen infrastructure is critical given the volume of hydrogen that will be required for maritime applications.
- Governments should focus on developing the hydrogen infrastructure and regulations, codes, and standards for the safe use and handling of hydrogen both on vessels and in ports.

A Closer Look at Total Cost of Ownership

As mentioned by several presenters, the cost comparison between fuel-cell-powered and conventionally or alternatively powered vessels is highly dependent on the type of vessel and corresponding requirements and specifications. Researchers from Argonne National Laboratory presented a preliminary analysis of the total cost of ownership (TCO) for three different types of vessels: a feeder container ship, an automobile/passenger ferry, and a tugboat. For each vessel type, two different powertrains and three different fuel types were considered: a low-sulfur marine gas oil (LSMGO)-diesel engine system, a liquefied natural gas (LNG)-diesel engine system, and a hydrogen fuel cell system. The TCO included the levelized costs of the powertrain and fuel storage, the lifetime fuel cost, and the cost of maintenance, for each of the three different types of vessels.

Results and findings from the preliminary TCO analysis include:

- The cost of hydrogen fuel dominated the TCO for all the three types of vessels.
- The harbor tug represented the most competitive potential business case for fuel cells, among the three types of vessels analyzed.
  - The preliminary analysis showed the fuel cell harbor tug could have the lowest capital cost.
  - The TCO of the fuel cell harbor tug was estimated to be lower than the LNG harbor tug, though about 15% higher than the diesel harbor tug.
- The total capital cost of a fuel cell ferry at $60/kW (a projected future cost) was estimated to be approximately 50% lower than that of an LNG ferry, though 20% higher than that of a diesel ferry.
- The TCO for a fuel cell ferry was calculated to be approximately 50% higher than for a diesel ferry. This finding was supported by TCO analysis presented by the FCH JU.
- As with the other vessel types analyzed, the capital cost of a fuel cell container ship was estimated to be less than that of a LNG containership: approximately 10% less in this case study.
- Based on the results and sensitivity analysis, further R&D, especially to increase fuel cell efficiency and/or reduce the cost of the hydrogen fuel, is needed for fuel cell vessels to achieve cost parity with the incumbent diesel vessels.

Conclusions

Based on participant feedback, near-term opportunities for demonstrating current state-of-the-art hydrogen and fuel cell technologies and to accelerate deployment of these technologies in maritime applications include:

- Deploy fuel cell systems in port-side applications such as drayage trucks, rubber tired gantry (RTG) cranes and other cargo handling equipment (CHE), which represent large volume applications that can enable hydrogen fuel economies of scale.
- Focus research and development on fuel cell propulsion systems in tugs, push boats, and ferries rather than trans-oceanic cargo container ships, since storing the volume of hydrogen required on-board cargo ships will be a major challenge.

Workshop participants identified the following critical challenges for accelerating broader deployment of hydrogen and fuel cell technologies in maritime applications:

- Improving the efficiency and durability of fuel cells at a lower cost, to compete with diesel engines.
- Establishing a hydrogen infrastructure for delivering hydrogen at a cost that is competitive with diesel.
- Researching on-board vessel hydrogen storage tanks to reduce capital cost.
- Developing and deploying vessels such as tugs and ferry boats near term to reduce emissions and support realizing fuel cost economies of scale.

Introduction

The H2@Ports Workshop was organized by the U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO) in collaboration with the U.S. Department of Transportation (DOT) Maritime Administration (MARAD) and the European Union Fuel Cells and Hydrogen Joint Undertaking (FCH JU). The Workshop was attended by over 100 participants, with representation from port authorities, ship system developers, power systems developers, vehicle and fuel cell manufacturers, academia, national laboratories, and government agencies.

The objectives of the Workshop were to:

- Assess the state of the art for maritime applications using hydrogen fuel cells
- Discuss operational requirements and lessons learned from early fuel cell maritime projects
- Understand current technology gaps and identify collaborative R&D opportunities
- Identify regulatory challenges and needed safety codes and standards

Presentations and panel discussions were broken down into eight sessions covering U.S. and non-U.S. government perspectives on hydrogen and fuel cells in both port and at-sea maritime applications; perspectives of stakeholders including port authorities and operators, ship builders, marine power system developers, vehicle developers for port applications, and fuel cell manufacturers; regulations, codes, and standards; and research and analyses studies. Speakers presented an overview of the current status of hydrogen and fuel cells technologies in their respective area of interest in the maritime industry and identified major challenges and opportunities for greater widespread deployment of hydrogen and fuel cells in ports and on vessels. Speakers served on discussion panels where they were asked to comment on questions related to the session topic. The views and recommendations are those of the workshop participants collectively rather than the views or recommendations of U.S. Department of Energy, specific individuals or industry representatives.

Participant feedback to identify the most pressing R&D needs or issues for acceleration of the development and deployment of hydrogen and fuel cell technologies in ports and on vessels is given in Appendix A, the workshop agenda is given in Appendix B, speaker bios are provided in Appendix C, and a list of the workshop attendees is given in Appendix D.

Presentations are available on the U.S. Department of Energy's H2@Ports Workshop website (https://www.energy.gov/eere/fuelcells/h2ports-workshop).

Session I — U.S. Government Perspectives on Hydrogen at Ports and At-Sea Marine Applications

Dr. Sunita Satyapal, Director, Fuel Cell Technologies Office, U.S. Department of Energy, "Hydrogen and Fuel Cells Overview: Opportunities for Ports & Maritime Applications"

DOE covers a broad portfolio of RD&D activities, and hydrogen is one part of the portfolio. Commercial hydrogen and fuel cell technologies are now available, but costs are still high. There are over 300,000 stationary fuel cells, 12,000 fuel cell cars, and 300 hydrogen refueling stations worldwide. Heavy-duty, rail, marine, and aviation applications are emerging. While the current uses have focused on transportation, hydrogen can be used across sectors of the economy and can help enable further utilization of renewable and existing nuclear power assets by providing a long-term energy storage solution. Increased penetration of renewables has increased the need for energy storage and grid services to address power/frequency fluctuations. Electrolyzers have demonstrated that they can reduce power/frequency fluctuations on a grid with high penetration of renewables. Hydrogen can also be used to monetize surplus electricity from the grid and provide storage for days to months. For example, one hydrogen cavern could provide about a 100 GWh of energy storage.

In the U.S., transportation is now the largest contributor to emissions. Hydrogen as well as other options (e.g., ammonia) are being pursued internationally as potential renewable, zero-emission marine fuels to help address these emissions challenges. In the U.S., DOE and MARAD are looking at hydrogen and fuel cell technologies for use at ports and on board ships. Equipment at the ports can include rail, cargo handling equipment (CHE), heavy-duty vehicles (e.g., drayage trucks), and harbor tugs. Clustering fuel cell applications in a port can drive hydrogen demand in port-based distribution complexes. Models indicate that a representative port-based industrial complex with "hub and spoke" hydrogen fueling stations connected by pipelines can decrease hydrogen costs to less than $6/kg. As part of this effort, DOE and MARAD developed and tested a hydrogen fuel cell power generator unit to replace diesel generators for refrigeration units. Field tests showed a ~30% energy efficiency gain over the diesel engine used for these refrigeration units at part loads. This fuel cell unit will next be tested for cold ironing (using shoreside electrical power to meet a ship's power demands while it is at berth, allowing it to turn off its main and auxiliary engines) application at Scripps Institution of Oceanography in San Diego, CA.

Maritime applications can enable large scale use of hydrogen, which aligns with DOE's H2@Scale vision in which hydrogen can enable energy security, economic value and environmental benefits. The goal of this Workshop is to identify R&D needs to accelerate technology development, address barriers to commercialization, and identify opportunities for collaboration.

Michael Carter, Acting Associate Administrator for Environment and Compliance, U.S. Department of Transportation – Maritime Administration, "Maritime Administration Office of Environment"

The MARAD Maritime Environmental and Technical Assistance (META) program objectives are to: (i) stimulate technology advances for improved sustainability, and (ii) demonstrate and inform the use of alternative fuels and energy technologies (including natural gas, advanced renewable "drop-in" biofuels, hybrid propulsion, and fuel cells) in maritime applications. Goals of the program are to validate and demonstrate alternative energy technologies, reduce air pollution emissions from ships and in and around ports, generate cost/benefit and technical data, and identify gaps. The shipping industry is very conservative, so demonstrations validating operability and cost are critical. In 2013, a memorandum of understanding (MOU) was established between the DOE and MARAD to evaluate fuel cell applications for port equipment and maritime vessels. Key issues identified at that time included safety, fuel storage, sources of hydrogen, cost, size/weight, power density of the system, and power integration and regulation.

The MOU resulted in a collaborative project with Sandia National Laboratories (SNL), Hawaii Ports, Young Brothers, and the U.S. Navy to demonstrate auxiliary power units (APU) for shore-shipboard power, using fuel cells to replace diesel generators to provide 100 kW of power to operate 10 refrigerated containers ("reefers"). The APU system was designed to fit in a standard 20 ft shipping container and provide 100 kW nominal power and ~200 hours of continuous operation for up to 10 reefers.

In a second project, with SNL and Red & White Fleet, a design feasibility study was performed for a high-speed zero-emissions ferry and shore-based hydrogen storage and fueling station serving vessels, cars, buses and trucks. The fueling station design was for 2,500 kg hydrogen/day capacity and 80% base utilization. The vessel was designed to carry 150 passengers. The modeled vessel operation entailed a 46 nautical mile route (round trip), with four trips per day. Each trip would use 500 kg of hydrogen. The performance requirements included a speed of 35 knots, zero emissions, and a 90% maximum continuous rating (i.e., power margin). On-board hydrogen storage provided enough hydrogen to allow for only one refueling per day.

MARAD has also been involved in a project for a fuel cell hybrid research vessel for Scripps Institution of Oceanography. In Stage I, a design and feasibility analysis of the fuel cell vessel indicated that a fuel cell vessel was cost prohibitive, however, it did provide zero emissions and quiet operation to support research needs. The study will evaluate more cost-effective alternative powertrain designs, including diesel electric, diesel electric/battery hybrid, and diesel/electric-hydrogen fuel cell hybrid designs in Stage II.

Concerns about the low volumetric energy density and the safety of hydrogen on board a ship have spurred interest in on-board reforming of fuels to hydrogen. MARAD and the U.S. Navy funded a project to evaluate a 10 kW fuel cell system using on-board fuel reforming to provide ship auxiliary power. Efforts have focused on the reforming process, with a key issue being the ability to reform high-sulfur diesel fuels.

To more fully address the issue of safety with gaseous and cryogenic fuels, a workshop on gas dispersion modeling was held in August 2019. The participants identified the top three hydrogen scenarios to be investigated based upon needs of the U.S. Coast Guard, classification societies (DNV-GL), and other stakeholders. Scenarios to be modeled included venting mast, bunkering (fueling), and gas dispersion in the fuel cell power room. The goal is to identify the shape and size of hazardous zones and to examine differences between hydrogen and natural gas as permitted by schedule and budget. Liquid and gaseous hydrogen releases will be investigated as permitted by schedule and budget. Modeling will be applicable to both vessel and port applications

Britney J. McCoy, Ph.D. U.S. Environmental Protection Agency (EPA), Office of Transportation and Air Quality, "H2 Fuel Cells at Ports: An Overview"

The goal of the EPA's Ports Initiative is that people living and working near ports across the country will breathe cleaner air and live better lives as a result of bold steps taken through a collaboration of industry, government, and communities to improve environmental performance and increase economic prosperity. The EPA's work to improve air quality around ports takes a two-pronged approach: (i) regulatory standards for emissions from new trucks, vessels, and equipment as well as for sulfur levels in fuels, and (ii) non-regulatory efforts to advance next-generation, clean technologies and practices at ports.

The EPA has developed reports to help identify smart infrastructure investments for reducing emissions at ports, including the *National Port Strategy Assessment: Reducing Air Pollution and Greenhouse Gases at U.S. Ports* (https://www.epa.gov/ports-initiative/national-port-strategy-assessment-reducing-air-pollution-and-greenhouse-gases-us), *Shore Power Technology Assessment at U.S. Ports* (http://www.epa.gov/ports-initiative/shore-power-technology-assessment-us-ports), and the *EPA and Port Everglades Partnership Emission Inventories and Reduction Strategies* (https://www.epa.gov/ports-initiative/epa-and-port-everglades-partnership-emission-inventories-and-reduction-strategies).

An assessment of fuel cell technologies is expected to be completed by December 2019. The study will identify current applications of fuel cells across U.S. ports and will assist EPA and port stakeholders in evaluating the technology and estimating the potential emissions impacts for nonroad, marine, and heavy-duty fuel cell applications. The EPA has identified 22 fuel cell demonstration and deployment projects at U.S. ports. Seven of these projects are for drayage trucks, five for power generation at the port, four for yard tractors or top loaders, four for hydrogen refueling stations, one for a portable light tower and one for a ferry boat.

High upfront costs of hydrogen and fuel cell technologies are barriers to adoption. Stakeholders want a return on investment (ROI) within 2 to 3 years. The EPA does not fund research, but has funds available for commercial-ready applications that can help reduce the barriers for adoption. Information on funding opportunities for ports and near port communities is available at https://www.epa.gov/ports-initiative/funding-ports-and-near-port-communities. One pathway for funding is the Diesel Emissions Reduction Act (DERA). DERA authorizes funding assistance to reduce diesel emissions from legacy engines and provide immediate health and environmental benefits to target areas. Fuel cells can be funded as a diesel replacement under DERA. Funding levels vary based on the technology cost share. Zero tailpipe emission diesel replacements are eligible for up to 45% and drayage replacements (manufactured in 2013 or later) are eligible for up to 50% DERA cost-share funding. Since 2008, fleets at marine and inland water ports have been a priority for DERA grants: $148 million has been spent on 152 clean diesel port projects from 2008 to 2018.

EPA’s Port Initiative website, including newsletter sign-up, is available at: https://www.epa.gov/ports-initiative

Leslie Goodbody, Air Resources Engineer, California Air Resources Board (CARB), “CARB Hydrogen and Fuel Cell Activities in Freight”

CARB’s goal is to protect communities near freight facilities, including seaports. CARB’s purview includes the ships at port, harbor vessels, material handling equipment, and trucks moving goods into and out of the ports. Their strategy to accomplish this includes supporting facility infrastructure/compliance and district facility-based measures and port initiatives, coordinating and expanding incentives for freight transition to zero-emissions operations, and pursuing stricter federal and international standards.

At seaports, CARB currently requires ships to control emissions at berth by using shore power or barge-based or land-based capture and control technologies. To increase compliance, CARB plans to include more CARB site visits, expand the type of vessels inspected, and hold ports, terminals, and technology providers accountable for doing their part. For harbor craft, the focus is on cleaner combustion for in-harbor use and new cleaner engines. CARB supports the introduction of zero-emissions technologies wherever possible. They are also considering regulations for cargo handling equipment to transition to zero-emissions technology. For freight movement, CARB has proposed a zero-emissions truck sales requirement for manufacturers that will start in 2024 and target increasing the percentage of zero-emissions class 4-8 trucks to 50% by 2030.

In addition to the regulatory programs, CARB has an incentive portfolio to help spur adoption of zero-emissions technologies. Several pathways are available for funding to reduce emissions at ports, including the Air Community Protection Program, Greenhouse Gas Reduction Fund (GGRF), and the Volkswagen settlement fund. Forty million dollars in funding for competitive projects for zero-emissions vehicles (ZEV) has been proposed for 2019-2020 from the GGRF. In addition, $423 million from the Volkswagen settlement fund has been allocated for ZEVs, with vouchers for up to $200,000 for ZEVs that replace diesel trucks. Projects relevant to ports fall under two categories. The first category, Class 8 Freight & Port Drayage Trucks, will be administered by the South Coast Air Quality Management District (AQMD), with $27 million available in the first installment, with up to $200,000 available for a new truck. The second category, Freight and Marine Projects, is administered by the Bay Area AQMD under a competitive solicitation, with $35 million available in the first installment. This category will provide funding up to $175,000 for each port CHE and heavy lift (over 8,000 lbs.) equipment and up to $2.5 million for shore power and ferry, tug or tow boat repower. An additional $740 million in funding is available through the Community Air Protection Program for mobile and stationary sources.

Current GGRF demonstration projects include ten hydrogen fuel cell Class 8 trucks and two large-capacity hydrogen refueling stations in the Port of Los Angeles (LA). The trucks will be Kenworth trucks employing Toyota fuel cell technology. The first truck is expected to be delivered soon, and the hydrogen stations are scheduled for completion in September 2020. Hyster-Yale and Nuvera are also being funded by California GGRF to develop and demonstrate a hybrid fuel cell top-loader at the Port of LA. The project will include development of a mobile hydrogen refueler. Finally, a fuel cell ferry is being designed, built, and demonstrated in San Francisco, CA. The ferry will have a top speed of 22 knots and carry up to 84 passengers. This work will be discussed further in Session IV.

Panel Discussion — Moderator: Peter Devlin, U.S. DOE-FCTO

In this panel discussion, challenges were identified for fuel cells and hydrogen technologies for maritime and ports applications including: hydrogen availability and storage, including insuring a reliable supply, hydrogen cost, and safety. The ports and the maritime industry operate with slim margins, and fuel costs are very important. It is difficult for hydrogen to compete with incumbent diesel and marine fuel oil (MFO) on a cost basis, and hydrogen costs must come down. Hydrogen storage costs are also a challenge. Fuel cell cost is not considered as much of a challenge.

Safety is a major concern, especially for on-board ship applications, where catastrophic failures are possible, and evacuation is not a simple option. Risk management and liability remain important challenges related to safety, regulations and standards for hydrogen use in maritime and port applications. Concerns were expressed that there is a lack of transfer of knowledge, safety learnings, and requirements from one application to another. The panelists and members of the audience suggested that codes and standards and lessons learned from the use of compressed natural gas (CNG) and liquefied natural gas (LNG) in ports could be a good starting point for developing hydrogen codes and standards for maritime applications. It was noted that the CNG/LNG industry has been successful with a very good safety record. Others were more skeptical that the experience from CNG/LNG is applicable and argued for starting with new risk assessment-based guidelines. The panel noted that while ships may seem similar to other applications, their operational differences can be significant. While maritime has its challenges, it also presents an opportunity that is not available with light duty vehicles: A critical mass of hydrogen demand can be reached with just a few ships, changing the scale and cost of hydrogen production and delivery.

Session II — International Government Perspectives on Hydrogen at Ports and At-Sea Marine Applications

Robert Missen, Head of Unit for Research, Directorate General for Mobility and Transport, European Commission (EC), "Hydrogen Maritime Applications EU Policy Perspective"

Transport and connectivity are essential for the European Union (EU) economy. Transportation is responsible for almost a quarter of the EU's greenhouse gas (GHG) emissions and is the main cause of reduced air quality in cities. After 2030, transportation is likely to be the largest emitter of CO_2 in the EU. Maritime transport is estimated to be responsible for about 2.5% of global GHG emissions. To meet the EU's commitment under the Paris Agreement and the EU's 2030 goals, transport emissions should be at least 60% lower in 2050 than in 1990. In 2014, the EU passed legislation requiring a minimum alternative fuels infrastructure be implemented through national policy frameworks that include hydrogen. The International Maritime Organization (IMO) has committed to reducing GHG emissions from international shipping by at least 50% by 2050 compared to 2008 with a strong emphasis on reaching zero emissions. Hydrogen and fuel cells are gaining support for their potential to reduce CO_2 emissions at the EU and international scale. Energy ministers of 28 European countries recently signed the "Hydrogen Initiative" that was launched in Linz, Austria. The European Commission (EC) is very enthusiastic about the potential for hydrogen, including its use as a marine fuel, and held two workshops to explore the opportunities for hydrogen and fuel cells in maritime applications, with the first one held in Valencia, Spain, in 2017 and the second one held in Brussels, Belgium, in 2018, which included 50 industrial stakeholders.

LNG may be a blueprint for hydrogen in shipping. A draft guideline for using LNG in maritime applications was presented to the IMO in 2004, interim guidelines were adopted in 2009, and the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) was adopted in 2015. Currently, there are 121 LNG ships in operation and 88 new ships on order. The sulfur cap that is to go into place in 2020 is expected to increase orders for LNG ships.

LNG reduces emissions, but additional work is needed to transition the maritime industry to zero-carbon fuels. This includes work on infrastructure to scale up renewable production of zero-carbon fuels and to improve the availability of these fuels at lower cost. Additional work on zero-emissions vessels includes scaling-up deployments, reducing capital costs, and developing supportive policies, regulations, standards, and rules. The EC is developing a framework for hydrogen as a marine fuel, including R&D on liquid and gaseous hydrogen storage technologies. Safety concerns include hydrogen releases, vacuum loss, pressure buildup in liquid hydrogen tanks due to rapid vaporization, potential ignition of oxygen, sloshing in the tank, embrittlement, ignition mechanisms, safety relief valves, diffusion, and trapping.

Mirela Atanasiu, Head of Unit Operations and Communications, Fuel Cells and Hydrogen Joint Undertaking (FCH JU), "EU Support for Maritime Activities"

The EU seeks to develop a fully integrated internal energy market that provides energy security while addressing the need for action on the climate by reducing GHG emissions. Hydrogen can help meet these goals by providing energy storage and sectoral integration between the energy, transport, heating, and industrial sectors. Hydrogen is seen as the best option for decarbonizing a number of sectors. In addition to CO_2 abatement, deploying hydrogen cuts local emissions, creates new markets, and secures sustainable employment in the EU. The FCH JU estimates that hydrogen and fuel cells can create 5.4 million jobs in the EU by 2050. The FCH JU is a strong public-private partnership with a focused objective to implement an optimal research and innovation program to bring hydrogen and fuel cell technologies to market readiness. The FCH JU program is structured across two main pillars — energy and transport — with a third cross-cutting area that addresses codes and standards, safety, education and consumer awareness. The energy pillar includes hydrogen production and distribution, fuel cells for stationary power and combined heat and power (CHP) production, and hydrogen storage for renewable energy integration. The transport pillar includes fuel cells for road and non-road vehicles and machinery, maritime, rail, and aviation applications, and refueling infrastructure.

Industry is interested in using hydrogen to decrease its carbon footprint. The cost of electrolyzers is decreasing, and electrolyzer companies are offering larger scale products that have drawn the interest of several big industries. Green hydrogen, made by a 10 MW electrolyzer using curtailed wind and a 6 MW electrolyzer using hydro-electric power, is being used at an oil refinery and a steel plant, respectively, in two FCH JU-funded projects. Another project is demonstrating a 2 MW solid oxide electrolyzer (SOEC) to provide hydrogen to a steel plant. In other FCH JU activities, 1,046 micro-CHP systems with a total of over 1 MWe capacity have been installed across the EU and have been operating for more than 5 million hours. An additional 2,000 units have also been deployed under a German initiative. The EU has successfully exported some of this technology to markets where hydrogen and fuel cells have more favorable market conditions, providing MW-scale fuel cells that use waste or byproduct hydrogen.

In the transport pillar, the EU supports the simultaneous rollout of fuel cell vehicles and the hydrogen infrastructure to support them. The EU has 10 original equipment manufacturers (OEMs) developing hydrogen fuel cell buses with 360 hydrogen-fueled buses already deployed. Prices for fuel cell buses have decreased by 66% since 2010, with the current cost being about 625,000€/bus. Cumulatively, fuel cell buses have driven more than 6 million kilometers throughout the EU.

Worldwide, hydrogen for trucks is gaining traction due to batteries' limited range. Initially, the FCH JU started using fuel cells as auxiliary power units (APUs) for trucks; however, this approach was found to be too expensive. The FCH JU shifted its focus to developing and testing trucks using fuel cells as range-extenders or for primary propulsion power. These efforts include the *REVIVE* project, which demonstrated fuel cell range extenders for garbage trucks in multiple European cities, and *H2 Haul*, looking at hydrogen for long-haul trucks. In other European activities, Hyundai recently signed a deal to sell 1,000 hydrogen powered trucks in Switzerland, and Norway has announced plans to have 1,000 hydrogen trucks by 2023.

Hydrogen and fuel cells are now being investigated in other transportation sectors, such as rail, aerospace, and maritime, where CO_2 abatement is more difficult. In the EU, 42% of the rail lines are not electrified: The trains using these lines are powered by diesel locomotives. The cost for a hydrogen fuel cell train is about half the cost of installing catenary electrification, which is estimated at €1 million/km). A fuel cell train began commercial operation in Germany in September 2018, with new fuel cell trains being planned for other EU countries. In 2016, the first four-seater airplane propelled by hydrogen took off from Bonn airport. Development of fuel cells for small business jets is ongoing, with demonstrations expected around 2030. Fuel cells are currently being developed for auxiliary power applications such as infotainment and use in kitchenettes on large airplanes, with maiden flights expected to begin in 2019.

Hydrogen is needed to reach the IMO target of 50% $C0_2$ reduction by 2050. The FCH JU has been active in developing hydrogen and fuel cells for maritime applications. Starting in 2016, the FCH JU funded *BIG-HIT* (Building Innovative Green Hydrogen Systems in Isolated Territories), a project on an island community in Scotland to evaluate hydrogen production, storage, transportation and utilization for heat, power and mobility. In 2017, the FCH JU began two shipboard fuel cell demonstrations: *MARANDA*, a hydrogen-fueled fuel cell-based hybrid powertrain system for dynamic positioning validated on board the research vessel *Aranda*, and *HySeas III*, which will be the world's first zero-emissions sea-going ferry. The *HySeas III* project will serve as a demonstration model for a circular economy for the local production of hydrogen fuel. In 2019, two additional maritime projects were added. The *FLAGSHIPS* project includes a fuel cell fluvial push-boat being demonstrated in Lyon, France, and a fuel cell powered RO-PAX (roll-on-roll-off-passenger-ship) ferry being demonstrated in the Stavanger region of Norway. A second maritime project, *H2Ports*, is demonstrating fuel cells employed in reach stackers, yard tractors and a mobile hydrogen refueling station (HRS) for use in port/harbor container terminals. Additional projects are expected from a 2019 solicitation in the areas of Next Generation Propulsion for Waterborne >5 MW on-board power, structuring research and innovation towards zero-emissions waterborne transport, and scaling-up and demonstration of a multi-MW fuel cell system for shipping.

Erik Schumacher, Divisional Head Stationary Fuel Cells, NOW - National Organisation Hydrogen and Fuel Cell Technology, "German Government Perspectives on Hydrogen at Ports and At-Sea Marine Applications"

At the national level, Germany wants to strengthen and stabilize its initiatives for alternative propulsion and energy sources in shipping and in ports with the focus on hydrogen and fuel cells, methanol, and electromobility. Germany was home to one of the first fuel cell-powered ship demonstrations, the *Alsterwasser*, a sightseeing passenger ship that operated in Hamburg from 2008 to 2013. The *Alsterwasser* was considered a technical success, but the project was ended because the hydrogen supply infrastructure failed to materialize. A major lesson learned from this project is that the application and the hydrogen infrastructure must be considered together.

Since 2009, German efforts to develop and deploy hydrogen and fuel cell technology are directed through the National Innovation Program, which has funded six marine-related projects. Three of these projects are fuel cell-focused: *Rivercell*, which uses methanol as a fuel, and *ELEKTRA* and *FC Ship Propulsion*, which use hydrogen as the fuel. The *ELEKTRA* project will develop and demonstrate an electric river push boat powered by three 100 kW fuel cells and two 1025 kWh batteries and designed for operating between Berlin and Hamburg and Berlin and Stettin. The ship will operate 16 hours per day with a minimum daily range of 130 km, with an average speed of 8.5 km/h and a maximum speed of 10 km/h. Hydrogen will be supplied to the ship using swappable compressed hydrogen tanks. Keel laying is scheduled to occur in November, 2019.

NOW has completed a soon-to-be-published study on renewable energy for fuel cells in inland vessels. The study recommends clustering fuel cell powered ships by matching frequented shipping routes and port locations with renewable energy sources and cities with high emissions. Technologically, there were few gaps identified for polymer electrolyte membrane fuel cells (PEMFCs). The technology is at a high technical readiness level (TRL) and has been proven to work in marine environments. R&D is still needed for solid oxide fuel cells (SOFCs) and high-temperature PEM fuel cells (HT-PEMFCs) for maritime applications. Local and global availability of hydrogen and other alternative fuels is a challenge. Development of an interface to the refueling station and standardization of safe, low-cost refueling procedures are needed. The maritime application for fuel cells is challenging, and it will be harder to achieve economies of scale than in other traffic sectors, such as cars, buses, and heavy-duty trucks, due to the individual design and construction of ships and the fuel cell propulsion systems. There are also regulatory challenges. The timescale for codes and regulations is long. Experience with LNG suggests a time scale of approximately 13 years from initial proposal to getting guidelines from IMO.

Steffen Møller-Holst, Vice President Marketing, Hydrogen & Fuel Cell Technologies, SINTEF, Chair for Transport, Hydrogen-Europe, "Recent Development in Norway: H2 Ships, National Programme, and International Cooperation"

Norway can play a key role within the international hydrogen and fuel cell community as a large-scale producer of hydrogen from renewable and fossil resources, an exporter of hydrogen and hydrogen technology, and as an early user of hydrogen in transportation and industrial sectors. Norway is particularly interested in hydrogen for the maritime sector, as the maritime industry is the second largest industry in Norway and is responsible for a significant portion of Norway's GHG emissions. SO_X and NO_X emissions are also a concern in Norway's World Heritage fjords, which are frequently visited by cruise ships. Norway's goal is to cut emissions from domestic maritime traffic and fisheries by 50% by 2030. The Norwegian parliament has announced zero-emissions regulations for cruise ships in Norwegian fjords starting in 2026. Norway expects to launch its National Hydrogen Strategy in 2020.

Norway has been one of the earliest adopters of zero-emissions ships and has been looking at zero-emissions fishing boats, ferries, and cruise ships since 2000. Recent hydrogen and fuel cell projects include the *SeaShuttle* H2/FC container ship project, the *Wilhelmsen/Equinor* liquid hydrogen pilot tanker, the *Hjelmeland* LH2/battery project, and the Trondheim zero-emissions high-speed passenger boat. A recent study looked at hydrogen requirements for various Norwegian ports. The state of the art for liquid hydrogen storage capacity is NASA's cryogenic hydrogen storage tank, which is about 20 m in diameter and holds about 270 tons of hydrogen in a volume of 3,800 m^3. Norwegian ports would require hydrogen storage volumes ranging from 15,000 to 165,000 m^3, illustrating the need for substantially larger cryogenic hydrogen storage tanks.

Ferries are another market segment where hydrogen and fuel cells are being pursued, and Norway is interested in demonstrating the first hydrogen car ferry. There are 130 routes served by 200 ferries in Norway that transport 20 million vehicles and 40 million passengers annually. The Norwegian government requires low-emissions or zero-emissions technology in all tenders for public ferries when the technology is available. A fuel cell car ferry pilot project was initiated in 2017. The project has determined the optimal FC/battery/H2-storage capacity for various operation profiles, designed the fuel cell system, performed the safety and risk assessments, and conducted testing in SINTEF's laboratories. Ferry service and pilot operation are planned for 2021.

Port real estate is valuable, and hydrogen storage at the port will require a large footprint. The city of Trondheim is investigating sub-sea hydrogen storage in ports as an alternative option. The storage would be integrated with hydrogen production and a hydrogen refueling station to provide hydrogen for car ferries, high-speed passenger boats, buses, heavy-duty trucks and, potentially, rail. In addition to freeing space at the port, sub-sea storage has the added safety benefit of reducing risk if there is a leak.

The area around Trondheim is supported by five high-speed passenger boats which have the same emissions as 600 buses. A preliminary study to investigate the feasibility of hydrogen as a fuel for these passenger boats is underway to determine the hydrogen infrastructure required, including hydrogen supply and bunkering, and will include a techno-economic assessment of the vessel. A route between Trondheim and Kristiansund was chosen. The trip takes about 3.5 hours and the boats would consume about 2.5 tons of hydrogen per day. Concept development and testing began in 2019, with procurement of vessels scheduled for 2020 and with operations to begin in 2023.

SINTEF & Norges Teknisk-Naturvitenskapelige Universitet (NTNU) have started an Ocean Space Center initiative. The initiative will cover a wide range of concepts, designs, and approaches. Governmental grants were secured last week. Plans are for construction to start in 2022 and the Ocean Space Center to be completed by 2025.

Eiji Ohira, Director General of NEDO's Fuel Cell and Hydrogen Group, "Japan's Activity on Hydrogen Energy"

Japan is a leader in implementing fuel cell and hydrogen technology and has aggressive plans to increase the role of hydrogen and fuel cells in Japanese society. There are currently 274,000 fuel cell CHP units in use in Japan along with about 3,200 fuel cell cars and 18 fuel cell buses. Japan has 103 hydrogen refueling stations selling hydrogen at around $10/kg and produces about 200 tonnes of hydrogen per year domestically. By 2020, the plan calls for 1.4 million fuel cell CHP units to be installed, 160 hydrogen refueling stations, 40,000 fuel cell cars, and 100 fuel cell buses, with annual hydrogen production capacity increasing to 4,000 tonnes/year. By 2030 the goal is to have 800,000 fuel cell cars, over 1,000 fuel cell buses, and over 5 million fuel cell CHP units with more than 900 filling stations selling hydrogen at a cost of $3/kg. This goal corresponds to a hydrogen demand of about 300,000 tonnes/year, which is expected to be supplied by both domestic and imported hydrogen. The New Energy and Industrial Technology Development Organization (NEDO) has developed a strategic roadmap addressing hydrogen supply and use in the power and mobility sectors to help achieve these goals. Targets include increasing the efficiency of liquefaction by decreasing the energy required to liquefy hydrogen from 13.6 to 6 kWh/kg of hydrogen by the early 2020s and decreasing electrolyzer costs from 200,000¥/kW (~$1840/kW) today to 50,000 ¥/kW (~$460/kW) by 2030. Improvements are expected to be accomplished through a combination of increasing scale, R&D, and regulatory improvements. Main strategies for reducing fuel cell vehicle costs include reducing the amount of platinum in the fuel cell and the cost of the expensive carbon fiber used in the hydrogen storage tank. From 2030 to 2050, the plan calls for a transition to CO_2-free hydrogen. Recent activities are targeting scaling-up hydrogen production via electrolysis to make green hydrogen more affordable. A project to demonstrate a 10 MW electrolyzer using solar power is underway at the Fukishima Hydrogen Energy Research Field, with construction set to be completed by the end of 2019.

Japan's efforts in the maritime arena have been directed toward shipping hydrogen and hydrogen use at ports rather than using hydrogen as a fuel for ships. Importing hydrogen will require infrastructure for large-scale transport and delivery of hydrogen by ship. Japan is involved in an international project to demonstrate a liquid hydrogen tanker ship with boil-off rates of only 0.1%/day and a project to demonstrate loading and unloading of liquid hydrogen at the port. Japan has also been studying hydrogen generation and use at the ports including for use in forklifts and tractors. Other maritime related hydrogen and fuel cell activities in Japan include *Raicyo N*, a Tokyo University of Marine Science and Technology vessel that is a battery-fuel cell hybrid (12.6 m length, gross tonnage 9.1 tons) utilizing 145 kWh of battery storage with a 7 kW PEMFC, and *PHEB-3*, at Osaka City University, where a Toyota Mirai is integrated with a small vessel (2.6 tons, 9.6 meters long) with a rated speed of 8 knots.

International Panel Discussion — Moderator: Elizabeth Connelly, U.S. DOE-FCTO

The panelists were asked what tools they found most effective for promoting hydrogen and fuel cell technologies. The panelists indicated that vessel demonstrations have been very effective for promoting hydrogen and fuel cells, but that it is important to lay out infrastructure and solve hydrogen supply issues. Hydrogen supply and demand must be developed along with the vessel applications if progress is going to be sustainable.

The panelists were asked if any of the projects involving hydrogen production by electrolysis intend to utilize the oxygen produced. Norway has plans to utilize the oxygen and heat produced for fish farming to increase growth and the FCH JU noted that several of their projects have talked with the refining and chemical industries about using the co-product oxygen.

The panelists were asked about the potential for the hydrogen industry to produce enough hydrogen to help decarbonize steel or other large industries. The panelists agreed that the existing water electrolysis market is not capable of producing enough hydrogen, but the industry does believe that they can scale up to meet those needs. The electrolysis industry is working on increasing capacity. For example, Nel has already increased its production capacity at its Notodden plant from 25 to 40 MW in 2018 and is planning to increase their company-wide production capacity to 1 GW/year.

Lastly, the panelists were asked about ways to make collaborations between countries easier and increase acceptance of hydrogen and fuel cell technologies by international organizations, such as IMO. The panelists indicated it would be beneficial to approach IMO with examples of successful hydrogen and fuel cell technology demonstrations that experienced safe operations. There was some concern that there is not enough experience shipping liquid hydrogen to build on, as there was in the case of LNG.

Session III — Infrastructure Stakeholders Perspectives: Port Authorities

Mercedes de Juan, Valencia Port Foundation, Project Manager, "H2Ports: Implementing Fuel Cells and Hydrogen Technologies in Ports"

The Port of Valencia is one of the busiest seaports in Europe, handling 76.4 million tonnes of total traffic and 5.2 million TEU containers in 2018 while directly and indirectly providing 19,800 jobs. Reducing CO_2, NO_X, and other emissions is critical given the high population density around the port, with the long-term goal of achieving zero-emissions operation. Key to decarbonizing the port is understanding the energy demand and associated emissions based on the various types of equipment and machinery that support port activities. Analysis of port activities identified rubber-tired gantry (RTG) cranes, yard tractors, reach stackers and forklifts as the major fuel-consuming equipment within the port, with RTG cranes and yard tractors accounting for nearly 90% of the fuel consumed.

A multi-step approach for decarbonizing the port is being undertaken, with the initial phase targeting low carbon approaches using liquefied natural gas (LNG) as a fuel and electrification of the powertrain, followed by the introduction of hydrogen and fuel cell technologies for achieving zero-emissions operation. Demonstration projects for low carbon approaches have included LNG-fueled and fully electrical yard tractors, and advantages and disadvantages have been identified for both technologies compared to their diesel counterparts. LNG-terminal trucks are a low-carbon option with refueling times and equipment costs similar to diesel, and LNG is readily available. Fully electric terminal trucks are a zero-emissions option: Electricity prices are lower than diesel fuel on a comparable energy basis, but refueling (recharging) times and equipment costs are higher than diesel.

Valencia was the first port to demonstrate hydrogen technologies, such as a fuel cell-powered reach stacker and a yard tractor. While the demonstrations will be deployed in the coming years, other tasks requiring attention are certification of equipment, hydrogen distribution throughout the port, training of staff, development of emergency protocols, and permitting, as well as addressing public perceptions regarding the use of hydrogen for implementing hydrogen technologies throughout the port. Education and awareness of hydrogen technologies is still needed, since not all port operators are prepared for making the transition to zero-emissions technologies. Cooperative innovation between technology providers and end users, and demonstrating financial feasibility including providing short-payback periods, are critical for implementing zero-emissions technologies.

Bjoern Pistol, Hamburg Port Authority, Head of Port Estate and Maritime Affairs, "Hydrogen in the Port of Hamburg"

The Port of Hamburg, despite being 60 miles inland, is the third largest port in Europe, handling 135.1 million tonnes of seaborne cargo, 8.7 million TEU containers, 9.9 million tonnes of inland cargo, and servicing 880,000 cruise ship passengers in 2018. In terms of cargo handled, it is similar in size to the ports of Los Angeles and Long Beach. Nearly 2 million people live within a 10-mile radius of the port. Port activities are responsible for more than 50% of the city of Hamburg's NO_X emissions. Fostering sustainability is key for the future of the port, with the port community working to reduce CO_2, NO_X and other emissions. The current focus is on LNG as a means of lowering the carbon footprint of the port.

It is expected that future port expansion will require the deployment of zero-emissions technologies. The Hamburg Port Authority (HPA) is taking a supportive and conceptual role in implementing hydrogen and fuel cell technologies to achieve zero-emissions operation. HPA rents out areas within the port for hydrogen start-ups and assists in the approval process; however, there is currently a lack of demand. HPA supports hydrogen initiatives by participating in the International Association of Ports and Harbors (IAPH), Clean Marine Fuels, and local shipping industry working groups. Hydrogen is a niche product in Hamburg, with four hydrogen refueling stations currently operating and one under construction. A local refiner, H&R Ölwerke Schindler GmbH, is demonstrating a 5 MW electrolyzer to produce hydrogen for use in petroleum processing.

Several hydrogen and fuel cell projects are in the works, including a fuel cell and battery-powered *ELEKTRA* push boat expected to enter regular service in 2020 and a test of a hydrogen-fueled harbor tugboat, and Becker Marine Systems is considering retrofitting five trucks with hydrogen fuel cells. Due to its location, the port of Hamburg has the potential to be a site for hydrogen production and storage. Northern Germany has a surplus of electricity produced from offshore wind parks that could be used to produce hydrogen, which in conjunction with ports in the region, could serve as an energy logistics system of the future. The port of Hamburg is considering installing a Siemens 100 MW electrolyzer to produce hydrogen at the port. They are also considering methanol, ammonia, and synthetic fuels as alternative fuels.

Infrastructure Stakeholders Panel Discussion — Moderator: Charlie Myers, Oak Ridge National Laboratory

Panelists were asked to identify the biggest challenges for bringing fuel cell-powered equipment and hydrogen into port terminals. The panelists agreed that the lack of an established hydrogen market is the major impediment. Establishing the hydrogen infrastructure is costly and no one is currently willing to invest in developing the infrastructure. Panelists agreed that terminal trucks represent the best initial application for demonstrating hydrogen and fuel cell technology within the ports. Fuel cell powered stack lift trucks fueled by mobile hydrogen refueling stations are being planned for the near term. However, more port demonstrations are needed to build the knowledge base and to identify best practices to accelerate the adoption of hydrogen and fuel cells. Another possible mechanism that was identified to promote hydrogen and fuel cells at ports was utilizing qualitative criteria on zero emissions when leasing new land.

The panelists were asked about prevailing attitudes or perceptions of workers and unions for adopting hydrogen in ports. Both panelists agreed that safety is a major issue, and that while the workers initially have a negative attitude towards the adoption of hydrogen technologies in the ports, their attitude changes when they see positive outcomes.

Finally, the panelists were asked what type of data would be needed from demonstration projects and how are they attracting original equipment manufacturers (OEMs) to these projects. Key were trial projects for demonstrating safety and both technical and economic feasibility. Ports need to both provide a stable regulatory framework and create initiatives to attract OEMs to demonstrate their technologies within the ports, since the infrastructure capital costs are high. It was also suggested that having both port and shipping interests come together and define a unified interest would further advance adoption.

Session IV — Industrial Perspectives: Ship Systems Developer

Joe Pratt, Golden Gate Zero Emission Marine, CEO& CTO, "Considerations for On-Board Hydrogen Fuel Cells"

Golden Gate Zero Emission Marine is constructing the *Water-Go-Round*, a fuel cell-powered 84-passenger ferry for use in the San Francisco Bay area with financial support from the California Climate Investments (CCI) program. The ferry is powered by three 120 kW fuel cell racks with 100 kWh of battery storage. Hydrogen is stored in a series of 250 bar storage tanks located on the roof with a combined capacity of 242 kg, which is enough hydrogen for 1-2 days of operation. The cruising speed is 16 knots with a top speed of 22 knots.

Greater hydrogen vessel deployment will drive infrastructure deployment, build supply chains, and enable the development of design and safety standards. Initial deployment of a single or small fleet of hydrogen fuel cell vessels that service ports in proximity along a coast, termed a "cluster strategy," could justify a cost-effective hydrogen production facility. Commercial vessels could range in hydrogen consumption from about 1 tonne/day for a tug to 6 tonnes/day for a small container ship to 32 tonnes/day for a large ferry to 55 tonnes/day for a large container ship. The "cluster strategy" works well for shorter ranges and is viewed as being a more promising approach for driving the development of the hydrogen infrastructure than initial deployment of hydrogen fuel cell vessels for trans-oceanic service. Risk-based analyses need to be developed to enable ship builders and fuel cell-power system manufacturers to develop the best designs.

Paul Helland, NCE Maritime CleanTech, Project Manager Innovation, "FLAGSHIPS: Clean Waterborne Transport in Europe"

In Europe, the *FLAGSHIPS* project is a multi-team, 6.8 million euro project to demonstrate two hydrogen fuel cell powered vessels in commercial applications: a push-boat (tugboat) operating as a utility vessel on the Rhône River in Lyon, France, and a passenger and car ferry operating as part of the local public transport network in the Stavanger region of Norway. The two ships will have a combined fuel cell power capacity of 1 MW.

The goal of the project is to raise global awareness of the readiness level of hydrogen-powered, zero-emissions water transport. The project began in 2019, and the ships are expected to be operational beginning in 2021 for an 18-month trial period. Expected outcomes include stimulating the development of a hydrogen fueling infrastructure, supply chains for marine hydrogen fuel cell vessels, and approved practices for the safe operation of hydrogen-fueled ships.

Per Brinchmann, Wilh. Wilhelmsen Holding, Vice President –Special Projects, "Hydrogen As Seen From a Shipping Company"

The use of hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs) for providing hydrogen on board ships should be considered first, before considering carrying liquid hydrogen on board, given the higher volumetric densities of hydrogen carriers relative to liquid hydrogen. While the goal of using hydrogen is zero emissions, the use of "grey" hydrogen (hydrogen produced from non-renewables) should be considered first as a means of keeping costs down while the technologies for producing renewable "green" hydrogen at a cost comparable to "grey" hydrogen are developed. A major challenge is that overall energy efficiency is less than 25%, whether gaseous or liquid hydrogen, ammonia, or LOHCs. Technology developers need to think broadly and be open to alternatives. Ship autonomy could help combat cost increases associated with hydrogen and fuel cells on container feeder ships.

Ship Systems Developer Panel Discussion — Moderator: Laurence Grand Clément, PersEE

Panelists were asked to comment on the readiness level of current fuel cell technology for marine applications. The panelists agreed that while there is always room for improvement, current fuel cell technology is ready for use in marine applications. However, there have not been enough demonstrations of fuel cell and hydrogen technologies in marine applications to develop the benchmark standards required for broad commercialization of the technologies and to fully address all the regulatory challenges to ensure safety.

Panelists were asked to comment on what is needed to implement different types of hydrogen fuels (gaseous hydrogen, liquid hydrogen, liquid organic hydrogen carriers) in maritime applications. One of the challenges faced is matching maritime requirements with the available hydrogen production and infrastructure, since maritime applications will require large volumes of hydrogen. This also provides an opportunity, as greater demand in maritime applications could make hydrogen more favorable in this sector than LDVs. Carriers such as ammonia provide the benefit of greater volumetric density — the volumetric density of liquid ammonia is 1.5 times that of liquid hydrogen — but the design and development of a system to generate hydrogen from the carrier presents its own challenges and risks on board the ship.

Bundling alternative power solutions and fuel supplies as an alternative to promote the transition to maritime fuel cell applications was discussed. The high cost of hydrogen is problematic, and it needs to be significantly reduced for these approaches to be feasible.

Maintenance was also raised as an issue, with concerns about corrosion expressed. However, others expressed the opinion that maintenance could be reduced compared to diesel engines with fuel cells, as the fuel cell itself does not have moving parts.

Session V — Industrial Perspectives: Power Systems Developers

Klaus Vänskä, Global Business Development Manager, ABB Marine & Ports, "Fuel Cells in Integrated Power System of Marine Vessel"

It is important to understand that marine vessels are individuals, with each vessel's design tailored for its specific operation. When designing any vessel one needs to consider: the type and size of vessel; the planned operation profile which determines the power system requirements; the codes, standards and regulatory requirements governing the design and operation of the vessel; the need for redundancy in the design; and normal and emergency operations, including requirements for the crew and, if applicable, passengers.

A conceptual design for a fuel cell powertrain was presented. It was noted that the integration of the fuel cell into the electrical infrastructure is not "one solution fits all." Some of the key challenges that need to be addressed are the nonlinear voltage-current relationship of fuel cells, which requires power conditioning. Fuel cells can produce high currents at low voltages, which leads to oversizing the system to withstand no-load voltages. Tighter power control integration compared to traditional system designs is required, and the ripple control method of power electronics may negatively impact the fuel cell lifetime. One benefit of fuel cell systems on cruise ships is that they are a valuable source of waste heat and water for doing laundry, washing dishes, etc.

Peter Brooks, Global Marine Account Manager, BAE Systems, "Get to Zero — Getting Transit Operators to Zero Emissions, No Matter Where They Are Today"

BAE Systems is a leading provider of power and propulsion systems and has been actively involved in fuel cell-powered bus and ferry boat demonstrations.

It views hydrogen availability and storage as two of the major challenges facing hydrogen and fuel cell technologies. Producing hydrogen at the point of consumption and using cost-effective electrolysis technology are keys to addressing availability. There are port applications, such as rubber-tired gantry (RTG) cranes, that offer relatively easy demonstration opportunities. Other port and marine opportunities can be addressed with step changes, as opposed to big leaps, when expanding markets. For example, BAE installed two bus systems to power a marine vessel.

Renaud Cornu, Senior Market Leader, GE Power Conversion, General Electric, "Hydrogen Fuel Cell Systems for Powering Zero-Emission Cruise Vessels!"

Action is needed for IMO to achieve a 50% reduction in CO_2 emissions by 2050, with zero emissions targeted by the end of the century. Although batteries are an option, their weight and charging requirements at ports are major challenges for marine power. Fuel cell-battery hybrid power systems represent a feasible option for large ships. The availability of low-cost electricity coupled with electrolysis for low-cost hydrogen production could make fuel cell systems feasible. GE and Nedstack have formed a partnership to develop a 2 MWe PEMFC power installation (FCPI). The FCPI is designed to operate on pure hydrogen or reformate for 20,000 hours. It is a turnkey skid-mounted or containerized unit optimized for ease of integration into hybridized electrical propulsion systems with advanced control features for monitoring lifetime, efficiency, and predictive maintenance.

Stefano Cantarut, Segment Manager Cruise and Ferry, Wärtsilä, "An Economically Feasible Approach Toward a Sustainable Future"

In the maritime industry, total cost of ownership (TCO) is the key factor for decision-making in the financial world, with a 20-year payback period for large marine applications. When the TCO of fuel cells and diesel technologies are compared, fuel cells are 10-30 times more expensive than reciprocating engines with less than one-tenth the expected lifetime, resulting in a significantly higher TCO even if the price of hydrogen were to decrease by at least 75% over the 20-year period. PEMFCs need a 35,000 hour lifetime to compete with marine diesel engines. To set a path towards a sustainable, economically feasible future will require a series of small steps, such as operating reciprocating engines on hydrogen (low capital expense [CAPEX] but high operating expense [OPEX]) or employing solid oxide fuel cells (SOFC) operating on LNG (high CAPEX but low OPEX), instead of going directly to hydrogen-fueled fuel cell systems (high CAPEX and OPEX). Designs that incorporate flexible system architectures that include multi-fuel, multi-technologies optimized into an integrated system will be key.

Power Systems Developers Panel Discussion — Moderator: Charles Myers, Oak Ridge National Laboratory

Panelists were asked to comment on the biggest technical and economic challenges for hydrogen and fuel cell technologies in marine applications. The major challenges centered around hydrogen — lack of infrastructure, lack of reliable availability, high cost, the lack of a regulatory framework to guide technology developers, and design constraints for on-board storage.

Panelists were asked to comment on what R&D government agencies should fund and what their priorities should be. The consensus was that governments should focus their priorities on developing hydrogen infrastructure, including production and storage, and regulations required for safe use and handling of hydrogen in ports and on ships. It was noted that the current business models are not profitable and that there is a need for more integrated demonstration projects (e.g., trucks, vessels, and other applications) to further development, reduce the risk, and encourage adoption by ship owners.

Panelists were asked to comment on what could be done to ensure safe hydrogen fuel ship operations. All panelists agreed that the lack of regulations for storage, handling, and use of hydrogen on board ships is a major hurdle for ship designers. It was suggested that on-board reforming of fossil fuels to produce hydrogen could be one option for promoting early adoption of fuel cell technologies, even though CO_2 emissions would still be an issue.

Session VI — Industrial Perspectives: Vehicle and Fuel Cell Manufacturers

Gus Block, Manager of Business Development, Hyster-Yale/Nuvera, "Making Things Better: Hydrogen Fuel Cells at Shipping Ports"

Ships transport 95% of the world's goods. Some shipping companies, such as Maersk, have declared their fleet will be carbon-neutral by 2050. For ports, reducing emissions and health risks while remaining competitive and financially sustainable, supporting the workforce, and building strong partnerships with stakeholders are the guiding principles for clean air action plans. Lithium ion batteries and fuel cells are two options for achieving zero-emissions power for the heavy-duty vehicles and crafts that move goods throughout ports. Hydrogen fuel cells offer the benefits of higher efficiency, less maintenance, and reduced compliance costs compared to diesels. While fuel cells should be able to meet all the requirements for all port heavy-duty applications, there is not "one size fits all" for fuel cell or batteries. To maximize efficiency through electrification will require diversity in applications for battery and fuel cell tailored truck configurations, optimizing the size of batteries and hydrogen systems based on a charging and refill strategy, and smart energy recovery.

Brian Lindgren, Director of Research & Development, Kenworth, "Kenworth Electrified Powertrain"

Kenworth is conducting demonstration projects that involve battery-electric power drives for trucks and tractors with either a compressed natural gas (CNG) engine or a hydrogen fuel cell for range extending. A 100 kWh battery provides a range of only 30 miles fully loaded, so batteries alone are not a good option. One project, a tractor, used a fuel cell range extender consisting of two Toyota Mirai fuel cells and 25 kg of on-board hydrogen storage (equivalent to 22 gallons of diesel) with a target zero-emissions range of 300+ miles.

Among the challenges facing hydrogen fuel cell powered trucks are the high cost of the fuel cell, the establishment of the supply base, the development of the fueling infrastructure, fuel cell systems capable of continuous high power on long grades, the complex cooling and electrical architectures required, and driver interface needs. Showing a positive return on investment (ROI) is also critical for the trucking industry to encourage adoption.

Joerg Ferchau, General Manager, Electrified Systems, Cummins, "Cummins Perspective on Fuel Cells"

Cummins is actively exploring PEMFCs and SOFCs for on-highway power applications and other applications, such as data centers. The advantages of PEMFCs include operating at lower temperatures (65°C-90°C), instantaneous startup and transient power response, zero emissions, and lower cost. The disadvantages include the strict hydrogen purity requirement and the high cost of hydrogen. Additional issues for PEMFCs include water management, humidification, pressure levels, and hydrogen storage and availability. The advantages of SOFCs include a wider range of fuel choices, considerably lower fuel costs, and slightly higher efficiency. The disadvantages include higher operating temperatures (600°C-900°C), NO_X and CO emissions (and CO_2 emissions if carbon-based fuels are used), longer startup times and slow transient response, and higher costs. Additional issues for SOFCs include brittle ceramics and oxidation of the anode. Among Cummins' current fuel cell projects are a fuel cell bus demonstration project in Costa Rica and a project with Microsoft for fuel cells operating on natural gas for powering data centers.

The four keys to the adoption of fuel cells are: (1) technologies that are efficient, durable, and have cold start capability and rapid transient response; (2) support by regulatory drivers such as zero carbon zones and financial subsidies to encourage initial investments; (3) hydrogen infrastructure that is readily available; and (4) favorable total cost of ownership based on the technology and fuel costs, the ability to store sufficient hydrogen on-board, and the cost of establishing the refueling stations.

Ryan Sookhoo, Director of New Initiatives, Hydrogenics, "The Energy Shift is Underway"

Hydrogenics is a fuel cell and electrolyzer manufacturer. Their fuel cell systems have been demonstrated or deployed in applications such as buses, trains, and trucks. Their fuel cell system marine demonstration projects include propulsion power for the *Zero/V* and *Water-Go-Round* vessels, testing and modeling of main propulsion (SINTEF and ABB) and dockside stationary power (see presentation by Lennie Klebanoff in Session VIII).

From their perspective, the fuel cell industry is still innovating the technology, and the time is right for demonstrating the safety and conducting risk analysis for fuel cell systems — but too early for regulatory requirements. For marine applications, a key question is how to safely store hydrogen below deck. Larger demonstration projects are required to address issues regarding the handling of the large amounts of hydrogen that will be needed at this scale and to develop methods for handling and utilizing the waste heat generated. Protocols will need to be established for delivery of large quantities of hydrogen in terms of availability, cost, and production.

Alan Mace, Market Manager, Ballard Marine Center of Excellence, Ballard, "Value of Fuel Cells and Hydrogen in Marine Applications"

Ballard is a fuel cell manufacturer actively participating in numerous fuel cell demonstration projects for portside operations, such as drayage and port yard trucks, and shipside operations, such as ferries, river boats, cruise ships and other high-power vessels. Ballard sees the benefit of fuel cells and hydrogen as a distributed power generation solution for marine applications in terms of its scalability, its high efficiency and reliability, low maintenance, and long lifetime, with small vessels being the initial application for vessels. While fuel cells offer the promise of lower maintenance, balance of plant (BOP) components have kept fuel cells from achieving lower maintenance than combustion systems. Accelerating the deployment of fuel cell technologies in maritime applications will require more hands-on experience with hybrid propulsion systems, increased availability of balance of plant components for marine fuel cell applications, hydrogen availability at commercial scale, and development of codes and standards for hydrogen fuel cell vessels. Ballard believes small vessels, such as small ferries, are the preferred platform for the initial deployments of fuel cells in maritime. Current prices, in for example, today's bus systems, are about $1/W. Ultimately, Ballard's target is $0.1-0.2/W.

Johan Burgen, Business Manager Marine, PowerCell Sweden, "A Paradigm Shift for Maritime"

As a European company, PowerCell Sweden noted that the European Union recently agreed to reduce CO_2 emissions from new trucks and buses by 30% by 2030 compared to the 2019 level. IMO is targeting 50% GHG reduction by 2050 compared to 2008 (based on total tonnage hauled) and is evaluating the potential to reduce GHG emissions by 40% by 2030 and 70% by 2050.

PowerCell develops fuel cell stacks and systems for marine applications with a test facility in Gothenburg harbor. Their marine demonstrations include the *Aranda* research vessel, which uses two 82.5 kW fuel cell powertrains, and the RoPax ferry concept project, which is looking at energy balancing using fuel cells and batteries. Electrofuels, such as "green hydrogen" and hydrogen carriers that utilize renewable electricity to generate hydrogen by electrolysis, are an area of interest to PowerCell.

Among the challenges fuel cells face for maritime applications are bridging the cost through government support (it was noted that Norway has provided funding for 12 marine fuel cell projects), bridging the gap between technology maturity and commercial expectations, and making hydrogen available at a low cost in large quantities.

Roel Van de Pas, CCO, Nedstack, "Let's Navigate Towards Zero-Emission Shipping!"

Nedstack is a leader in the high-power PEMFC market, specializing in containerized power plants for high-power (MW) applications. Its technology is already deployed at several ports including Groningen Seaport, Port of Antwerp, and Yusob Kantang Port (YKP) in Thailand. Nedstack fuel cell technology has been deployed in *NemoH2*, a passenger canal boat that uses two 40 kWe fuel cells and stores 24 kg of H_2 on board at 35 Mpa, with a capacity of 88 crew and guests. Recently, Nedstack and GE announced a partnership to develop multi-MW fuel cell systems for cruise vessels.

There are major challenges that hydrogen and fuel cells must overcome for widespread deployment in maritime applications. It must be recognized that maritime applications are vastly different from automotive applications and that the fuel cell supply chain that has evolved for automotive applications is not compatible with maritime applications. Maritime applications require fuel cell systems that produce higher power, are more robust, and last longer. There is a need to quantify and then communicate the market potential for maritime hydrogen and fuel cell technologies to motivate component suppliers.

Port authorities are law makers, and regulations should be invoked for maritime fuel cell projects that are aimed at creating instructional freedom to act. There is a need for policies that encourage flag states to provide waivers for hydrogen and fuel cell technologies and port authorities to create innovation spaces within their ports.

There needs to be a coordinated effort between ship owners and ports for implementing fuel cell and hydrogen technologies. There is the perception that fuel cell and hydrogen technologies are experimental, unregulated, and uncertain, and, therefore ship owners are waiting for the ports to provide the infrastructure and vice versa. There is a need to develop a mechanism for coordinating the ship owners and port authorities and operators to facilitate the transition to hydrogen and fuel cell technologies.

There are different options for achieving zero emissions within the ports, and there is no clear understanding of the most promising energy systems for achieving the goal. There needs to be a better understanding of the most and least promising energy systems options, including fuel bunkering, to guide future planning by port authority decision makers.

IMO and the maritime industry use different definitions for scope, power rating, etc. than those defined in the IEC 62282 standards. There is a need to develop standard definitions that enable the fuel cell and hydrogen adopters in the maritime industry to make better-informed decisions.

Demonstration projects often bring to light new safety issues that need to be addressed related to fuel cell installations and hydrogen storage and distribution within the ports. There is the need for standardized safety codes and goals.

The current reference standards for verifying fuel cell systems for maritime applications, IEC-62292-3, does not address the sea-worthiness of fuel cell power systems — to withstand cavitation effects, rough seas, etc. There is a need for demonstration programs to establish standards to address the operating environments unique to the maritime industry.

Vehicle and Fuel Cell Manufacturers Panel Discussion — Moderator: Dimitrios Papageorgopoulos, U.S. DOE- FCTO

Panelists were asked to identify the short- or long-term challenges that need to be overcome and the low-hanging-fruit opportunities. Reducing pollution in ports is a common goal across all ports, with portside activities being a major contributor. Deploying fuel cells to power equipment used in portside applications and for drayage and short haul trucks could be a short-term success; however, the higher cost of hydrogen compared to diesel makes it difficult to justify the transition. Diesel engines power the vast majority of vessels used in inland waters and rivers. Although the power demands for these vessels are less than 1 MW, fuel cell technology is too expensive for the vessel owners to make the switch to fuel cell power systems.

The cost of "green" hydrogen was considered a long-term challenge. Panelists were asked what can be done to reduce the cost of hydrogen and who is responsible for driving the cost down. It was noted that the price of hydrogen is not driven solely by production costs and that the demand for hydrogen by users outside of the fuel cell industry is considerably greater. Treating hydrogen as a commodity and developing a hydrogen commodities market coupled with incentivized production could lead to lower costs. Producing hydrogen using excess grid capacity was identified as an option for lowering hydrogen production costs. Infrastructure investments for bulk delivery and storage also need to be in place to lower the cost. The costs of fuel cells were also discussed. While some of the fuel cell manufacturing is automated, there is still considerable manual handling of parts, which adds to costs. This will likely continue for the foreseeable future, as there are concerns that further automation may impact quality.

Panelists were asked to express their thoughts on the use of hydrogen carriers as an alternative to using hydrogen. The panelists agreed that liquid fuels are attractive in terms of easing safety concerns and issues with regulations, codes, and standards, bunkering requirements, and storage portside. However, concerns were expressed about using hydrogen carriers for technologies that require high-purity hydrogen and challenges for fuel reforming on board vehicles.

Panelists were asked what specific R&D government agencies should be funding and what the priority needs would be. There was no consensus, with responses ranging from enabling change at the local level, including developing a single actor responsible for raising funding and implementing infrastructure development, to funding R&D to scale up the technology to accelerate early adoption.

Session VII — Regulations, Codes and Standards

Laurence Grand Clément, CEO, Persee, "From MARANDA to FLAGSHIPS, RCS Learnings"

The *MARANDA* project is the first hydrogen fuel cell deep-sea vessel funded by FCH JU. The 165 kW fuel cell-battery hybrid powertrain will be used for dynamic positioning of the *Aranda* research vessel. Hydrogen is stored on board using a 350-bar hydrogen storage container that could be removed from the vessel, transported on the roads and refilled at any 350-bar hydrogen refueling station. Getting ship approval was a more lengthy and costly process than anticipated.

For *MARANDA*, the fuel cell is not critical to ship operation, as it only supports dynamic positioning. However, there were still difficulties with obtaining ship approval. Among the issues were those related to material fitness, where marine codes indicate the use of plastics is to be limited (as flammable mass) but PEMFCs utilize a considerable amount of plastic. There was issue with code compatibility between on-road codes for hydrogen transport and hydrogen for use on a ship. For example, the swappable storage system needed to meet codes and standards for on-road transport and for use on board the ship was not consistent, and it was difficult to find a supplier who was willing to address both code requirements simultaneously. In other instances, codes and standards were not in place, which led to individual interpretation for the application, making it difficult for manufacturers and suppliers. The difficulties with regulations, codes, and standards for *MARANDA*, where the fuel cell system is a supplemental system and not integral to the operation of the ship, suggests that getting regulatory approval of a ship with a fuel cell powertrain would be more difficult. Areas of concern include hydrogen refueling standards, refueling station permitting, and demonstration of safety measure effectiveness in new maritime applications.

The development of LNG-fueled ships was suggested as a roadmap for how to develop hydrogen fuel cell ships. For LNG-fueled ships, the timeframe for getting codes and standards in place was approximately 15 to 20 years. The timeframe for developing and adopting codes and standards for hydrogen and fuel cells needs to be shorter. However, other alternative fuels to hydrogen are being considered, and there is competition both in the market and for time on the schedules of the appropriate regulating agencies. Collaboration and coordination across other vehicles and other non-marine applications must be increased to accelerate the development of hydrogen and fuel cell regulations, codes, and standards if hydrogen and fuel cells are to be used in the maritime industry.

Olav Hansen, Senior Principal Risk Management Consultant, Lloyd's Register, "Regulations, Codes and Standards"

Lloyd's Register (LR) is involved in hydrogen risk-based design and R&D support for hydrogen and fuel cells for maritime applications for several projects in the EU and Norway, including *HyDime*, *HySeas III*, *Hydroville*, and the Brodrene fast ferry concept. LR has expertise in hydrogen safety for other applications including hydrogen production plants, hydrogen refueling stations, and hydrogen for industrial uses in various industries such as metals and ammonia production.

For low-flashpoint fuels, like hydrogen, IGF codes apply. However, there are no prescriptive rules for hydrogen in the IGF codes, which means it needs to follow an alternative design approach that is risk-based. Hydrogen properties are unique, and hydrogen risks are different from those for LNG. Hydrogen has a much broader flammability range, from 4% to 75%, a higher flame velocity, and a lower ignition energy. It is recommended that hydrogen's unique properties need to be considered, and it should not be treated "just like LNG," with the need for a risk-based assessment of hydrogen to be performed. One should assume there will be a worst-case release that will ignite at the worst moment, and one should apply the IGF-3.2.18 requirement that states "a single failure in a technical system or component shall not lead to an unsafe or unreliable situation." Quantitative criteria such as fatalities per 100 million work hours (FAR typical average is 1.0) or fatalities per billion passenger per km (NMA criterion 2002: 1) are useful in determining the risk.

Some of the main risks with a hydrogen vessel are related to hydrogen storage and bunkering. The risks vary with design, but risk management can include optimizing the boil-off gas vent mast or emergency venting to limit falling liquid hydrogen or high-pressure blasts and limiting simultaneous operations at the vessel and in the harbor when refueling. Challenges appear greater for cryogenic and high-pressure storage than for low-pressure uses, such as in the fuel cell room. Safe solutions for hydrogen storage below deck are likely required for wider commercial implementation.

Tools exist for helping evaluate the consequences of a liquid hydrogen release. Modeling provides a more cost-effective method than experiments. Modeling can help determine sonic jet hazard distances and cloud sizes, concentration profiles inside ventilated spaces, ignition probability, etc. Computational fluid dynamics (CFD) modeling can be used to look at liquid hydrogen release scenarios and to help determine bunkering distances, vent mast and total confined space (TCS) releases, etc. Most of the relevant physics can be modeled. Risk modelling should be performed early in the design phase, so that it is still relatively painless to change designs if an issue is discovered.

There is little global experience for hydrogen use in maritime applications, and prescriptive rules could kill innovation and be non-optimal for most designs. A risk-based guidance is recommended. Bunkering risk studies are needed and lessons learned by doing studies using an alternative design approach will help increase knowledge and understanding of hydrogen safety.

Anthony Teo, Technology and LNG Business Development Director, DNV-GL, "DNV-GL Perspective — Regulations, Codes, and Standards"

Maritime is DNV-GL's core industry, with a strong presence in all ship segments and 200 maritime offices across the world, and insight into alternative fuels and zero-emissions ships. There are currently over 300 zero-emissions ships with batteries in operation or under construction. The majority of these are ferries, with 100 in operation and 75 under construction.

Most classification societies have established rules covering fuel cells and to some extent low flashpoint liquids. DNV-GL offers two class notations for fuel cells: FC (power), for ships where the fuel cells are used for essential, important, or emergency services, and FC (safety) where fuel cells are not used for essential, important, or emergency services. DNV-GL does not have fuel-specific requirements for hydrogen, and no prescriptive hydrogen requirements are available. The use of hydrogen falls under the IGF Code (Part A) that requires an "Alternative Design" approach be followed.

In the alternative design process the safety equivalence of the alternative design must be demonstrated by a risk-based approach. This should include a preliminary analysis identifying hazards and failure scenarios, a quantitative analysis of selected scenarios and comparison to conventional design, and a report of the assessment.

DNV-GL has both computational tools and the major hazards research and testing facility that enables them to develop and validate safety models. An example was provided showing a hydrogen gas leak dispersion in a building. Due to the different kinds of fuel cells, the procedures and requirements for approval and certification of these systems will need to be developed together with the manufacturers. DNV-GL has started the Maritime Hydrogen Safety Joint Development Project (*MARHYSAFE*) to help develop the knowledge required for safe and reliable on-board hydrogen storage, bunkering and use of hydrogen in shipping. Partners include the Norwegian Maritime Authority, Norwegian Public Roads Administration, Norwegian Defence Materiel Agency, Standards Council of Canada, Air Liquide, Scandines, RCCL, Equinor, and others.

Koichi Nishifuji, Manager of Technical Solution Department, ClassNK, "Liquified Hydrogen Carrier Pilot Project in Japan"

Nippon Kaiji Kyokai (ClassNK) is an international classification society in Japan. They have about 20% share of the world classification of cargo vessels by gross tonnage, with about 130 sites in the world for ship surveys. ClassNK has been providing guidelines for safety requirements for the design and construction of liquefied hydrogen carrier vessels and for fuel cell systems on board ships, based on the results of R&D and discussions with the IMO. Recently, ClassNK has been involved in *HySTRA* (Hydrogen Energy Supply-Chain Technology Research Association) a liquid hydrogen carrier pilot project in Japan. The liquid hydrogen carrier is to provide approximately 1250 m^3 of liquid hydrogen storage in a type C tank. The rules for liquid hydrogen carriers fall under application of IGC code for products not listed in Chapter 19, which states that "the administration and the port administration involved in such carriage shall establish a tripartite agreement based on a provisional assessment and lay down preliminary suitable conditions of carriage based on the principles of the Code." In 2014, ClassNK received approval to develop interim recommendations for carriage of liquefied hydrogen in bulk as proposed by Australia and Japan. In September 2016, draft interim recommendations were endorsed and, in November 2016, the interim recommendations for carriage of liquid hydrogen in bulk were adopted by the IMO. The application for the interim recommendation to the pilot liquid hydrogen carrier was agreed upon by Australia and Japan in January 2017.

The design basis for the pilot liquid hydrogen carrier considered the following hazards related to hydrogen: low temperature hazard, hydrogen embrittlement, permeability, low density and high diffusivity, ignitability, high pressure hazard, health hazard, and a wide range of flammable limits. To qualify the novel technology, a cyclic process of setting performance targets, performing technology assessments to analyze how to assure the functions, performing a risk assessment to identify failure modes and risks, and planning and carrying out a qualification, was followed. This process included experiments demonstrating venting of liquid hydrogen for verification and validation of CFD and physical effects modeling software. ClassNK re-structured and supplemented the interim guidelines with additional requirements. Items to be considered in the assessments include predicting the venting scenario and procedures, including prevention and mitigation of vent fires to flashback and explosion, isolation philosophy and comprehensive hydrogen fire control, and safety measures in case of blackout on the ship.

Safe operation of the liquid hydrogen carrier will be verified in the trials/tests phase for several months in 2020. The results of these studies will contribute to further development of commercial liquid hydrogen carriers and amendments to the IGC Code and IGF Code to include safety requirements intended for commercial hydrogen carriers and for us of hydrogen as ship fuel.

LCDR Frank Strom, USCG Sector San Francisco, Chief, Inspection Division, "Implementation of International Standards for Maritime Hydrogen Fuel Cells"

There has been recent interest in using hydrogen and fuel cells for vessel power and propulsion. In the U.S., a project has been undertaken to develop a hydrogen-powered passenger ferry. The applicable codes and standards for hydrogen-fueled ships are being developed. In 2004, development of international standards for gas-fueled ships was proposed. Interim guidelines were adopted in June 2009, and IGF code adopted in 2015, which entered into force in 2017. The codes included considerations for safety of the fuel system, including tank placement, tank and piping requirements, gas detection system certification, fire detection, and installed fire-fighting systems. While the code did not specifically address hydrogen as a fuel, hydrogen is allowed under options for alternative design. The alternative design route requires a risk assessment be performed per the IGF Code. For U.S. federal regulations, one must establish equivalency to design standards in Title 46, Code of Federal Regulations — Shipping. The equivalency is determined on a design basis and is vessel-specific.

Panel Discussion — Moderator: Lionel Boillot, FCH JU

The panel discussion focused on what can be done to speed up or facilitate hydrogen fuel for maritime applications without implementing prescriptive codes. Panel members indicated that there is no one-size-fits-all solution since each vessel is typically custom-built, not mass produced. There is some push to get regulatory codes and standards in place soon; however, panel participants indicated there is not enough accumulated experience and all the facts and data needed are not available. Prescriptive codes too early could stifle development, while an accident will slow things down considerably. Sharing knowledge and blending public and private safety-related efforts may help. The IMO Sub-Committee on Carriage of Cargoes and Containers discussed hydrogen-related topics at its meeting in September 2019, including design principles for fuel cell power installations and alternative metallic materials for cryogenic service in ships. Other organizations, such as the Society of International Gas Tanker and Terminal Operators (SIGTTO), are looking at marine hydrogen issues. Unique experimental facilities are needed for the safety experiments. Getting hydrogen included in the Society for Gaseous Marine Fuel (SGMF) may help since they are now focused on LNG. Finally, the question of crew certification and licensing requirements was brought up, since ship crews and shore personnel will need to be trained to handle hydrogen and hydrogen-related emergencies.

Session VIII — Recent Research and Analyses

Lennie Klebanoff, Technology Staff, Sandia National Laboratories, "Development of a Containerized 100 kW Fuel Cell System for Maritime Applications"

U.S. DOE, MARAD, Sandia National Laboratories (SNL), Hydrogenics, the U.S. Coast Guard (USCG) and others have partnered to develop and demonstrate a 100 kW fuel cell system for the marine environment that will reduce emissions and be a viable alternative to diesel-based systems. The goals of the project were to demonstrate that variable loads favor fuel cells over diesel engines in terms of energy efficiency and to lower the technology risk of port fuel cell deployments by gathering performance data of hydrogen PEMFCs in the marine environment. Initial deployment was in Honolulu, HI, where the system was used to replace a diesel generator that powered up to 10 refrigerated containers (reefers) from August 2015 to June 2016. Feedback from the initial deployment indicated users did not like that they could not tell what the unit was doing. Upgrades included an improved user interface to indicate fuel cell operational status. The next deployment will be at Scripps Institution of Oceanography. Scripps plans to use the containerized system at the Nimitz Marine Facility in San Diego to supply shore power to its research vessel, the *Robert Gordon Sproul*. The *Sproul* requires 480 VAC three-phase shore power 24 hours per day while in port. The ship is generally in port for approximately a week at a time, and then out to sea for 2-3 days. The average power requirement is 30 kW, with peak power as high as 50 kW during the day and evening loads of around 15 kW, which can be met by the containerized fuel cell system. The Nimitz Marine Facility location is fully compliant with relevant NFPA and hydrogen supplier requirements for hydrogen storage and delivery. Finding sites compliant with all the NFPA requirements and additional requirements from the site's insurance carriers can be difficult.

Nico Bouwkamp, Technical Program Manager, California Fuel Cell Partnership, "Fueling Analysis"

Refueling patterns vary based on the type of vehicle and application. For short-haul drayage trucks and line-haul trucks refueling at the fleet site or yard, the number of vehicles using a refueling station per day will depend on the fleet size. One would expect peak times for refueling at beginning and end of the day, resulting in back-to-back fueling. The acceptable refueling time is 10-15 minutes per fueling. For current diesel technology, the dispenser maximum flow rate is 22 to 63 gallons/minute (63 gallons/minute rate requires dual hoses). For short-haul drayage and line-haul trucks using a truck stop for refueling, truck stops generally have 8 to 10 dispensers. The refueling time depends on the truck operator's schedule and the peak times at the truck stop. Hydrogen refueling for buses and heavy-duty trucks is currently at 350 bar with rates of 120 grams per second (g/s) requiring 5-10 minutes to fill 30-60 kg of hydrogen. While 700 bar storage and refueling is used for light duty vehicles, it is still in development stage for commercial truck applications. Target commercial truck refueling rates for 700 bar range from 200-300 g/s, corresponding to 10-15 minutes to fill 60-100 kg of hydrogen. Current SAE J2600 standards are limited to 60 g/s (3.6 kg/min). Liquid hydrogen delivery can provide higher refueling rates; however, there is limited to no commercial development of liquid hydrogen or cryo-compressed hydrogen refueling. Maritime vessel fuel capacity and refueling times vary substantially, depending on the vessel. Commercial vessels, such as small tug boats, carry between 1,500 to 25,000 gallons of fuel, while larger vessels, such as container ships, cruise ships, and ocean-going barges can carry from 1 to 10 million gallons of fuel. There is a question of how fast these maritime vessels can be filled if they were converted to hydrogen. Hydrogen plants or retail station for transfer of hydrogen from liquid hydrogen currently use 500 bar rates for fueling tube trailers. Fueling of NASA's space shuttle is believed to have taken days, and months to fill the liquid hydrogen storage tanks used to store that hydrogen. For maritime, we would require similar amounts but with back-to-back refueling. The technology, codes and standards, and infrastructure to do this need to be developed.

Lindsay Steele, Senior Research Scientist, Pacific Northwest National Laboratory, "Hydrogen Fuel Cell Applications in Ports: Feasibility Study at Multiple U.S. Ports"

Pacific Northwest National Laboratory (PNNL) has performed a feasibility study of fuel cell applications at multiple ports nationwide. The study collected information on the inventory of equipment used by port and terminal tenants, associated daily usage, and fuel consumption. Port-side and ship-side uses of hydrogen and fuel cells were investigated. Potential port-side usage included rubber tire gantry cranes, straddle carriers, container handlers, container reach tackers, yard tractors, and drayage trucks. Shipside applications included harbor craft, ferries, ocean going vessels, and ship-to-shore power for hotels, reefers, pumps, and lighting. Information was gathered from port emissions inventory reports, port authorities and terminal operators, and satellite/aerial image analysis.

Port fuel usage was estimated from EPA emissions data and known fuel consumption rates. CO_2 emissions were converted to diesel consumption using the U.S EIA emissions coefficient of 22.4 lb. of CO_2 released per gallon of diesel. This value was used to estimate hydrogen demand using the conversion that one gallon of low sulfur diesel is equivalent to 1.126 kg of hydrogen on an equal energy basis. The port terminal equipment demands were estimated at 56 kg/day for a container handler, 45 kg/day for an RTG crane, 46 kg/day for a straddle carrier, 33 kg/day for a reach stacker, 21 kg/day for a yard tractor, and 5 kg/day for a forklift. For the Port of Seattle Tacoma/Northwest Seaport Alliance (NWSPA), the total hydrogen demand estimated from the emissions inventory was approximately 53,000 kg of hydrogen/day. Potential hydrogen demand at the larger ports, such as the Ports of Long Beach and LA were estimated at approximately 465,000 kg/day and 349,000 kg/day, respectively.

The total potential hydrogen demand for U.S ports (19 ports) was estimated to be over 500,000 tonnes per year, assuming that the entire cargo-related vehicle fleet at these ports was converted to hydrogen fuel cell technologies. In comparison, about 10 million tonnes of hydrogen was produced in the U.S. in 2018, mostly for petroleum refining and ammonia production. The highest port-side demand by equipment type would be from drayage trucks. The second highest demand is from yard tractors and container-handling equipment. The high potential hydrogen demand at ports suggests that hydrogen pipelines are justified for hydrogen delivery and would be preferred over truck delivery even for the lowest adoption rates. To optimize hydrogen utilization and lower hydrogen fuel costs, adoption rates should be matched to hydrogen generation capacity growth.

Lionel Boillot, Project Manager, FCH JU, "EMSA Study Fuel Cells in Shipping and TCO Considerations"

The European Maritime Safety Agency (EMSA) performed a study on the use of fuel cells in shipping to determine which technologies show the most promise, identify regulatory gaps, review existing standards, and perform safety assessments on the three most promising technologies. The EMSA reviewed recent maritime fuel cell projects with various applications ranging from APUs to main propulsion systems, for vessels spanning small passenger ships to large cargo vessels. These also included various types of fuel cells, including PEMFC, HT-PEMFC, molten carbonate fuel cell (MCFC) and SOFC, and fuels ranging from diesel to hydrogen. For example, *E4Ships-SchIBZ* (SOFC), *MC-WAP* (MCFC), and *U.S. SSFC* (PEM and MCFC) used diesel as the fuel; *FellowSHIP* (MCFC) and *FELICITAS* (SOFC) used LNG; *METHAPU* (SOFC), *Rivercell* (HT-PEM), and *PA-X-ell* (HT-PEM) used methanol; and *ZemShip* (PEMFC), *MF Vagen* (HT-PEM), *Hornblower Hybrid* (PEMFC), and *Rivercell-ELEKTRA* (HT-PEM) used hydrogen. PEMFC, HT-PEMFC, and SOFC were determined to be the three most promising fuel cell technologies for maritime applications based on maturity and relevance. PEMFC is a mature technology that is compact and lightweight. It provides tolerance for cyclic operation and has a relatively low cost. However, PEMFC requires very pure hydrogen and complex water management to keep the system operating well. HT-PEM draws on some of the benefits of PEMFC but addresses some of the cons. HT-PEM is more fuel flexible, avoids the complex water management system, and provides waste heat for heating purposes. SOFC technology is just starting to become mature. It offers efficiency up to 60% and the opportunity for waste heat recovery to provide high-quality heat. SOFC is very fuel flexible; however, it is less flexible toward cyclic operation.

The EMSA also performed risk analysis as part of this study. Multiple failure scenarios were investigated. The most critical failures were related to the strong exothermic reaction of reformer material, internal leakage in fuel cell module, high energy collision penetrating liquid hydrogen tanks, rupture of compressed hydrogen tank, leakage of hydrogen-rich gases, failure of electrical power output conditioning system, thermal runaway of on-board energy buffer, loss of active purging system, and vehicle crash penetrating. Detailed safety studies considering hydrogen specific properties and conditions in shipping applications are needed.

A preliminary business case was performed to determine the total cost of ownership (TCO) for a small 100-passenger ferry traveling approximately 115 nautical miles per day. The study indicated that the fuel cell ferry has the potential to meet the same operational requirements as the diesel. Challenges include regulatory framework, permitting and economics. The fuel cell ferry would likely yield a significant (~50%) cost premium over the diesel ferry but provide significant CO_2 emissions reductions, especially if "green" hydrogen was used. The CAPEX of the ferry and refueling infrastructure are decisive factors and can vary considerably based on regional differences. Reducing the price of hydrogen from 3.50 to 2.50 €/kg led to a reduction in TCO of 2-5 €/nm or 5-10%. The estimated annualized TCO for the fuel cell ship was 50% higher than for the diesel ship.

Rajesh Ahluwalia, Manager, Fuel Cell and Hydrogen, Argonne National Laboratory, "Total Cost of Ownership (TCO) Analysis for Maritime Applications"

To achieve IMO regulations to cut sulfur dioxide emissions, ships must either use scrubbers to reduce their SO_2 emissions or switch to the lower-sulfur marine gas oil (MGO). New IMO regulations will reduce the sulfur content in marine fuels from the current levels of 3.5% to 0.5%. Ships operating in emission control areas (ECAs) have more stringent requirements, reducing the sulfur content to less than 0.1% as in low-sulfur MGO (LSMGO). Ships using MGO will need to shift to using LSMGO after entering ECA zones. Currently, the cost difference between MGO and LSMGO is small.

Hydrogen fuel cells can play an important role in curbing the emissions and regulated and unregulated pollutants in maritime applications. However, hydrogen and fuel cells must also compete with LSMGO and liquefied natural gas combustion engines on a total cost of ownership (TCO) basis. Argonne National Laboratory has performed TCO studies to compare hydrogen and fuel cells for maritime applications with diesel engines operating on LSMGO, using DOE FCTO hydrogen cost targets for the hydrogen cost. Initial results from three application were presented: a harbor tug, an auto/passenger ferry, and a container ship.

A container ship case was studied, using the LNG-fueled container ship, the *Isla Bella*, as the model for the fuel cell ship. The *Isla Bella* is 233 m long and 32 m wide, and can carry 2100 TEUs (about 36,571 tonnes). The TCOs were determined for the LNG-fueled ship, a diesel-fueled version of the ship, and a PEMFC version with liquid hydrogen storage. The fuel cell ship replaced the 25 MW diesel propulsion engine and three 1.74 MW auxiliary diesel engines with one 26 MW PEMFC. The fuel cell ship has four 820 m^3 storage tanks, which provided sufficient hydrogen for one round trip. The CAPEX for the fuel cell ship was lower than that for the LNG-fueled ship by about 10%, but higher than the CAPEX for the diesel-fueled ship by about 50%. The main contributor to the CAPEX for the fuel cell ship was the liquid hydrogen storage system, while the main contributor for the LNG- and diesel-fueled ships was the power plant. The major contributor to the TCO for all three cases was the fuel cost, with the fuel cost being more than 70% of the TCO for all three cases. The fuel cost for the fuel cell ship was nearly double the fuel cost for the diesel ship, with the fuel cost for LNG-ship being slightly lower than the fuel cost for the diesel-fueled ship, resulting in the TCO for the LNG-fueled ship being about 10% less than that of the diesel-fueled ship. For the duty cycle for the container ship, the three systems offer comparable efficiencies: approximately 49% for LSMGO and 50% for LNG and hydrogen options. The lower cost of the fuel cell system compared to the diesel power plant suggests there is room to increase the efficiency and durability of the fuel cell system at the expense of higher CAPEX. Since fuel costs dominate, this may be beneficial.

A similar TCO study was performed for a ferry with a capacity of 1,200 passengers and 124 cars. Again, an LNG-fueled version of a ferry was used as the basis for the study. The fuel cell version uses a 4.5 MW PEMFC system to replace two 2.25 MW propulsion engines and three 300 kW auxiliary gensets. The LNG or liquid hydrogen storage tanks are sized so that the ferry refuels once every five days, which requires two 43 m^3 tanks for LNG or two 95 m^3 tanks for liquid hydrogen. For the ferry duty cycle, the fuel cell system has higher efficiency than the diesel engine, 52% vs. 43%, respectively. The CAPEX for the fuel cell system is about 20% higher than that for the diesel-fueled option and about 50% lower than the CAPEX for the LNG system. The largest contributor to the CAPEX for the fuel cell is the fuel storage system, while the largest contributor for the diesel and LNG cases is the diesel power plant. The TCO for the diesel-fueled ferry is the lowest, with the TCO for the LNG-fueled ferry about 10% higher and the TCO for the fuel cell ferry being about 50% higher than the diesel-fuel ferry, assuming a hydrogen cost of $4,000/tonne. The fuel cell option's TCO would be equal to the other options' TCO if efficiency is increased to 60% and the hydrogen cost decreased to $2,360/tonne.

A similar study was performed for a harbor tug using natural gas as the baseline and LSMGO for comparison. For the fuel cell tug, a 4.5 MW PEMFC replaces two 1.8 MW propulsion engines and two 100 kW auxiliary power gensets. The LNG and liquid hydrogen tanks are sized so the tug needs to refuel once every four days, which requires a 25 m^3 tank for LNG or a 41 m^3 tank for liquid hydrogen. For the tug duty cycle, the fuel cell tug has an efficiency of 57% compared to 38% for the diesel-fueled and LNG-fueled tugs. The CAPEX for the fuel cell tug is nearly identical to the CAPEX for the diesel-fueled tug, and the CAPEX for both tugs is about 60% lower than the CAPEX for the LNG-fueled tug. On a TCO basis, the hydrogen fuel cell tug is competitive with both the LNG- and diesel-fueled tugs even at a hydrogen cost of $4,000/ton. The fuel cell tug reaches the breakeven point at 65% duty-cycle efficiency and a hydrogen cost of $3,450/ton.

Q&A — Moderator: Pete Devlin, U.S. DOE-FCTO

Cold ironing was discussed as an interesting potential application for fuel cells, but costs appear to be high. The participants commented that you need to decrease costs or incentivize ship owners or ports to pay the higher costs associated with this or other clean technologies if they are to be deployed.

Some opportunities for further development were identified, including fuel cells for auxiliary power applications, higher efficiency fuel cells, more durable membrane electrode assemblies (MEAs), and more available and more reliable balance-of-plant components for fuel cell systems.

Workshop Concluding Remarks — Dr. Sunita Satyapal. Director, U.S.-DOE FCTO and Mirela Atanasiu, Head of Unit, FCH JU

The next steps for advancing the use of hydrogen and fuel cell technologies in ports and on ships include conducting more in-depth analyses of the opportunity and uses of hydrogen and fuel cells in maritime applications, developing technical and cost targets to guide R&D, identifying barriers and opportunities for RD&D and safety codes and standards, and focusing on global collaboration.

List of Abbreviations

APU	auxiliary power unit
AQMD	Air Quality Management District
BIG-HIT	Building Innovative Green Hydrogen Systems in Isolated Territories
BOP	balance-of-plant
C	Celsius
CA	California
CAPEX	capital expense
CARB	California Air Resources Board
CCI	California Climate Investments
CFD	computational fluid dynamics
CHE	cargo handling equipment
CHP	combined heat and power
CNG	compressed natural gas
DERA	Diesel Emissions Reduction Act
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EC	European Commission
ECA	emission control area
EMSA	European Maritime Safety Agency
EPA	U.S. Environmental Protection Agency
EU	European Union
FAR	fatal accident rate
FC	fuel cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCPI	fuel cell power installation
FCTO	Fuel Cell Technologies Office
Ft	foot
g/s	gram per second
GGRF	Greenhouse Gas Reduction Fund
GHG	greenhouse gas
GWh	gigawatt hours
HPA	Hamburg Port Authority
HRS	hydrogen refueling station
HT-PEM	high temperature polymer electrolyte membrane
HySTRA	Hydrogen Energy Supply-Chain Technology Research Association
IAPH	International Association of Ports and Harbors
IGF	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization

kg	kilogram
kg/min	kilogram per minute
km	kilometer
km/h	kilometers per hour
kW	kilowatt
kWe	kilowatt electric
kWh	kilowatt hour
LA	Los Angeles
lbs	pounds
LDV	light-duty vehicle
LNG	liquefied natural gas
LOHCs	liquid organic hydrogen carriers
LSMGO	low sulfur marine gas oil
m	meter
M	million
MARAD	Maritime Administration
MARHYSAFE	Maritime Hydrogen Safety Joint Development Project
MCFC	molten carbonate fuel cell
MCH	methylcyclohexane
MEA	membrane electrode assembly
META	Maritime Environmental and Technical Assistance
MFO	marine fuel oil
MOU	memorandum of understanding
Mpa	megapascals
MT	million ton
MW	megawatt
MWe	megawatt electric
NASA	National Aeronautical and Space Administration
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NFPA	National Fire Protection Association
NMA	National Medical Association
NTNU	Norwegian University of Science and Technology
NWSPA	Northwest Seaport Alliance
OEM	original equipment manufacturer
OPEX	operating expense
PEM	polymer electrolyte membrane
PEMFC	polymer electrolyte membrane fuel cell
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RCCL	Royal Caribbean Cruises Ltd.
RD&D	research, development and demonstration
ROI	return on investment
RO-PAX	roll-on-roll-off-passenger-ship
RTG	rubber-tired gantry

SAE	Society of Automotive Engineers
SGMF	Society for Gaseous Marine Fuel
SIGTTO	Society of International Gas Tanker and Terminal Operators
SNL	Sandia National Laboratories
SOEC	solid oxide electrolyzer
SOFC	solid oxide fuel cell
TCO	total cost of ownership
TCS	total confined space
TEU	twenty-foot equivalent unit
TRL	technical readiness level
U.S.	United States
UK	United Kingdom
USCG	U.S. Coast Guard
VAC	volts of alternating current
YKP	Yusob Kantang Port (Thailand)
ZEV	zero-emissions vehicle

Appendix A — Participant Feedback

Workshop participants were asked to provide written responses to identify the most pressing R&D needs or issues to address the acceleration, development and deployment of hydrogen and fuel cell technologies in ports and on vessels. Responses were collected and categorized into the following six categories: Fuel Cell Technology, H_2 Fuel, Data and Information Sharing, R&D Needs, Regulations and Standards, and Crosscutting.

Fuel Cell Technology

- Need high energy density for large ships and long missions.
- PEM technology might need some small incremental improvement going forward but the most important focus needs to be on cost of H_2. Secondarily, on improving the efficiency of H_2 fuel cell systems, which likely means improved BOP and better system integration.
- H_2 and fuel cells need to be demonstrated at scale to show the cost feasibility of H_2 and PEMFC. But, PEMFC for ships will be somewhat “custom” for each vessel. Therefore, it will be difficult to see the benefits of scale. Therefore, probably best to focus on vehicles, which are repeatable — for example 500 drayage trucks or reach stackers. Therefore, a large scale demonstration project for land-based port vehicles is needed. Suggest to do this at a Texas or Gulf Coast port which already has good H_2 infrastructure with the potential to convert grey H_2 to green H_2.
- Focus on trucks, tractors, RTG cranes first. Focus on cold ironing second.
- Balance of plant: Tier 2, supplier engagement to get closer to H_2 readiness.
- Focus on fuel cell durability and efficiency (cost).

H_2 Fuel

- Engage with power utility companies (renewables) to increase H_2 generation
- There must be a RH_2 pathway for fuel cells to compete with other low carbon options. Green electrolytic hydrogen is an option for grid scale storage.
- H_2 demands are large, distribution costs (H_2 distribution infrastructure) needs to be addressed if total cost of H_2 can ever be competitive.
- Bunkering needs, if met, by onsite production.
- Propulsion will be most challenging for cargo/container ships. On board storage to meet current operations seems way too daunting.
- Level playing field on prices
  - Cut tax for existing fuels
  - Subsidize/support H_2 infrastructure
  - Get clear regulations in place
- Availability of H_2 is bigger issue across all sectors.
- Assess feasibility of onsite fuel hub where mobile refuelers can load and bring fuel to fuel cell equipment. It could start with LH_2 hub that delivers GH_2 to mobiles. The hub could transition to pipeline or onsite production, whatever makes more sense for the site/location.
- Build LH_2 infrastructure.

- H_2 refueling for ships needs much higher rates than for other applications (cost of H_2).
- Large scale H_2 production at ports to reduce transmission and bunkering costs.
- Focus on entire value chain from production to end use, get H_2 suppliers on-board.
- The fueling infrastructure needs to be shared between different segments vessels/comms/light truck/rail/etc.

Data and Information Sharing

- Need to develop targets for hydrogen (or carrier) and fuel cell systems for marine applications, for the transition from the current systems (combustion engine system)
- Get feedback from all early adopters in auto, freight, buses, and stationary applications.
- Work on strategy to increase public awareness on H_2 and safety
- Data availability from port authorities for demand assessment.
- Help ports with emissions inventory – MOVES (EPA motor vehicle emission simulator) is not trivial.
- Jointly quantify and disseminate potential to the maritime industry.
- Predictability for investors/industry during the early stage (low volume).
- Establish targets for maritime applications.
- Feedback from public funded projects to R&D for next generation.
- Cost targets and what incentives and financial risk mitigation opportunities that can be viable.

R&D Needs

- Research H_2 carriers that can be fed directly to the fuel cell - H_2 fuel format (liquid/solid/super fluid/compressed gas).
- Develop a "H_2 Cluster" demonstration including fuel storage, equipment APU, CHE, tractor, drayage.
- Current priorities in FC and H_2 fuel (high to low - 1 to 10)
  - Fuel cell technology
    - Hotel power supply at port
    - Vessel's auxiliary power
    - High scale (>2 MW) demonstration project
    - Port mobility equipment
  - H_2 fuel
    - H_2 delivery cost
    - H_2 storage cost
    - H_2 generation and LH_2 supply
- At-sea application: build vessel to prove feasibility and safety of H_2 as a marine fuel.
- Harmonized TCO analysis of ports and sea applications.
- Detailed analysis of LH_2 infrastructure dedicated for port application.

- LH_2 boil-off management system.
- How to develop fuel cells that match diesel lifetime — 25 years.
- Trade-offs between fuel cell efficiency, durability and cost.
- Market entry applications for fuel cells for maritime.

Regulations and Standards

- Safety and regulations need to be standardized and lessons learned from previous projects need to be shared and captured in regulations.
- Fuel cells need to be certified to demonstrate the safety level. The site handling of H_2 by ports and end users needs to be standardized and shared.
- U.S. government support on H_2 projects needs to be stepped up to similar levels in Europe/Norway.
- Need to develop regulations and standards for H_2 refueling to ships.
- Standards and regulations need to get in sync.
- Build a regulatory toolkit for ports that want to act/facilitate but don't have the oversight.
- Need clarifications of safety regulations/requirements for making design and manufacturing of hydrogen carrying/propelled vessels more efficient and cost competitive.
- Better understanding of the IGF Code or path would be helpful in structuring demos, projects, JIPs, etc.
- Need to consider crew training and workforce development while industry begins to consider H_2 fuel cell for vessel propulsion. USCG license course. Curriculum would be good idea.
- Design & operations / safety regulations needed for sea applications.
- Work on storage, safety and regulations for sea and port applications.
- There will be security considerations and an increased risk port-wide as H_2 activities increase.

Crosscutting

- Adopt "Climate Neutral" stewardship for different communities affected.
- Develop working groups - interagency, interindustry, OEMs, and international collaboration.
- Action engineering working group for projects needed.
- Selection committee to get project funding — need "Steering Committee."
- Spread projects around geographically.
- Critical areas to succeed include: fuel cell durability (>50,000 hrs), business cases, public procurement, stringent emissions regulations, H_2 fuel costs reduction and production volume.

Appendix B — Workshop Agenda

Sept 10-12, 2019
Commandant Room, 10th Floor
Marines' Memorial Club & Hotel | San Francisco, CA

Tuesday, September 10 | Day 1

7:30 AM **Breakfast**

8:00 AM **Welcoming Remarks**

Elaine Forbes, Director, Port of San Francisco

Session I — U.S. Government Perspectives on Hydrogen at Ports and At-Sea Marine Applications

8:15 AM **U.S. Department of Energy**

Sunita Satyapal, Director, U.S. Department of Energy Fuel Cell Technologies Office (DOE-FCTO)

8:30 AM **U.S. Maritime Administration**

Michael Carter, Acting Associate Administrator for Environment and Compliance, U.S. Department of Transportation Maritime Administration

8:45 AM **U.S. Environmental Protection Agency**

Britney McCoy, Environmental Engineer, Office of Transportation & Air Quality, Transportation and Climate Division

9:00 AM **California Air Resources Board**

Leslie Goodbody, Engineer, Innovative Heavy Duty Strategies

9:15 AM **U.S. Government Panel Discussion**

Moderator: Pete Devlin, U.S. DOE-FCTO

9:45 AM **Break & Network**

Session II — International Government Perspectives on Hydrogen at Ports and At-Sea Marine Applications

10:15 AM **European Commission**

Robert Missen, Head of Unit for Research, Directorate General for Mobility & Transport

10:30 AM **FCH JU**

Mirela Atanasiu, Head of Unit Operations and Communications

10:45 AM **Germany/NOW**

Erik Schumacher, Divisional Head Stationary Fuel Cells, NOW - National Organisation Hydrogen and Fuel Cell Technology

11:00 AM **Norway/SINTEF**

Steffen Møller-Holst, Vice President Marketing, Hydrogen & Fuel Cell Technologies

11:15 AM **Japan**

Eiji Ohira, Director General of NEDO's Fuel Cell and Hydrogen Group

11:30 AM **International Panel Discussion**

Moderator: Elizabeth Connelly, U.S. DOE-FCTO

12:00 PM **Lunch & Network**

Session III — Infrastructure Stakeholders Perspectives: Port Authorities

1:00 PM **Port of Los Angeles**

Chris Cannon, Chief Sustainability Officer/Director of Environmental Management

1:15 PM **Valenciaport Foundation**

Mercedes de Juan, Project Manager

1:30 PM **Hamburg Port Authority**

Bjoern Pistol, Head of Port Estate and Maritime Affairs

1:45 PM **Infrastructure Stakeholders Panel Discussion**

Moderator: Charlie Myers, Oak Ridge National Laboratory

2:00 PM **Break & Network**

Session IV – Industry Perspectives: Ship Systems Developer

2:30 PM **Golden Gate Zero Emission Marine**

Joe Pratt, CEO & CTO

2:45 PM **NCE Maritime CleanTech**

Paul Helland, Project Manager Innovation

3:00 PM **Wilh. Wilhelmsen Holding**

Per Brinchmann, Vice President – Special Projects

3:15 PM **Ship Systems Developer Panel Discussion**

Moderator: Laurence Grand Clément, PersEE

3:45 PM **Day 1 Closing Remarks**

4:15 PM **Adjourn**

6:00 PM **Dinner — Hosted by FCH JU**

Wednesday, September 11 | Day 2

7:30 AM **Breakfast**

Session V — Industry Perspectives: Power Systems Developers

8:00 AM **ABB Marine & Ports**

Klaus Vanska, Global Business Development Manager

8:15 AM **BAE Systems**

Peter Brooks, Global Marine Account Manager

8:30 AM **General Electric**

Renaud Cornu, Senior Market Leader GE Power Conversion

8:45 AM **Wärtsilä**

Stefano Cantarut, Segment Manager Cruise and Ferry

9:00 AM **Power Systems Developers Panel Discussion**

Moderator: Charlie Myers, Oak Ridge National Laboratory

Session VI — Industry Perspectives: Vehicle & Fuel Cell Manufacturers

9:30 AM **Hyster-Yale/Nuvera**

Gus Block, Manager of Business Development

9:45 AM **Kenworth**

Brian Lindgren, *Director of Research & Development*

10:00 AM **Cummins**

*Joerg Ferchau, General Manager, Electrified Powe*r

10:15 AM **Hydrogenics**

Ryan Sookhoo, Director of New Initiatives

10:30 AM **Break & Network**

11:00 AM **Ballard Marine Center of Excellence**

Alan Mace, Market Manager

11:15 AM **PowerCell Sweden**

Johan Burgren, Business Manager Marine

11:30 AM **Nedstack**

Roel Van de Pas, CCO

11:45 AM **Vehicle & Fuel Cell Manufacturers Panel Discussion**

Moderator: Dimitrios Papageorgopoulos, U.S. DOE-FCTO

12:15 PM **Lunch & Network**

Session VII — Regulations, Codes and Standards

1:15 PM **PersEE**

Laurence Grand Clément, CEO

1:30 PM **Lloyd's Register**

Olav Hansen, Senior Principal Risk Management Consultant

1:45 PM **DNV-GL**

Anthony Teo, Technology and LNG Business Development Director

2:00 PM **ClassNK**

Koichi Nishifuji, Manager of Technical Solution Department

2:15 PM **U.S. Coast Guard (USCG)**

LCDR Frank Strom, USCG Sector San Francisco

2.30 PM **Regulations, Codes and Standards Panel Discussion**

Moderator: Lionel Boillot, FCH JU

3:00 PM **Break & Network**

Session VIII — Recent Research and Analyses

3:30 PM **Development of a Containerized 100 kW Fuel Cell System for Maritime Applications**

Lennie Klebanoff, Technology Staff, Sandia National Laboratories

3:45 PM **Refueling Analysis**

Nico Bouwkamp, Technical Program Manager, California Fuel Cell Partnership

4:00 PM **Hydrogen Demands at Ports**

Lindsay Steele, Senior Research Scientist, Pacific Northwest National Laboratory

4:15 PM **FCH JU TCO Analysis/EMSA study**

Lionel Boillot, Project Manager, FCH JU

4:30 PM **Total Cost of Ownership (TCO) Analysis for Maritime Applications**

Rajesh Ahluwalia, Manager, Fuel Cell and Hydrogen, Argonne National Laboratory

4:45 PM **Session VIII — Q&A**

Moderator: Pete Devlin, U.S. DOE-FCTO

5:00 PM **Participant Feedback**

5:15 PM **Adjourn**

Thursday, September 12 | Day 3

8:00 AM **Bus Pick-up**

Location: Marines' Memorial Club & Hotel
609 Sutter St, San Francisco, CA 94102

9:00 AM **Tour of Water-Go-Round, Golden Gate Zero Emission Marine**

Location: Bay Ship & Yacht
2900 Main St., Alameda, CA 94501

11:00 AM **Bus Departure**

12:00 PM **Bus Drop-off**

Location: Marines' Memorial Club & Hotel
609 Sutter St, San Francisco, CA 94102

Appendix C — Speaker Bios

Rajesh Ahluwalia, Manager, Fuel Cell and Hydrogen, Argonne National Laboratory

Rajesh Ahluwalia joined Argonne National Laboratory after receiving his PhD in mechanical engineering in 1977. He is a senior engineer and the leader of the Fuel Cell and Hydrogen Group in Argonne's Energy Systems Division. He is currently a Principal Investigator of several DOE funded projects on analysis of fuel cell systems for transportation, systems analysis of on-board hydrogen storage options, hydrogen production and delivery, electrocatalysts for fuel cells (ElectroCat), and a Thrust Leader in DOE Fuel Cell Technologies Office's Fuel Cell Performance and Durability (FC-PAD) consortium.

Mirela Atanasiu, Head of Unit Operations and Communications, Fuel Cells and Hydrogen Joint Undertaking

Mirela Atanasiu is the Head of Unit of Operations and Communication in the Fuel Cells and Hydrogen Joint Undertaking, FCH JU (Public-Private Partnership between European Industry and Research Community, and European Commission) since 2016. Previously, for more than 12 years she was a Senior Project Manager and Research Programme Officer in the FCH JU and European Commission. She holds an M.Sc. in Chemical Engineering (specialty Materials Science) and an M.Sc. in Economics (specialty Cybernetics and Economic Analysis).

Gus Block, Director of Corporate Development, Nuvera

Gus Block is a co-founder of Nuvera Fuel Cells, a company established in 2000 to provide hydrogen and fuel cell solutions for on- and off-road vehicles. Gus currently serves on the Governor's Zero Emissions Vehicle Commission in Massachusetts, is Chair of the Communications and Marketing Committee of the Fuel Cell and Hydrogen Energy Association, and is Co-Chair of the Goods Movement, Heavy Duty, and Clean Ports Sector Action Group of the California Hydrogen Business Council. Mr. Block earned a mechanical engineering degree from The Cooper Union for the Advancement of Science and Art, and as a Fulbright Fellow developed a wind-powered electrolyzer in Sri Lanka.

Lionel Boillot, Project Manager, Fuel Cells and Hydrogen Joint Undertaking

Lionel Boillot is project manager at the Fuel Cells and Hydrogen Joint undertaking (FCH2 JU). He is an engineer. He has been working on interregional cooperation projects INTERREG in Spain, then on public transport in Ireland. He has been working for 10 years in the European institutions, as project manager for innovation and research projects. Now, within the FCH2 JU, he is in charge of large innovation projects for hydrogen and fuel cells in transport applications: cars, buses, trucks, and ships.

Per A. Brinchmann, VP Special Projects, Wilh. Wilhelmsen Holding ASA

Since his graduation as naval architect at the Norwegian Technical University in Trondheim in 1978, Per has held a number of leading positions in the Norwegian maritime supplier, service and ship-owning industry. For the past 16 years he has been employed by the Wilhelmsen group, most of his time as head of the technical department. Mr. Brinchmann has throughout his career been engaged in technology development within maritime safety, environment and efficiency.

Mr. Brinchmann is now heading Wilhelmsen's activities within renewables and autonomy technology, which includes several projects on hydrogen logistics and on-board use as fuel. He is also chairing the BoD of Massterly AS, the Kongsberg – Wilhelmsen joint venture for autonomous vessel operations.

Peter Brooks, Global Marine Account Manager, BAE Systems

Peter Brooks is the Account Manager responsible for the Global Marine business within the BAE Systems Power and Propulsions organization. He joined BAE Systems in 2018 to lead the marine business, previously having over twenty years of electrification experience with Cummins and Caterpillar. Mr. Brooks' broad experience of marine solutions includes electric-hybrid, batter electric, and hydrogen fuel cell-based architectures.

Stefano Cantarut, Segment Manager Cruise & Ferry, Wartsila

As Segment Manager Cruise & Ferry, Stefano Cantarut translates the customer's values and needs in hard facts. There is the "compass" that guides him while exploring different technologies and fuel alternatives, looking for the perfect machinery setup for the next new vessel.

Ten years of international experience in Wartsila, both in the new build and after sales services, coupled with a Master of Science degree in Materials Engineering gave Mr. Cantarut the right "hands on" approach to tackle daily business needs with innovation in mind.

Michael Carter, Acting Associate Administrator for Environment and Compliance, U.S. Department of Transportation, Maritime Administration (MARAD)

Michael Carter serves as the Acting Associate Administrator for Environment and Compliance at the U.S. Department of Transportation, Maritime Administration (MARAD). He currently has responsibility for MARAD's Office of Environment, Office of Safety, and Office of Maritime Security. He has been with MARAD for over 22 years, covering environmental issues related to MARAD operations, the maritime transportation industry and other government agencies.

Mr. Carter and his staff developed and now implement the MARAD Maritime Environmental and Technical Assistance Program (META). The program, which was launched formally in 2010, focuses on maritime innovation founded on collaboration among Federal agencies, such as DOE, DOD, EPA, USCG, and NOAA, state agencies, the maritime industry, and academia to address emerging environmental challenges facing maritime stakeholders. Recent efforts have included ballast water treatment technology testing and verification, underwater hull fouling, and port and vessels air emissions, alternative fuels, and alternative energy.

Mr. Carter and his staff maintain a strong international presence on these same issues, serving in various capacities as technical experts on the U.S. Delegation to the IMO, Marine Environment Protection Committee (MEPC), Pollution Prevention and Response Subcommittee (PPR) and the International Organization of Standards (ISO).

Before joining the Maritime Administration in August 1995, Mr. Carter was in private environmental law practice. He received his law degree from Catholic University in 1985 and his undergraduate degree in Forestry and Wildlife Management from Virginia Polytechnic Institute and State University in 1982.

Renaud Cornu, Senior Sales, Passenger Vessels, GE Power Conversion

After achieving a degree in civil engineer, Renaud Cornu has worked in business development and sales since 1996. Mr. Cornu joined GE Power Conversion (then Converteam) 11 years ago when his passion for sailing led him towards a career in the marine industry. Today he leads the sales activities for the Passenger Vessel segment for GE's Power Conversion business.

Mercedes de Juan, Project Manager, Valenciaport Foundation

Mercedes de Juan started her career in the area of R&D projects collaborating with ITT Industries in the development of a sewage treatment plant, aimed to be used for watering. In 2006, she started to work in Asfibe Shipyards, collaborating in the implementation of quality and environmental policies. In 2009, she was responsible for the construction in Union Naval Valencia. That year, Ms de Juan started to work for Balearia in the implementation of maintenance systems, becoming Director of Innovation in 2011. Since February 2014, she has been working for the Valenciaport Foundation as LNG specialist engineer.

She holds a master's degree in Naval Architecture & Marine Engineering from the Polythechnic University of Madrid. She has taken part of different training courses specializing in plastic materials, project management, safety applied to passenger vessels, ship maintenance, etc.

Joerg Ferchau, General Manager, Electrified Power, Cummins

Joerg Ferchau is an accomplished technology executive and entrepreneur, with over 30 years of Silicon Valley background in technical and operating roles in start-up and Fortune 500 companies.

His professional experience includes Director to CEO roles in a broad range of industries including automotive, information technology, network security, and military/aerospace. Ferchau has been dedicated to the electrification of commercial vehicles since 2006 and recently joined Cummins after the company he co-founded was acquired by Cummins in 2018.

In his current role as the General Manager of Electrified Power Systems, Mr. Ferchau is focused on expanding Cummins' market position in hybrid, electric, and fuel cell transportation applications.

Prior to Cummins, Mr. Ferchau held senior management roles in business and product development at EDI, SanDisk, Compaq, Tandem, and GE. He began his career in mechanical engineering and is an inventor/co-inventor in over 25 patents.

Elaine Forbes, Executive Director, Port of San Francisco

Elaine Forbes leads the Port to responsibly manage the waterfront as the gateway to a world-class city and advances environmentally and financially sustainable maritime, recreational, and economic opportunities to serve the City, Bay Area region, and California.

At the recommendation of the Port Commission, Mayor Edwin Lee appointed Elaine Forbes Executive Director of the Port on October 12, 2016. Ms Forbes is one of ten women Port Directors in the United States. Before her appointment as Executive Director, she served as Deputy Director for Finance and Administration for the Port for six years.

Prior to joining the Port, Ms Forbes held executive management and leadership positions at both the San Francisco Planning Department and the San Francisco International Airport. She also worked for the San Francisco Board of Supervisors Budget Analyst's Office providing fiscal and policy analysis and evaluating and reporting on complex municipal issues.

Before beginning her tenure with the City and County of San Francisco in 2000, she worked as a redevelopment agency planner for the City of Oakland. She also has worked for several non-profit land use policy and economic development organizations including the Urban Strategies Council and the California Budget Project.

Ms Forbes holds a master's degree with honors from the University of California, Los Angeles, in Community and Economic Development, as well as a Bachelor of Arts degree with honors from Mills College in Oakland. She is also a member of the Phi Beta Kappa Society. She was born in San Francisco and resides in the Castro neighborhood with her partner.

Leslie Goodbody, Air Resources Engineer, California Air Resources Board

Leslie Goodbody has been with CARB for 14 years, currently working in the Innovative Strategies Branch on heavy-duty zero-emission truck and bus deployment projects. She is the Grant Liaison for five projects that together involve building and deploying 19 fuel cell delivery vans, 25 fuel cell transit buses, two high-capacity hydrogen fueling stations, and 10 battery electric transit buses plus supporting charging infrastructure. Ms Goodbody is also overseeing administration of $150 million in Volkswagen Environmental Mitigation Trust funding for Zero-Emission Class 8 trucks and low-NO_X trucks and freight equipment. Before joining the Innovative Strategies Branch, she worked in CARB's Advanced Clean Cars group focusing on hydrogen fueling and charging infrastructure for light-duty vehicles. She has a bachelor's degree in Environmental Resources Engineering from Humboldt State University and 31 years of work experience in both the private and public sector.

Paul Helland, Project Manager Innovation, NCE Maritime CleanTech

Paul Helland holds the position of Project Manager Innovation in the cluster organisation NCE Maritime CleanTech (NCE MCT). NCE MCT represents one of the world's most complete maritime commercial hubs. NCE MCT cluster organisation uses the Norwegian maritime expertise, built up over generations, as a springboard for the development of new energy-efficient and environmentally friendly technologies. NCE MCT focus on establishing sustainable innovation projects with commercial potential and work together for new clean maritime solutions.

Some of Mr. Helland's focus areas within NCE MCT are projects related to electrical propulsion systems driven by batteries and hydrogen driven fuel cell systems.

Mr. Helland has an MBA degree in Strategic Leadership and Economics from the Norwegian Arctic University of Tromsø (UiT) and a BSc. degree in Automation from the Western Norway University of Applied science (HVL). Before joining the NCE MCT cluster administration He worked as a Principal Surveyor in the class society DNV-GL for 12 years, where some of his expertise areas was automation- and electrical systems. Before DNV-GL he has work experience at Wartsila, Kongsberg Maritime, DeepOcean and Oceaneering.

Leonard E. Klebanoff, Principal Scientist, Sandia National Laboratories

Lennie Klebanoff was born in Washington D.C. and raised in nearby Bethesda Maryland. He received his B.S. in Chemistry and M.S. in Organic Chemistry from Bucknell University, Lewisburg PA. He received a Ph.D. in Physical Chemistry from the University of California-Berkeley. After Berkeley, Mr. Klebanoff did a post-doc stint at the National Bureau of Standards (now NIST).

From 1987 to 1997, Mr. Klebanoff was a Professor of Chemistry at Lehigh University, Bethlehem, PA conducting R&D on the magnetic properties of surfaces, eventually attaining the rank of full professor of Chemistry with tenure.

After 12 years away from the San Francisco Bay Area, he returned in 1997, taking a position at Sandia National Laboratories in Livermore, CA. By 2003, his interests began to take him into the alternative energy arena, where he served with State of California officials to develop Governor Schwarzenegger's Blueprint for a Hydrogen Highway in California.

In 2006, Mr. Klebanoff was named the Director of the U.S. DOE Metal Hydride Center of Excellence (MHCoE), an 18-insitution center to advance the science of solid-state storage of hydrogen using metal hydrides. He continues his Sandia hydrogen storage work today within the current HyMARC consortium. Mr. Klebanoff has also been involved in DOE and DOT-funded fuel-cell market transformation projects since 2006, most recently investigating fuel cells for port-side power and evaluating the feasibility of hydrogen fuel-cell vessels, such as ferries and ocean-going research vessels. He has published over 100 scientific papers, edited one book and has 29 patents (filed and issued).

Brian Lindgren, Director of Research & Development, Kenworth

Brian Lindgren is director of research & development for Kenworth Truck Company, a PACCAR company. He is responsible for guiding the technology roadmap for Kenworth's commercial vehicle product line, identifying and developing concepts to improve vehicle aerodynamics, freight efficiency and sustainability, and providing technology to assist drivers in improving on-road safety.

Under Mr. Lindgren's direction, Kenworth's R&D team has designed and built several proof-of-concept heavy trucks with electric powertrains, utilizing range-extending technologies including hydrogen fuel cells, near-zero emission natural gas engines and natural gas-fueled microturbines. These projects benefitted from funding sources including the U.S. Department of Energy, California Energy Commission, California Air Resources Board, California's South Coast Air Quality Management District and California's San Joaquin Valley Air Pollution Control District.

In his 40 years at the company, he has held positions in Engineering, Marketing and Sales, and has headed the R&D team since 2011. Mr. Lindgren holds a bachelor's degree in Mechanical Engineering from Cal Poly San Luis Obispo and is a registered Professional Engineer.

Alan Mace, Market Manager, Ballard Power Systems

Alan Mace has more than 20 years experience in the fuel cell industry in product development, customer service and product management roles. In his current position as Market Manager, he is responsible for market development activities for Ballard's heavy-duty power modules including definition of customer requirements, and market and value analysis. His experience includes a strong technical background on fuel cell products and applications.

Prior to his fuel cell career, Mr. Mace developed machinery for pulp, paper, and web processing applications, as well as high-speed machine vision systems for food processing.

Britney McCoy, Environmental Engineer, Office of Transportation & Air Quality, Transportation and Climate Division, U.S. Environmental Protection Agency

Britney McCoy is an environmental engineer for the U.S. EPA specializing in heavy-duty diesel sector air emission controls for the U.S. EPA Clean Diesel and DERA programs over the last 8 years. She serves as the technology assessment lead for EPA's Ports Initiative. Ms McCoy's current research interests have centered on diesel engine after-treatment retrofits, the prioritization of public funding for diesel emission control technologies, EPA's Clean School Bus Program, black carbon emissions in the Arctic, and advanced technology opportunities in port operations.

As the Director of Educational Experiences for STEMLY, a non-profit advocacy organization, she works to create bridges to STEM fields for underrepresented student populations in Washington, D.C. Her life's motto is "I'm simply trying to create some meaning out of life while improving the environment and changing lives at the same time." She holds a Ph.D. in Engineering & Public Policy and a M.S. in Environmental Management and Science from Carnegie Mellon University, and a B.A. in Engineering and Government & Law from Lafayette College.

Robert Missen, Head of Unit for Research, Directorate General for Mobility & Transport, European Commission

Originally from the UK, Robert Missen is a civil servant with the European Commission. For over twenty-five years he has worked in the Directorate General responsible for Transport, concentrating first on policy in the road transport sector, before moving to Aviation Security, where he was notably responsible for the adoption of EU legislation following the events of 11 September 2001.

Between 2010 and 2016, Mr. Missen was Head of Unit responsible for Maritime and Land Transport Security and, since October 2016, he is Head of Unit for transport research and innovation.

Having experience in land, sea and air policy, his role is to bring together the research needs of policy with the funding opportunities under the EU research budget.

Steffen Møller-Holst, Vice President Marketing, Hydrogen & Fuel Cell Technologies, SINTEF

Steffen Møller-Holst holds a MSc. in Chemical Engineering (1990) and a PhD in PEM fuel cells (1996), both from the Norwegian University of Science and Technology (NTNU). Between 1997 and 1999, Dr. Møller-Holst was Research Fellow at Los Alamos National Laboratory, NM, USA. He has close to 30 years' experience within hydrogen technologies, initially from more than a decade of PEM fuel cell development, ranging from catalyst synthesis, via single cell characterization to fuel cell stack development. Over close to two decades, Dr. Møller-Holst has also contributed to shaping the political agenda in Norway, as advisor to the Ministry of Petroleum & Energy and the Ministry of Transportation (2006-2014), and since 2015 as Chairman for the Norwegian Hydrogen Association. Currently, he is in charge of SINTEF's significant hydrogen project portfolio, counting 28 FCH JU-funded projects since 2010, and a wide range of nationally funded activities. Moreover, he has contributed to the establishment of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and has been Chair for the Transport Pillar of FCH JU since 2008. Currently, Dr. Møller-Holst is involved in implementing technologies, both for production (electrolyser directly linked to wind park) as well as fuel cells in heavy duty trucks (ASKO/Scania) and a passenger car ferry (Fiskerstrand Holding).

Koichi Nishifuji, Manager of Technical Solution Department, ClassNK

Koichi Nishifuji received his Bachelor's degree in Mechanical Engineering and Materials Science from Yokohama National University. He has worked for ClassNK since 1994. At ClassNK, he has been responsible for plan approval and field survey of machinery part of general ships and cargo part of liquefied gas carriers. In his current role, Mr. Nishifuji leads the approval and safety assessment of new technologies including liquefied hydrogen carriers and ships using alternative fuels such as LNG, LPG, methanol and hydrogen.

Eiji Ohira, Director General, Fuel Cell and Hydrogen Group, New Energy and Industrial Technology Development Organization (NEDO)

Eiji Ohira is the Director General of the New Energy and Industrial Technology Development Organization (NEDO)'s Fuel Cell and Hydrogen Group within the Advanced Battery and Hydrogen Technology Department. In this capacity, he is responsible for the overall strategy, execution and coordination of NEDO's research, development and demonstration project on fuel cell and hydrogen.

He has also coordinated fuel cell and hydrogen activities with international stakeholders, through International Energy Agency's Technology Collaboration Program (IEA TCP: Advanced Fuel Cell & Hydrogen), and International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).

Mr. Ohira joined the NEDO in 1992, just after graduation from the Tokyo University of Science. He served as a visiting scholar at the Massachusetts Institute of Technology in 1997-1998.

Before taking up the current position in April 2013, he served in several positions, including Representative at NEDO Asian Representative Office, Director of the Energy Storage Technology Division.

Bjoern Pistol, Head of Port Estate and Maritime Affairs, Hamburg Port Authority

Bjoern Pistol is Political Scientist (M.A.) and Industrial Engineer for Maritime Logistics. He worked as office manager in the German Federal Parliament and he was the chairman of the Green Party in the state of Schleswig-Holstein from 2001 to 2004. After he worked for one year with the Hamburg Port Authority, he joined UNICONSULT Universal Transport Consulting GmbH as management consultant for ports and logistics in 2008. He took over a new position at Siemens Wind Power as Global Head of Logistics Strategy in 2012. Mr. Pistol was responsible for the continuous improvement of the worldwide transport and logistics processes and he managed the logistics related aspects of the merger between Siemens Wind Power and Gamesa in 2017. Mr. Pistol started his job at the Hamburg Port Authority as Head of Port Strategy in September 2017, being responsible for all topics related the strategic development of the Port of Hamburg with a special focus on digital development and sustainability. He became Head of Port Estate and Maritime Affairs and member of the management board in April 2019.

Erik Schumacher, Divisional Head Stationary Fuel Cells, NOW- GmbH

Erik Schumacher is the Divisional Head for stationary fuel cells and fuel cells in ship applications at the NOW GmbH. NOW GmbH (National Organisation Hydrogen and Fuel Cell Technology) is, beside other programmes, responsible for the coordination and management of the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP) and the Electromobility Model Regions programme of the German Federal Ministry of Transport and Digital Infrastructure (BMVI).

In this function he is responsible to evaluate, and support R&D Projects and market activation activities based on fuel cells for the heating market, the energy or industrial sector. The current focus is on large fuel cell for ship applications.

Before joining NOW in 2013, he worked for 13 years in the predevelopment department of General Motors/OPEL. Here he was, amongst others, the responsible System Engineer for Fuel Cell Systems as well as for Lithium Ion propulsion batteries.

Ryan Sookhoo, Director of New Initiatives, Hydrogenics

Ryan Sookhoo is the Director New Initiatives at Hydrogenics Corporation. Since joining Hydrogenics in 2006 as Project Manager for PEM fuel cell development and commercialization, he has been a dedicated member of the research and development program. In his current role, Mr. Sookhoo is fortunate to be involved in the early stages of new technology adaptation. As a leader in hydrogen generation and fuel cell industries, Hydrogenics has given him the opportunity to work with various industries and help to define many of tomorrow's energy and power solutions. Mr. Sookhoo holds a Bachelor's in Electrical Engineering and believes that passion, innovation and focus are crucial to success. He is a registered professional engineer.

Lindsay Steele, Senior Research Scientist, Pacific Northwest National Laboratory

Lindsay Steele joined Pacific Northwest National Laboratory in fall of 2009 as a Senior Research Scientist. After receiving his Ph.D. in Experimental Condensed Matter Physics, he worked in the private sector leading product and process design and development in mainstream manufacturing of Liquid Crystal, Light Emitting Diode, and Active Matrix avionics displays along with Solid State Lighting technologies. Since joining PNNL, Mr. Steele has been involved in a wide range of energy efficient technology research. He has provided technical leadership and support within PNNL's Energy and Environment Directorate including DOE Energy Efficiency Standards and Test Procedures development program. In addition, he has been leading PNNL's work for DOE in assessing the impact of their R&D investments for several Energy Efficiency & Renewable Energy office programs (Advanced Manufacturing and Hydrogen and Fuel Cell Technologies). This work has focused on the technical feasibility, barriers to development and adoption of over 2000 technology, process, component and material R&D projects and has resulted in numerous DOE program office summary reports and technology articles. Over the past decade Mr. Steele has tracked and analyzed the Fuel Cell Technologies Office R&D project and patent portfolios and more recently the H2@Scale initiatives in maritime applications.

Frank Strom, Lieutenant Commander, U.S. Coast Guard Sector San Francisco

LCDR Frank Strom has spent most of his 14-year Coast Guard career in the prevention program, focused on improving safety of commercial vessels and facilities through inspections, examinations, and regulatory development. He holds a master's degree in systems engineering from the Naval Postgraduate School and has been stationed in New York, California, and Washington, D.C. He currently serves as the Chief, Inspection Division at Coast Guard Sector San Francisco where his staff is overseeing the construction of the Water-Go-Round. Previously, he served as the Chief, Machinery Branch and the Chief, Outer Continental Shelf Branch at the Coast Guard Marine Safety Center.

Roel van de Pas, COO, Nedstack

Roel van de Pas is Chief Commercial Officer at Nedstack Fuel Cell Technology BV. Within the NFCT board of directors Mr. Van de Pas is responsible for the commercialization and industrialization of the Nedstack PemGen™ fuel cell power installation portfolio with a strategic focus on the maritime industry. Complementing his position at Nedstack, Mr. Van de Pas is a board member at the Dutch Hydrogen and Fuel Cell Association (NWBA). Mr. Van de Pas holds a DBA in Business Administration, a Master's in Public Administration and a Bachelors in Transport Systems Engineering. Prior to joining Nedstack, Mr. Van de Pas has held different board positions — for 8 years — at e-Traction in the new energy powertrain industry. His first encounters with the maritime domain where in 2007 when working at Veolia Transport as a project manager whom — amongst others — were an operator of ferries over inland waterways.

Klaus Vänskä, Global Business Development Manager, ABB Marine & Ports

Klaus Vänskä has over 20 years of experience in maritime industry and 17 years of that in different R&D and Technology management positions. Currently he is a Global Business Development manager at ABB's Marine & Ports business unit. He is specialized in energy efficient vessel concepts, renewable energy sources and efficient solutions for sustainable shipping.

Appendix D — List of Attendees

Name	Company/Organization
Rajesh Ahluwalia	Argonne National Laboratory
Mirela Atanasiu	European Commission - FCH JU
Richard Berman	Port of San Francisco
Gus Block	Nuvera Fuel Cells
Lionel Boillot	FCH2 JU
Nico Bouwkamp	California Fuel Cell Partnership
Per Brinchmann	Wilh. Wilhelmsen Holding
Peter Brooks	BAE Systems Inc
Joe Burgard	Golden Gate Zero Emission Marine
Johan Burgren	PowerCell Sweden AB
Virginia Buys	U.S. Coast Guard
Marie Byrd	U.S. Coast Guard Sector San Francisco
Stefano Cantarut	Wartsila / Marine Engineering
Michael Carter	U.S. Department of Transportation Maritime Administration
Yesid Castano-Cerpa	The Building People
Peter Chen	California Energy Commission
John Christensen	National Renewable Energy Laboratory subcontractor
Andre Coleman	Port of San Francisco
Elizabeth Connelly	National Renewable Energy Laboratory
Renaud Cornu	GE Power Conversion
Hannah Davelman	British Consulate-General San Francisco
Mercedes de Juan	Fundación Valenciaport
Peter Devlin	U.S. Department of Energy
Lloyd Diaz	U.S. Coast Guard
Joerg Ferchau	Cummins
Elaine Forbes	Port of San Francisco
Leslie Goodbody	California Air Resources Board
Laurence Grand Clement	Persee
William Hall	Matson
Olav Hansen	Lloyd's Register
Paul Helland	NCE Maritime CleanTech
Jamie Holladay	Pacific Northwest National Laboratory
David Hume	Contractor - U.S. Department of Energy
Katsuya Ishikawa	KAWASAKI HEAVY INDUSTRIES, LTD.
Will James	Savannah River National Laboratory
Chris Jenks	California Energy Commission
Carolyn Junemann	USDOT Maritime Administration
Zoltan Kelety	Scripps Institution of Oceanography
Yusuke Kidoura	ClassNK
Lennie Klebanoff	Sandia National Laboratories

Name	Company/Organization
John Kopasz	Argonne National Laboratory
Theodore Krause	Argonne National Laboratory
Brian Lindgren	Kenworth Truck Company
Timothy Lipman	Lawrence Berkeley National Laboratory
Gordon Loebl	Hornblower Cruises & Events
Alan Mace	Ballard Power Systems
Britney McCoy	U.S. Environmental Protection Agency
Sean Miki	NEDO
Robert Missen	European Commission
Steffen Moeller-Holst	SINTEF
Pietro Moretto	Joint Research Centre of the European Commission
Charles Myers	CSRA/Oak Ridge National Laboratory
Sean Newlin	Bay Area Air Quality Management District
Koichi Nishifuji	ClassNK
Eiji Ohira	NEDO
Narendra Pal	Golden Gate Zero Emission Marine
Dionissios Papadias	Argonne National Laboratory
Dimitrios Papageorgopoulos	U.S. Department of Energy
Eric Parker	U.S. Department of Energy
Joe Pratt	Golden Gate Zero Emission Marine
Stephen Radmard	Golden Gate Zero Emission Marine
Mark Richards	U.S. Department of Energy
Dhilon Rodricks	Wartsila
Sunita Satyapal	U.S. Department of Energy
Keith Schmid	Plug Power
Susan Schoenung	Longitude 122 West, Inc.
Erik Schumacher	NOW - National Organisation Hydrogen and Fuel Cell Technology
Jo Sletbak	Royal Norwegian Consulate General in San Francisco
Ryan Sookhoo	Hydrogenics Corp.
Lindsay Steele	Pacific Northwest National Laboratory
Frank Strom	U.S. Coast Guard - Sector San Francisco
Anthony Teo	DNV GL
Arnoud Van de Bree	Nedstack Fuel Cell Technology BV
Roel Van de Pas	Nedstack Fuel Cell Technology BV
Klaus Vanska	ABB Marine & Ports
Chengfeng Wang	Bay Area Air Quality Management District
David Wooley	Environmental Center, Goldman School Public Policy, UC Berkeley
Howard Wright	U.S. Coast Guard - Sector San Francisco
Jonathan Zimmerman	Sandia National Laboratories

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