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TECHNOLOGY ASSESSMENT: OCEAN-GOING VESSELS

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Acronyms and Abbreviations

ºC – Degrees Celsius
ACS – Air Cavity System
AF – Anti-Fouling
AIS – Automatic Identification System
AMECS – Advanced Maritime Emissions Control System
ATC – Alaska Tanker Company
BC – Black Carbon
BIMCO – Baltic and International Maritime Council
BTU – British Thermal Unit; mm BTU – one million British Thermal Units
CAAP – Clean Air Action Plan
CARB – California Air Resources Board
CO – Carbon Monoxide
CO_2 – Carbon Dioxide
COGAS – Combination gas and steam turbine system
Con-Ro – Container/Ro-Ro combination vessel
CORDIS – Community Research and Development Information Service
CPP – Controlled pitch propellers
DWI – Direct Water Injection
DWT – Dead Weight Tonnage
ECA – Emissions Control Area
EEDI – Energy Efficiency Design Index
EEOI – Energy Efficiency Operational Indicator
EEZ – Exclusive Economic Zone
EGR – Exhaust Gas Recirculation
EGR-HPE – Exhaust Gas Recirculation-High Pressure Economizer
ESD – Energy saving device
ESI – Environmental Ship Index
EU – European Union
FEU – Forty-foot Equivalent Unit
FR – Foul Release
FWE – Fuel/Water Emulsions
GHGs – Greenhouse Gases
GWP – Global Warming Potential
GTT – Gaztransport & Technigaz
HAM – Humid Air Motor
HERCULES – Higher Efficiency, Reduced Emissions, Increased Reliability and Lifetime, Engines for Ships
HC – Hydrocarbons

HFO – Heavy Fuel Oil
HR – Hour
IACCSEA – International Association for Catalytic Control of Ship Emissions to Air
ICCT – International Council on Clean Transportation
IEEC – International Energy Efficiency Certificate
IEEE – Institute of Electrical and Electronics Engineers
IMarEST – The Institute for Marine Engineering, Science, and Technology
IMO – International Maritime Organization
JIT – Just In Time
KG – Kilograms
KW – Kilowatt
LH2 – Liquid Hydrogen
LNG – Liquefied Natural Gas
LPG – Liquefied Petroleum Gas
LSFO – Low Sulfur Fuel Oil
MAAP – Multi-Angle Absorption Photometer
MALS – Mitsubishi air-lubrication systems
MARAD – U.S. Department of Transportation's Maritime Administration
MARPOL – International Convention on the Prevention of Pollution from Ships
MCR – Maximum Continuous Rating
MDO – Marine Diesel Oil
MDT – Man Diesel & Turbo
METS-1 – Marine Exhaust Treatment System-1
MGO – Marine Gas Oil
MOU – Memorandum of Understanding
MPH – Miles Per Hour
MSC – Mediterranean Shipping Company
MSS – Micro Soot Sensor
MTI – Monohakobi Technology Institute
MW – Megawatts
MWh – Megawatt-Hour
NM – Nautical Miles
NOx – Nitrogen Oxides
NYK – Nippon Yusen Kaisha
OGV – Ocean-Going Vessel
PAX – Photoacoustic extinction meter
PCC – Pure Car Carrier
PCTC – Pure Car Truck Carrier
PLS – Pulse Lubricating System

PM – Particulate Matter; PM 2.5 - Particulate Matter 2.5 microns or less
PM 10 - Particulate Matter 10 microns or less
PPM – Parts per Million
POLA – Port of Los Angeles
POLB – Port of Long Beach
ROG – Reactive Organic Gases
Ro-Ro – Roll On-Roll Off
RTA – Required Time of Arrival
SAM – Scavenging Air Moistening
SCR – Selective Catalytic Reduction
SECA – Sulfur Emissions Control Area
SEEMP – Ship Energy Efficiency Management Plan
SFAP – Sustainable Freight Action Plan
SIP – State Implementation Plan
SOx – Sulfur Oxides
SPC – Self-Polishing Copolymer
STC – Surface Treated Coatings
TAP – Technology Advancement Program
TEU – Twenty-foot Equivalent Unit
TSS – Traffic Separation Scheme
UCR – University of California Riverside
ULCC – Ultra Large Crude Carrier
ULCV – Ultra Large Container Vessel
ULSFO – Ultra-low Sulfur Fuel Oil
U.S. – United States of America
U.S. EPA – United States Environmental Protection Agency
USCG – United States Coast Guard
VLCC – Very Large Crude Carrier
VOC – Volatile Organic Compounds
VSR – Vessel Speed Reduction
WHR – Waste Heat Recovery
ZEV – Zero Emission Vehicles

EXECUTIVE SUMMARY

One of the California Air Resources Board's (CARB) objectives is to transition on-road and off-road mobile sources to zero tailpipe emissions everywhere possible, and near-zero emissions with clean, low carbon renewable fuels everywhere else to meet air quality and climate goals. The purpose of this ocean-going vessel technology assessment is to provide an assessment of the current and projected development of technologies over the next five to ten years that can be used to reduce emissions from OGVs. This Technology Assessment will help inform and support CARB planning, regulatory, and voluntary incentive efforts, including:

- California Sustainable Freight Action Plan,
- State Implementation Plan development,
- California's Climate Change Scoping Plan,
- Funding Plans,
- Governor's Zero-Emission Vehicle Action Plan, and
- California's coordinated goals to reduce greenhouse gases (GHG) and petroleum use by 2030 and 2050.

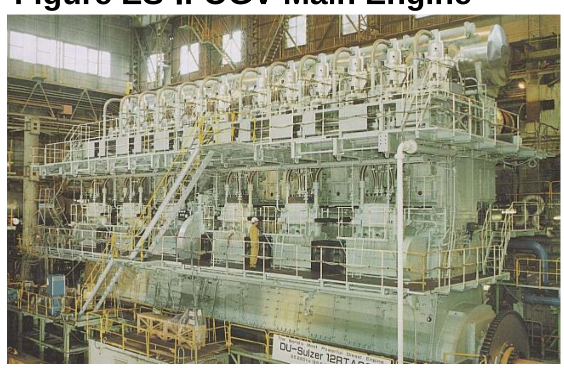
The scope of this Technology Assessment will focus on conventional and advanced technologies applicable to ocean-going vessels.

1. What are ocean-going vessels?

Ocean-going vessels (OGV) are large vessels designed for deep water navigation. Types of OGVs include large cargo vessels such as container vessels, tankers, bulk carriers, and car carriers, as well as passenger cruise vessels. These vessels transport containerized cargo, bulk items such as vehicles, cement, and coke, liquids such as oil and petrochemicals, and passengers. OGVs travel internationally and may be registered by the United States Coast Guard (USCG) as a U.S.-flagged vessel, or under the flag of another country (foreign-flagged vessel). The majority of vessels that visit California ports are foreign-flagged vessels.

2. What types of engines are found on ocean-going vessels?

Figure ES-I: OGV Main Engine



OGVs generally have multiple engines and boilers on board. Typically, with the exception of passenger cruise ships, OGVs will have a single large two-stroke main engine used for propulsion, and several smaller four-stroke auxiliary "generator-set" engines. Passenger cruise vessels and some tankers use a different engine configuration referred to as "diesel-electric." These vessels use large four-stroke diesel generator sets to provide electrical power for both propulsion and ship-board electricity.

Main engines on OGVs are designed to propel large vessels, thus the engines themselves are much larger than traditional diesel engines. For example, a nine cylinder K98MC-C MAN engine produces about 40 megawatts (MW), enough energy to power 30,000 houses for a year. The 65 feet long by 60 feet high engine is as tall as a five-story building, weighs about 1,500 tons, and costs about $15 million. Main engines are referred to as "Category 3" engines by United States Environmental Protection Agency (U.S. EPA), and have a displacement of greater than 30 liters per cylinder.

Auxiliary engines on OGVs generally provide power for uses other than propulsion. They are four-stroke diesel engines that are smaller than the main engines. Most OGVs have more than one auxiliary engine. Auxiliary engines are usually coupled to generators used to produce electrical power. On cargo vessels, most auxiliary engines are used to provide ship-board electricity for lighting, navigation equipment, refrigeration of cargo, and other equipment. Passenger cruise vessels, and some tankers, are unique in that they use auxiliary engines and generator sets to provide electrical power for both propulsion and ship-board electricity.

Auxiliary boilers are fuel-fired combustion equipment designed primarily to produce steam for uses other than propulsion, such as heating of residual fuel and liquid cargo, heating of water for crew and passengers, powering steam turbine discharge pumps, freshwater generation, and space heating of cabins. Boilers used to provide propulsion are called steamships and are not included in this assessment because there are very few still in service.

3. What ocean-going vessel technologies were assessed?

Staff looked at conventional and advanced technologies applicable to OGVs for this technology assessment. These technologies were categorized into the following areas:

- Alternative Fuels
- Engine Technologies
- Engine Support Technologies
- After-Treatment (Exhaust) Controls
- At-Berth Technologies
- Alternative Supplemental Power
- Vessel Efficiency Improvements

This does not represent the full universe of applicable technologies. Staff focused on the technologies showing the most promise for commercialization within the next ten years, and will continue to monitor and evaluate new technologies and product advancements.

4. What are the preliminary findings from the technology assessment?

Although OGVs are already a relatively efficient mode of transporting goods (in terms of emissions per ton-mile), significant additional emission reductions are possible. Technologies are available that will move vessels at dockside toward CARB's long-term goal of zero and near-zero emissions. For vessels at sea, significant emission reductions and efficiency improvements are also possible, particularly as new vessels are built. Promising technologies include systems for recycling heat energy, advanced designs for hull, propellers and rudders, optimization of the draft and speed for a given route and arrival time, and monitoring the fouling of hulls and propellers. Engine technologies are also an essential factor for achieving the potential benefits and include electronic controls that improve fuel efficiency, liquefied natural gas (LNG) engines, or diesel engines with selective catalytic reduction (SCR) after-treatment. As discussed in this Technology Assessment, many of these technologies are already being implemented by vessel and engine manufacturers to improve efficiency and comply with state, federal, and international regulatory requirements as they design and build new vessels.

Existing regulations at the state, federal, and international levels will achieve significant progress in the next five to ten years. For example, international Tier III oxides of nitrogen (NOx) standards for new 2016 vessels will reduce NOx emissions by 80 percent within Emission Control Areas (ECAs) when compared to 2012 baseline vessels. Vessels at dockside in California are now increasingly turning off their diesel generators and plugging in to shore-side electrical power. However, there is more to be done, and there are many technologies that can move vessels well beyond these significant reductions as discussed in this assessment. To accelerate the implementation of these technologies, CARB staff is pursuing the following actions in the next few years:

- Advocating with national and international partners for new International Maritime Organization (IMO) Tier IV NOx and particulate matter (PM) engine standards,
- Exploring more aggressive GHG emissions reductions targets above and beyond existing IMO goals,
- Defining criteria for a "Low Emission Ship Visit" and develop seaport incentive programs to encourage these vessels to visit California ports, and
- Proposing amendments to CARB's Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth in a California Port (referred to as the At-Berth Regulation) to expand the use of shore-side power and other technologies and increase the number of vessels and OGV marine terminals required to control emissions at berth.

In addition to CARB's efforts to advocate for stricter standards to control local and regional pollutants that impact the health of people living in California port communities, CARB is also focusing on GHG emissions reductions from OGVs. Commercial shipping is the fastest growing sector in terms of GHG emissions. Recognizing the projected adverse effects of global climate change, more aggressive GHG emissions reductions targets above and beyond those currently set at the international level need to be established in order to reduce the negative effects of global climate change and achieve California's ambitious air quality and climate goals. CARB staff are exploring the development of a new Tier IV NOx and PM standard, as well as accelerated GHG emissions reductions goals, and invite input regarding targets that the agency can advocate for on an international level.

Some of the key technologies needed to reach these goals and achieve tighter standards for OGVs are listed below:

New Vessels and Engine Retrofits

- LNG engines
- SCR
- Exhaust heat recovery
- Advanced ship design (including more fuel-efficient engines, optimized hull and propellers)

In-use Strategies

- Expand use of at-berth technologies (e.g., shore-side power, fuel cells, and emissions capture and control systems)
- Bring cleaner vessels to California (e.g., vessels meeting Tier III or stricter standards)
- Propeller and hull maintenance
- Alternative fuels
- Operational improvements (e.g., logistics, scheduling, weather routing)

Collaborative efforts are underway to better understand the opportunities that these technologies could provide. The two major OGV engine manufacturers, MAN Diesel & Turbo (MDT) and Wärtsilä, have worked together with industry partners on a joint project called HERCULES (Higher Efficiency, Reduced Emissions, Increased Reliability and Lifetime, Engines for Ships) since 2002 to develop new technologies for marine engines that are designed to increase engine efficiency and reduce fuel consumption and carbon dioxide (CO_2) emissions, reduce gaseous and particulate emissions, and increase engine reliability. The initial phases of the HERCULES project (A, B, and C) reached completion in 2015, and showed results of 1 percent to 2 percent improvement of fuel consumption with correlated CO_2 emission reductions, a 50 percent reduction in PM and total hydrocarbons, and an 80 percent reduction for NOx as a result of a variety of optimization strategies and exhaust after-treatments. Moving forward, the next phase of the project 'HERCULES-2' will target development of a large, adaptable fuel flexible marine engine, utilizing combinations of exhaust gas after-treatment, advanced combustion techniques, new fuels, and control systems to enhance reliability and economy of the engines (Hercules, 2017).

Another effort, the "Green Ship of the Future," is a collaborative effort seeking to reduce CO_2 by 30 percent, sulfur oxides (SOx) by 90 percent, and NOx by 90 percent with the focus on ship design, machinery, propulsion, operation and logistics. Today, this open private-public partnership has approximately 40 companies working together to identify innovative technologies and operational strategies to meet the Green Ship of the Future emission reduction targets. These efforts are being driven in part by GHG and NOx emissions requirements developed by the IMO, but no completion date was established to implement these voluntary efforts on a wider scale. Another recent effort by the European Research Association, “Vessels for the Future,” is focusing on ambitious emission reduction goals for 2050. Specifically, the initiative is aiming to reduce vessel CO_2 emissions by 80 percent, and NOx and SOx emissions by nearly 100 percent. This effort would be a public-private partnership composed of private companies, research institutes, academic organizations and other interested associations. The group is planning to target research in several maritime technologies: new materials and processes, fuels and propulsion systems, information and communication technology, hull water interaction, energy management and novel vessel design concepts.

5. What are the main challenges to reducing emissions from ocean-going vessels?

While numerous emission reduction technologies are available or under development, there are several challenges to maximizing the deployment of these technologies. These challenges are briefly described in this section.

- Vessels visiting California represent a small portion of the global fleet

There are about 55,000 OGVs worldwide. The vast majority of OGVs travel internationally with routes that change depending on market demand and the cargo they are transporting. Because of this, OGVs that visit California ports will change from year to year. In a given year, about 2,000 of these vessels will visit California seaports and a significant percentage will not return the next year. Based on data from the California State Lands Commission, over the years 2007-2015 there were 7,210 unique vessels that visited California seaports. Of these vessels, about 30 percent made only 1 port call in the 8 year period. To maximize the emissions benefits of emission reduction technologies, a large pool of vessels in the global fleet would need to embrace these technologies.

- Technologies require significant investment

Building an OGV requires a significant capital investment and depends on a variety of factors, specifically the desired cargo or passenger capacity. As an example, for container vessels, the number of twenty foot equivalent units (TEUs), meaning one standard 20 foot shipping container, that the vessel can carry will dictate how large the vessel needs to be and, in turn, the costs. The largest capacity container ships in use can carry over 20,000 TEUs, the largest of which is the OOCL Hong Kong at 21,413 TEUs at a cost of over $150 million (Schuler, 2017). In comparison, the world’s largest cruise ship, Harmony of the Seas, can carry over 8,600 passengers/crew and cost nearly $1 billion to build (Zhang, 2016).

Given the high cost of a new build, vessels are not often owned by a single individual, but rather by multiple individuals, consortiums of investment funds, and/or shipping companies. Many of these vessels are also offered for charter and are not operated by the owner(s). Because of the vessel costs, owners may be hesitant to experiment with new technologies that may add additional costs to an in-use vessel. However, as new vessels are built, the cost for new technologies is generally less than a retrofit and can be more easily incorporated into the cost of a new vessel and amortized over the life of the vessel.

- OGVs have long lifespan

Many of the technologies are only applicable to new builds so the penetration of these technologies will occur as the fleet turns over. Since OGVs are designed to remain in service for 25 years or more, it can take many years to realize the benefits of new technologies incorporated into a new vessel design.

- Zero/near-zero emission technologies not currently available for vessels at sea

Other than nuclear power, technologies are not currently available for vessels at sea that can achieve our long-term goal of zero and near-zero emissions. Nevertheless, significant reductions are still possible using existing technology such as LNG, biofuels, SCR, more efficient vessel design, and other technologies.

- Challenging to retrofit

Engines on OGVs are very large and account for a significant portion of the capital costs associated with retrofitting. This can lead to hesitancy on the owner's part to experiment with new technologies that may add additional costs to the vessel. A rough estimate of the engine cost is $300 to $400 per kilowatt (kW) (DNV-GL, 2012). For a typical 40,000 kW main engine, that translates into a cost of $12 million to $16 million. Because the vessel is typically built around the large main engine, space is limited which makes retrofits involving modifications, such as large control equipment or changes in piping, either impossible or extremely expensive. Also, as the operator of the vessel is typically responsible for the fuel costs, there is less incentive for the owner(s) of the vessel to pay for expensive retrofits that may cost in the millions of dollars to reduce fuel consumption if the vessel is chartered out.

- Fuel availability

OGV operators are subject to the availability of fuels at the ports where they travel, and there are more than 400 ports around the world that have marine fuel bunkering operations. Based on inspection data collected by CARB from 2009-2011, about 80 percent of the bunkered fuel sampled from OGVs visiting California ports came from six regions: United States (U.S.), Asia-Korea, Asia-China, Asia-Singapore, and Northern Europe. A vessel operator that wants to use a cleaner or alternative fuel needs to ensure that the fuel is available at all or most of the ports that it may use for bunkering.

Fuel is the biggest operating expense -- by some estimates about 80 percent of a cargo vessel operating cost, dwarfing crew labor costs and even the annualized capital cost of purchasing the vessel. As a result, emission reduction technologies that involve more expensive cleaner fuels can have a significant impact on operating costs.

- Operate in a marine environment

Many emission control technologies face unique challenges when operating in a marine environment. Air pollution control equipment may be subject to extreme weather, vibration, and a corrosive environment. This may require the use of more rugged electronic equipment and special materials, potentially increasing costs.

6. What additional work and research is needed?

While significant efforts are being made to reduce vessel emissions, there are still knowledge gaps where additional research and work is needed. Some of these areas include:

- Determine how to assist in the implementation of a robust fueling infrastructure for alternative fuels like LNG (e.g., funding, permit assistance, and site location),
- Investigate the most effective approaches to encourage vessel operators to retrofit older vessels and purchase the cleanest new vessels capable of emissions reductions that exceed regulatory requirements,
- Evaluate approaches to bring the cleanest vessels to California ports and to ensure that the cleanest and most efficient vessels are being designed and built;
- Validate the emission control effectiveness and economics of emerging technologies, and
- Test the long-term durability of technologies not yet proven in a marine environment.
- Solicit feedback from industry (including engine manufacturers, ship builders, and other stakeholders) regarding the establishment of Tier IV NOx and PM standards, along with accelerated GHG emissions reductions targets.

7. What are the next steps to support further emissions reductions from OGVs?

A number of steps can be taken to support further emission reductions from OGVs. These include: (1) the formation of partnerships, (2) support for research and demonstration projects, and (3) incentive programs and regulations.

As discussed previously in Question 5, OGVs travel and bunker fuel internationally, and they are mostly registered and built overseas. Due to these challenges, partnerships with federal and international organizations are needed to support cleaner vessel development. These efforts may include the following:

- Collaborate with U.S. EPA, USCG, and other partners to advocate for new IMO Tier IV NOx and PM standards, and vessel efficiency targets for OGVs not covered by IMO efficiency regulations,
- Track research and demonstration projects by the Department of Defense, U.S. Navy, and others on biofuels and propulsion technology,
- Work with the Pacific Coast Collaborative on reducing emissions from west coast ports,
- Work with national and subnational jurisdictions through the Memorandums of Understand (MOU) and the United Nations Green Freight Action Plan to advocate for marine-related actions,
- Work with ship operators, engine manufacturers, and others on standards for renewable biofuels, and
- Work with partners to develop a robust liquefied natural gas fueling infrastructure.

Support for research and demonstration programs to evaluate emerging technologies can help identify the technologies with the most promise to reduce emissions. These efforts may include:

- Support NOx retrofit technology demonstrations for in-use vessels not subject to IMO Tier III NOx standards,
- Evaluate the effectiveness of emission control technologies and other innovative on-board technologies on black carbon, NOx, SOx, PM, GHGs, and
- Seek federal funds from the U.S. Department of Transportation's Maritime Administration (MARAD) and the U.S. Department of Energy for technology and fuel demonstration projects.

Finally, CARB regulations and incentive programs can require or provide the impetus for vessel operators to pursue the cleanest available technologies. These instruments may include the following:

- Develop an OGV renewable biofuels market through proposal of an amendment allowing the option to include these fuels in the Low Carbon Fuel Standard if it is adopted, or inclusion in the Cap-and-Trade Regulation,
- Define criteria for a Low Emission Ship Visit and achieving early implementation of clean technologies via incentive programs,
- Support existing and develop new incentive programs to help offset the costs of existing and emerging technologies (both shore side and vessel based), and
- Amend CARB's At-Berth Regulation to include other technologies and increase the number of vessels required to control emissions at berth in order to achieve additional emission reductions.

I. INTRODUCTION AND PURPOSE OF ASSESSMENT

This chapter provides background information on the motivation for the technology assessment and the process used to develop the assessment. It also provides a brief description of the parameters that were evaluated as staff researched technologies for OGVs.

A. Purpose of the Technology Assessment

The California Air Resources Board's (CARB) objective is to transition on-road and off-road mobile sources to zero tailpipe emissions everywhere possible, and near-zero emissions with clean, low carbon renewable fuels everywhere else, to meet air quality and climate goals. The purpose of this ocean-going vessels (OGV) technology assessment is to provide an assessment of the current and projected development of technologies over the next five to ten years that can be used to reduce emissions from OGVs. This Technology Assessment will help inform and support CARB planning, regulatory, and voluntary incentive efforts, including:

- California Sustainable Freight Action Plan,
- State Implementation Plan development,
- California's Climate Change Scoping Plan,
- Funding Plans,
- Governor's Zero-Emission Vehicle Action Plan, and
- California's coordinated goals to reduce greenhouse gases (GHG) and petroleum use by 2030 and 2050.

The technology assessment will focus on conventional and advanced technologies applicable to OGVs. Some of these technologies are currently in use and others are in developmental stages for use on OGVs. Some examples include:

- LNG dual-fuel engines,
- Advanced fuel injection,
- Electronically controlled cylinder lubrication systems,
- Automated engine monitoring/optimized combustion control systems,
- Exhaust gas recirculation,
- Advanced turbo charging,
- Selective catalytic reduction,
- Exhaust gas scrubbers,
- Shore-side electrical power (cold ironing),
- Fuel cells,
- Sails,
- Propeller and hull design,
- Speed reduction,
- Exhaust heat recovery, and
- Enhanced hull and propeller maintenance.

B. Process

Staff conducted a literature review for each prospective technology. They contacted and interviewed people with knowledge and expertise in such technologies from various institutions, including, but not limited to: national laboratories, university researchers, technology experts, engine manufacturers, original equipment manufacturers, dealers, fuel suppliers, retrofit companies, port operators, and engineering consultants.

C. Technology Assessment Elements

For each technology, CARB staff gathered information on the elements listed below.

1. Technology Description – A description of the technology and how it works, including the advantages and disadvantages of the technology.

2. System/Network Suitability and Operational Infrastructure Needs - The requirements for the technology including fueling needs, fuel storage, operating range.

3. Technology Readiness – A description of the stage of development (e.g. research and development, prototype/pilot demonstration, pre-commercial demonstration, or commercially available) is discussed for each technology. Completed or planned demonstration projects and the results are described. A discussion is included of the scope of commercial introduction (number in use), how widely available it is (where, what types of fleets/applications), and sales rate estimates (current, five years and ten years from now).

4. Economics - Current costs (e.g. capital, operational, maintenance) are discussed, if known, at current production levels and anticipated costs if production can be expanded. A comparison is made to conventional technology costs, both at current production levels and potentially widespread deployment levels. Potential returns on investment or payback period are discussed.

5. Emissions Reductions – The per-unit emissions levels for GHG, criteria pollutants, and toxic air contaminants that can be achieved from the technology are discussed.

6. Next Steps to Demonstration/Deployment – A discussion of the issues and deployment challenges that may impede deployment or become a barrier to commercialization.

These elements are discussed further in Chapter III for the technologies evaluated in this assessment. CARB staff undertook thorough reviews of the majority of available technologies during the process of writing this assessment. Technology is ever-evolving, however, and it should be noted that this document serves only as a snapshot of the many technologies that may be available to help achieve emissions reductions from OGVs in the future.

II. OVERVIEW OF OCEAN-GOING VESSELS, EMISSIONS, AND CONTROL PROGAMS

This chapter discusses the various types of OGVs, engines, and fuels currently used by this sector. Information on emissions from OGVs and other implemented emission control programs are also discussed.

A. Fleet Characteristics

OGVs are large cargo vessels designed for deep water navigation. Types of OGVs include container vessels, tankers, bulk carriers, refrigerated cargo (or reefer) vessels, general cargo vessels, roll on-roll off (or Ro-Ros) and auto carriers, and passenger cruise vessels. These vessels transport a myriad of goods, including containerized cargo, bulk items such as vehicles, cement, and grains, liquids such as oil and petrochemicals, and passengers. OGVs travel internationally and may be registered by the U.S. Coast Guard (U.S.-flagged), or under the flag of another country (referred to as foreign-flagged). The majority of vessels that visit California ports are foreign-flagged vessels.

Container Vessels

Figure II-1: Container Vessel

Container vessels (Figure II-1) are cargo vessels that carry standardized truck-sized containers. These containers have capacities measured in TEUs (Twenty-foot Equivalent Units). One TEU refers to a container with external dimensions of 8'x8'x20'. Capacity is sometimes also measured by FEUs (Forty-foot Equivalent Units, 8'x8'x40'), since the majority of containers used today are 40 feet in length. Many vessels also have a number of electrified container slots that will accept refrigerated containers, which is a trend that is expected to grow as larger container vessels install more reefer plugs on board.
Newer, larger container vessels are able to transport between 5,000 and 22,000 TEUs whereas older vessels built prior to 1970, typically hold less than 1,000 TEUs (Maersk, 2014). Container vessels are growing in size due to the greater efficiencies provided in terms of cost, fuel use, and emissions per TEU transported. However, there are limits to vessel size due to constraints, such as the need to fit through the Panama Canal, and the eventual need for a dual-motor, two propeller configuration. Most container vessels, like most other OGVs, are propelled by a single large slow-speed two-stroke diesel engine. Most container vessels also have several smaller medium speed four-stroke auxiliary engines. The auxiliary engines provide electrical power for lighting, navigation equipment, and other ship-board uses.

Passenger Cruise Vessels

Figure II-2: Cruise Vessel

Passenger cruise vessels (Figure II-2) are passenger vessels used for pleasure voyages. These vessels typically stop at ports, where there are coordinated activities for their passengers. As with other types of vessels, the size and capacity of these vessels has increased steadily over the years.

Table II-1 provides an example of how passenger cruise vessel sizes have changed over the past 40 years (Royal Caribbean, 2014). The largest cruise vessel to date, Harmony of the Seas, was completed in 2016 and is operated by Royal Caribbean International. At a length of 1,188 feet and 226,963 gross tons, it can hold slightly more than 5,400 passengers.

Table II-1: Trends in Typical Size of Passenger Cruise Vessels

Year Built	Tonnage	Number of Passengers
1970	18,420	377
1980	37,600	707
1990	74,140	975
2000	137,300	1,557
2010	225,282	5,400
2016	226,963	5,479

Cruise ship propulsion is typically provided by several diesel engines coupled to generators. These generators produce electrical power that drives electric motors coupled to the vessel's propellers. This arrangement provides the option to run the vessel at a slower speed while operating fewer engines at their peak efficiency, as opposed to a single engine at low, relatively inefficient loads. The same engines that are used for propulsion are also used to generate auxiliary power on-board the vessel for lights, refrigeration, etc. Some vessels have the electric motor outside the ship's hull in an azipod, which is a propeller mounted on a steerable pod containing the electric motor that drives the propeller. This method eliminates the need for a rudder as the pod can be rotated to provide thrust in any direction. Some vessels also have a combination of a fixed propeller and azipods.

Ro-Ro Vessels

Figure II-3: Ro-Ro Vessel

Roll on-Roll off (Ro-Ro) vessels (Figure II-3) traditionally carry wheeled cargo such as automobiles, heavy duty vehicles, or railway carriages. These vessels have built-in ramps, which allow the cargo to be "rolled on" and "rolled off" the vessel when at port. Typically, new automobiles are transported by vessel around the world on Ro-Ros called Pure Car Carriers (PCCs) or Pure Car-Truck Carriers (PCTCs), also often referred to as Auto or Vehicle Carriers. The largest Ro-Ro currently in service is called The Höegh Target, with a capacity of over 8,500 cars. Smaller ferries that operate across rivers and other short distances often have similar ability to transport wheeled cargo, such as automobiles, however the term Ro-Ro is generally reserved for OGVs. A subset of Ro-Ro vessels do exist with the capacity to carry both automobiles and containers or passengers on longer cross-ocean voyages, referred to as a Con-Ro and Ro-Pax vessels, respectively. These vessels exist for mostly niche voyages, such as California to Hawaii loops.

Reefer Vessels

Figure II-4: Bulk Reefer Vessel

A reefer vessel (Figure II-4) is a heavily insulated ship that operates essentially as a large, floating refrigerator or freezer. It is typically used to transport perishable commodities which require temperature-controlled transportation, such as fruit, meat, fish, vegetables, dairy products, and other foods. On board bulk reefer vessels, cargo can be stored below deck in large divided holds, allowing for varying temperatures for different cargo types. Bulk reefer cargo is often loaded in palletized form, and can be unloaded using cranes, conveyor belts, and forklifts. Modern day reefers are typically designed to carry refrigerated containers on deck; these refrigerated containers are standardized sizes, same as non-refrigerated containers, but contain an internal refrigeration unit and requires an external power source. On containerized reefer vessels, refrigerated containers are plugged in to power the refrigeration unit. The rise in popularity of refrigerated container reefer vessels has caused a decline in the bulk reefer industry, as refrigerated containers make for an easier, more efficient way to move cargo. The typical capacity for a containerized reefer is less than 1,000 TEUs, though the largest specialized containerized reefers, owned by Dole Chile, can carry up to 2,000 TEUs.

Bulk Carriers

Bulk carriers (Figure II-5) are used to transport dry or liquid items in bulk, such as mineral ore, fertilizer, wood chips, grain, chemicals, or food grade liquids such as fruit juices, and are classified into four main categories, as shown in Table II-2. Dry bulk carriers have large box-like hatches on their deck, designed to slide outboard for loading, with cargo stowed in holds below deck. Dry bulk carriers primarily carry dry cargo that is shipped in large quantities and does not need to be carried in packaged form. Principal dry bulk cargos are comprised of coal, iron ore, bauxite, phosphate, petcoke, potash, nitrate, and grains such as wheat, corn, and soy. The advantage of carrying such goods in bulk is that packaging costs can be greatly reduced and loading and unloading operations can be expedited. Liquid bulk carriers are similar to dry bulk carriers, but contain specialized tanks that allow for the transportation of liquids, both refrigerated and non-refrigerated.

Figure II-5: Dry Bulk Vessel

Table II-2: Bulker Classifications

Classification	Deadweight Tonnage (DWT)
Handysize	10,000 – 35,000
Handymax/Supramax	35,000 – 59,000
Panamax	60,000 – 80,000
Capesize	> 80,000

General Cargo Vessels

General cargo vessels (Figure II-6) are built to carry a wide variety of dry non-bulk cargo that often does not fit well on other, more specific vessel types, such as large construction equipment or windmill blades. General cargo vessels are also capable of transporting things such as non-refrigerated food products, steel/steel scrap, containers, and bagged cargo, as business demands. General cargo vessels are typically smaller than 20,000 DWT.

Figure II-6: General Cargo Vessel

Tanker Vessel

Figure II-7: Tanker Vessel

Tanker vessels (Figure II-7) are vessels designed to transport liquids in bulk, many of which are labeled as hazardous cargo. Most tankers are designed with specialized tanks to hold liquids that present a high pollution risk, some of which require special heating/cooling systems. As such, there is a strong emphasis on safety when it comes to tanker operations. Tankers can range in size from several hundred tons to several thousand tons and are designed to sail along a variety of routes, from coastal voyages to transoceanic voyages. Tankers, much like bulk carriers, are classified using DWT and there are six main classifications as shown in Table II-3.

Table II-3: Tanker Classifications

Classification	Deadweight Tonnage (DWT)
Seawaymax	10,000 – 60,000
Panamax	60,000 – 80,000
Aframax	80,000 – 120,000
Suezmax	120,000 – 200,000
Very Large Crude Carrier (VLCC)	200,000 – 315,000
Ultra Large Crude Carrier (ULCC)	315,000 – 520,000

A wide range of products are carried by tankers, including: crude oil or other hydrocarbon products, such as Liquid Petroleum Gas (LPG), LNG; and chemicals, such as ammonia, chlorine, and styrene monomer, asphalt, and even fresh water. Different products require different handling and transport, thus special types of tankers have been built, such as chemical tankers, oil tankers, product tankers, and LNG/LPG carriers.

B. OGV Engine Types

Figure II-8: OGV Main Engine

OGVs propulsion is driven by very large diesel engines. Typically a cargo vessel will possess a single two-stroke main engine used for propulsion and several smaller auxiliary “generator-set” engines for shipboard electrical needs. Passenger cruise vessels and some tankers use a different engine configuration referred to as diesel-electric. These vessels use large four-stroke diesel generator sets to provide electrical power for both propulsion and ship-board electricity. Based on a survey conducted by CARB staff in 2008, MAN Diesel & Turbo (MDT), Wärtsilä, and Mitsubishi are the primary manufacturers of OGV main engines.

Main engines on OGVs propel very large vessels; therefore, the engines themselves are also very large, as seen in Figure II-8. For example, a nine cylinder K98MC-C MDT engine produces about 40 MW, enough energy to power 30,000 houses. The 65 feet long by 60 feet high engine is as tall as a five-story building, and weighs about 1,500 tons. Main engines are referred to as Category 3 engines and have a displacement of greater than 30 liters per cylinder.

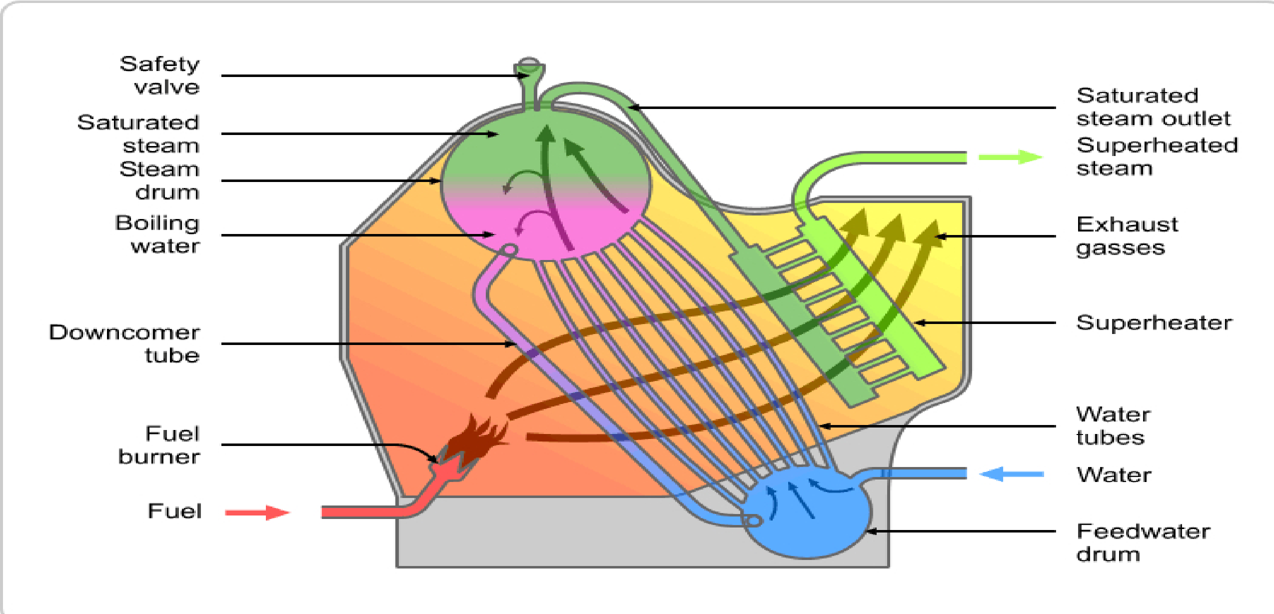
Ship-board electricity is most often produced by auxiliary engines (Figure II-9). These diesel engines provide power for uses other than propulsion (except as noted for diesel-electric vessels). Auxiliary engines are usually coupled to generators used to produce electrical power. Most OGVs have more than one auxiliary engine which is commonly four-stroke and smaller than the main engines. On cargo vessels, most auxiliary engines are used to provide ship-board electricity for lighting, navigation equipment, refrigeration of cargo, and other equipment.

Figure II-9: Three OGV Auxiliary Engines

Passenger cruise vessels, and some tankers, use a configuration that is referred to as diesel-electric. These vessels use large diesel generator sets to provide electrical power for both propulsion and ship-board electricity.

In addition to diesel main and auxiliary engines, most OGVs have boilers. A boiler is a closed vessel in which water is heated under pressure to produce steam. In marine boilers, the steam is used for a variety of purposes such as: heating residual fuel, producing hot water and space heating for passengers or crew, distilling seawater to generate fresh water, driving steam turbine pumps to offload crude oil or other petroleum products carried by tankers, and driving steam turbines for ship propulsion on steamships.

Figure II-10: Example of a Marine Boiler



(Engineering-Marine, 2010)

Marine boilers (see Figure II-10) vary in size from small auxiliary boilers used on most cargo vessels primarily to heat residual fuel, to large boilers used to propel steamships. Boilers used to provide propulsion to steamships are very rare and few steamships are still in service. Boiler output is typically rated in terms of steam capacity (weight of steam produced per hour at a given pressure). Cargo ship auxiliary boilers are typically rated in the one to ten tonnes steam per hour range, while tankers, using boilers to power steam turbine discharge pumps, will typically be rated above ten tonnes per hour. Boilers may also be rated by their power or thermal output (e.g., MW, horsepower, or British thermal units/hour (BTU/hr)) (CARB, 2008).

C. OGV Engine Manufacturers

There are many auxiliary engine manufacturers; however, only six manufacturers account for almost 92 percent of the engines surveyed (CARB, 2008). These auxiliary engine manufacturers are shown in Table II-4.

Table II-4: OGV Auxiliary Engine Manufacturers

Engine Maker	Number of Engines	Percent of Total Engines
MDT	806	32
Daihatsu	691	28
Wärtsilä	380	15
Yanmar	375	15
MAK	56	2
Other	192	8

There are also several main engine manufacturers, although three companies are responsible for the majority of the engines produced. As shown in Table II-5, MDT, Wärtsilä, and Mitsubishi produce the majority of the engines surveyed (CARB 2008).

Table II-5: OGV Main Engine Manufacturers

Engine Maker	Number of Engine Makes	Percent of Total Engines
Man Diesel & Turbo (MDT)	479	67
Wärtsilä	131	19
Mitsubishi	88	12
Other	13	2

D. California Activity

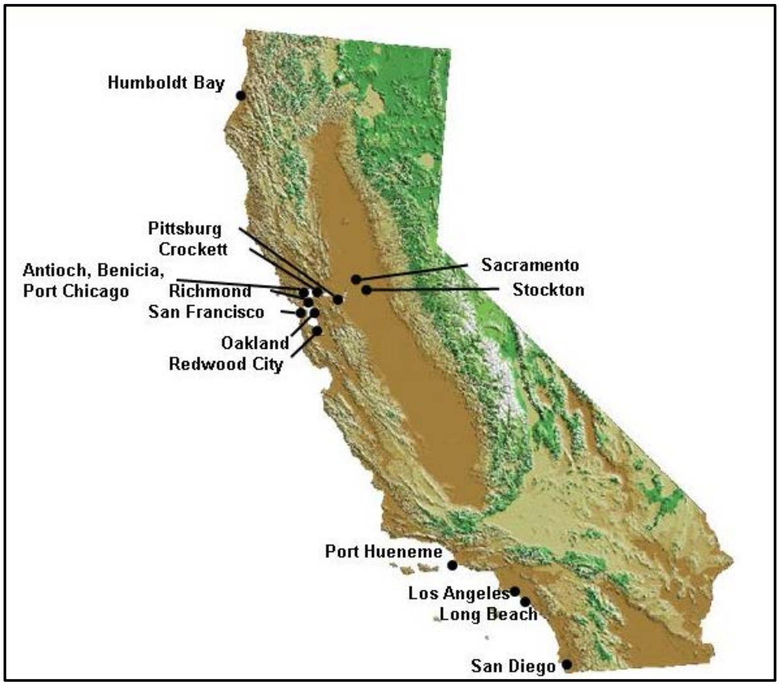
California is a key player in international shipping. All of the vessel types described in this document visit California ports delivering and receiving products used in California, the U.S., and the rest of the world. The coastline of California stretches more than 800 miles, from Mexico in the south to Oregon in the north. California is home to many seaports, including three mega-ports (Los Angeles, Long Beach, and Oakland), and several smaller ports. From 2009 through 2016, OGVs averaged 8,970 port calls annually. Table II-6 provides the annual number of calls by OGVs to California ports. Figure II-11 shows 16 of the key ports in California and their approximate locations.

Table II-6: California's Port Calls

Year	Total Number of Port Calls
2009	9,342
2010	8,655
2011	9,525
2012	9,020
2013	9,003
2014	8,936
2015	8,681
2016	8,597

(California State Lands Commission)

Figure II-11: California's Ports



The Port of Los Angeles (POLA) and Port of Long Beach (POLB) comprise the largest port complex in the U.S. and are key players in global freight movement. Together, they handle a fourth of all container cargo traffic in the U.S. In 2016, POLA recorded 1,251 container vessel calls with a container throughput of about 8.9 million TEUs (POLA, 2016a). Likewise, POLB saw 919 container vessels call the port with a throughput of around 6.7 million TEUs (POLB, 2016a).

The total number of containership visits at POLA and POLB decreased 15 percent and 31 percent respectively from 2005 to 2016. However, container throughput for that same 11 year time period increased 18 percent at POLA and 1 percent at POLB. This is indicative of the current trend of larger container vessels calling these particular ports. In fact, since 2005, TEUs per vessel visit is up 40 percent at POLA and 46 percent at POLB (POLA, 2016a; POLB, 2016a).

According to the Port of Oakland's website, more than 99 percent of containerized cargo moving through Northern California comes through their terminals. Oakland's cargo volume makes it the fifth busiest container port in the U.S. (Oakland, 2014). The Port of Oakland's most recent Emission Inventory in 2015 shows the port had 1433 vessel calls with about 2.3 million TEUs in throughput (Oakland, 2015). Total vessel call for Oakland during the ten year period from 2005 to 2015 decreased around 2 percent, with container throughput remaining steady (only around a 0.03 percent increase). This is also indicative of the current trend of increasing vessel size and capacity calling on California ports.

Container ships and tankers are the most common types of vessels calling at California ports. Data from the California Lands Commission (shown in Table II-7) indicate container and tanker vessels account for over half of the California port visits in 2015. The remaining six categories of vessels each account for 11 percent or less of vessel visits.

Table II-7: 2016 California Port Calls by Vessel Type

Vessel Type	Percentage of Total Calls
Container	44.3%
Tanker	21.0%
Ro-Ros/Auto Carriers	11.5%
Bulk Carriers	7.9%
Passenger Cruise Vessels	7.4%
Other	5.1%
General Cargo	2.8%
Total	**100%**

Ships typically travel in designated shipping lanes (similar to airplane flight paths, called Traffic Separation Schemes or TSS) in high traffic areas near California's ports. For example, there are designated shipping lanes that OGVs use within the Santa Barbara Channel and approximately 25 nautical miles (nm) south of the POLA and POLB. Similarly, there are designated shipping lanes within the San Francisco Bay and surrounding areas north to approximately Point Reyes, west to the Farallon Islands, and south to Half Moon Bay. Outside of the port areas, vessels are generally free to choose their routes, although certain vessel-specific requirements may apply.

OGVs typically will have more than one fuel type on-board the vessel. Most vessel operators use heavy fuel oil (HFO or residual fuel) in their main propulsion engines, auxiliary diesel engines, and auxiliary boilers. HFO is composed primarily of the heaviest fraction of the distillation of crude oil and is highly viscous, and the least expensive marine fuel available. Due to the high viscosity, heating is necessary for HFO to flow properly. Vessel operators can also use marine distillate fuel oils (MGO) in these engines and boilers, and will typically have distillate fuels available for use in emergency generators on-board the vessel. Vessels also keep low or ultra-low sulfur fuel oils (LSFO or ULSFO) or MGO on board for main engine propulsion when transiting inside ECAs and inside California regulated waters.

There are also vessels that use LNG as a fuel, most often on LNG tanker vessels ("LNG carriers"), as these vessels can operate using the natural boil-off gas from their LNG cargo. Aside from LNG tankers, there is also now a growing trend of other vessel types with the capability to use LNG fuel, for both new builds and retrofits. These vessels are typically dual-fueled engines that can operate on heavy fuel oil, distillate, or LNG where needed to meet tightening global emissions standards.

E. Regulatory Setting

Over the last 15 years, several actions were taken to reduce emissions from OGVs at the international, federal, state, and local levels. These are briefly described in this section.

1. <u>IMO Regulations</u>

The IMO is the United Nations agency with authority over maritime safety, security and the prevention of marine pollution from ships. The international air pollution standards for OGVs are found in Annex VI to the International Convention on the Prevention of Pollution from Ships (abbreviated as MARPOL).

MARPOL Annex VI

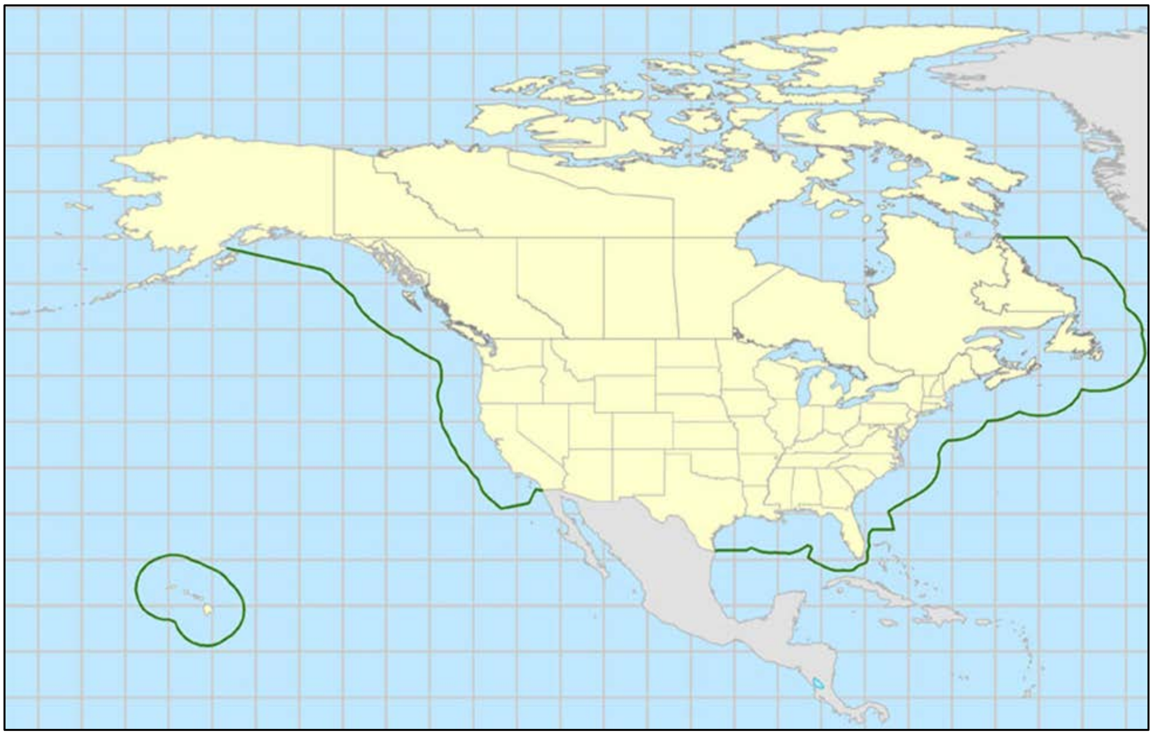
IMO Annex VI of the MARPOL Convention was adopted in 1997, and became effective in May 2005 (12 months after being accepted by 15 countries representing over 50 percent of the world's shipping tonnage). Initially, Annex VI established some relatively modest emission controls for OGVs. It limited marine fuels to 4.5 percent sulfur, and provided a process for the creation of ECAs, which require the use of 1.5 percent sulfur fuel (generally heavy fuel oil). Annex VI also established modest NOx standards (Tier I) for diesel engines greater than 130 kW installed on vessels constructed on or after January 1, 2000. On October 9, 2008, IMO adopted amendments to Annex VI that put in place more stringent standards to control NOx and SOx from OGVs. The amendments include additional (Tier II and Tier III) new engine NOx standards, additional requirements for pre-2000 engines that were previously not controlled, and fuel sulfur limits. In July 2011, further amendments to the MARPOL were adopted. They added a new chapter on energy efficiency for ships to MARPOL Annex VI to make mandatory the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. These requirements will be discussed in more detail later in this section.

Fuel Sulfur Limits

The current Annex VI requirements phase in progressively more stringent fuel sulfur limits to control emissions of SOx and PM. On a global basis, the fuel sulfur limit was reduced from 4.5 percent to 3.5 percent in 2012, and will reduce to 0.5 percent in 2020.

Under the 2008 amendments to Annex VI, there are special fuel sulfur limits for ECAs. Inside ECAs, the sulfur level would drop from 1.5 percent sulfur to 1 percent sulfur in July 2010, and then to 0.1 percent in January 2015. The U.S. and Canada jointly applied for an ECA designation covering SOx and NOx in July 2009. On March 26, 2010, the IMO officially designated waters of the U.S. and Canadian coastlines as an ECA, referred to as the North American ECA. The region applies to the U.S. and Canadian Exclusive Economic Zones (EEZs), generally considered to be the area 200 nm offshore in the regions shown in Figure II-12 with the exception of the area around Florida due to the Bahamas EEZ. The North American ECA began implementation in August 2012, with a 1 percent sulfur limit that dropped to 0.1 percent sulfur in January 2015. The ECA also requires new vessels built on or after January 1, 2016, to meet Tier III NOx standards when operating in the ECA. On July 15, 2011, the U.S. received approval from IMO to extend the ECA to the Caribbean waters around Puerto Rico and the U.S. Virgin Islands. Implementation began on January 1, 2014, for this region. Northern Europe also has a designated Sulfur ECA to control SOx emissions in the Baltic Sea North Sea, and English Channel, often referred to as the SECA.

Figure II-12: North American Emission Control Area



New Engine NOx Standards

Table II-8 lists the IMO new engine NOx standards under MARPOL Annex VI. The Tier II standards are estimated to achieve approximately a 20 percent reduction in NOx emissions compared to Tier I standards, while Tier III standards achieve an 80 percent reduction from the Tier I emissions levels. The Tier I and II standards apply globally, while Tier III standards only apply in NOx ECAs, where it is envisioned that add-on emission controls such as SCR would be utilized as needed. Since the U.S. was granted approval for a NOx ECA designation, the Tier III standards apply to vessels built on or after January 1, 2016, that also travel through the North American ECA.

Table II-8: New Engine NOx Emissions Limits Under IMO Annex VI

Emissions Tier	Date	NOx Limit (g/kW-hr)*		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17	$45n^{-0.2}$	9.8
Tier II	2011	14.4	$44n^{-0.23}$	7.7
Tier III**	2016	3.4	$9n^{-0.2}$	2.0

* Where n is the rated engine revolutions per minute (RPM)

** Tier III standards apply only within NOx Emission Control Areas.

The 2008 amendments to Annex VI also specify that the Tier I standards (previously applicable only to engines installed on ships beginning January 1, 2000) become applicable to existing engines installed on ships built between January 1, 1990, and December 31, 1999. This applies for engines with a displacement greater than or equal to 90 liters per cylinder and a rated power output greater than or equal to 5,000 kW, subject to the availability of approved engine upgrade kits.

Initial Strategy on Greenhouse Gas Reductions

Presently, the maritime industry accounts for around 2-3 percent of global GHGs (roughly the same amount as the entire country of Germany), but this percentage is projected to increase by up to 250 percent by 2050 due to industry growth associated with increasing global trade demands (Stefanini, 2018; Saul, 2018a). The shipping industry has been absent from in previous global GHG reduction efforts, including the Kyoto Protocol and Paris Agreement, due to the fact that the bulk of GHG emissions from this industry occur outside national boundaries (Jordan, 2018). However, reducing GHGs from the shipping industry is at the forefront of discussions on the international level.

In April 2018, IMO's Marine Environment Protection Committee (MEPC) adopted the Initial Strategy to Reduce Greenhouse Gas Emissions from Ships, which represent the first GHG emission reduction targets for the global shipping industry. This initial strategy does not include specific action plans, but rather represents a framework for further action and discussion. The intersessional working group originally tasked with developing the initial GHG emissions reduction strategy at IMO has been directed to meet in December 2018 to develop follow-up actions and directives on how to obtain the goals set out in the initial strategy. The working group will report to the next session of the MEPC (MEPC 73), which meets 22-26 October 2018 (gCaptain, 2018).

Main elements of the initial strategy include:

- Carbon intensity of ships to decline through implementation of further phases of the energy efficiency design index (EEDI), described in section below, for new ships to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate,

- Carbon intensity of international shipping to decline to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008, and
- GHG emissions from international shipping should peak and begin declining as soon as possible to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while pursuing efforts to phasing GHG emissions out in order to follow a pathway of CO_2 emissions reductions consistent with the Paris Agreement temperature goals (IMO, 2018).

The goal of the Paris Agreement is to limit threats from climate change by keeping global temperature rise during the 21st Century to under the widely accepted mark of 2 ºC above pre-industrial levels, while pursuing efforts to remain around the 1.5 ºC mark (UNFCCC, 2017). However, representatives from Pacific Island nations state that a 50 percent reduction of GHG emissions from 2008 levels by 2050 is not ambitious enough to reach this goal and avoid existential threats from climate change for their own nations. Many Pacific island nations are a mere 6.5 feet above sea level and are threatened by rising sea levels associated with climate change due resulting from increasing GHG emissions (Hand, 2018).

Full decarbonization of the shipping industry by 2035 or 2050 is supported by Pacific Island nations such as the Marshall Islands, which serves as one of the top three largest ship registrars in the world (Stefanini, 2018). European Union (E.U.) nations agree that 70-100% reduction over 2008 levels is possible by 2050 using alternative fuels, wind assisted ships, and electric engines (NY Daily News, 2018). Other countries, such as Brazil, Panama, and Saudi Arabia do not support a blanket percentage decrease and instead support a per tonnage decrease in CO2 emissions. Embracing full decarbonization is also not strongly supported by many developing nations due to the high associated costs. IMO's initial strategy of a 50 percent reduction from 2008 levels by 2050 is considered by many as a compromise on the way to decarbonizing the shipping industry by 2100 (Stefanini, 2018).

IMO is now tasked with developing the elements of the GHG emissions reduction framework, including establishing a research and development effort to explore and fund new technologies designed to reduce GHG emissions from ships. A finalized strategy is to be adopted by IMO in 2023, with a review set for 2028 – 10 years from the adoption of the initial strategy to assess feasibility and updated available data (Saul, 2018a).

Energy Efficient Design Index (EEDI)

The 2011 IMO amendments to Annex VI set in place the first ever efficiency standards for new ships. Beginning in 2013, the regulations established EEDI standards that become progressively more stringent over time. The EEDI is based on design specifications and sea trials of new ships. To meet these efficiency targets, vessel operators need to use more energy efficient hulls, equipment, and engines on new vessels. As with other IMO regulations, the ship's flag state is responsible for ensuring compliance with the EEDI, and compliance is demonstrated by the issuance of an International Energy Efficiency Certificate (IEEC) by the relevant maritime administration or vessel classification society (ICCT, 2011).

The EEDI requires a minimum energy efficiency level per capacity mile (e.g., tonne-mile) for different ship types and size segments. The categories of ships covered include oil and gas tankers, bulk carriers, general cargo ships, refrigerated cargo carriers, and container ships. Together, these vessel categories account for over 70 percent of the CO_2 emissions from the new-build fleet. The regulations do not cover passenger vessels, mixed-use vessels, other specialty vessels, and vessels below 400 gross tons. For vessel types not covered, EEDI formulas are expected to be developed in the future.

EEDI regulations went through an initial two year phase zero from 2013 to 2015; during this time period, new ship designs were required to meet the baseline reference level for their ship type. After 2015, efficiency levels became more stringent than the reference level in five year increments (EPA, 2011), as follows:

- 10 percent more efficient by 2015,
- 20 percent more efficient by 2020, and
- 30 percent more efficient by 2025.

The EEDI is expected to stimulate continuous innovation and technical development that will improve ship fuel efficiency and reduce CO_2 emissions. Since the EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to the industry (as long as the minimum energy efficiency level is met), ship designers and builders have the flexibility to use the most cost-efficient equipment and technologies to comply with the regulations. While these changes will add capital and implementation expenses related to next-generation ship designs and technology, these costs are expected to be offset by projected savings (ICCT, 2011).

Ship Energy Efficiency Management Plan (SEEMP)

The IMO requires operators of both new and existing vessels to develop and maintain a SEEMP. The SEEMP, a complement to the EEDI, provides a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The guidance on the development of the SEEMP for ships incorporates best practices for fuel-efficient ship operation. The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimize the performance of a ship (IMO, 2014).

The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using monitoring tools like the Energy Efficiency Operational Indicator (EEOI). For example, the EEOI enables operators to measure the efficiency of a ship in operation and to gauge the effect of any changes in operation, such as improved voyage planning, more frequent propeller cleaning, or the introduction of new equipment such as waste heat recovery or a new propeller (IMO, 2014).

A vessel's SEEMP document is expected to change over time, and many companies already use a similar plan to reduce fuel costs. The SEEMP regulations only require that ships have a plan; approval of the plan and tracking of the vessel's progress by the flag state administration is not required.

2. Federal Regulations

U.S. EPA is implementing a coordinated strategy to reduce emissions from OGVs. It includes measures adopted under the Clean Air Act and implementation of the international standards for marine engines and their fuels contained in Annex VI to MARPOL.

U.S. EPA adopted regulations in 2003 and 2007 that established the Tier I, II, and III, NOx emission standards for OGV Category 3 engines that are equivalent to the international standards for these engines contained in Annex VI. U.S. EPA standards only apply to U.S.-flagged vessels and allow for enforcement under U.S. laws. As noted earlier, the U.S. was also granted approval by IMO to implement an ECA which applies to all OGVs, regardless of where they are registered or flagged.

Additionally, in 2004, U.S. EPA acted to limit the sulfur content of diesel fuels for non-road applications. For marine use, the rule limited the fuel sulfur content of diesel fuels to 500 parts per million (ppm) in 2007 and 15 ppm in 2012. The rule does not apply to marine diesel oil or heavy fuel oil.

3. California Regulations

California OGV Clean Fuel Regulation

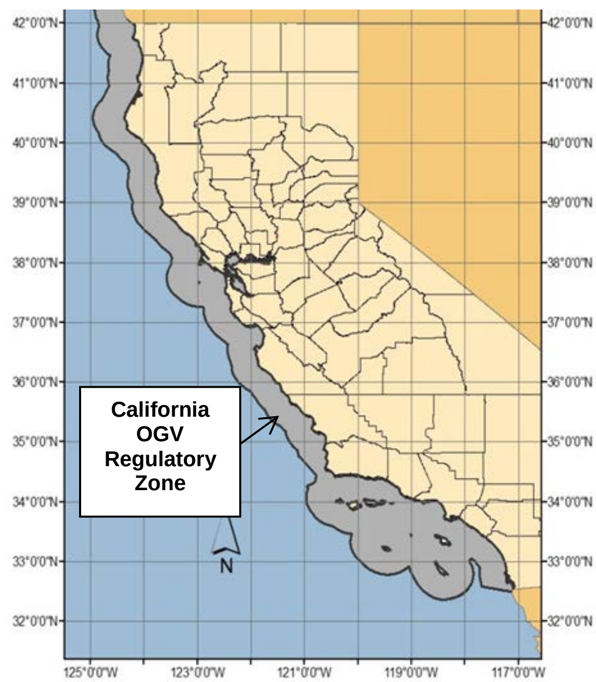
In response to growing concerns regarding port-related pollution, in 2005 CARB approved the regulation entitled Emission Limits and Requirements for Auxiliary Diesel Engines and Diesel-Electric Engines Operated on Ocean-Going Vessels within California Waters and 24 nm of the California Baseline. This regulation required the use of cleaner marine distillate fuels in OGV auxiliary engines beginning on January 1, 2007. However, due to a successful legal challenge, enforcement of the regulation was suspended in May 2008. Prior to the court ruling, the regulation was successfully implemented for over 14 months.

In 2008, CARB adopted the Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 nm of the California Baseline (also known as the California OGV Clean Fuel Regulation) (CARB CCR, 2008). Beginning July 1, 2009, the California OGV Clean Fuel Regulation required vessel operators within 24 nm of the California coastline and islands to use cleaner distillate fuels in their main engines, auxiliary engines, and auxiliary boilers (See **Figure II-13**). The California OGV Clean Fuel Regulation requires that vessel operators switch from the use of standard high sulfur heavy fuel oils (up to 3.5 percent sulfur) to marine distillate fuels within the regulatory boundary. The fuel standards were implemented in phases as shown in Table II-9.

Table II-9: Fuel Requirements for Ocean-Going Vessels

Fuel Requirement	Effective Date	CARB's California OGV Fuel Requirement Percent Sulfur Content Limit
Phase I	July 1, 2009	Marine gas oil (MGO) at or below 1.5% sulfur or Marine diesel oil (MDO) at or below 0.5% sulfur
	August 1, 2012	Marine gas oil (MGO) at or below 1.0% sulfur or Marine diesel oil (MDO) at or below 0.5% sulfur
Phase II	January 1, 2014	Both marine gas oil (MGO) and marine diesel oil (MDO) at or below 0.1% sulfur

Figure II-13: California OGV Clean Fuel Regulation Regulatory Zone



The use of these cleaner fuels resulted in immediate and dramatic reductions in diesel PM and SOx emissions, as well modest reductions in NOx emissions.

Beginning in 2015, requirements under the North American ECA dictated the use the 0.1 percent sulfur fuels, which is expected to result in similar emission reductions to the California OGV Clean Fuel Regulation if vessels comply using marine distillate fuels with ≤ 0.1 percent sulfur to comply with the ECA. If CARB finds that the ECA achieves equivalent emissions reductions, the California OGV Clean Fuel Regulation allows CARB's Executive Officer to sunset the California regulation and rely on the Federal ECA requirements.

As of April 2016, CARB's Executive Officer concluded that Federal ECA standards alone are unlikely to achieve required emissions reductions within Regulated California Waters. CARB staff assessed several additional factors after implementation of the 2015 federal ECA regulations, including:

- Differences in the overwater boundaries of the North American ECA regulation and the California OGV Clean Fuel Regulation
- California impacts due to exemptions granted under IMO Regulation 3, which provides temporary exemptions from the fuel sulfur requirements

The California OGV Clean Fuel Regulation remains in effect until the Executive Officer issues written findings that the federal requirements are expected to achieve the necessary emissions reductions that are presently being enforced in the California OGV regulations.

At-Berth Regulation

Depending on vessel and cargo type, OGVs can remain at berth for time periods ranging from several hours to multiple days loading and unloading cargo. While at berth, OGVs use auxiliary engines to provide electrical power to operate on-board equipment. These auxiliary engines, which primarily run on marine gas oil, contribute a significant portion of NOx, PM, SOx, and GHG emissions, particularly in coastal regions and around the ports. These emissions then contribute to on-shore air quality problems and result in health impacts to the local communities surrounding the ports.

In December 2007, CARB adopted the Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth in a California Port (also known as the At-Berth Regulation) to reduce emissions from diesel auxiliary engines on container ships, passenger ships, and refrigerated-cargo ships while berthing at a California port (CARB CCR, 2008). This measure requires ships to plug into cleaner land-based electricity sources (or equivalent) while at the dock to avoid running the auxiliary engines to power the ship while it is being unloaded; this results in the reduction of NOx, diesel PM, CO_2, and SOx emissions.

The At-Berth Regulation applies to fleets using the Ports of Los Angeles, Long Beach, Oakland, San Diego, San Francisco, and Hueneme. The regulation provides vessel fleet operators visiting these ports with two options to reduce at-berth emissions from auxiliary engines: option 1) turn off auxiliary engines for most of a vessel's stay in port and connect the vessel to some other source of power, most likely grid-based shore power; or option 2) use alternative control technique(s) that achieve equivalent emission reductions. At this time, most vessel fleets are complying by plugging into grid-based electricity. As shown in Table II-10, compliance began on January 1, 2014, for most fleets and is being implemented in three phases.

Table II-10: CARB's Reduced On-board Power Generation Requirements for Compliance with the At-Berth Regulation

Effective Date	Fleet Requirements[1]
January 1, 2014	50% of visits and 50% of at-berth power generation
January 1, 2017	70% of visits and 70% of at-berth power generation
January 1, 2020	80% of visits and 80% of at-berth power generation

The At-Berth Regulation allows the use of alternative technologies to achieve required emission reductions. These alternatives may include ship-side technologies, such as post-combustion devices, alternative fuels, cleaner engines, or shore-side technologies including distributed generation or emission-capture-and-treatment devices (sometimes referred to as bonnet systems). These technologies, although attractive for early deployment for NOx and diesel PM reductions, will most likely be less effective in reducing GHG emissions when compared to grid-based electricity.

Two California programs, the Proposition 1B: Goods Movement Emission Reduction Program (Prop 1B program) and the Carl Moyer Memorial Air Quality Standards Attainment Program (Carl Moyer program) have helped expedite the installation of shore power infrastructure and adoption of shore power vessels. Approximately $75 million from the Prop 1B program was used to help fund the installation of 37 shore power berths at the ports of Oakland, Long Beach, Los Angeles, and Hueneme. The Carl Moyer program supplied $1.8 million for retrofitting vessels and an additional $2.3 million for installing shore power berths.

CARB is currently pursuing amendments to the At-Berth Regulation that would reduce emissions from additional vessels not currently subject to the regulation, further decreasing the health impacts from vessels on nearby communities.

Short Lived Climate Pollutants (SLCP) Strategy

Black carbon is a component of diesel particulate matter emissions from OGVs (as well as other diesel powered equipment). In addition to the health impacts associated with black carbon, it is classified as a short lived climate pollutant. SLCPs are especially potent contributors to climate change which act within a shorter timeframe than longer-lived greenhouse gases such as carbon dioxide. Black carbon and other SLCPs are collectively estimated to be responsible for 40 percent of current net climate forcing, and are a high priority for control in California's climate change efforts. To address these emissions, a SLCP Reduction Strategy was developed pursuant to Senate Bill 605 and 1383. The SLCP Strategy lays out a range of options to accelerate SLCP emission reductions in California. A specific target for anthropogenic black carbon was

[1] The visit requirement is based on the percentage of a fleet's visits to the port that meet the on-board auxiliary diesel engine operational time limits. The at-berth power generation requirement is based on the percent reduction of the fleet's on-board auxiliary-diesel-engine power generation while docked at the berth from the fleet's baseline power generation. Any Container or Reefer fleet making 25 or more visits in a year to a California port or any Passenger vessel making 5 or more visits to a California port will be subject to the will be subject to the At-Berth Regulation.

set at 50 percent below 2013 levels in 2030. The SLCP Strategy includes measures in the State Implementation Plan, which includes diesel control measures for OGVs.

4. Local Air Districts and Port Authorities

While some of the local air pollution control agencies enforce regulations to control emissions from OGVs (e.g., District rules to control VOC emissions from tankers during loading and lightering operations), most of the local programs for OGVs are implemented by ports. Port authorities in California have developed a number of measures for OGVs which are typically implemented through incentive programs or lease agreements.

Clean Air Action Plan (CAAP)

POLA and POLB (also known as San Pedro Bay Ports) have a comprehensive air quality program for OGVs (and other port equipment). In 2006, with updates in 2010 and 2017, the San Pedro Bay Ports adopted the San Pedro Bay Ports Clean Air Action Plan (CAAP), which is designed to reduce the emissions from a variety of port sources, including OGVs. Updates to the CAAP in 2017 focused on innovative strategies needed to assist with planning and developing infrastructure necessary to support zero-emissions freight transport at the ports.

The plan includes reductions from Port ordinances, regulations, green lease agreements, environmental mitigation requirements, and voluntary and incentive efforts such as the Green Ship Incentive Program and Vessel Speed Reduction (VSR) Incentive Program. The Ports of Los Angeles and Long Beach have developed the necessary infrastructure for vessels to utilize shore power at dockside and some are adding provisions to leases to require use of the infrastructure, which complements CARB's statewide At-Berth Regulation. Prior to the implementation of CARB's OGV Clean Fuel Regulation, the San Pedro Bay Ports also developed the Vessel Main Engine Fuel incentive program, which covered the cost differential between dirty heavy fuel oil and cleaner burning low sulfur distillate fuel (0.2 percent sulfur) that complied with the California OGV Clean Fuel Regulation.

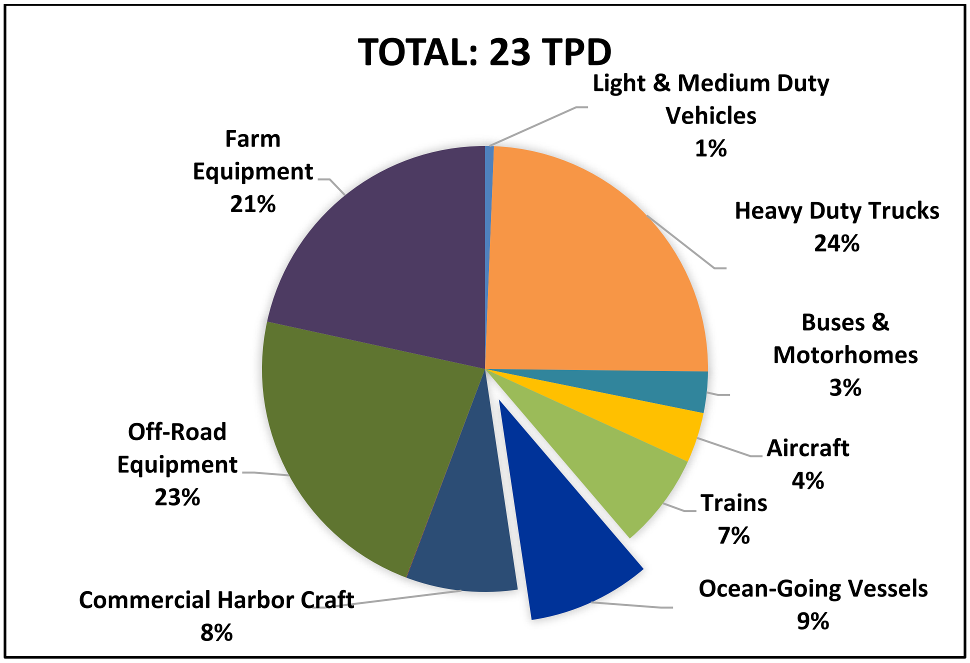
Environmental Ship Index (ESI)

The Port of Los Angeles participates in a voluntary Environmental Ship Index (ESI) Program, which rewards vessel operators for reducing diesel PM and NOx from OGVs. When an operator goes beyond what is required for compliance by bringing their newest and cleanest vessels to the Port, including demonstrating technologies onboard their vessels, they are rewarded with incentive grants. ESI also encourages use of cleaner technology and practices in advance of regulations (POLA, 2014). The San Pedro Bay Ports are currently considering additional measures to maximize the number of vessels visiting ports that meet Tier III IMO NOx standard of 3.4 grams per kW hour (g/kW-hr).

F. Emissions Summary

OGVs contribute nearly 10 percent to the statewide mobile source diesel PM_{10} emissions inventory in California. As Figure II-14 shows, OGVs represent the fourth highest contributor to statewide diesel PM_{10} emissions behind the categories of Heavy Duty Vehicles, Farm Equipment, and Off-Road Equipment.

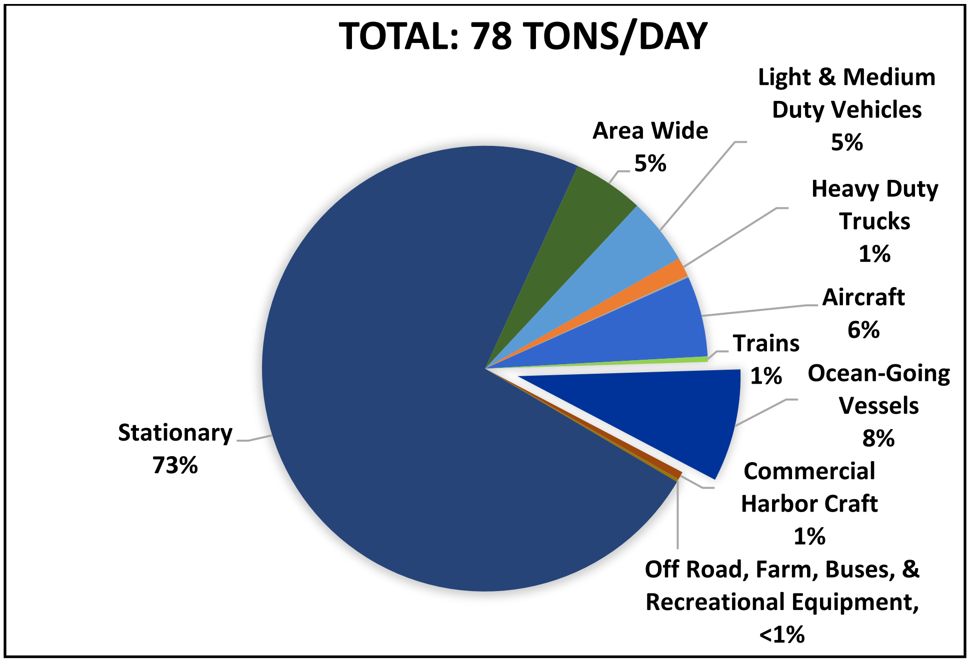
Figure II-14: 2016 Diesel PM_{10} Emissions – Mobile Sources Only



(CARB Emissions Inventory, 2016)

OGVs also account for nearly 8 percent of statewide SOx emissions, as shown in Figure II-15. SOx emissions from OGVs have declined significantly over the past 10 years, largely as a result of the California OGV Clean Fuel Regulation, which requires use of 0.1 percent distillate fuels in California waters.

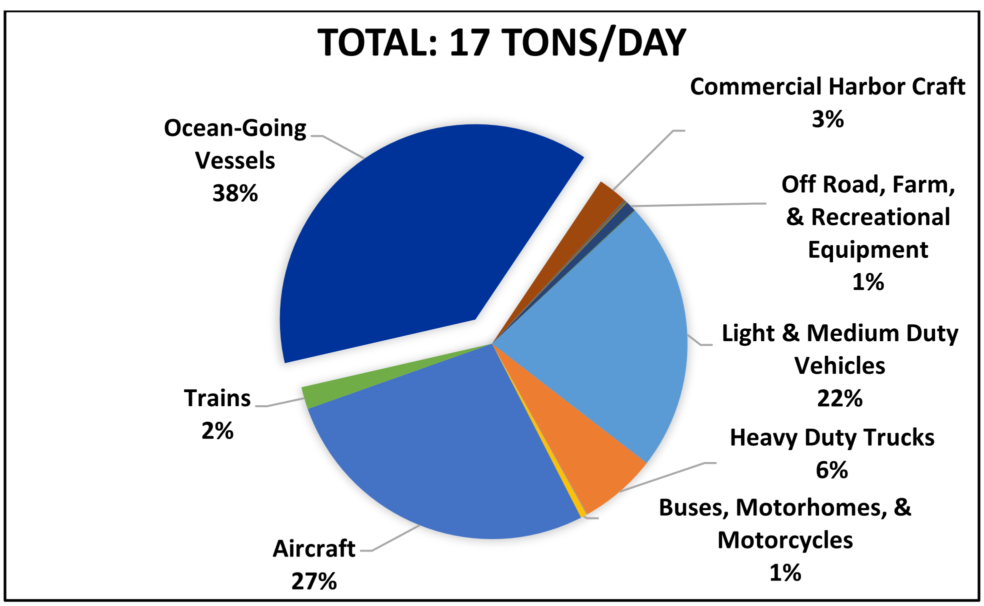
Figure II-15: 2016 Statewide SOx Emissions



(CARB Emissions Inventory, 2016)

However, when considering only mobile sources, OGVs represent the highest level of SOx emissions statewide at almost 40 percent. This is shown in Figure II-16.

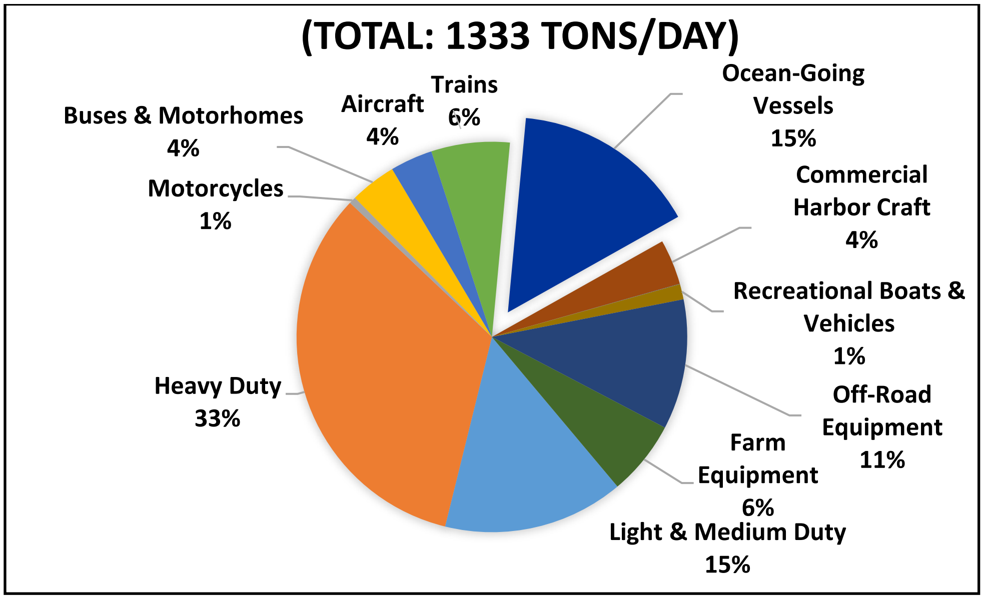
Figure II-16: 2016 Statewide SOx Emissions – Mobile Sources Only



(CARB Emissions Inventory, 2016)

OGVs also account for a large source of NOx emissions accounting for 15 percent of statewide mobile source NOx emissions (Figure II-17).

Figure II-17: 2016 Statewide NOx Emissions – Mobile Sources Only



(CARB Emissions Inventory, 2016)

The 2016 statewide emissions estimates for diesel PM_{10}, NOx, SOx, carbon monoxide (CO), CO_2, and reactive organic gases (ROG) from OGVs are presented in Table II-11. These estimates include emissions that occur within a 100 nm zone of the California coast. Emissions that occur in California inland waters such as emissions from OGVs transiting to the ports of Stockton and Sacramento are also included in the estimates. Container vessels are shown to be the largest contributor to emissions from OGVs, followed by tankers. Combined, these 2 vessel types account for over 80 percent of the emissions from OGVs.

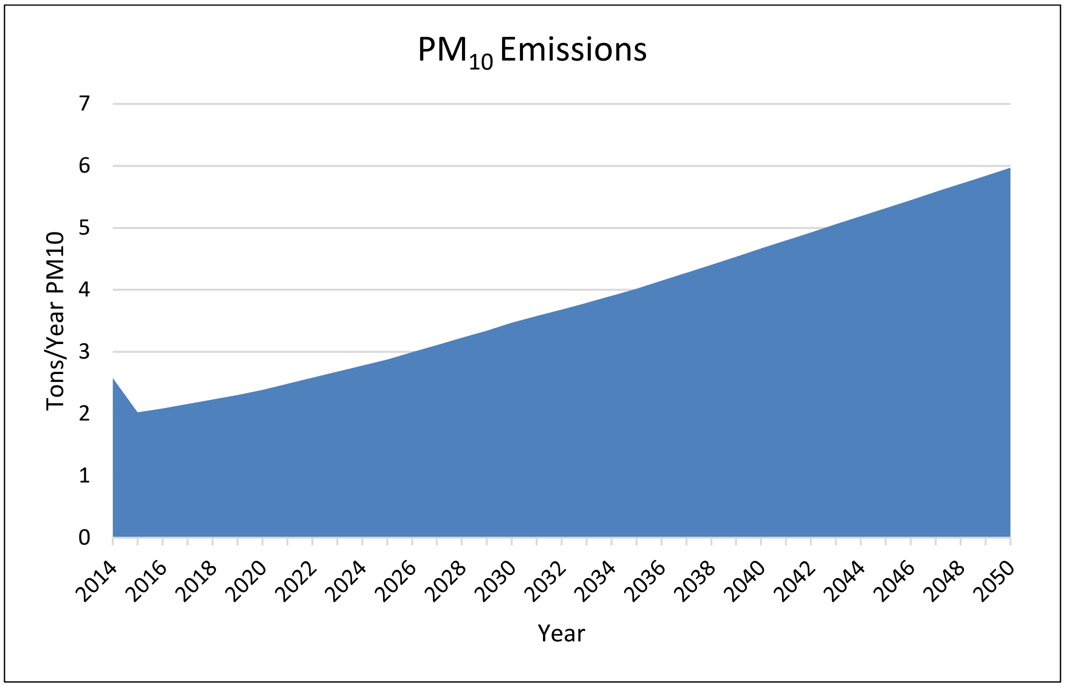
Table II-11: 2016 OGV Emissions (Tons/Day) in California

Year	Vessel Type	Diesel PM_{10}	SOx	NOx	CO	CO_2	ROG
2016	Ro-Ro/Auto	0.2	0.4	13.5	1.0	589.6	0.7
	Bulk	0.1	0.2	7.5	0.6	344.9	0.4
	Container	1.1	2.8	125.1	8.2	4057.7	7.5
	Cruise	0.2	0.6	17.1	1.5	906.0	0.8
	General	0.0	0.0	0.8	0.1	37.9	0.0
	Reefer	0.0	0.0	0.3	0.0	16.0	0.0
	Tanker	0.5	2.0	31.1	2.5	1983.6	1.7
	Total	2.1	6.0	195.4	13.8	7935.8	11.2

(CARB Emissions Inventory, 2016)

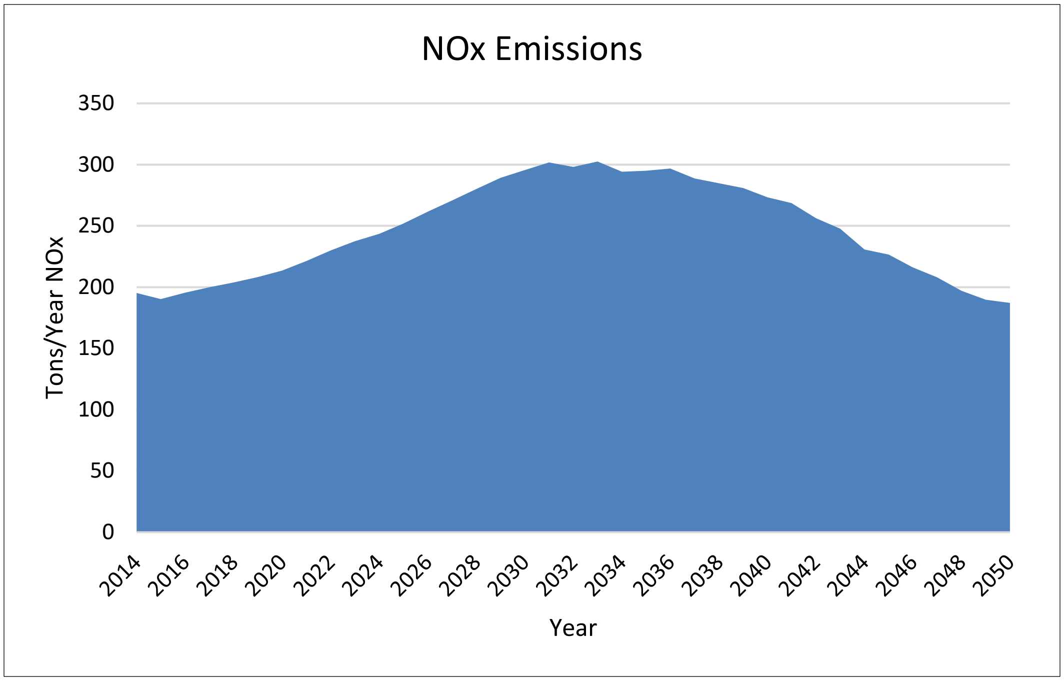
Significant progress has been made in reducing emissions from OGVs during the past decade, particularly with respect to SOx, largely as a result of the California OGV Clean Fuel Regulation. However, the progress made in reducing NOx is more modest. Figure II-18, Figure II-19, and Figure II-20 show the emissions trends projected through 2050, which includes current and future emission controls in place at the international, federal, state, and local levels. The primary method to achieving NOx reductions are through the installation of newer tier engines. As such, significant NOx reductions are not anticipated until after 2040, when the introduction of Tier III engines to California is expected. These figures stress the need for continued reductions from OGVs, as growth in the industry is projected to increase emissions and overcome many of the benefits expected from current emission control programs.

Figure II-18: OGV Diesel PM_{10} Emissions Trends



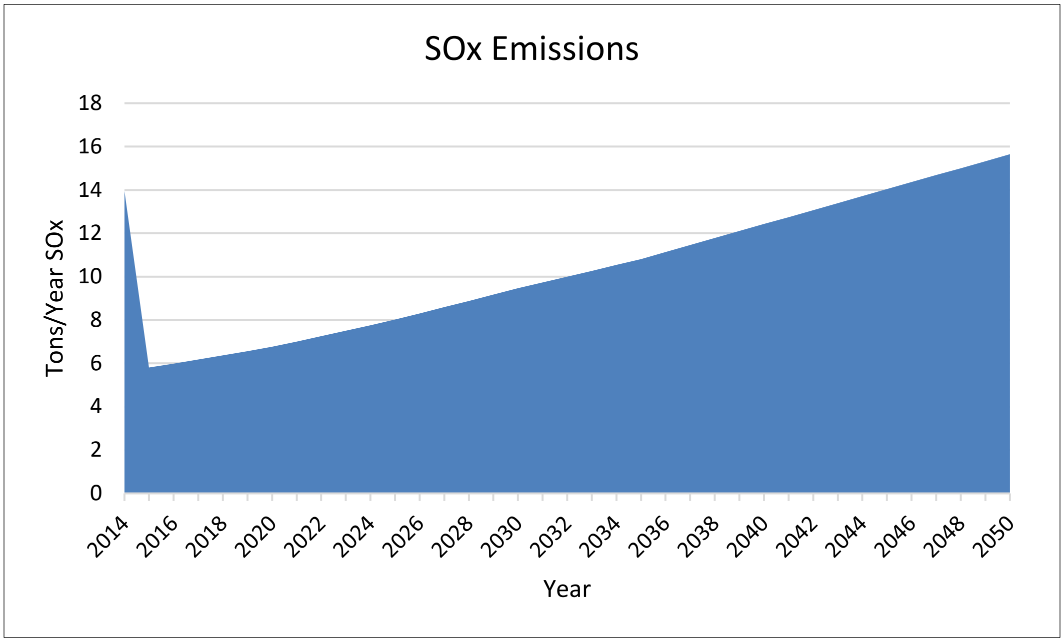
(CARB Emissions Inventory, 2016)

Figure II-19: OGV NOx Emissions Trends



(CARB Emissions Inventory, 2016)

Figure II-20: OGV SOx Emissions Trends



(CARB Emissions Inventory, 2016)

III. ASSESSMENT OF OCEAN-GOING VESSEL EMISSION REDUCTION TECHNOLOGIES

A. Alternative Fuels

There are a number of alternative fuels that can be used in OGVs including, natural gas, biodiesel, methanol, dimethyl ether, and many others. Even nuclear power is a potential alternative power source for some vessels (Chryssakis, 2014). However, when taking into account worldwide availability, infrastructure, safety, and other considerations, liquefied natural gas (LNG) appears to be the most promising option for OGVs at this point in time. As such, for this technology assessment, we limited our evaluation to LNG.

<u>Liquefied Natural Gas</u>

1. Technology Description

LNG is natural gas (mostly methane) that is liquefied by cooling it to about -160 degrees Celsius (^{o}C). As a liquid, LNG occupies only a fraction (1/600) of the volume of natural gas, and only about 40 percent of the volume of compressed natural gas, making its use more suited to the long voyages typical of OGVs.

LNG is a cleaner-burning fuel relative to traditional petroleum marine fuels, and its use may result in an estimated 20 percent reduction in fuel cycle (well-to-propeller) GHG emissions compared to conventional petroleum fuels (WPCI, 2016). Although engine manufacturers claim substantially lower exhaust emissions of NOx, SOx, and PM, more testing and data is needed in this area.

The use of LNG by marine vessel operators is expected to increase due to low natural gas prices, and because it can be used to meet emissions standards within ECAs established under the IMO. Due to increasing interest in LNG, marine engine manufacturers now offer many engine models that can use LNG, in both LNG-only and dual-fuel applications. Existing diesel engines can also be retrofitted for the use of LNG, with associated vessel modifications to provide for storage of LNG on board. LNG carriers (vessels specially designed to transport LNG) utilize the excess gas due to natural boil off of their cargo to power the vessel's main engine; LNG boil off is regularly used to fuel LNG carriers, so the technology is mature.

Despite the advantages of LNG, there are many challenges that exist to embracing LNG as a primary bunkering fuel. LNG vessel bunkering infrastructure is not in place in most regions, including the U.S. The storage and delivery system for LNG on OGVs occupies about 2.5 to 3 times the volume of traditional petroleum marine fuels. The extra space is necessary due to both a lower energy density compared to petroleum fuel, and the insulation required to maintain cryogenic conditions (MDT, 2012a). LNG-fueled vessels are also more expensive, due mostly to the fuel storage and delivery systems.

2. System/Network Suitability and Operational/Infrastructure Needs

LNG has been used on a full range of vessel types and applications, both new builds and retrofits, and its use is predicted to expand over the long-term, driven by low natural gas prices and new vessel emissions regulations.

The fueling infrastructure is expected to be the biggest hurdle to expand use of LNG in California. There are a number of different ways that OGVs can bunker LNG, including the following:

- Tanker truck to vessel,
- Terminal storage tank to vessel,
- Loading prefilled tanks, and
- Vessel (bunker barge) to vessel.

The preferred option for many operators would be via bunker barges, unfortunately neither the LNG barges nor the California-based coastal storage tanks needed to supply these barges are currently available.

Tanker Truck to Vessel

Under this option, a tanker truck would arrive at a pier or wharf and a hose would be connected between the tanker truck and the vessel. While vessels can be bunkered this way, the process would require several trucks depending on the vessel size and distance to be travelled by the vessel using LNG. A vessel operating in the Pacific Hawaii trade is likely to need between 1,000 and 3,000 cubic meters of LNG or more (25 to 75 tanker truck loads based on a tanker trailer capacity of about 40 cubic meters). While this is a cumbersome process, it may still be considered as a temporary option by some operators until the infrastructure is in place for more efficient fueling methods, such as the “vessel to vessel” option discussed later in this section.

Terminal Storage Tank to Vessel

Bunkering vessels directly from landside tanks is an efficient fueling option if the infrastructure is in place. But, as it would take many such facilities to supply vessels at their various ports of call, making this a longer-term option if it is pursued.

Loading Prefilled Tanks

Another potential fueling option under consideration is the use of portable fuel tanks. Under this option, preloaded tanks would be transferred to a vessel in shipping containers. When empty, the tanks would be removed from the vessel and replaced with loaded tanks. While this approach could be implemented relatively quickly, there would be many containers needed for such applications, and they would take up more volume than a permanent vessel tank holding the same volume of LNG. There would also be many fuel tank connections to handle, which could be cumbersome.

Vessel to Vessel

Most vessels currently bunker traditional petroleum fuels by bunkering barge, and this would be the preferred method for most operators to bunker LNG as well. One advantage of this option is the flexibility to deliver fuel to wherever the vessel is located, and the ability to offload cargo landside while simultaneously bunkering fuel on the other side of the vessel. However, there is currently only one LNG bunkering barge in the U.S. at this time and landside tanks are needed on the West Coast, and ideally in many other ports to supply these barges, unless the barges are to be supplied by tanker trucks.

Infrastructure Outlook

In California, it is expected that the LNG infrastructure will eventually be put in place, as LNG-capable vessels are already being built both in the U.S. and globally. There are locations in the U.S. where construction is already underway on LNG bunkering infrastructure (e.g., Jacksonville, Port Fourchon), however, CARB staff found no confirmed publicly available plans at this point for California.

Figure III-1: M/V Isla Bella

Tightening international standards for emission reductions spurred LNG bunkering infrastructure projects both in the U.S. and abroad. Harvey Gulf International Marine in Port Fourchon, Louisiana completed the first LNG bunkering terminal facility in the U.S., providing support to offshore support vessels (Ship & Bunker, 2016a), but OGVs are not served at this facility.

Jacksonville, FL has multiple projects in development to serve OGVs trading between Florida and Puerto Rico. In January 2016, TOTE Maritime bunkered their first LNG fueled container vessel, the M/V Isla Bella, at the Port of Jacksonville using a specially designed mobile pumping skid. An LNG bunkering terminal is under construction in Jacksonville that will serve as the main bunkering port for TOTE’s LNG fleet, with completion scheduled for early 2018. Once finished, the facility is expected to be the first complete coastal LNG storage facility in the U.S., and will include construction of North America’s first LNG bunker barge, the Clean Jacksonville (Northstar, 2016). Barge bunkering facilities are expected to commence early in 2018 (SEA-LNG, 2018). Future projects are also underway at Jacksonville between Crowley

Maritime and Eagle LNG, with construction expected to wrap up in mid to late 2019 (Eagle LNG, 2018).

LNG bunkering terminals are also increasing in availability in Europe and parts of Asia. European LNG bunkering facilities exist in at least five port cities, and some northern European countries, such as Norway, utilize LNG technology on numerous passenger ferries and coastal ships. China is experiencing an increased interest in LNG as a marine fuel due to raising concerns over poor air quality in major cities across the country. Trials are currently ongoing at Shanghai's Yangshan Port and Waigaoqiao Port, with plans to evaluate LNG technology in inland rivers, including the Yangtze River. Officials in the Shanghai/Nanjing region introduced regulation to encourage use of LNG as a marine fuel, with the goal of increasing LNG infrastructure at ports in the region by end of 2018. Since 2010, Chinese shipping companies have commissioned 30 dual-fuel capable vessels, and LNG bunkering is already available at the ports of Zhoushan and Nanjing (Ashworth, 2015). Other Asian countries such as Japan, Korea, and Singapore are also considering LNG bunkering infrastructure development. The Maritime and Port Authority (MPA) of Singapore announced several initiatives in October 2016 designed to increase the use of LNG as a marine fuel; this is expected to encourage the use of LNG with the numerous vessels that bunker at Singapore, particularly on the Asia to Europe trade (Hellenic Shipping News, 2016).

The vessel-side concerns are reduced somewhat by dual-fuel technology, which allows vessels to use diesel fuel in the interim while waiting for the LNG infrastructure to develop. Collaboration between shipping companies, LNG fuel providers, and shore-side terminals will be crucial to the expansion of LNG as a viable fuel option.

LNG Use Beyond ECA Zones

Currently, the interest in LNG is greatest for vessel operators travelling on regular routes where much of the travel falls within SOx ECA zones, as reflected by some of the existing vessel projects (e.g., Hawaii-California and Washington-Alaska strings). Assuming that the LNG fueling infrastructure is put in place in California, the pool of vessels that choose to use LNG may grow because LNG-capable vessels built for other regions where ECA travel is common may also choose to use LNG when visiting California. LNG may also become increasingly common if additional ECA zones are established, and there may be opportunities for cooperative efforts with other regions, such as China and other the Pacific Rim countries interested in installing LNG infrastructure to reduce port emissions. Finally, the interest in LNG is anticipated to increase significantly when the IMO global 0.5 percent fuel sulfur limit is implemented in 2020.

LNG Retrofits

The engines used in OGVs can generally be modified to use LNG at a reasonable cost, though the size and cost of LNG tanks represents a challenge for retrofit applications.

A number of factors will determine whether it is economically feasible for vessels to retrofit, including:

- Amount of time the vessel operates in ECAs,
- Remaining useful life of the vessel,
- Installed tank cost and impact due to displaced cargo space,
- Cost of delivered LNG relative to traditional compliant fuels,
- Availability of fueling infrastructure, and
- Implementation date of the IMO global 0.5 percent sulfur fuel limit in 2020.

A few LNG retrofit applications are underway at this time. In 2015, MARAD agreed to fund $900,000 to TOTE Maritime to retrofit the vessel Midnight Sun into an LNG powered vessel on the grounds that this vessel would then be used as a test vessel to record emissions data before and after the conversion to LNG. MARAD also intends to use operational data to support other companies when evaluating the feasibility of converting to LNG power for future potential retrofitting opportunities. In addition to the Midnight Sun, TOTE also intends to retrofit the vessel North Star. Retrofits for the vessels are expected to finish in 2020 and 2021. Once the retrofits are finished, the vessels will resume round trip trade between Port of Tacoma, Washington and Port of Anchorage, Alaska (Schuler, 2018a).

MARAD also provided $730,000 to Pittsburgh Region Clean Cities to retrofit a tow boat to LNG fuel for pre- and post-conversion emission studies, among other projects to support alternative technologies designed to lessen the impact of maritime industry on the environment (Tregurtha, 2015).

Due to the variety of factors affecting the economics of the LNG retrofit applications, it is difficult to predict whether this option has the potential to be widely adopted.

3. Technology Readiness

The use of LNG to fuel diesel engines in OGVs is well established, with the first commercial LNG carrier Methane Princess entering service in 1964; LNG carriers utilize the boil off of their own cargo as fuel. Much of the LNG infrastructure was built around the trading of LNG fuel using tanker vessels. The use of LNG as a fuel for other types of OGVs has been slower to develop, with the first LNG-powered container vessel entering service in 2015. Much of this delay is related to the limited availability of bunkering sources for large OGVs. Orders for new build non-tanker OGVs using LNG as fuel are increasing; as of October 2016, 86 LNG fueled ships are in operation globally, with 93 on order. Currently, ferries and passenger vessels are the most common non-tanker vessels for the LNG engine market, but growth for LNG orders is expected to be highest in the tanker, auto carrier, cruise ship, and container markets over the coming years (Chiotopoulos, 2017).

A few examples of on-going and future U.S.-based LNG projects are detailed below:

- Matson, Inc. ordered the building of LNG adaptable vessels – 2 container vessels with a 3,600 TEU capacity at a cost of $418 million to be delivered in 2018 (Matson, 2015) and 2 combination container/Ro-Ro (con-ro) vessels designed to carry 3,500 TEUs and 800 vehicles at the expense of $511 million to be delivered in 2019 and 2020. The new vessels are expected to operate on the company's Hawaii to U.S. West Coast domestic trade route (Bonney, 2016).
- TOTE Maritime took possession of two 3,100 TEU LNG capable container vessels on the company's U.S.-Puerto Rico trade (Bonney, 2016).
- Crowley Maritime christened an LNG capable tanker in 2016 and is in the process of building 2 more LNG con-ro vessels with a 2,400 TEU/400 vehicle capacity that were set to be delivered in 2017 (Bonney, 2016).
- Pasha Hawaii is utilizing a 1,400 TEU/1,200 vehicle LNG con-ro for services from Hawaii to the U.S. mainland (Matson, 2015).

Interest in LNG inside the U.S. is spurred in part by the Jones Act, which requires vessels participating in coastal trade between U.S. ports and territories to be U.S.-built and flagged. OGVs built inside the U.S. can cost significantly more than a vessel built overseas, thus the life span of the vessel must be longer to recoup the higher capital costs of a new build vessel. The average age of a U.S. Jones Act ship is around 33 years old, whereas the average age for the global fleet is 13 years old (Jallal, 2016). Keeping vessels in service longer means that ship owners need to look farther into the future for what technologies may be most cost-optimal. Installing dual-fuel engines into new build vessels allows ship owners and operators to not only utilize LNG as a cheaper fuel source, but also to be prepared for the growing interest in LNG in North America.

Outside the U.S., interest in LNG as a marine fuel is increasing as a way to meet tightening emissions standards, particularly in the cruise ship industry. Carnival Corporation ordered nine LNG-powered cruise ships, with delivery dates ranging from 2018 to 2023 (Schuler, 2018b). Royal Caribbean Cruises also ordered the building of 2 LNG capable vessels in Finland to be delivered in 2022 and 2024 as part of their new "Icon Class" (RCL, 2016).

Non U.S. based container ship owners and auto carrier fleets are gradually exploring the LNG market as well. Nippon Yusen Kaisha (NYK) Line recently took possession of the world's first LNG-fueled RoRos in September 2016 for operation in Europe, with a sister ship scheduled to be delivered at a later date (NYK Line, 2016). China's COSCO Container Line also signed on to receive three 20,000 TEU dual-fuel LNG capable container vessels (LNG World News, 2015), and CMA CGM recently committed to expanding the use of LNG and will conduct a study focused on the development of a bunkering vessel geared towards container ships. LNG-powered bulker vessels are still in developmental infancy, with the world's first LNG powered bulker vessel having been recently built and delivered by Hyundai Mipo Dockyard of South Korea in late 2017 (LNG World News, 2018).

The rise in LNG projects indicates a growing worldwide interest in LNG as a marine fuel source. However, the availability of LNG as a marine fuel remains an issue and shipping companies, such as NYK Line, recognize the need for additional research regarding the logistics of how to develop the LNG bunkering infrastructure necessary to support an increase in LNG powered vessels (Trauthwein, 2016).

LNG Engine Availability

Engine manufacturers offer a wide range of LNG-capable marine engines. For OGVs, most of these engines are dual-fuel engines. Dual-fuel engines are based on existing diesel engines that are re-designed to be able to operate on natural gas, HFO, and MDO/MGO. These vessels offer the flexibility to operate on traditional diesel fuels if LNG is unavailable.

For dual-fuel engines, there are two predominant technologies used by the manufacturers: (1) Diesel-cycle engines, used by MDT, and (2) Otto-cycle engines used by Wärtsilä, MDT, and other manufacturers. For the Diesel-cycle engines, when in gas mode, these engines use a small amount of diesel fuel for the pilot injection, about 3 percent of the total fuel used, along with LNG to power the engine. However, at low loads (around 10 percent), the engine will need to switch to using 100 percent diesel fuel instead of LNG (MDT, 2014a). Otto-cycle engines typically use about 1 percent to 3 percent diesel in the pilot injection. Some of the available LNG-capable main and auxiliary marine engines are discussed in this section.

Main Propulsion Engines

MDT offers dual-fuel Diesel-cycle two-stroke and Otto-cycle four-stroke main engines. For the slow-speed two-stroke engines, MDT uses Diesel-cycle ("GI" series) engines. This technology is available in a full range of power outputs from about 5 MW to over 80 MW. MDT also offers the following Otto-cycle four-stroke medium-speed ("DF series") main engines:

- L51/60 DF (about 6 MW to 9 MW),
- V51/60DF (about 12 MW to 18 MW), and
- L35/44 DF (about 3 MW to 5 MW).

Wärtsilä manufactures several Otto-cycle, slow-speed, two-stroke dual-fuel main engines. They also manufacture a number of Otto-cycle four-stroke medium speed engines that can be used for main or auxiliary engines:

- 20DF (about 1 MW to 1.5 MW),
- 34DF (about 3 MW to 8 MW),
- 46DF (about 6 MW to18 MW), and
- 50DF (5 MW to 18 MW).

Auxiliary Engines

There are a number of manufacturers of dual-fuel auxiliary (generator) engines for OGVs. These companies include: MDT, Wärtsilä, Rolls-Royce/Bergen, Caterpillar/MAK, and others. These engines use the four-stroke, medium-speed, Otto-cycle technology.

Engine Conversion

If a vessel owner opts to retrofit their vessel for LNG fuel, many of the conventional diesel engines (upon which the new dual-fuel engines are based) can be modified to be dual-fueled. According to Wärtsilä, their diesel engines can be retrofitted to dual-fuel if there is a dual-fuel engine with the same parent engine and series (Wärtsilä, 2014). Similarly, MDT reports that all MDT's slow-speed two-stroke engines can be retrofitted, with the older-technology mechanically controlled engines first requiring upgrades to be electronically controlled before the conversion to a dual-fuel engine (MDT, 2014). MDT also reports that their medium-speed four-stroke engines can be retrofitted, but that there are more technical challenges with these retrofits, such as engine de-rating when converting them. For many vessels that retrofit to use LNG, both the main and auxiliary engines are expected to be converted to dual-fuel capability. According to the most recent data available to CARB staff, 68 dual-fuel engines were either in operation or on order as of October 2016, and this number is anticipated to rise approaching 2020 before the IMO global sulfur cap takes effect (Chiotopoulos, 2017).

4. Economics

There is increased interest in the use of LNG when natural gas prices are well below prices of traditional petroleum marine fuels. There was a sharp decline in oil prices in 2015, which lowered global LNG prices from an average of $15.60/MMBtu in 2014 down to $9.77/MMBtu in 2015. This resulted in a price difference of an average of $1.32/MMBtu throughout the year, as opposed to the $6.80/MMBtu average for 2014 (IGU, 2016). When LNG and oil prices are close, there is no financial incentive for fleets to spend money to retrofit vessels for natural gas operations; as a result, progress towards developing LNG as a mainstream marine bunkering fuel slowed in 2015. However, as oil prices recover, it is anticipated that the demand for LNG as a marine bunkering fuel will grow. Current low natural gas prices are expected to persist due to 50 percent increase in global supplies (Ship & Bunker, 2016).

In addition to the cost of the fuel itself, LNG can be used to meet fuel sulfur limits within ECAs and, in some cases, NOx limits without the use of emission control devices. This makes LNG fuel especially attractive for vessels on regular routes within ECAs. It is difficult to accurately predict delivered LNG fuel prices in California because the infrastructure allowing OGVs to bunker LNG in the U.S. is extremely limited, and the liquefaction and distribution costs can account for a major fraction of the delivered cost. Due to the low energy density of methane, LNG must be liquefied in order to store enough energy to be used for fueling a vessel. According to a 2014 study funded by

Transport Canada and numerous industry members, this liquefaction process accounts for around 50 percent of the cost of bringing LNG to the market (Transport Canada, 2014). Also, LNG storage requires specialized tanks due to the cold temperatures it must be stored (around -160°C), making the cost of storage more expensive than traditional marine fuel oils.

Beyond the potential price advantage of LNG over traditional petroleum fuels, there are other factors that affect the economics of using this fuel, both positive and negative. One of the most important factors is the amount of time the vessel travels within ECA zones. This is due to savings derived from LNG's naturally low SOx and NOx emissions compared to traditional fuels. Within SOx ECAs, if LNG is not used, the 2015 fuel sulfur limit of 0.1 percent will require the use of higher cost distillate fuels such as MGO, or the use of scrubbers. For NOx ECAs, such as the North American ECA, the use of conventional petroleum fuels may require the use of expensive exhaust treatment controls such as SCR.

Additional economic concerns associated with the use of LNG including the following:

- Capital costs for cryogenic fuel tanks, piping, safety equipment, and the incremental cost of a dual-fuel engine,
- Training of crew on new safety and handling techniques,
- Costs associated with more frequent bunkering,
- Loss of cargo space taken up by larger LNG tanks, and
- Higher maintenance costs.

MDT conducted a study considering these factors in 2012. Under one scenario, a 2,500 TEU container vessel operating 65 percent inside European ECAs was analyzed and results showed significant annual cost advantages for this vessel when using LNG. The study also provided payback times for vessels of various sizes (2,500 TEU to 18,000 TEU) and percentages of operation within ECAs, assuming operation starting in 2015. For vessels operating within ECAs 65 percent of the time, the payback period was roughly 1 to 2 years, depending on vessel size. For vessels operating within ECAs only 10 percent of the time, the payback period was roughly 2 to 4 years. Thus, the amount of time the vessel spends inside an ECA must be considered versus the vessels remaining lifespan to determine if LNG is economical for the vessel owner. This study revealed that the economics of using LNG are driven primarily by the LNG tank system cost and the fuel price differential. This study provided a range from around $1,000 to $5,000 per cubic meter for tank cost. The tank size will vary widely with the size of the vessel, the route within the ECA zone (where LNG would be used), and whether the tank is sized for a round trip capacity or, alternatively, it is assumed to bunker LNG at the destination port before returning to the home port (MDT, 2012b).

Regarding the cost to retrofit an existing engine to a dual-fuel engine, Wärtsilä estimates that an engine conversion would be around 20 percent to 25 percent of the original engine cost (Wärtsilä, 2013).

5. Emissions Reductions

Marine engines operating on LNG have lower emissions of SOx, NOx, PM, and in some cases GHGs, when compared to traditional petroleum fuels. Some of these emissions benefits result from the fuel properties of LNG, while other benefits vary with the type of engine.

The 2014 Transport Canada study found that using LNG as a marine fuel resulted in SOx reductions of over 85 percent for dual-fuel engines (up to 100 percent for pure gas engines), NOx reductions up to 85 percent for Otto-cycle engines and up to 35 percent for Diesel-cycle engines, CO_2 reductions of about 20 percent to 29 percent, overall GHG reductions around 7 percent to 19 percent, and PM reductions around 85 percent as compared to fuel oils of any type (Transport Canada, 2014).

Although it is clear that using LNG can reduce emissions, there is some uncertainty in some of the estimated emission reductions - especially for PM. There is relatively little publicly-available information that documents in detail the testing procedures used to measure the emissions and associated emission reductions from these large marine engines. As such, there is a need for emissions testing of these engines while operating in gas mode. This testing should include emissions of NOx, SOx, PM, CO, CO_2, methane, hydrocarbons (HC), and potentially other emissions associated with natural gas engines, such as ammonia and formaldehyde. Next, we discuss the available information for some of the primary pollutants from these engines.

Sulfur Dioxide

Using LNG results in substantial reductions in SOx emissions compared to traditional fuels. SOx emissions are directly related to fuel sulfur content, and LNG fuel has little or no sulfur. There is generally always a small amount of diesel used when a vessel operates in gas mode, with the diesel fuel from the pilot injection accounting for 1 percent to 3 percent of the fuel used. In addition, Diesel-cycle dual-fuel LNG engines must switch to the use of pure diesel fuel at low loads, which typically occurs when vessels maneuver near ports or terminals. As a result, SOx emissions will not be completely eliminated. Nevertheless, dual-fueled engines in gas mode are expected to be able to meet the 2015 SOx ECA requirements (Wärtsilä, 2012a; Wärtsilä, 2013; MDT, 2012b).

Nitrogen Oxides

The use of LNG will help marine engines meet, and in some cases exceed, the IMO NOx standards shown in Table III-1. The U.S. is currently proposing amendments to the NOx Technical Code to address compliance with Tier III NOx standard using dual-fuel LNG engines that can operate on either HFO, diesel fuel or LNG (MEPC, 2014).

Table III-1: IMO NOx Standards

Tier	Vessel build date (on or after)	Total weighted cycle emission limit (grams/kW-hr) n= engine's rated speed (RPM)		
		n<130	130≤n≤1999	n≥2000
I	2000	17	$45n^{-0.2}$	9.8
II	2011	14.4	$44n^{-0.23}$	7.7
III	2016*	3.4	$9n^{-0.2}$	2.0

*Applies only within NOx ECA zones.

New marine diesel engines on OGVs must now meet IMO Tier II NOx standards, while meeting Tier III standards while operating in NOx ECA zones. Engines operating on LNG (both Otto-cycle and Diesel-cycle) can easily achieve NOx emissions levels well below the Tier II standards, offering additional emission reduction opportunities. For the more challenging Tier III standards, only the Otto-cycle LNG engines in gas mode can meet (and exceed) these emissions levels without the use of additional exhaust emission controls. Wärtsilä, manufacturer of Otto-cycle main and auxiliary engines, reports that in gas mode their dual-fuel engines can achieve NOx levels below the IMO Tier III NOx standards with no added exhaust treatment control (Wärtsilä, 2012a; Wärtsilä, 2012b; Wärtsilä, 2013). Per Wärtsilä, the company's dual-fuel engines operate using a lean-burn combustion technology that is inherently lower in NOx emissions, with the potential to reduce NOx emissions by up to 90 percent. For the Diesel-cycle LNG engines, MDT reports that their dual-fuel engines can meet the Tier II NOx standards without exhaust after-treatment, and Tier III with the use of exhaust after treatment (MDT, 2012c). Per MDT, these LNG engines can lower NOx emissions by 20 percent to 30 percent in comparison to their diesel-fueled counterparts because water vapor formed during combustion has a cooling effect, removing some of the temperature spikes where NOx is generated.

Particulate Matter

LNG-fueled vessels produce less PM than diesel fueled vessels due to the fact that LNG fuel does not contain aromatic compounds. Dual-fuel engines utilizing a diesel pilot injection will produce more PM than a spark ignition engines, though still considerably lower PM emissions than a traditional diesel engine (Corbett, 2015). Engine manufacturers show large emission reductions with the use of LNG, compared to heavy fuel oil (Wärtsilä, 2012a). On the other hand, there is very little test data available on PM emissions because there is no regulatory standard for PM. Some sources indicate PM emissions at around 0.1 g/kW-hr or lower (Kristenen, 2012; Wärtsilä, 2014). MDT reports a higher figure of about 0.3 g/kW-hr TO 0.5 g/kW-hr of PM emissions (MDT, 2012a). For reference, CARB estimates PM emissions of 0.24 g/kW-hr for marine diesel engines on OGVs using low sulfur (0.1 percent) distillate fuels.

Greenhouse Gases (GHGs)

The primary GHG emissions from marine engines operating on LNG is CO_2. The combustion of LNG results in lower CO_2 emissions relative to marine diesel fuels because it offers the inherent advantage of releasing less carbon per unit of energy than petroleum-based diesel fuels (ICCT, 2013). However, LNG engines can allow a certain amount of methane slip, which is unburned natural gas that leaves the exhaust stream. This can significantly reduce the GHG advantages of using LNG because the global warming potential (GWP) of natural gas is, by some estimates, 25 times the GWP of CO_2 (IPCC, 2007).

The amount of methane slip will vary with the engine type. On OGVs, auxiliary engines are typically four-stroke engines, whereas the majority of main engines are two-stroke. The amount of methane slip is found to be higher in the four-stroke Otto-cycle engines compared to the two-stroke Diesel-cycle engines (Chryssakis, 2014). This is consistent with research conducted by MDT, which measured methane slip for their ME-GI (two-stroke dual-fuel engine) at 0.2 g/kW-hr, and noted that four-stroke Otto-cycle LNG engines typically have methane slip of four to eight g/kW-hr (Juliussen, 2011). This paper further estimated that their Diesel-cycle dual-fuel engine (when using LNG) results in a global warming potential 20 percent lower than their comparable engine using diesel fuel. A 2013 paper released by the ICCT also estimated Otto-cycle marine engine methane emissions at four g/kW-hr (ICCT, 2013), which is within the range noted by MDT.

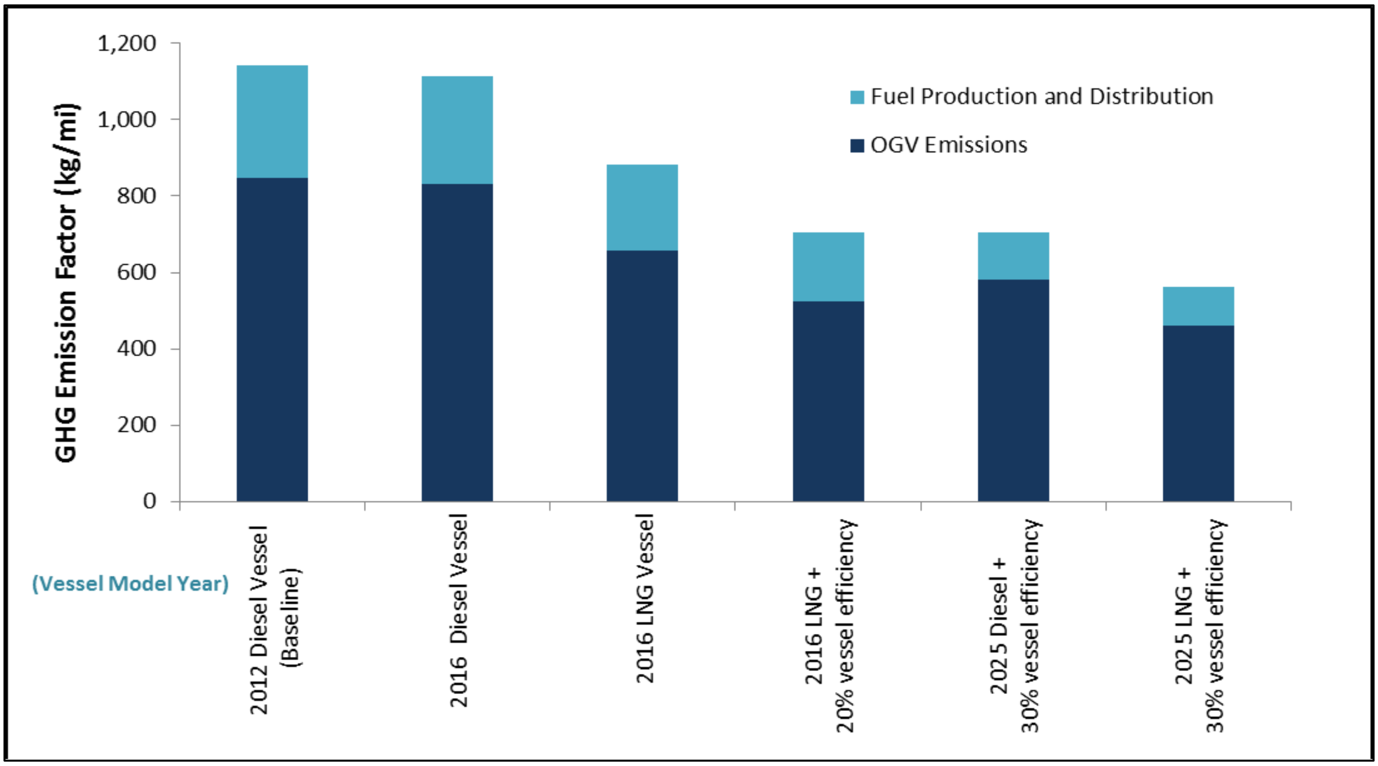
To limit the amount of methane slip in Otto-cycle gas engines, Wärtsilä utilizes catalyzers to oxidize unburnt methane and has made improvements to the geometry of the combustion chamber of their gas Otto-cycle engines. Optimizing the shape of the combustion chamber lowers the percentage of unburned methane gas that becomes trapped in the chamber, reducing methane emissions (Pospiech, 2014).

Methane slip typically refers to methane emissions resulting from direct engine operations. Methane leakage includes methane emissions that result from the bunkering or upstream processes associated with the production, storage, and transportation of LNG. In a recent study prepared by researchers for the U.S. Department of Transportation Maritime Administration, case studies investigating GHG emissions indicated that a significant portion of methane leakage occurs in association with the upstream LNG process, not the actual operation of the engine (Corbett, 2015). This same research study found GHG reductions of 6 percent to 15 percent for compression ignition LNG engines, whereas a spark ignition LNG engine showed an actual *increase* in GHG of 5 percent to 13 percent (Corbett, 2015). These estimates of GHG emissions look only at the vessel engine exhaust emissions, and do not represent a full fuel-cycle (well to propeller) analysis.

In a separate study, CARB staff estimated the well to propeller GHG emissions from diesel and LNG OGVs for the following vessels (shown in Figure III-2):

- 2012 baseline diesel-powered vessel,
- 2016 diesel vessel,
- 2016 LNG vessel,
- 2016 LNG vessel that is 20 percent more efficient than the 2016 vessel,
- 2025 diesel vessel that is 30 percent more efficient than the 2016 vessel, and
- 2025 LNG vessel that is 30 percent more efficient than the 2016 vessel.

Figure III-2: "Well to Propeller" GHG Emissions



Note: OGV emissions reflect CO_2 from combustion of fuel as well as methane slip (for LNG).
Assumed vessel efficiency improvements of 30 percent in 2025 (IMO).
Fuel carbon intensities based on updates to LCFS (April 2015), with methane leakage rate of 1.15 percent.

These emissions estimates are expressed in kilograms (kg) of GHG per mile of travel for a typical new container ship while operating on either diesel fuel or LNG. The estimates also incorporate expected improvements in vessel efficiency over time, resulting partly from the IMO EEDI regulations discussed in Chapter II. For the LNG vessel estimates, it was assumed that the main engine operated on the Diesel-cycle, and the auxiliary engines operated on the Otto-cycle. The assumptions used to develop these estimates are detailed in Appendix A.

As shown in Table III-2, using the assumptions detailed in Appendix A, vessels operated on LNG could offer greater GHG reductions than diesel powered vessels of the same model year and efficiency. For example, the GHG emissions from a 2016 LNG vessel are about 21 percent lower than a diesel-powered vessel. However, there are some simplifying assumptions used to develop these estimates that may not reflect true conditions. One of the key assumptions is that fuel production and distribution is based on North American infrastructure, while vessels bunker fuel in locations worldwide. Another assumption is that the LNG vessel would be powered by a Diesel-cycle main engine. This assumption was made because the market leader (MDT) in propulsion engines for large OGVs manufactures this type of dual-fuel LNG engine. Some percentage of main propulsion engines for OGVs will also be Otto-cycle engines manufactured by Wärtsilä, the second largest manufacturer of OGV engines, among other companies. The GHG benefits of a vessel powered by an Otto-cycle main engine would be smaller, although Otto-cycle engines provide other emissions benefits, such as greater NOx emissions reductions.

Table III-2: GHG "Well to Propeller" Emissions (kg/mi)

Vessel	Fuel Production & Distribution	Vessel Emissions	Total	Percent Reduction from 2012 Baseline
2012 Baseline	296	846	1142	0%
2016 Diesel	284	830	1114	2%
2016 LNG	225	656	881	23%
2016 LNG with 20% vessel efficiency improvement	180	525	705	38%
2025 Diesel with 30% vessel efficiency improvement	124	581	705	38%
2025 LNG with 30% vessel efficiency Improvement	103	459	562	51%

In addition to the analysis in Table III-2, there are studies that examine the fuel cycle GHG emissions from LNG marine vessels. A 2013 report by ICCT analyzes the well to propeller GHG emissions from LNG vessels supplied with fuel via eight different pathways. While not California specific, the study may provide some insights. According to this analysis, the benefits of LNG are much less than the widely reported GHG reductions of 20 percent to 30 percent, which are based only on the fuel's lower carbon content. Specifically, for the eight fuel pathways examined, they found the largest benefit to be an 18 percent reduction in GHG emissions, and at the other end, a 5 percent increase in GHG emissions (ICCT, 2013). It should be noted that the report assumed a much higher main engine methane slip estimate than CARB used, which would result in smaller GHG benefits than CARB staff analysis.

The ICCT report notes a number of factors that reduce the GHG benefits of LNG, including methane slip, and numerous steps and processes in the supply chain that consume energy (e.g., liquefaction), and that involve methane leakage (e.g., methane recovery, storage, transport, and bunkering). The report also notes that implementing a number of best practices could significantly reduce GHG emissions, yielding larger benefits from the use of LNG, and changing the outcomes to GHG reductions of 12 percent to 27 percent, based on the same 8 pathways.

Another recent study prepared for the U.S. Maritime Administration can be compared to CARB results as it includes California specific routes and engine methane slip estimates that more closely match those used in CARB estimates. This study provides full fuel cycle GHG (and other pollutant) emissions estimates for the use of natural gas and distillate diesel fuels. The study analyzed different vessel types (OGVs, coastal vessels, and inland tug/tow vessels), different routes, and various fuel pathways, and has the advantage of looking at vessel routes originating from California ports. Specifically, it analyzed OGVs travelling routes from the POLA/POLB to Shanghai, and POLA/POLB to Hawaii, under 11 different LNG fuel pathways. The results of these estimates show fuel cycle GHG emissions ranging from 13 percent to 20 percent lower with LNG, as compared to the use of low sulfur distillate fuel. The lower end of this range (13 percent) reflects natural gas imported from Qatar, while the greatest benefits for LNG (20 percent) were seen for North American natural gas extracted from an existing well (Elk Hills, CA) and delivered by pipeline to an existing liquefaction plant (Boron, CA). A liquefaction plant at a large volume gas pipeline close to POLB was also included to reflect a future possibility (also about 20 percent lower GHG compared to low sulfur diesel) (Corbett, 2014).

5. Next Steps to Demonstrate Technology

Marine engines that operate on LNG are already commercially available, and offer substantial emission reduction benefits compared to diesel-fueled engines. A few LNG-ready vessels are already built for California routes and for other regions in the U.S. Therefore, engine technology demonstrations are unnecessary. However, additional support for the implementation phase is necessary to address remaining barriers to the use of LNG.

The primary barrier is the lack of fuel bunkering infrastructure. Ideally, large OGVs will be refueled with LNG by bunker vessels that can receive the LNG, maintain it in a cryogenic state, and deliver it to LNG powered vessels without travelling very far. The infrastructure needed for this system includes LNG bunkering vessels, and liquefaction and storage facilities at marine terminals at or near California's major ports (e.g., Los Angeles/Long Beach and Oakland). To provide the volumes of LNG necessary in a mature LNG bunker fuel market, substantial storage and liquefaction facilities will be necessary at or near the ports, similar to the kind of facilities that now support petroleum based bunker fuels today. A more remote facility, where the fuel is transported a greater distance to the receiving vessels, will increase the cost of the fuel. There is also the economic challenge of installing infrastructure large enough to provide "economies of scale" and accommodate future growth, while not being fully utilized in the early stages of use.

Beyond the infrastructure needs, there are additional concerns as well, such as where the large volumes of LNG required to support the marine market would be produced, permitting and regulatory hurdles, community concerns regarding LNG storage facilities, leakage of methane during production and distribution, and differences in how the marine and gas industries operate. The natural gas industry operates under long-term contracts, whereas vessel operators prefer to purchase fuel as needed (Reuters, 2013).

To address the barriers that remain for LNG, coalitions of government agencies, natural gas utilities, port authorities, marine fuel suppliers, and vessel operators could be formed to find solutions to challenges facing the industry, such as:

- Finding potential locations for liquefaction and storage facilities,
- Identifying other potential (non-marine) customers of LNG for a facility,
- Addressing public concerns about natural gas storage facilities,
- Educating communities about the emissions benefits of natural gas,
- Identifying regulatory obstacles and providing input on pending regulations, and
- Addressing financial risks faced by early adopters.

State or federal government agencies could also help support the use of LNG by providing incentives, funding, and regulatory assistance with the infrastructure permitting process.

B. Engine Technologies

Prior to 2016, meeting Tier I and II standards could be achieved with modifications to the OGV engine set up. But, with the introduction of stricter Tier III standards, achieving compliance requires more extensive changes to the engine to meet required emissions reductions (Motorship, 2016). There are several technologies that can be applied to OGV engines to reduce emissions and improve performance. Technologies evaluated for this assessment include advanced fuel injection, electronically controlled lubrication systems, electronic engine monitoring and control, ultra-slow-speed diesel engines, and engine de-rating. Many of these technologies are well established, have been available for many years, and continue to improve incrementally over time, achieving even lower emissions and greater fuel efficiency. This is particularly true of the electronically controlled engine functions. Many of these technologies also pay for themselves due to improvements in fuel efficiency.

Vessel owners often have a choice of whether or not to include these technologies on new vessel purchases, and despite their advantages, owners sometimes choose older technology engines with lower up-front costs. Many of these technologies are not used in existing, older vessels, but could be installed as retrofits. Policies to encourage vessel owners to use the latest technologies in vessels visiting California (either new builds or existing vessels) could substantially reduce emissions and improve efficiency.

Advanced Fuel Injection

1. Technology Description

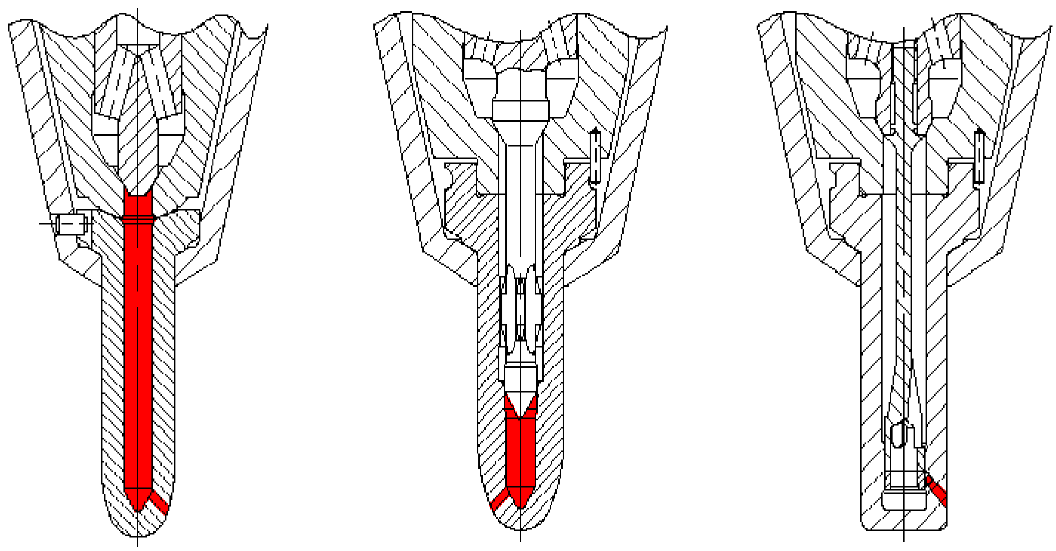
There were a number of important advances in fuel injection systems over the years, including common rail systems, electronic controls, and slide valves. Some of these technologies, such as common rail and electronic controls, were used in diesel truck engines for many years, and were only later adapted for use in marine engines. These technologies have the potential to help reduce fuel consumption and emissions, especially at low engine loads.

Common rail is one of the major advances in fuel injection. With this system, fuel is injected into the cylinders from a single manifold (or common rail). The manifold is essentially a tube that runs along the cylinders containing fuel pressurized by pumps. In practice, not all systems use a single common rail for all cylinders in the engine. Some systems use manifolds that only supply two or three cylinders each, or there can be individual systems for each cylinder that are not fed by a common rail, but achieve the same benefits (MDT, 2011a). In any case, the key advantage of all these systems is that the fuel pressure is independent of the engine speed. This is unlike conventional mechanical systems, where fuel injection pressure is provided for each cylinder by individual pumps driven by the engine camshaft, and thus linked to engine speed.

The common rail system allows for full injection pressure at all loads, and allows for better fuel atomization and the flexibility to tailor the fuel injection process to the engine load using electronic controls. Engines with common rail generally also use electronic control systems to optimize fuel injection. These systems monitor input signals such as crankshaft speed, engine load, intake air temperature, and available fuel pressure to send the appropriate signal to the fuel injectors to provide optimized injection pressure, timing, and volume (MDT, 2011a; Wärtsilä, 2007a). This results in lower fuel consumption and emissions at lower loads, when vessels are near ports, or when they are slow steaming (traveling at speeds lower than standard cruise speed). Other advantages of electronically controlled fuel injection systems include smoother engine operation, the ability to adjust injection timing while the engine is running, and fewer moving parts because there are no longer mechanical fuel pumps for each cylinder.

Another feature of advanced fuel injection systems is new technology fuel injectors. Conventional fuel injectors can retain a small amount of fuel after injection in a channel within the injector. The fuel in this channel (the sac volume) can drip into the combustion chamber and burn incompletely (Royal Belgian Institute, 2008). One approach to reducing these emissions is the mini-sac injector with a smaller sac volume. Another approach is the use of slide valve injectors that completely eliminate the sac volume. Figure III-3 shows each type of injector.

Figure III-3: Fuel Injector Designs (MDT)



The potential challenge with fuel injectors (both conventional and slide valves) is that they can be designed for lower NOx (with the tradeoff of slightly higher fuel consumption) or for maximum fuel efficiency (and higher NOx).

Another development in fuel injector technology is the MDT EcoNozzle, which is designed to optimize the fuel injection pattern for reduced fuel consumption without an increase in NOx emissions. This technology comes standard on all new MAN B&W engines and can be retrofit on all model MC engines (Marine Log, 2013a). The technology is expected to be released for other engine models after additional testing confirms that the fuel saving benefits apply to other engine models as well.

2. System/Network Suitability and Operational/Infrastructure Needs

Common rail and electronic control systems are available in new engines (both two-stroke and four-stroke) from both of the major engine manufacturers, MDT and Wärtsilä. While there are no major network or operational constraints for the use of engines with common rail and electronically controlled fuel injection, vessel operators still sometimes purchase the conventional mechanically controlled engines, even though there is little price premium for the new technology engines. For existing vessels, retrofits are possible for most engines. MDT reports that they can retrofit their two-stroke engines, and MDT product literature states that many of their four-stroke engines can be easily upgraded (MDT, 2014a). Nevertheless, cost may be a constraint for operators of older vessels, especially for vessels nearing the end of their useful life.

Regarding slide valves, this is an MDT product that only applies to their two-stroke engines. It is standard on new engines, and a retrofit option for older engines. The

MDT EcoNozzle is only available on one engine model at this time. Wärtsilä uses the mini-sac fuel injectors.

3. Technology Readiness

Common rail fuel injection systems (with electronic controls) have been available on new engines for over ten years, depending on the manufacturer and specific engine model. It was first offered on four-stroke engines, which are similar to landside diesel engines that already used common rail systems. Manufacturers currently offer both conventional and common rail fuel injection systems for new engines, and they use engine model designations to indicate whether the engine uses mechanically or electronically controlled fuel injection. For example, MDT two-stroke engines are electronically controlled (designated as ME engines) or mechanically controlled (designated as MC engines). Similarly, Wärtsilä has two-stroke RT-flex electronically controlled engines and RTA mechanically controlled engines.

Slide valves were first introduced in 2002 and are now a standard feature in new MDT engines. They can also be retrofitted on many older large MDT engines (with a 60 centimeter bore or larger). According to MDT, over 20,000 slide valves were already retrofitted (MDT, 2014b). The EcoNozzle is just now being introduced as a retrofit option for one MDT engine model.

4. Economics

Common rail systems with electronically-controlled fuel injection systems come standard on most new engines, although engines with conventional fuel injection are still available. MDT reports that the cost difference between these two systems is minimal (MDT, 2014a). For retrofits, MDT estimates the cost to convert a mechanically controlled MC engine to an electronic fuel injection would be roughly $450,000 to $500,000 (MDT, 2014a). The cost to retrofit the smaller four-stroke engines is expected to be much less.

For slide valves, the retrofit is relatively simple. In many cases, the older fuel injectors are simply removed and replaced with the new slide valve injectors. According to MDT's presentation at the 2006 *Faster Freight Cleaner Air* Conference, the cost of retrofitting slide valves was estimated at $25,000 for a 12 cylinder two-stroke engine (MDT, 2006). The EcoNozzle is also a straightforward retrofit option, and can be conducted during the regularly scheduled replacement of the injector nozzles. The installation of the EcoNozzle is described as a low cost retrofit product with a payback period of three to five months (Diesel Facts, 2014).

5. Emissions Reductions

Advanced fuel injection systems are assumed to reduce emissions in marine engines, though there is little publicly available data quantifying specific benefits. For common rail systems with electronic controls, the benefits are mainly achieved at lower loads. At higher design engine loads, there is little benefit because the mechanically controlled fuel injection systems are optimized for this use. But at lower loads, the advantages of electronically controlled systems are apparent. MDT product literature showed lower emissions of smoke, NOx, and fuel consumption for their four stroke engines with common rail, as compared to their engines without this feature. Specifically, for smoke and fuel consumption, there are emissions reductions found at loads below 25 percent. For NOx, the differences were noted at all loads up to nearly 100 percent (MDT, 2011a).

Regarding the use of slide valves, MDT reports that emission reductions of PM, HC, and NOx are possible (MDT, 2014b). Specifically, they estimate reductions in hydrocarbon emissions of about 30 percent, and noted tests resulting in 30 percent NOx emission reductions (MDT, 2014c). However, MDT noted that the reduction in NOx is due to changes in the nozzle spray pattern rather than the slide valve feature of the fuel injector (Royal Belgian Institute, 2008).

In a 2013 test conducted for POLA/POLB, a representative MDT test bed engine was evaluated with conventional valves, conventional low-NOx valves, and slide valves at a number of load points. The testing showed PM emissions up to 50 percent lower than conventional valves at low loads, and over 90 percent less hydrocarbon emissions with the slide valves. The slide valves also showed slightly higher NOx than both of the conventional valves at loads below 75 percent, as increasing fuel efficiency results in the tradeoff of higher NOx emissions (Starcrest, 2013).

The MDT EcoNozzle reportedly results in a 2 percent fuel savings in the MDT S50MC-C engine model. This is expected to yield similar reductions in air pollutants. Additional testing is underway to determine the fuel savings in other engine models.

6. Next Steps to Demonstrate Technology

Many vessel operators are already choosing the advanced fuel injection features when they order a new vessel, although there are still some operators choosing older mechanically controlled engines due to higher capital costs of newer technologies. There are also some vessels that could benefit from retrofitting these technologies. Incentive programs could encourage vessel operators that frequent California to retrofit these technologies or choose the cleanest new engines when placing new vessel orders.

Electronically Controlled Cylinder Lubrication Systems

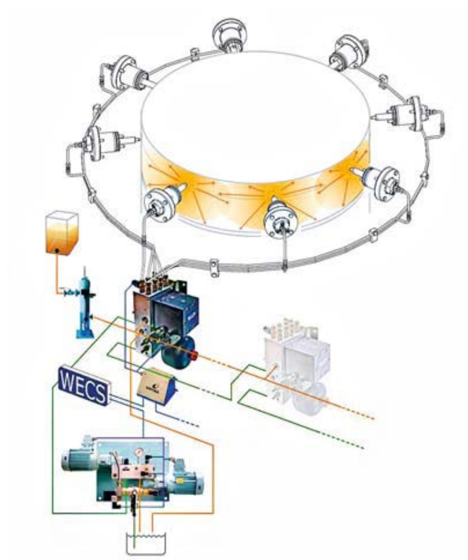
1. Technology Description

The slow-speed two-stroke main engines used to propel most OGVs use a separate lubrication system for the cylinder, piston and rings. The cylinder lubricant is designed to provide three functions: (1) provide an oil film between the cylinder liner and piston rings to prevent wear, (2) neutralize sulfuric acid formed from high sulfur fuels, and

(3) clean the cylinder liner and ring pack (Christensen, 2010). This specialized lubricant is injected at several locations along the circumference of the cylinder liner. After it is injected, it is then lost, partly as gaseous and particulate emissions through the exhaust stack and partly as sludge from the piston underside (Christensen, 2010). Because it must be repeatedly applied, it is an ongoing expense to the vessel operator, as well as a continuous source of exhaust emissions. For perspective, cylinder lubricant in older systems is applied at a feed rate of somewhat less than 1 percent of fuel consumption, and the cost is roughly 1 percent of vessel operating cost.

In response to rising lubricant prices, as well as environmental concerns, manufacturers moved to electronically controlled cylinder lubrication systems that more precisely apply lubricant and can reduce consumption. Specifically, MDT offers the Alpha lubrication system, and Wärtsilä offers the Pulse system (see Figure III-4). These systems more precisely deliver the oil dosage needed, based on the fuel sulfur content and the engine load (i.e., amount of fuel entering the cylinders). By some estimates, these systems reduce cylinder oil consumption by about 20 percent to 50 percent (MDT, 2012d; Wärtsilä, 2014).

Figure III-4: Pulse Lubricating System (Wärtsilä)



2. System/Network Suitability and Operational/Infrastructure Needs

These systems only apply to the slow-speed, two-stroke main engines used to propel cargo vessels; they are not applicable to four-stroke engines. These systems have been offered on new engines for several years, and can be easily installed as a retrofit option for engines that do not already have them.

3. Technology Readiness

Electronically controlled lubrication systems are currently available in new engine models, with both of the major manufacturers of slow-speed two-stroke engines

(MDT and Wärtsilä) offering them for many years. For example, they were first offered around 2000 by MDT, and are now standard on new MDT engines. Wärtsilä introduced the Pulse Lubricating System (PLS) in 2006, when it became standard on new builds. The potential for this technology is therefore in retrofit applications. Both MDT and Wärtsilä offer retrofit kits for their engines not currently equipped with these systems.

4. Economics

Lubrication systems come standard on new slow-speed two-stroke engines, so the cost of this feature alone cannot be estimated. For retrofit installations, the engine manufacturers do not report costs directly. However, the manufacturers do report lubricant savings in the tens of thousands of dollars annually, which often exceed $100,000 annually depending on engine size, and a payback period of two years or less due to lower lubricant feed rates. For example, it is estimated that a 6,500 TEU container vessel with a 12-cylinder Wärtsilä engine retrofitted with their PLS could save nearly 100 tons of cylinder lubricant and about $170,000 annually (Christensen, 2010). Similarly, the estimated cylinder lubricant savings with retrofits of MDT engines with the Alpha Lubrication systems range from $75,000 to $228,000 annually, depending on engine model (Doosan, 2007). MDT estimates payback periods of less than two years for retrofits of their “Alpha Adaptive Cylinder Oil Control” system, on most of their mechanically controlled engines (MDT, 2011b).

5. Emissions Reductions

The lubrication systems discussed in this section are shown to reduce the feed rate of the lubricant by about 20 percent to 50 percent; Starcrest’s 2013 testing with POLA/POLB (previously discussed in the Advanced Fuel Injection section) also indicated PM and gaseous (hydrocarbon) emissions reductions, but specific results were unavailable. Regarding PM emissions, the percent reduction with electronic lubrication systems will vary with the PM emissions contribution from cylinder oil as a fraction of the overall PM. The 2013 testing for POLA/POLB also found that PM derived from cylinder lubricating oil is a significant source PM emissions when low sulfur (<0.1 percent) fuel is used, but again, no specific results were provided (Starcrest, 2013).

6. Next Steps to Demonstrate Technology

Electronically controlled lubrication technology is a well-established retrofit option for many vessels that do not already have it on their main engines.

<u>Electronic Engine Monitoring and Control</u>

1. Technology Description

Electronic (automated or intelligent) engine controls can encompass both monitoring of key engine parameters, and automatic adjustment based on the results of these monitoring systems. Modern marine engines now have electronic controls that can control the operation of the fuel injection system, exhaust valve, cylinder lubrication, turbocharger, and other parameters. The manufacturers also use electronic systems to coordinate all of these systems (i.e., the overall operation of the engine) to reduce fuel and lube oil consumption, reduce emissions, and enhance reliability (MDT, 2012e).

2. System/Network Suitability and Operational/Infrastructure Needs

There are no significant technological or operational barriers for the use of these systems. Both of the major marine engine manufacturers offer a variety of these products on their new engines, and they are becoming more advanced over time. Some of the more advanced features may only be available on the larger two-stroke engine models. Manufacturers offer retrofit kits for many of these systems, with the hardware and software needed for many older conventional engines (MDT, 2012e; Rolle, 2011).

3. Technology Readiness

Electronically controlled systems are commercially available, with the most advanced systems offered on the larger, two-stroke engine models. Products have evolved over the last 15 years, starting with electronically controlled fuel injection, exhaust valves, and cylinder lubrication systems. Since then, manufacturers have further refined and coordinated of all these systems.

4. Economics

There are many different versions of electronically controlled systems, which are constantly evolving, and incorporating new features. Due to the variability of these systems, costs could not be estimated.

5. Emissions Reductions

Electronically controlled systems can provide emission reductions in two ways. First, there will be small reductions in emissions due to incremental improvements in fuel consumption, and the optimization of engine operation at lower loads. For example, reductions in fuel consumption of approximately 2.5 grams per kW-hr (roughly 1.5 percent) were found across the entire engine load range when using Wärtsilä's "Intelligent Combustion Control" system (Rolle, 2011). This would reduce CO_2 and other pollutants as well. Secondly, these systems provide the flexibility to operate in various low emission modes to meet local environmental regulations, such as IMO NOx limits.

6. Next Steps to Demonstrate Technology

Electronically controlled monitoring and control technology is well-established as standard equipment or an upgrade option on new two-stroke engines. It is also a retrofit option for many older engines. Incentive programs may help to convince vessel operators to purchase the most advanced engines on new vessel builds, and to consider retrofitting engines where kits are available.

Ultra Slow-Speed Diesel Engines

1. Technology Description

Ultra slow-speed engines have a higher stroke to bore ratio and lower rated speeds than standard slow-speed, two-stroke main engines. This design allows for greater engine efficiency, as well as the use of new technology propellers with larger diameters and slower rotational speeds. These changes reduce fuel consumption and associated emissions, and help vessels comply with IMO vessel efficiency requirements.

2. System/Network Suitability and Operational/Infrastructure Needs

While such engines are already available, they are only available for the slow-speed, two-stroke main engines used to propel cargo vessels, and only for new builds. This technology is best for vessel designs that can accommodate the larger propellers used with these engines – typically tankers and bulk carriers.

3. Technology Readiness

The use of these engines is well established. MDT offers G-type ultra-slow-speed engines since late 2010 (Diesel Facts, 2013). Prior to the introduction of the G-type engines, MDT offered (and continues to offer) the S-type super slow-speed engines, which operate at slower speeds than the engines used to propel most container vessels, but not as slow as the G-type engines. The S-type engines, which have been available for many years, are used in tankers, bulk carriers, and some larger container vessels.

4. Economics

Cost data for new ultra slow-speed engines was not available. However, these engines are expected to result in net savings to vessel operators due to lower fuel consumption. Along with being more fuel efficient, ultra-slow-speed engines also enable the use of more efficient larger diameter, lower speed propellers. These changes are estimated to result in an overall efficiency improvement of 4 percent to 9 percent. As an illustration, an MDT case study of a VLCC tanker estimated fuel savings of $9 million to $16 million over a 25 year time horizon with a G-type engine (standard or de-rated respectively) and optimized large diameter propellers (Motorship, 2011).

5. Emissions Reductions

Ultra slow-speed engines, in conjunction with optimized large diameter propellers, are estimated to result in an overall efficiency increase of 4 percent to 9 percent. While much of this improvement is due to the propeller design, it is the ultra-slow-speed engine that enables the use of this propeller, since these engines are directly coupled to the vessel's propeller shaft without a transmission to modify the shaft speed. This increase in efficiency is expected to result in similar reductions in fuel consumption and CO_2 emissions, as well as associated reductions in other pollutants.

6. Next Steps to Demonstrate Technology

This technology is well established, but would only apply to a subset of new vessels – certain tankers and bulk carriers. Benefits may be possible by implementing programs to preferentially introduce these new vessels to California routes.

Engine De-rating

1. Technology Description

Engine de-rating is a well-established method of reducing fuel consumption and associated CO_2 emissions. Marine engines are generally offered in de-rated versions that achieve lower maximum power, or maximum continuous rating (MCR), but greater fuel efficiency. In a simplified example of engine de-rating, a vessel operator requiring a certain power level for a new vessel may choose a de-rated engine with an extra cylinder. This larger, de-rated engine may provide similar power output as the standard, smaller engine, but with lower fuel consumption. Engine de-rating does not have to involve a larger engine with an additional cylinder, as long as the de-rated engine has adequate power output for the application. Interest in de-rated engines tends to rise and fall with fuel prices. However, there may be a more sustained interest now due to the IMO's vessel efficiency rules.

2. System/Network Suitability and Operational/Infrastructure Needs

De-rated engines are already available for most marine engine models. In fact, manufacturers of slow-speed two-stroke engines offer their engines at any power rating point within a power/speed layout diagram – a shape defined by four points on a graph of engine power versus engine speed (Wärtsilä, 2008). This allows the customer the flexibility to choose a given engine model with the desired MCR and engine speed for a particular vessel and propeller. It also allows an operator to choose an engine with lower fuel consumption at a reduced power rating.

An existing engine can also be de-rated for fuel savings, if a lower maximum speed is acceptable for the vessel. But, de-rating an existing engine would involve engineering studies and significant changes to the vessel, including installation of new engine and turbocharger components and a new optimized propeller. Engine de-rating would also leave the vessel unable to obtain its original rated max speed in the future. These retrofit costs are estimated at about $1 million to $4 million (MDT, 2013a).

3. Technology Readiness

The use of de-rated engines is well established, and have been offered for decades in new-builds and in some applications as a retrofit on existing vessels. Many vessel operators with ships optimized for maximum speed are reportedly now expressing an interest in retrofits such as de-rating that will sacrifice speed for greater fuel savings (Vesterager, 2013).

4. Economics

A larger de-rated engine, such as an engine with an extra cylinder, will represent an additional investment. However, the fuel savings will in many cases provide an acceptable payback time for vessel operators. In a 2008 document, Wärtsilä presented case studies of four vessel types installed with a standard engine and a de-rated engine with an extra cylinder, without increasing engine power. The studies estimated payback periods ranging from 2.5 to 7 years based on higher incremental engine costs of about $1 to $2 million, and fuel prices ranging from $400 to $600 per ton. Wärtsilä's 2008 study also noted reductions in fuel consumption rating from 2 percent to 3.4 percent, and also noted that de-rating does not have to involve purchasing an engine with an extra cylinder (Wärtsilä, 2008).

A similar case study by MDT for a tank vessel compared a standard five cylinder engine to a de-rated six cylinder engine. This study estimated a reduction in fuel consumption of 2.9 percent but did not estimate a payback period (MDT, 2009).

5. Emissions Reductions

Reductions of 2 percent to 3 percent in fuel consumption are possible using de-rated engines. Similar percent reductions in CO_2 are expected, along with other emission reductions associated with reductions in fuel consumption.

6. Next Steps to Demonstrate Technology

This technology is well established, and many vessels already utilize de-rated engines. Existing vessels not ordered with de-rated engines could retrofit their engines, but this would be a costly change, and the vessel operator may not be able to consider this for vessels that cannot operate with an engine with lower rated power output.

C. Engine Support Technologies

Exhaust gas recirculation, turbocharging, and systems that add water to fuel are technologies that can reduce NOx emissions from diesel engines and in some cases fuel consumption.

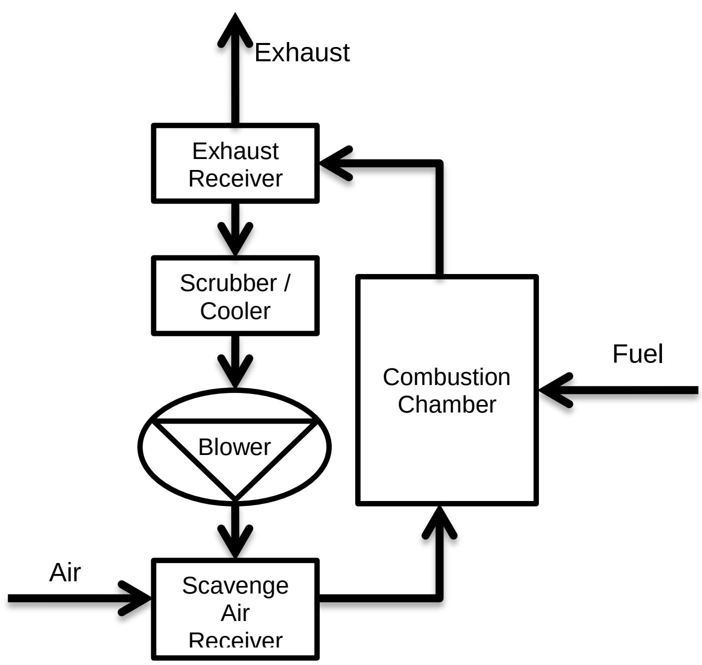
Exhaust Gas Recirculation

1. Technology Description

Exhaust gas recirculation (EGR) is a method to reduce the formation of NOx in marine diesel engines. EGR systems add a portion of the engine exhaust, after cleaning and cooling with a scrubber, back into the combustion chamber. The addition of this conditioned exhaust gas with intake air lowers the oxygen content in the combustion chamber and provides additional gases that can absorb heat, reducing combustion chamber temperatures and NOx formation. See Figure III-5 for an example of an EGR flow chart.

In this process, some of the oxygen in the intake air is replaced by CO_2 from the combustion process. This replacement slightly decreases the amount of oxygen available for combustion and increases the heat capacity of the intake air, thus reducing the combustion temperature peak and the formation of thermal NOx. The downside of EGR is that the lower-temperature diesel combustion is less efficient, so it may create more particulate matter and it burns more fuel.

Figure III-5: EGR Flow



2. System/Network Suitability and Operational/Infrastructure Needs

In the marine sector, fuels typically have higher sulfur levels compared to land based diesel equipment categories. Marine fuels typically range from heavy fuel oil with up to 3.5 percent sulfur (35,000 ppm) to cleaner marine gas oil at 0.1 percent sulfur (1000 ppm) compared to 15 ppm for on-road diesel (CARB Diesel). EGR is sensitive to sulfur content of the fuel being combusted, as higher sulfur contents can lead to the formation of sulfuric acid resulting in component corrosion and increased particulate exhaust levels. The particulate matter in the exhaust, if recirculated back into the cylinder, can increase engine wear. Therefore, EGR works well with exhaust gas scrubber technologies that remove sulfur and PM from exhaust gas prior to recirculating back to the intake. When using a scrubber to remove sulfur, the buildup of acid in the scrubber system can be neutralized with sodium hydroxide and stored before it can be discharged (MDT, 2012c).

There are many benefits to EGR over alternative NOx reduction technologies. The main components of an EGR system (air receiver, scrubber, cooler, and blower) are all integrated into a vessel's engine, making for a small overall footprint without changing a vessels infrastructure. Because EGR systems are computer controlled, the system operates without crew intervention. An EGR system is able to operate at a wide range of engine loads, including very low loads. Lastly, some EGR systems are capable of operating at Tier III, but have the option to reduce fuel usage and operate in an optimized Tier II mode (Alfa Laval, 2014).

3. Technology Readiness

EGR technology has been successfully demonstrated on a wide-spread basis for on-road and off-road diesel engine categories and stationary power plants. Recently, it has successfully migrated to OGVs due to 2016 IMO Tier III NOx requirements. This technology was first demonstrated as a retrofit in 2010 on the OGV Alexander Maersk. The Alexander Maersk has since logged more than 2,200 hours operating the EGR system. The Maersk Cardiff was also built with EGR. This vessel operated at Tier III for more than 1000 hours and operated on a fuel optimized Tier II mode for more than 350 hours (Alfa Laval, 2014). The vessel was also utilized to thoroughly test the Aalborg EGR-High Pressure Economizer (EGR-HPE) boiler in a joint project supported by the Danish Energy-Technological Development and Demonstration Program (EUDP) and Aalborg University. The EGR boiler was designed by Alfa Laval in partnership with MDT) to enhance efficiency of a standard EGR unit. The EGR-HPE boiler allows waste heat recovery to occur lower engine loads than standard EGR systems when the vessel is operating with Tier III standards, and could present additional slow steaming opportunities for vessels versus using standard waste heat recovery systems alone (Marine Log, 2015).

The two dominant engine makers, MDT and Wärtsilä, are currently marketing and manufacturing EGR equipped propulsion and auxiliary engines for new vessels built in 2016 and later. Penetration into the California vessel fleet may increase since operation in the North American ECA will require Tier III standards for new vessels. Even so, growth will be slower for the OGV sector due to limited growth in the industry and low vessel turnover. Introduction of Tier III engines is expected to be hampered by the high number of ship orders laid with Tier II engines prior to 2016.

4. Economics

The cost estimates to use EGR to meet IMO Tier III standards (for vessels built in 2016 and later operating in ECAs) are in the range of $51-$62/kW for capital expenses, with operational expenses ranging from $2.8-$4.1/MWh and a fuel penalty, due to less efficient combustion, of about 0.6 g/kW-hr (2012, Danish Ministry of the Environment). For a vessel with a 40,000 kW slow-speed two-stroke main engine and three 1900 kW auxiliary engines, the differential in vessel costs would include capital cost in the range of $2.3 million to $2.8 million and operating costs in the range of $0.8 million to $1.1 million per year, including the additional fuel costs (CARB, 2008).

5. Emissions Reductions

Typically, NOx reduction is almost linear to the ratio of recirculated exhaust gas (i.e., replacing 10 percent of the intake air with recirculated exhaust produces 10 percent reduction in NOx) (MDT, 2013b). Most EGR systems today can reduce NOx emissions between 10 percent and 40 percent. Though the feeding of lower oxygen content exhaust through EGR reduces cylinder temperatures and NOx emissions, this has a potential net disbenefit on reducing combustion efficiency which may result in additional unburned hydrocarbon, PM, and CO_2 formation, as well as in some cases may see a potential (1 percent) increase in fuel consumption. The electrical loads of the EGR system could account for 2 percent of the main engine power (Kristenen, 2015).

Due to more stringent IMO Tier III requirements that began in 2016 for new vessels operating in ECAs, engine manufactures are producing EGR systems that can achieve even greater reductions. Tier III standards require a reduction on the order of 65 percent below Tier II standards (IMO, 2014). To meet the more stringent Tier III NOx requirements, engine manufacturers are designing and manufacturing engines with EGR systems combined with engine tuning that are achieving NOx reductions in the range of 50 percent to 80 percent. Because the Tier III requirements only apply to new vessels, the focus of EGR development is on new two-stroke, slow-speed propulsion engines and new four-stroke medium speed auxiliary engines.

6. Next Steps to Demonstrate and Deploy Technology

Since retrofits are not required under the current or upcoming regulatory requirements at the state, federal, or international level, there is currently little demand for EGR retrofits in the marine sector. But both MDT and Wärtsilä, the two largest manufacturers of large marine two stroke propulsion engines, offer retrofit-able versions of EGR. The Alexander Maersk was one of the first large marine vessels to be retrofitted with EGR, demonstrating NOx reductions on the order of 50 percent (Royal Belgian Institute, 2013). To comply with more stringent Tier III requirements, EGR is being deployed for vessels ordered for 2016 and later.

Water Technologies

1. Technology Description

The NOx reduction technology based on water in the fuel is shown to have some success in operation. Water in the combustion chamber reduces temperature peaks during the combustion process, which results in lower NOx emissions in two-stroke and four-stroke engines. In general, there are three possibilities to bring the water into the cylinder: use of fuel/water emulsions (FWE), direct water injection (DWI) into the combustion chamber, and humidification of the aspirated combustion air in a Humid Air Motor (HAM). All three possibilities have been demonstrated in practical operation.

- HAM systems use heated intake air which is saturated with water vapor which can be from heated seawater or fresh water. This mixture of air and water vapor is injected into the cylinder. One way to increase efficiency is to use the excess heat from the engine to heat up the incoming water stream. If that does not provide enough heat, boilers may need to be used to heat the water. The ratio of water to fuel is generally about 3 times greater and may achieve reductions of 70 percent to 80 percent (Fournier, 2006).
- FWE mixes water directly into the fuel. The emulsion process can be improved by including a fuel mill into the system that grinds the fuel to create better mixtures and more complete combustion. Emulsion of water can occur until approximately 30 percent fuel. At that point, there could be an increase in PM. This technology must use fresh water, so distillation of seawater would need to be done onboard or fresh water would need to be acquired at port. This system can be turned on and off relatively easily, so vessel owners could turn it on closer to port to reduce NOx emissions (Fournier, 2006).
- DWI directly injects water into the combustion cylinder, with fresh water also required for injection. The water is generally injected at 200-400 bar and is injected right before the fuel stream. The water to fuel ratio can range from 40 percent to 70 percent which will require significant onboard tankage. The system can be turned on and off as necessary (Fournier, 2006).

2. System/Network Suitability and Operational/Infrastructure Needs

Water technologies require either a fresh supply of water, or a water purification system. This requires a storage tank onboard the vessel and extra water supply when the ship is at port. If the vessel purifies their own water supply, a water distiller that can keep up with the demand of the water system is needed.

All three water technologies could be used on new or existing vessels. Space may be a constraint for some vessels as new pumps, storage tanks, additional boilers, and mixing vessels may need to be installed to operate the water technology. HAM systems generally can replace the intercooler on the vessel.

3. Technology Readiness

DWI technology has been used in operation on vessels since the late 1990's. In 1999, Wärtsilä tested DWI on the passenger ship MS Silja Symphony, with results indicating a 60 percent NOx reduction. Then in 2005, Wärtsilä's DWI system was commercially installed on another 23 ships. Overall, Wärtsilä reports NOx reductions of 50 percent to 60 percent (Lövblad, 2006).

MDT has a version of DWI that they call the Scavenging Air Moistening (or SAM) system that reduces NOx by spraying fresh water into the scavenging air. It is injected in three stages, starting with seawater and in later stages using fresh water. The scavenging air is almost fully saturated and in each stage condensate must be collected and drained into its corresponding tank. MAN reports NOx reductions of 20 percent to 30 percent (Lövblad, 2006).

The Viking Line's MS Mariella installed a HAM system which has operated for more than 27,000 hours. The system requires no warm up time and is shut down 15 minutes before stopping the engine to dry up the engine cylinder to avoid corrosion while the engine is turned off. Tests of this system show NOx emission reductions of 70 percent to 85 percent (Lövblad, 2006).

CARB, in conjunction with the POLA and POLB, tested a FWE system on the APL Singapore. The technology was provided by Sea to Sky Pollution Solutions. The vessel was tested over a 15 day transpacific voyage by UC Riverside and MAN. The results showed a NOx reduction of 30 percent (TAP, 2012).

Major manufacturers have commercially available systems that can be installed in a matter of weeks in most cases and can be done in port or while the vessel is under way.

4. Economics

The cost for direct water injection in a new build is between $57/kW for a small engine to $27/kW for a large engine. Annual operational and management costs for DWI systems range from $41,000 for small engine to $340,000 for large engines. The cost for a humid air motor ranges between $192/kW for a small engine to $162/kW for a large engine. Annual operational and management costs for HAM systems range from $3,000 for small engine to $24,000 for large engines. Finally, FWE systems cost approximately $550,000 to $750,000 depending on the availability of water tanks and the need for a distillation unit (Fournier, 2006).

5. Emissions Reductions

Table III-3 lists the estimated NOx reductions that could be achieved with the three water technologies. Testing done by CARB in conjunction with POLA and POLB showed approximately 30 percent reductions in NOx, though exceeding the optimal water-to-fuel ratio can result in higher soot formation. As water technologies are designed as primarily a NOx reduction technology, no available estimates of associated PM or GHG benefits are known.

Table III-3: Estimated NOx Emission Reductions for Water Technologies

Water Technology	NOx Emission Reductions
Humid Air Motor	Up to 70%
Water Emulsion	Up to 30%
Water Injection	Up to 50%

6. Next Steps to Demonstrate and Deploy Technology

Water technologies are established technologies commercially available for purchase. This technology could reduce emissions in both new and existing fleets, and can potentially take up less space onboard compared to a technology like SCR. Unfortunately, with this technology there are no fuel efficiency benefits, so there is no cost benefit to vessel operators. Reductions in NOx would therefore most likely need to be incentivized or regulated to realize reductions onshore. Tier III NOx emission standards are in place for new ships as of 2016, but vessels will likely need to use a combination of SCR and/or EGR to realize Tier III NOx reductions.

Advanced Turbocharging

1. Technology Description

Turbocharging has a long and successful history of use in diesel engines. The first turbocharger for a diesel engine was delivered in 1924; this was the beginning of intensive research and development of the technology (ABB, 2014). The technology was first introduced in four-stroke engines, but the two-stroke engine, with its low exhaust-gas temperatures and dependence on a blower for the gas exchange, presented significant difficulties due to the low turbocharger efficiency at the time. Not until compressors and turbines with higher efficiencies were developed did turbocharging two-stroke marine engines become a practical proposition. Thereafter, the use of exhaust gas turbocharging increased rapidly, helping the two-stroke engine to achieve dominance as a direct drive, slow-running marine engine.

The main purpose for using turbocharging is to improve power output through increased air capacity. Turbocharging was traditionally used to increase engine power without having to increase the engine size (power to weight ratio) or to lower fuel consumption by increasing engine efficiency. The power output of an internal combustion engine is dependent on the amount of air and fuel in its cylinders. Turbochargers supply air to the engine at a high pressure, so more air is forced into the cylinders and is available for combustion. A turbocharger is driven by the engine’s exhaust gas. The exhaust gas exits at a high flow rate with a temperature approaching 600°C and is directed at high velocity onto the blades of a turbine, which is attached by a shaft to a compressor wheel. As the turbine rotates, it rotates the compressor. The compressor draws in ambient air, compresses it and feeds it via an after-cooler to the engine’s air receiver, where it passes to the cylinders. Because the air has a higher pressure and higher concentration of oxygen, the combustion process is more efficient. While the concept is fairly straightforward, the turbocharger design is complex and must be finely tuned to the engine operating parameters. Turbocharging can increase engine output by up to four times, with up to 75 percent of engine power dependent upon the turbocharger.

2. System/Network Suitability and Operational/Infrastructure Needs

The two-stage turbocharger is a recent development in turbocharging for large marine engines. This system uses two specially designed turbochargers of different sizes connected in series to create pressure ratios higher than the best single stage turbocharger. Their performance is carefully chosen to give the level of air delivery required by the specific application. The turbine of the larger turbocharger is located upstream of the turbine of the smaller unit in the exhaust gas flow from the engine. Similarly, the output of the compressor of the larger turbocharger is fed into the compressor of the smaller turbo charger. This arrangement readily produces very high turbocharging pressure ratios.

3. Technology Readiness

In 1952, the first ship to be powered by a turbocharged two-stroke diesel engine was launched (the tanker Dorthe Maersk). Since then, turbocharging became common place in large marine engines. While turbocharging has been available for decades, new advanced designs tailored to marine engines are resulting in greater efficiency and performance benefits (MDT, 2014d). MDT reports that 20,000 high efficiency turbochargers are currently in operation for large marine engines (MDT, 2014e).

4. Economics

In 2009, U.S. EPA estimated the cost of engine modifications to meet Tier III standards, including two-stage turbocharging, between $2.4/kW for a 48 MW low speed engine to $9.5/kW for a 4.5 MW medium speed engine. (EPA, 2009).

5. Emissions Reductions

Turbocharging's higher pressure ratios can significantly increase power output and reduce fuel consumption (reducing brake specific fuel consumption by 1 percent to 4.5 percent). Because of the lower fuel consumption while maintaining power, CO_2 emissions, as well as gaseous and particulate emissions can be reduced.

Until recently, turbocharging was used to increase engine power or lower fuel consumption by increasing the efficiency of the engine. Now, turbocharging is also being used to lower exhaust emissions for NOx. The increased air pressure in the cylinder due to turbocharging can be used in combination with other engine modifications such as Miller valve timing in combination with turbocharging. This can be used to reduce NOx emissions without increasing fuel consumption. To reduce the temperature peaks which promote the formation of NOx, early closure of the inlet valve causes the charge air to expand and cool before start of compression. The resulting reduction in combustion temperature reduces NOx emissions.

6. Next Steps to Demonstrate and Deploy Technology

Turbocharging technology is widely deployed. Advanced two-stage turbocharging with valve control is being deployed in both retrofit and new builds (Marine Log, 2013b). Although turbocharging is not new, it is being used with greater effect in tandem with other advances like automated engine monitoring systems.

D. After-Treatment Technologies

The use of exhaust after-treatment controls such as selective catalytic reduction and exhaust gas scrubbers are well adapted for land-based diesel engines and are emerging as options for reducing emissions from OGVs.

Selective Catalytic Reduction

1. Technology Description

Selective catalytic reduction (SCR) is a highly effective control technology for reducing NOx emissions from combustion sources, including marine diesel engines. SCR systems treat exhaust gases with ammonia or urea and route it through a catalytic converter. In the catalytic converter, a selective chemical reaction takes place that targets NOx, breaking it down into nitrogen and water. Catalysts are typically made of a ceramic substrate incorporating active catalytic materials such as precious metals or metal oxides. SCR systems can reduce NOx emissions by over 90 percent, depending on a number of factors, such as the catalyst used, fuel quality, and engine exhaust temperature.

2. System/Network Suitability and Operational/Infrastructure Needs

SCR systems are installed on the engine exhaust system and the necessary equipment is fully housed on the vessel. Therefore, SCR does not require any external infrastructure changes. As an engine after-treatment technology, SCR systems are sustainable and the operational needs are similar to other engine technologies, including training for maintenance, operation and repairs.

Catalysts on SCR systems can last for five to six years depending on the operating conditions of the engine, fuel sulfur content, and whether the vessel is only using the SCR system for some portion of its voyages, such as within an Emission Control Area (ICCT, 2014). Catalysts can be disposed of or recycled when needed, although care must be taken due to heavy metals that may accumulate on the catalyst.

In marine SCR systems, exhaust gases are typically treated with urea, which is a feedstock consumed at a rate of about 7 percent of the fuel consumption. Urea is widely available at ports across the globe, being commonly used in agricultural and industrial applications. Even with an increase in the use of SCR for marine vessels, marine use of urea is expected to account for less than 1 percent of the worldwide urea consumption by 2020 (ICCT, 2014).

Some limiting factors for SCR effectiveness are exhaust temperature and fuel sulfur levels. The NOx reduction reaction is effective only within a given temperature range, depending on the type of catalyst used and the exhaust gas composition. Optimum temperatures vary from 250°C to 427°C. Typical SCR systems tolerate some temperature fluctuation, but will not operate optimally at the low exhaust temperatures that correspond to vessel main engines operating at low load conditions such as vessel maneuvering or reduced speed operations.

On two-stroke engines, due to their high efficiency, the exhaust temperatures tend to be on the lower end of the required exhaust temperature range. Consequently, the SCR is placed before the turbo systems. This means that the SCR needs to be installed in the engine room and not in the funnel. However, even with this placement, it can still be a challenge to meet the required temperature when these engines operate at lower loads (e.g., maneuvering) where the temperature may be below 300°C. For four-stroke engines (e.g., generator sets and cruise ship engines), the exhaust gas temperature is higher. Therefore, low exhaust gas temperatures are less challenging.

For low load situations, use of SCR systems can be designed to ensure sufficient exhaust temperature. This may include reducing the level of charge air cooling or modifying the injection timing. Another approach to increase the exhaust temperature would be to use burner systems during low-power operation. According to MDT, the SCR system is best suited for steady high-load conditions, and is less suited for low-load operation and maneuvering in coastal and harbor areas (DME, 2012). If the exhaust temperature is too low, the urea or ammonia can potentially form hydrogen sulfate which gradually blocks the catalytic converter, reducing the effectiveness and potentially producing sulfate particulate matter.

SCR systems operate best with engines using low sulfur fuels. If there is too much sulfur in the exhaust, sulfur oxides can be oxidized to sulfate species which can foul the catalyst and increase sulfate particulate matter emissions (Jayaram, 2009). Because of the low sulfur requirement, the use of SCR would be ideal in SOx Emission Control Areas which limit fuel sulfur to 0.1 percent (1,000 ppm).

3. Technology Readiness

SCR is a proven technology for diesel engines on OGVs, with over 500 installations on a variety of vessels and engines (Azzara, 2014). In fact, four bulk vessels operating between California and South Korea have been using SCR to reduce their NOx emissions by up to 90 percent since the 1990s (USS-POSCO, undated). Many new build vessels are using SCR to comply with the 2016 IMO Tier III NOx standards (Fairplay, 2015, Wärtsilä, 2015).

SCR systems are easier to install on new builds compared to retrofit installations. The catalysts and urea storage can take up significant amounts of space onboard vessels, making SCR retrofits uncommon on OGVs. There have also been retrofits on OGV auxiliary engines, which are significantly smaller than main propulsion engines, and on smaller bulk cargo vessels and ferries.

CARB staff is not aware of SCR use on marine boilers. This may be due to the lack of NOx standards as a regulatory driver. Marine boiler exhaust is also lower in NOx than diesel engines. Nevertheless, SCR is used on stationary source boilers, so it may be feasible for marine applications as well.

4. Economics

The cost of an SCR system depends on a number of factors including size and whether the system is rebuild or retrofit. In 2009, U.S. EPA estimated the cost of SCR system range between $43/kW for a 48 MW low speed engine to $82/kW for a 4.5 MW medium speed engine (EPA, 2009). Operational costs will vary depending on engine operation, and include regular maintenance and monitoring, purchase of urea or ammonia, and periodic replacement and disposal of the ceramic catalyst. The ongoing cost of the urea or ammonia makes up a significant percentage of the operational costs, and is highly dependent on the amount of time the vessel uses the SCR system, typically when the vessel is operating in an ECA zone.

The International Association for Catalytic Control of Ship Emissions to Air (IACCSEA) estimated that the capital costs of an SCR system (including installation) would be about $500,000 for a 20,000 DWT vessel with a ten MW main engine. Considering this same vessel, IACCSEA estimates a cost over the lifetime of a vessel (assumed at 25 years) would range from approximately $1.8 million (1,500 hours per year in an ECA) to $5.3 million (8,000 hours per year in an ECA). IACCSEA has also developed a calculator to enable vessel owners or operators to conduct a cost benefit analysis using a variety of customizable factors (IACCSEA, 2013).

5. Emissions Reductions

SCR systems are designed solely to reduce NOx emissions and are very effective in this task, with the ability to reduce NOx emissions by over 90 percent. In the North American ECA, SCR systems are currently being used on some vessels to meet the 2016 IMO Tier III NOx standards. This represents about an 80 percent reduction in NOx from the Tier I IMO NOx standard implemented in 2000.

The reductions achieved by SCR systems depend, in part, on the amount of ammonia or urea injected. If there is insufficient ammonia or urea, the system will not achieve maximum control of NOx emissions. On the other hand, too much will result in ammonia slip. Ammonia slip refers to emissions of unreacted ammonia that result from incomplete reaction of the NOx and the reagent. Ammonia slip may cause formation of ammonium sulfates which can plug or corrode downstream components. In the U.S., permitted ammonia slip levels are typically two to ten ppm. Ammonia slip at these levels do not result in plume formation or human health hazards. Process optimization after installation can lower slip levels (ICAC, 1997).

6. Next Steps to Demonstrate and Deploy Technology

Due to its effectiveness in NOx emissions control, the use of SCR systems is increasing in response to the 2016 Tier III IMO NOx requirements. While the 2016 Tier III standard represents significant progress, additional reductions in NOx could be achieved through a future effective Tier IV standard. For the majority of slow-speed two-stroke engines propelling OGVs the Tier III NOx standard is 3.4 g/kW-hr. CARB staff envision a future Tier IV standard of about 1 g/kW-hr could be achieved with state of the art SCR, or a combination of SCR and other NOx control technologies discussed in this document.

This standard would represent a 94 percent reduction from the Tier I standard. We note that similar NOx emissions reductions have been achieved on marine vessels for many years. The USS POSCO vessels mentioned in the Technology Readiness section represent one example. Two-stroke engines on Ro-Ro vessels in 1999-2000 achieved 2 grams NOx per kW-hr (Azzara, 2014). We also note that NOx emissions standards already in place for other diesel engine sources are similar to a 1 g/kW-hr emissions level. The current new engine U.S. EPA Tier IV NOx standard for many harbor craft and locomotive engines is 1.3 g/bhp-hr (or about 1.7 g/kW-hr). The current U.S. EPA and CARB standard for diesel truck engines is 0.2 g/bhp-hr (or 0.27 g/kW-hr).

Currently, there are very few demonstrations of SCR as retrofits on either propulsion or auxiliary engines. Increased deployment of retrofit SCR installations would depend on regulatory or incentive programs designed to reduce NOx emissions. Prior to developing programs that would require retrofits, the viability for OGVs would need to be thoroughly assessed and demonstrated.

Scrubbers

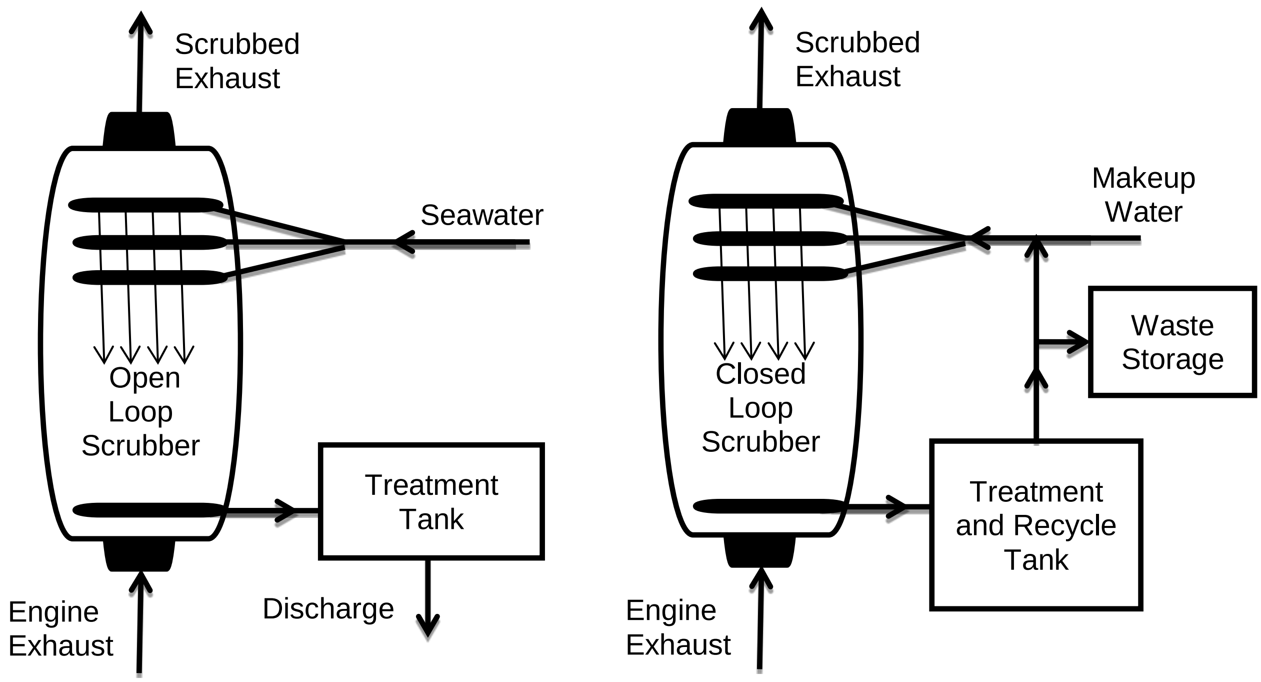
1. Technology Description

Scrubbers are exhaust after-treatment devices that remove pollutants in the exhaust stream through contact with a sorbent material. While there are both wet and dry types of scrubbers, the designs used for marine vessels are generally wet scrubbers that deliver a fine spray of fresh or seawater that contacts the pollutants within the exhaust stream. These systems are primarily designed to remove SOx, but they also remove particulate matter and, to a lesser degree, NOx emissions.

Scrubbers can be classified as closed loop systems, open loop systems, and hybrids of both. Closed loop systems use freshwater that is chemically treated to increase the pH level (usually with caustic soda) which is necessary to effectively reduce SOx emissions. These systems continuously treat and recycle the water, so there is little or no discharge overboard. As such, they are often used in large freshwater lakes, inland waterways and sensitive areas.

Open loop systems use seawater and discharge it to sea after treatment to remove particulates and other pollutants. These are simpler designs that do not need to chemically treat the water because of the natural alkalinity of seawater. However, they rely on the alkalinity of the open seas, which may not be adequate for some areas, and there can be constraints in areas where discharge is not allowed. Figure III-6 depicts a simplified schematic for open loop and closed loop scrubber designs.

Figure III-6: Open Loop and Closed Loop Scrubber Diagrams



Hybrid systems use seawater, but have the capability of recycling their water while operating for a limited time in sensitive inland waterways. These are the most flexible systems and are able to operate in all ECA zones, but they are also the most complex.

Scrubbers can be used to control the emissions from both main and auxiliary engines. There can be a common system that controls all engines or individual systems for each engine.

2. System/Network Suitability and Operational/Infrastructure Needs

Scrubbers can be installed as a retrofit option, or ideally on vessel new builds. For retrofit applications, there are a number of factors that make installations on some vessels challenging. Depending on the size of the scrubber, there can be space constraints in the engine room or funnel. For external applications, the size and weight of scrubber systems can affect the surface area subject to wind, the stability of the vessel, and vessel heel. Other potential considerations include exhaust backpressure, and the adequacy of the on-board electrical power (Bureau Veritas, 2014; SOCP, 2011).

There can also be some operational considerations. For open loop systems, there are some regions (Alaska and northern Baltic Sea) where the scrubbers will be less effective due to low seawater alkalinity (Wärtsilä, 2007b). Another consideration for open loop systems is compliance with wastewater discharge requirements in different jurisdictions. These requirements could present an operational challenge for some routes. Both of these operational issues can be addressed through the use of closed loop or hybrid scrubbers, but these are more complex systems.

3. Technology Readiness

Scrubbing systems have been used for years in industrial applications such as refineries, but they are relatively new to marine vessels. This is quickly changing with the implementation of the January 1, 2015, 0.1 percent sulfur limit for fuels used within ECAs. The IMO, European Union (EU), and U.S. EPA all allow vessels to utilize alternative technologies, such as scrubbers, to meet emission reduction standards for lower sulfur fuel. In response, numerous systems are being installed by vessel operators. These systems are made by several different manufacturers, including Alfa Laval/Aalborg Industries, Couple Systems GmbH, DuPont/Belco Technologies, Ecospec, Hamworthy Krystallon, Klaveness Group Clean Marine, Marine Exhaust Solutions, Mitsubishi Heavy Industries, and Wärtsilä (DNV-GL, 2013; Marine Link, 2014). Wärtsilä had 45 vessels contracted as of March 2014, for a total of 94 scrubbers for both new building and retrofit projects (Marine Log, 2014). No more updated numbers were immediately available to CARB staff at the time of publication of the assessment.

4. Economics

The costs associated with scrubbers include both the capital costs for the equipment and installation, and ongoing operating costs. Vessel operators that travel on routes within ECAs are in many cases estimating that total costs for scrubbers will be less expensive over time than the higher incremental cost of the low sulfur distillate fuel, as compared to higher sulfur heavy fuel oil. The payback period will depend on a number of factors such as the capital and operating costs of the system, reduced fuel costs from being able to use less expensive high sulfur heavy fuel oil, and the distance the vessel travels within an ECA on its regular routes. The payback period for scrubbers would be much higher for vessels with relatively little travel in ECA zones, due to the higher capital costs of scrubbers. Vessel owners must also consider the remaining lifespan of a vessel. For example, a study by the Baltic and International Maritime Council (BIMCO) found that if a vessel has a remaining lifespan of around 10 years, the vessel would need to transit inside an ECA around 33 percent of the time for a scrubber to be more cost effective than using MGO (BIMCO, 2013). Payback periods ranging from one to ten years are estimated for various projects and may be affected by outside economic issues, including fluctuating oil/gas prices (DNV-GL, 2013).

Capital costs vary with the scrubber design and whether the installation is a retrofit or new build. DNV estimated capital costs at up to about $216 per kW of engine power for retrofit or large installations, and as low as $152 per kW for small vessels and new builds (DNV-GL, 2013). A study funded by MARAD estimated capital costs for different vessel types and found similar results for some vessels and higher costs for others. For a 4,000 TEU trans-Pacific containership powered by a 36 MW engine, the study estimated the total capital costs for scrubber installation (including installation, commissioning, and engineering) would be \$5.3 million to \$6.4 million (about \$147 to \$178 per kW of engine power) for wet scrubbers, depending on the scrubber design. For smaller vessels, the study estimated capital costs that resulted in much higher costs per kW of engine power. For example, it estimated that installing a wet scrubber on a smaller 10 MW tanker would result in capital costs of about \$4 million to \$4.7 million, or about \$400-\$470 per kW of engine power (SOCP, 2011).

Ongoing operating costs include the cost of consumables such as caustic soda for closed loop and hybrid systems, power requirements to operate pumps and other scrubber systems, maintenance and crew time. DNV estimated these operating costs at 1 percent to 3 percent annually of the capital costs, or \$0.4/MWh to \$1/MWh of engine size, depending on vessel size. Similarly, the MARAD–funded study estimated these costs at 4 percent annually of the equipment costs (SOCP, 2011).

5. Emissions Reductions

The driver for scrubber installations is the IMO SOx ECA requirement in 2015 to use 0.1 percent sulfur fuel, or equivalent technologies, and the global fuel sulfur limit of 0.5 percent in 2020. Marine scrubbers are primarily designed to remove SOx emissions, and they are very effective. Scrubbers also reduce PM to various degrees, and can sometimes reduce small amounts of other pollutants such as NOx, which are more effectively controlled by SCR, or exhaust gas recirculation.

Most manufacturers report that their systems remove 98 percent to 99 percent of SOx (DNV-GL, 2013). Regarding PM emission reductions, manufacturer claims vary widely, from 30 percent to 85 percent or more (DNV-GL, 2013). However, PM emission reduction claims may not always be based on the results of test methods approved by air pollution control agencies.

Rigorous emission reduction tests of scrubber performance have shown SOx reductions similar to manufacturer claims and PM reductions somewhat lower than expected. Testing of a Hamworthy/Krystallon scrubber controlling 3 auxiliary engines on the container vessel APL England demonstrated SOx emission reductions ranging from 98 percent to 99 percent, PM reductions of 56 percent to 70 percent, and NOx reductions of 2 percent to 5 percent, when using heavy fuel oil at 2.3 percent to 2.5 percent sulfur (Bluefield, 2013). When 0.5 percent sulfur distillate fuel was used, emission reductions ranged from 95 percent to 98 percent for SOx, 68 percent to 75 percent for PM, and 2 percent to 8 percent for NOx. Additional testing of this vessel by the University of California at Riverside (UCR), which was focused on black carbon PM emissions, showed relatively similar results. Emission reductions of SOx average greater than 96 percent, and reductions in PM were measured from 40 percent to 50 percent with the engines operating on heavy fuel at 0.92 percent sulfur (Johnson, 2013).

6. Next Steps to Demonstrate Technology

Scrubber technology is already demonstrated and is rapidly being deployed to meet the ECA 0.1 percent sulfur fuel requirement. An increase in the installation of scrubbers (for new builds and as retrofits) is expected due to the upcoming IMO 0.5 percent global fuel sulfur limit that will be implemented in 2020. If there were a regulatory incentive in place, such as a PM emissions standard for OGVs, then research and development would likely focus on scrubber designs that achieve high levels of control of both SOx and PM emissions. This will be increasingly important with the approach of the 0.5 percent sulfur global fuel standard in 2020.

E. At-Berth Technologies

When OGVs are at-berth, the main propulsion engine is shut down and OGVs typically will have the auxiliary diesel engines operating to provide power for electrical generation that is used for lighting, refrigeration of cargo, and other equipment. Technologies are available to reduce emissions from the operation of the diesel auxiliary engines and include the use of shore-side electrical power and shore-based control systems that can be connected to the vessel while at-berth. The evaluations for these technologies are presented in this section.

Shore-side Electrical Power (Shore Power)

1. Technology Description

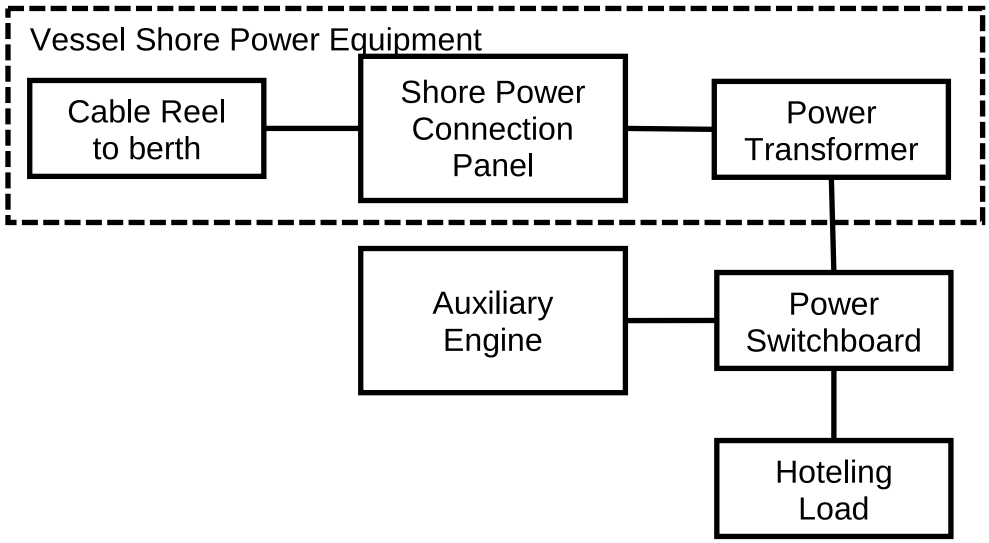
Electrical power for ship operations can be provided to a ship at berth via electrical cables using shore power allowing the vessel to shut down their auxiliary engines. Shore power can either be taken directly from the grid or be locally generated at the port using fuel cells, gas turbines, micro-turbines, and combined cycle units.

2. System/Network Suitability and Operational/Infrastructure Needs

Shore power requires installation of equipment both at the terminal and on the vessel. Providing shore power at a terminal involves upgrading equipment at the main substation, installing a shore power substation near the berth, installing one or more shore power connection points at the berth, and running power cabling between these three points. The specific equipment at each point depends greatly on the needs of the vessels at the berth. Container vessels connect at 6.6 kilovolts (kV) and generally draw less than 3 MW of power while at berth. Cruise vessels connect at either 6.6 kV or 11 kV, and can draw upwards of 10 MW of power while at berth. Differences between vessels require terminal infrastructure to be robust to accommodate each vessel safely.

Equipping a vessel with shore power requires installing a cable reel system to connect to the shore power connection point at a terminal, a connection system to safely relay the power to the vessel, and lastly a transformer to condition the power to the voltage required by the vessel. See Figure III-7 for a flow chart example. The container reel and connection system can either be installed directly on the vessel, or made modular in a specially outfitted shipping container.

Figure III-7: Shore Power Connections



3. Technology Readiness

Grid connected shore power berths are available at major California ports including: Hueneme, Long Beach, Los Angeles, Oakland, San Diego, and San Francisco. In California, most container, refrigerated cargo, and cruise fleets are required to comply with CARB's At-Berth Regulation and are plugging into shore power at these ports. Outside of California, some ports are experimenting with shore power, by including the option for vessels to plug-in.

Installing the infrastructure necessary for grid based shore power is a major hurdle for ports. As an alternative to installing the infrastructure for grid shore power, the Sandia National Labs evaluated the feasibility of using a barge mounted hydrogen fuel cell to provide electricity for the ship at berth. Vessels with high power loads, such as cruise ships and reefers, may not be good candidates due to space limitation on board the barge (Pratt, 2013). In addition to providing power while at berth, a barge mounted system could also potentially provide power to vessels anchored near the port. This method of shore power would still require vessels to install the shore power infrastructure on board, which may not be cost effective for some low powered vessels such as bulk carriers or Ro-Ro/auto carrier vessels.

4. Economics

Infrastructure for shore power costs from $1 million to $5 million per berth (CARB, 2007). The requirements for a shore power installation vary in project complexity, power availability, and number of connection points. Equipment cost for vessels are between $150 thousand to $1 million.

5. Emissions Reductions

While operating on shore power, a vessel's auxiliary engines are turned off resulting in zero emissions from the auxiliary engines during the time shore power is used. Although shore power reduces emissions in and around the port, there are emissions associated with the generation and transport of electricity to provide power to the vessels. Emissions associated with shore power usage are dependent on the make-up of resources in the grid.

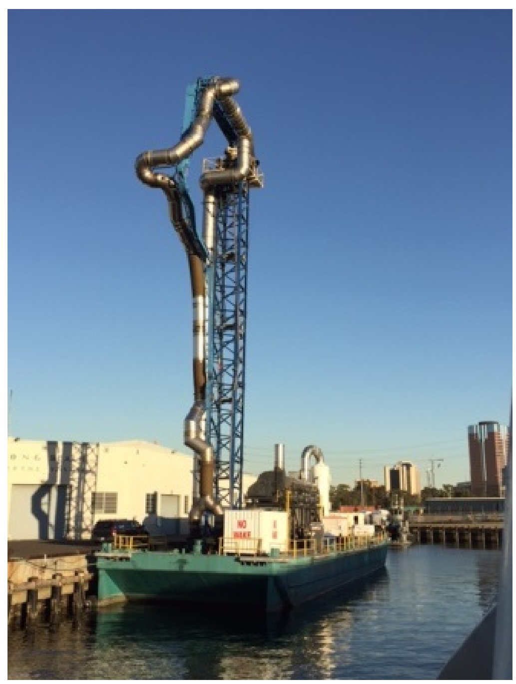
6. Next Steps to Demonstrate and Deploy Technology

Shore power is deployed across California for container, refrigerated cargo, and passenger vessels. Shore power is being explored at many ports internationally. To ensure that shore power continues to be compatible as it is rolled out, new installations should follow the Institute of Electrical and Electronics Engineers (IEEE) Electrical Shore-to-Ship Connections working group's guidelines. Ports should continue to work together on best practices as new shore power projects are deployed (POLA, 2014).

<u>Shore- and Barge-Based Emission Control Systems (connected at dockside)</u>

1. Technology Description

Figure III-8: AMECS Barge System



Shore-based emission control systems include exhaust gas scrubbing technologies and after-treatment technologies that allow for the capture of auxiliary engine emissions as they exit the stack and treat the exhaust before it is released to the atmosphere. There are also shore side electrical pumps to assist in offloading product from tankers (typically steam turbine pumps are used for offloading). There are currently two barge based systems on the market: the Marine Exhaust Treatment System-1 (METS-1) developed by Clean Air Engineering Maritime, Inc., and the Advanced Marine Emissions Control System (AMECS) developed by Advanced Cleanup Technologies, Inc. These systems are both located at POLA/POLB, and are used by container vessels as an alternative technology to fulfill emission reduction requirements at berth to comply with CARB's At-Berth Regulation.

The barge based exhaust cleanup systems captures the vessel's exhaust directly from the exhaust stack, using long, flexible ducting to transfer the exhaust smoke back to the barge to be cleaned. Flexible ducting is brought by crane to the vessel's stack. The current systems operate under a strong vacuum to reduce any leakage of air from the exhaust. Once on the barge, the system reheats the exhaust and injects urea so that a selective catalytic reduction system can remove NOx. The system also passes the exhaust through a particulate filter. In addition to engine exhaust, these systems have the potential to also capture and clean boiler exhaust.

Bonnet technology can also be utilized via a land-based system. A shoreside system demonstration is currently planned for use on bulk vessels at POLA beginning in 2018.

2. System/Network Suitability and Operational/Infrastructure Needs

Barge-based exhaust cleanup systems are capable of connecting to a vessel's stacks with a crane mounted ducting system. The barge is towed in place with a tug boat next to a vessel at-berth. These systems have the potential to capture and control the emissions from a range of vessels at berth, and possibly from vessels while anchored. There are times when the barge may be unable to safely connect to a vessel. For example, there may be safety concerns if a crane works a vessel while opposite the barge or if strong winds are occurring. Additionally, the control barge may share the same footprint of a bunker barge, so when vessels are being refueled at-berth, the vessel may be unable to use the barge based control system. Different vessel types may also have different concerns Providers of barge-based systems are aware of many of these operational concerns, however, and take steps to mitigate them. Taking operational challenges into consideration, a barged based emission control system may be a cost effective option for reducing emissions from vessels that visit infrequently or are unable to connect to shore power, with little to no modification to the vessel.

3. Technology Readiness

To meet the goal of eliminating at-berth ship emissions, continued work on alternative shore power technology is needed to assist vessels and terminals where shore power infrastructure is not feasible or available. Alternative shore power technologies have been demonstrated and are now being deployed. Two systems, the Marine Exhaust Treatment System version 1 (METS-1) and the Advanced Maritime Emission Control System (AMECS) received approval in 2015 for use on container vessels as an alternative to shore power for compliance with CARB's At-Berth Regulation. Clean Air Engineering's METS-1 was developed at POLA as part of a terminal lease obligation. Advanced Cleanup Technologies' AMECS was developed through San Pedro Bay Ports Technology Advancement Program (TAP).

4. Economics

Since the technology is still new, accurate cost information is difficult to estimate. Initial system costs will likely decrease as the designs are streamlined and multiple systems are built. ACTI estimates that when dozens of systems are built they will sell for $8 million each (Maio, 2014).

5. Emissions Reductions

Testing required by the At-Berth Regulation shows that these systems reduce over 80 percent NOx and 85 percent PM when connected to a vessel's auxiliary engine under approved operating parameters.

6. Next Steps to Demonstrate and Deploy Technology

Although these shore-based and barge-based emission control systems are effective at reducing PM and NOx emissions on container vessels, more testing is needed on other vessel types, including tankers, auto carriers, general cargo, and bulk cargo. Additional work with stakeholders is needed to identify and implement methods (e.g., incentives, regulations, and lease agreements) to encourage or require deployment of additional shore power or alternative shore power systems beyond what's needed to comply with CARB's At-Berth Regulation.

F. Alternative Supplemental Power

An emerging area of research and demonstration are technologies to provide alternative supplemental power to replace or augment the power produced by diesel engines on OGVs. As discussed, solar, wind, and fuel cells are all potential technologies to provide supplemental clean power to OGVs.

<u>Solar/Battery Electric</u>

1. Technology Description

Solar panels are emerging as a functional power source on land. Currently, solar panels are being tested to see if the move to a marine environment can be successful. While solar panels cannot provide enough power to completely replace a diesel engine on a ship, they do have the potential to replace a portion of a vessel's energy needs, resulting in fuel savings. Solar panels coupled with an on-board electric motor could result in clean emission free electricity for the vessel to use at sea or in port.

2. System/Network Suitability and Operational/Infrastructure Needs

There are two major obstacles to solar power on vessels. Solar panels take a significant amount of space on-board vessels. Because of this, application is currently limited to vessels that have space on deck such as tankers or Ro-Ros. Additionally, solar panels only produce power when there is sunlight, and a back-up power source, such as a diesel engine or battery back-up system, is needed for inclement weather or night time use. Battery technologies are also expensive and would require significant space on-board to store sufficient back-up power for vessels.

A 2009 IMO GHG study evaluated a hypothetical tanker that had the entire deck covered with solar panels. Solar efficiencies were estimated at 13 percent (current average), 30 percent (current most efficient systems), and 60 percent (future most efficient systems). Even with the 60 percent efficiency, the panels were only able to produce approximately 2 MW of energy. Tanker ships of this size generally have an 18 MW engine and 1 MW auxiliary engine. As a result, even with a large number of solar panels and a high efficiency, solar panels could only supply a small portion of the electrical needs of a vessel (IMO, 2009).

3. Technology Readiness

While some ships have used solar panels to power small electronics like auxiliary lights, there have been limited demonstrations for the use of solar power on vessels where solar has provided a larger portion of the power demand. Two examples where solar power was used to replace a larger portion of the ship's total electricity usage are on the vessels Auriga Leader and the Emerald Ace.

The M/V Auriga Leader's is a Ro-Ro with 328 solar panels installed on the deck (see Figure III-). The ship's new solar array is the result of a demonstration project organized by POLB, Toyota, and Tokyo-based shipping company NYK Line. The project aims to reduce ships' dependence on diesel fuel while vessels are docked and unloading cargo at port. The Auriga Leader is the first craft to direct solar power into the ship's main electrical grid. Energy from the 328 panels is helping to power the ship's thrusters, hydraulics and steering gear, providing about 10 percent of the ship's total electricity usage. A ship the size of the Auriga Leader needs about 400 kW of energy while at port (Parsons, 2009).

Figure III-9: Deck of Auriga Leader with Solar Panels

The Emerald Ace was built as a hybrid car carrier, and is equipped with a hybrid electric power supply system that combines a 160 kW solar generation system, jointly developed by MHI, Energy Company of Panasonic Group, and MOL - with lithium-ion batteries that can store 2.2 MWh of electricity. Conventional power generation systems use diesel-powered generators to supply on-board electricity while berthed. On the Emerald Ace, electricity is generated by the solar power generation system while the vessel is under way and stored in the lithium-ion batteries. The diesel-powered generator is completely shut down when the ship is in berth, and the batteries provide all the electricity it needs, resulting in zero emissions at the pier (MOL, 2012). Outside the U.S., Scandinavian countries are already utilizing battery technology on ferries in the Baltic Sea. Scandinavian countries have taken a global leadership role in utilizing battery technology for coastal ferries. The world's first battery powered ferry was constructed by Norled and started service in Norway, encouraged by the country's Green Coastal Shipping Programme (DNV, 2016). The battery uses only 150 kW-hr per voyage, and ship owner Norled reports a 60 percent reduction in fuel costs since the Ampere began operation. In 2017, Finland is expected to take delivery of their nation's first battery powered ferry. The yet unnamed ferry will have a diesel engine on board to provide additional power boost when necessary, such as when sailing through ice, but will otherwise run on battery power and will charge at port between crossings (Navigator, 2016).

4. Economics

At this time, solar is a very new technology for ships and cost data is unavailable. As with most solar systems, the cost will depend on what type of system is installed. Solar panels alone will be less expensive than a system that also has a battery back-up system.

5. Emissions Reductions

It is difficult to estimate the emission reductions that could be realized from the use of alternative forms of energy. The number of solar panels that can be installed can vary from ship to ship and this in turn will impact the amount of emission reductions that can be realized from an individual ship. Emission reductions will be dependent on the amount of load that can be shifted from the diesel engines to the solar array. Based on existing demonstrations, it was shown that solar panels can meet approximately 10 percent of the auxiliary load. As solar systems become more efficient this percentage will likely rise.

6. Next Steps to Demonstrate and Deploy Technology

This technology is in the early stages of demonstration on OGVs and more information and studies are needed to demonstrate that the solar panels can handle the harsh marine environment and are applicable to a wide variety of vessels and operating conditions. Currently solar panels can only account for a small portion of the electrical needs of a vessel. Information on solar efficiencies, battery capacities, and return on investment needs to be developed to help promote solar power as a viable alternative power source on marine vessels.

Wind Propulsion

1. Technology Description

Wind propulsion is an ancient technology that ships have used for centuries. With the invention of the combustion engine, wind power saw a sharp decline in use for powering ships. Due to new regulations being put in place and high fuel prices, ship operators are increasingly looking to wind power to lower fuel consumption. Wind power cannot be used in all applications, however. The vessel must be sailing with the prevailing wind to gain any benefit of the sails and the vessel needs to be in cruise mode for use of the sails. Sails are not an option for vessels when they are in ports or while maneuvering.

There are various types of wind power that are being researched currently to help reduce fuel and thereby GHG emissions including: traditional sails, kites, and Flettner type rotors (IMO, 2009). A brief description of Flettner type rotors and the kite systems is provided for reference.

A rotor ship, or Flettner ship, is a ship designed to use the Magnus effect for propulsion (see Figure III-). The Magnus effect is a force acting on a spinning body in a moving airstream, which acts perpendicularly to the direction of the airstream. German engineer Anton Flettner was the first to build a ship which attempted to tap this force for propulsion (Enercon, 2013).

Figure III-10: The E Ship 1 with Flettner Rotors

Kite systems are attached to the bow of the ship and can extend and retract to catch the wind. The kite flies in a figure eight pattern to maximize the efficiency. The benefit of kit systems are that they are small systems which can be retrofitted to almost any vessel, automated operation, and it takes only 15 minutes to raise and lower the system. SkySails is one manufacturer who did successful demonstrations as described in the following sections.

2. System/Network Suitability and Operational/Infrastructure Needs

Kites and sails are most effective for slower speed ships as the delta between the ship speed and wind speed will be the greatest. Ships sailing at 18 knots with a wind speed of 18 knots will see no benefit. There are operational constraints as well. Sails and kites would need to be lowered in ports and during maneuvering to ensure the safety of the vessel and crew. The crew would also need to be trained on operation of the sail systems.

3. Technology Readiness

Modern wind power technologies are still in the early stages of development. There has been limited testing in Europe to show the effectiveness of these systems. Much of the current testing is limited to scale or in-lab testing. Testing done by Technical University of Berlin found that fuel savings of 5 percent to 20 percent were possible. Under ideal weather conditions and routing plans, those savings could be increased to 15 percent to 44 percent (IMO, 2009). Staff is aware of two major full scale demonstrations of wind power. The first is a Skysails demonstration that took place in Europe; the second is the E-Ship 1 which was developed by ENERCON.

Figure III-11: The MV Beluga SkySails

The MV Beluga SkySails set sail from Germany to Venezuela and traveled 11,952 miles using the SkySail. The result was a fuel savings of 20 percent for the entire trip. They used a 160 square meter kite and in the future they plan to test a kite that is more than 3 times the size of the original, at 600 square meters. At optimal conditions, the SkySail can provide 2,000 kW of propulsion power. The SkySail costs approximately $5 million Euros (about $6.7 million) for this demonstration (Reuters, 2010). Final production costs will be around $3 million for the system according to the manufacturer. The payoff time would be approximately four to five years. Operational costs are estimated to be $0.09-$0.10/kWh.

Since its maiden voyage in 2010, the E-Ship 1, developed for transporting ENERCON wind turbine components, has covered more than 170,000 sea miles – primarily in the North and Baltic Sea, North and South Atlantic Ocean and the Mediterranean Sea. Using the Magnus Effect, the four innovative Flettner rotors provide the main engine with additional drive and account for more than 15 percent of the savings (Enercon, 2013).

The rotor sails on the ENERCON-developed E-ship 1 allow operational fuel savings of up to 25 percent compared to same-sized conventional freight vessels. These are the results of the analysis of the comprehensive measurement data compiled during numerous voyages through various waters around the globe in conjunction with a project supported by the Deutsche Bundesstiftung Umwelt (DBU).

4. Economics

Cost information is limited at this time. As stated in the previous section, the SkySail demonstration cost about $6.7 million. SkySail representatives stated that final manufactured systems should cost $3.06 million to retrofit an ocean-going vessel, and $2.88 million when the kite system is designed in as part of a newly built ocean-going vessel. The ROI will vary depending on the route of the vessel and the speed that they travel and, based on initial tests, a six to seven year payback could be achieved (SkySails, 2014).

5. Emission Reductions

Based on initial estimates, the product could reduce fuel use by 5 percent to 20 percent (IMO, 2009). The Energy Technologies Institute (ETI) stated that Flettner rotors could be especially effective at reducing fuel consumption for bulker and tanker vessels, potentially offering a double digit percentage in fuel savings (Schuler, 2017). This type of application could be used on both new and retrofit applications; however, application of wind power will be dependent on how much space a vessel has on deck for the different options. Additionally, the vessel must travel at slower speeds to reduce their fuel usage. If the vessel travels at the same speed as the wind, they will see no benefit to the system.

6. Next Steps to Demonstrate and Deploy Technology

This technology is still in the early stages of development. Manufacturers need to continue to demonstrate its effectiveness over the long term and show reduced fuel consumption.

Viking Line has installed a functioning Flettner rotor sail from Norsepower Rotor Sails on their LNG-fueled ferry Viking Grace, making it the first passenger vessel in the world to utilize this technology. The rotor sail is around 79 feet tall and 13 feet in diameter, and is expected to help reduce fuel consumption and CO_2 emissions by up to 900 tonnes annually. Viking Lines intends to increase the utilization of wind power by installing two Flettner rotors on a separate new build vessel due for delivery in 2020 (gCaptain, 2018).

Industry representatives have indicated that there are more planned demonstrations on the way to test the effectiveness of these systems. One such demonstration is expected in 2018, with a Maersk owned tanker vessel. Maersk Tankers agreed to provide a 110,000 DWT product tanker to be retrofit with two 30m tall by 5m diameter rotor sails, also supplied by Norsepower Rotor Sails. Fuel consumption is expected to be reduced by an estimated 7 percent to 10 percent sailing on a typical trade route for a product tanker. Testing and analysis of the sail is scheduled to run through 2019 (Schuler, 2017).

Fuel Cells

1. Technology Description

Fuel cells are an emerging technology for application on OGVs. Fuel cells convert the chemical energy of the fuel, typically hydrogen or natural gas, to electric power through electrochemical reactions. Natural gas can be used to generate hydrogen for use in fuel cells. Because OGVs require a large amount of electricity, fuel cells can currently only be used as a supplemental system or for auxiliary power.

Several fuel cell types exist, and their names reflect the materials used in the electrolyte. The properties of the electrolyte membrane affect the allowable operating temperatures and the nature of electrochemical reactions and fuel requirements. During the last decades several different fuel cell technologies have been proposed and developed, and their levels of maturity, realistic efficiency potential, and future prospects vary significantly. Fuel cell efficiencies range from 35 percent to 50 percent for the technologies listed (DNV-GL, 2012). Two fuel cell types that could be used for marine applications are:

- Proton Exchange Membrane Fuel Cell (PEMFC) fueled by hydrogen is the most widespread and developed fuel cell technology. It operates on hydrogen, which needs to be of high quality as impurities will damage the membranes. High temperature PEM (HTPEM) is a modified version of PEMFC with a novel membrane that can withstand temperatures up to 200°C (DNV-GL, 2012).

- Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) technologies are high-temperature fuel cells that are flexible regarding choice of fuel: methanol, ethanol, natural gas, biogas, and hydrogen are most commonly used. MCFC is the more mature of these two technologies, while SOFC is considered to have the greatest potential in terms of efficiency and power density (DNV-GL, 2012).

2. System/Network Suitability and Operational/Infrastructure Needs

The major barrier to the use of fuel cells is currently the high capital cost of the system. It is estimated that fuel cells can cost in excess of $3,000 per kW of power output. For comparison, a diesel engine costs approximately $300 - $400 per kW. Once the fuel cell is installed, the operational costs are less than the use of distillate fuels in a diesel engine. This is because there are reduced fuel costs and maintenance costs associated with fuel cells. It is too early at this stage to predict the total cost of ownership for marine fuel cells, and compare this to diesel engines.

3. Technology Readiness

DNV tested a 330 kW natural gas system on the Norwegian vessel Viking Lady for over 7,000 hours. Efficiency on the fuel cells ranged from 44.5 percent to 55 percent when the heat exchanger was operational. This is comparable to a diesel engine with an average efficiency of 40 percent to 50 percent. Emissions tests on the Viking Lady fuel cells were unable to detect any NOx, SOx, or PM emissions. DNV concluded that the test demonstrated a successful deployment of fuel cells in the marine environment; however, more research and development is needed before fuel cells can be used to complement existing powering technologies of vessels (DNV-GL, 2012).

Sandia National Laboratory and Red and White Fleet recently completed a joint two year study into the technological and economic feasibility of a high speed passenger ferry that would utilize hydrogen fuel cell technology. Previous hydrogen fuel cell technology was limited to small, slow vessels on rivers and lakes, but there is increasing interest in utilizing the technology for commuter ferries in the San Francisco Bay to reduce OGV emissions. The conceptual ferry, called SF-BREEZE, would utilize PEM fuel cell technology to obtain zero emission power while reaching speeds of 35 miles per hour (mph) and carrying a max passenger load of 150 people. The structure of the ferry had to be designed to accommodate the heavier weight of hydrogen fuel cells in comparison to diesel engines, while also keeping passengers separate from the fuel cells for safety. The feasibility study concluded September 2016 with conditional design approval from the American Bureau of Shipping, indicating that the conceptual design researchers developed would likely be compliant with existing rules and regulations. But as expected, this prototype ferry was found to have a considerably higher capital cost and higher operating and maintenance cost (around 2.5-3 times higher) than a typical modern diesel engine ferry. A cost optimization study is now underway for the SF-BREEZE, with the goal of bringing the vessel to a ready-to-build state (Pratt, 2016).

4. Economics

As a result of the limited availability of infrastructure, capital costs and price of operating and maintaining an OGV using fuel cells are considerably higher than an OGV with a modern diesel engine at this time. For the conceptual hydrogen fuel cell ferry SF-BREEZE, a social economic benefit is expected despite higher capital and operating costs. The socio-economic benefit associated with operating a fuel cell ferry like the

SF-BREEZE instead of a comparable ferry with Tier IV diesel engines is expected to range from $2.6 million to $11 million basis a 30-year lifetime of the ferry given the estimated NOx, PM, and GHG emission reductions. The capital and operating expenses of a hydrogen fuel cell vessel such as the SF-BREEZE today are expected to continue decreasing as the technology matures and is utilized in other vehicle and marine projects (Pratt, 2016).

Over the lifetime of the fuel cell, there is a potential for the maintenance and fuel costs to be reduced when compared to diesel engines, but this depends on fuel oil prices. Low fuel oil prices are an inhibitor to alternative fuel sources at the present time, but can be a more feasible option as oil prices climb.

5. Emissions Reductions

Fuel cells can eliminate SOx, NOx, and PM emissions. If fuel cells could be used in place of auxiliary diesel engines, large reductions in emissions could be realized. GHG emission reductions can be realized if renewable fuel sources are used. For the SF-BREEZE ferry project, significant reductions over Tier IV standards were found when the prototype was compared to a diesel fuel engine ferry at Tier IV standards. Emissions tests found that when using renewable production methods for liquid hydrogen (LH2), well-to-well GHG emissions were reduced by 75.8 percent over the diesel fuel vessel, while NOx reductions of 99.1 percent were found and PM decreased by 98.6 percent. However, using non-renewable production methods showed an actual increase in GHG and PM (up to 2.5 times the amount) for a similar diesel fuel powered engine on a per passenger basis and only a 51.3 percent reduction in NOx (Pratt, 2016).

6. Next Steps to Demonstrate and Deploy Technology

Similar to LNG marine fuel, one of the biggest hurdles facing the advancement of fuel cell technology is availability of parts and infrastructure. In order for fuel cells to become more widely used, long-term demonstrations are needed to prove durability in a harsh marine environment. Additionally, the high capital costs need to decrease. One area which could see increased adoption is the cruise ship industry. Cruise ships will benefit from the reduction of noise and vibrations, as well as from reduced local emissions while in port and cruising in environmentally sensitive areas. Most cruise ships today are diesel-electric, and a fuel cell installation could more easily be integrated into the vessel designs.

Another study of fuel cells funded by the German government, called e4ship, recently concluded that PEM and high-temperature fuel cells on board OGVs could reduce emissions (particularly in port and inside ECAs) while improving energy efficiency. A sub-project SchIBZ focused on the use of a hybrid low-sulfur diesel fuel cells with a capacity of 100 to 500 kW for use as a main power source for any type of vessel. A containerized hybrid 50 kW fuel cell was successfully installed on a German general cargo vessel (Motorships, 2016). This is among a growing number of projects testing fuel cell technology on small vessels, such as passenger ferries. More testing and demonstrations are needed before widespread use of fuel cells on board large OGVs is likely.

G. Vessel Efficiency Improvements

Given that fuel is the most significant operating cost for OGVs, vessel operators are always interested in finding ways to improve efficiency and reduce fuel costs. With the adoption of the IMO EEDI and EEOI programs, there is also increased focus on finding technologies that can improve OGV efficiency. In this section, we provide discussions on several technologies and operational strategies that will help to improve fuel economy and improve the overall efficiency of the OGV. It should also be noted that vessel operators, especially passenger cruise ship operators, are also achieving greater efficiency by taking advantage of landside technology, such as LED lighting and more efficient air conditioning systems.

Hull Friction Reduction – Hull coatings

1. Technology Description

Marine life such as barnacles and algae attach themselves to the bottom of ships and increase the amount of friction experienced by the vessel as it travels through water which in turn increases fuel consumption. Since fuel cost is a major component of the ship's operational costs, hull friction reduction is a large area of research. There are various different solutions to address the issue of hull friction management including enhanced maintenance of the vessel's hull and the use of specialized coatings. This section focuses on hull antifouling (AF) coatings. Modern hull AF coatings are low or copper free, tributyl-tin free and generally fall into the three categories described in the following paragraphs.

Ablative antifouling coatings, also called self-polishing copolymer (SPC) coatings, typically contain biocides mixed into co-polymer paint. The surface of the paint gradually dissolves by contact with seawater which reveals fresh biocides in the layers beneath the ablated layer. Several coatings of paint can be built up to provide longer effectiveness of the paint. Paint manufacturers make several types of these coatings depending on the service speed of the vessel (fast, medium, and slow).

Foul release (FR) or low surface energy coatings act to prevent hull fouling by providing a low friction surface making it difficult for marine organisms to attach. The lifetime of these coatings may be limited as they are prone to wear and damage from hull cleaning methods. An example of this type of hull coating is a silicon coating with a gel application. The gel forms an insoluble layer between the seawater and silicon layer. This creates a layer that is perceived as a liquid by organisms so they do not attach to the ship's hull. Surface treated coatings (STC) consist of large glass-platelets suspended in a reinforced vinyl ester resin. The hull coating is conditioned by divers following ship launch and additional cleanings are performed as needed. Since the coating type is hard, the long-term service life of these coatings can be up to 20 years (SPBP, 2012).

Table III-4 lists a variety of pros and cons to each type of hull coating (Hydrex, 2011). These details provide a general overview of the benefits of each coating over the lifetime of the vessel. It is important for vessel owners to balance the cost of the coating, longevity and protection, and environmental concerns of application and biofoul release of the coatings.

Table III-4: Typical Hull Coatings Pros and Cons

Coating Type	Protection and longevity	Fuel saving properties and conditions	Need to dry-dock for re-painting	Environmental concerns	Cost
Typical AF coating system (SPC)	Soft coating. Fairly easily damaged. Three to five years before AF coating needs to be re-placed. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2 percent to 4 percent fuel penalty. Sailing with a slimed hull equals up to a 20 percent fuel penalty. Effectively reduces higher fuel penalties.	Five to eight dry dockings required for paint alone during ship's service life including one to three full blasting and repainting. Multiple coats and lengthy curing times can mean two to three weeks in dry dock for a full repaint.	Contaminates marine environment with toxic biocides, harming marine life, the food chain and humans. Pulse release of biocides if cleaned in water. High VOC content when applied. Limits fuel consumption and GHG emissions from effects of heavy fouling. Prevents some non-indigenous species (NIS) but facilitates others	Overall cost including application and reapplication, maintenance and additional fuel consumption is twice that of the vinyl ester STC and about one third more than that of an FR coating. Initial application is cheaper than either of the other options.

(Hydrex, 2011)

Table III-4 (Cont.): Typical Hull Coatings Pros and Cons

Coating Type	Protection and longevity	Fuel saving properties and conditions	Need to dry-dock for re-painting	Environmental concerns	Cost
Typical FR coating system	Soft coating easily damaged. Three to five years before FR coat needs repair/reapplication. Full recoating required 1 to 3 times in 25 years.	Smoothest tested surfaces when unfouled. Usually sails with slime = up to 20 percent fuel penalty. Can foul badly if vessel has long layups.	Five to eight dry dockings required for paint alone during ship's service life including one to three full blasting and repainting. Multiple coats and lengthy curing times can mean as two to three weeks in dry dock for a full repaint.	Does not contain biocides but leaches potentially harmful oils, alters enzymes in barnacle glue; some silicones catalyzed by highly toxic dibutyltin laurate. Medium VOC. Some reduction in fuel consumption GHG emissions. Can help limit spread of NIS.	Overall cost including application and reapplication, maintenance and improved fuel consumption is one and a half times that of the vinyl ester STC and about two thirds that of an AF coating. Initial application is the highest of the three.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts lifetime of vessel with only minor touch-ups. No repaint required.	Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save 20 percent or more on fuel compared to AF or FR coating.	Applied once to hull. No need to repaint beyond minor touchups during routine dry docking. Usually applied in two homogenous coats with two to three hours min. and no max. in between coats.	Non-toxic in application, use, conditioning and cleaning. Low VOC. Combined with cleaning gives lowest fuel consumption/GHG emission. Cleaned before ships sail prevents spread of NIS.	Overall cost including application, maintenance and fuel savings is half that of an AF and about two thirds that of an FR coating. Initial application is higher than AF, lower than FR. Cleaning costs are included.

(Hydrex, 2011)

2. System/Network Suitability and Operational/Infrastructure Needs

Hull coatings are applied to all vessels when they are new to protect the hull from the corrosive marine environment. Hull coatings need to be applied while the vessel is at dry dock for its initial build or when the coating needs to be replaced. The infrastructure is currently in place to accommodate the vessels that need to reapply the hull coatings.

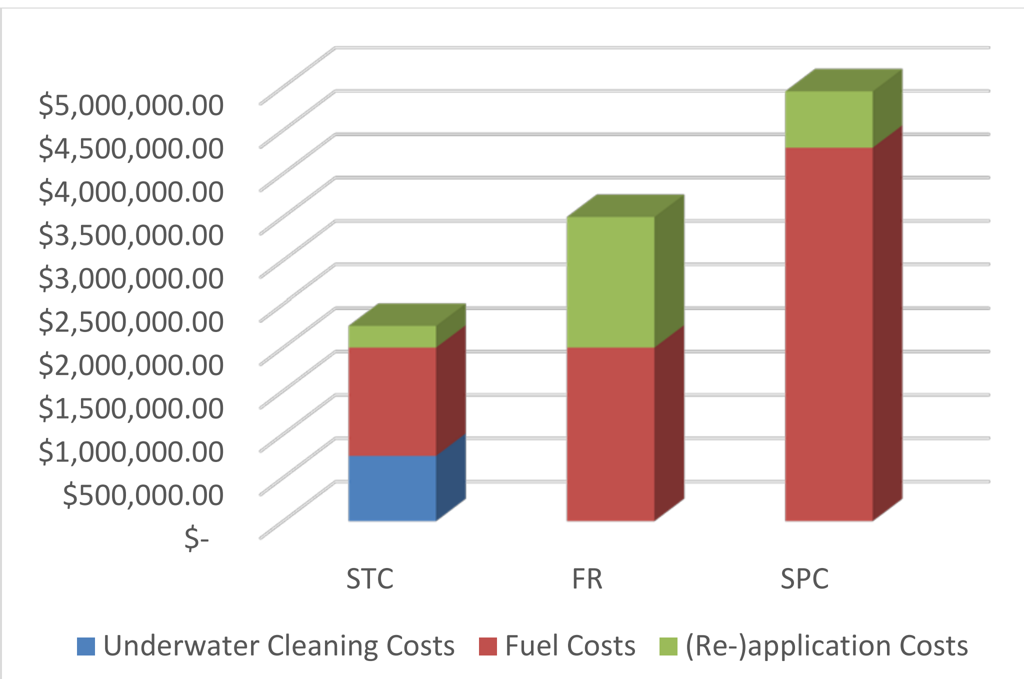
3. Technology Readiness

Manufacturers of hull coatings have experimented and developed their formulas to increase the life and/or effectiveness of the hull coatings, and the current technology is developed, stable, and widely available. All new vessels choose the coating with their optimal cost and fouling resistance characteristics to have applied. Over the lifetime of the vessel the coating may need to be reapplied to protect their vessel from fouling and corrosion.

4. Economics

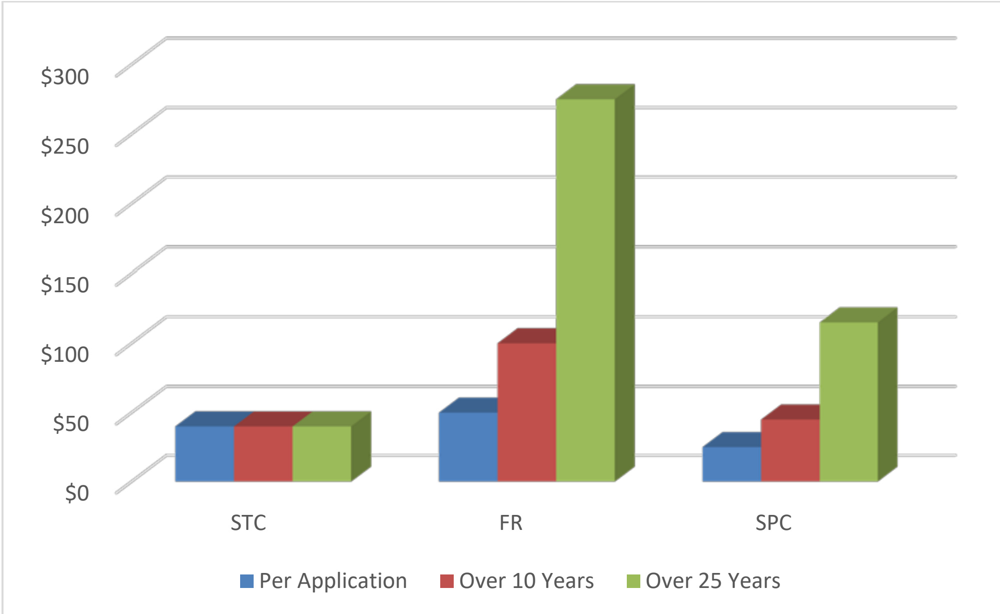
New hull coatings can be applied to new or existing ships. A new coating will require dry dock to remove the old coating and apply the new one. Typical costs of new coatings range from $2 million to $5 million dollars depending on the type of coating. STC coatings are hard coatings that do not need reapplication as the coating lasts the lifetime of the vessel. However the coatings must be cleaned. This can be done at dry dock or in the water. Costs to clean the hull can range from $54,000 to $1.1 million for dry dock cleaning and $16,000 to $222,000 for in water cleaning (GWADF, 2013). As can be seen in Figure III-12 and Figure III-13, over 25 years STC coatings are the least expensive followed by FR and finally SPC coatings.

Figure III-12: Total Cost of New Hull Coating



(Hydrex, 2011)

Figure III-13: Paint Costs per m²



(Hydrex, 2011)

5. Emissions Reductions

As the hull becomes contaminated by marine organisms, the friction on the ship can go up by as much as 20 percent. By using a specialized hull coating, it can net a savings by as much as 5 percent of fuel consumption (IMO, 2009). Fuel savings will be the greatest at higher vessel speeds and is limited at lower speeds.

6. Next Steps to Demonstrate and Deploy Technology

Hull coatings are a well-established technology, and these coatings are widely used by vessel operators, and these coatings are continuously improving with new advances in technology. We expect that they will lead to gradual improvements in vessel efficiency in future years. The IMO's EEDI requirements to increase efficiency 30 percent by 2025 will likely spur ship builders to use the best available hull coatings on new builds. Vessel operators will likely continue to apply these coatings as needed to reduce fuel consumption as much as possible, while considering coating durability and cost considerations.

Hull and Propeller Optimization

1. Technology Description

Hull and propeller designs have been refined over many years to optimize vessel efficiency and fuel savings. Ideally, the most advanced designs are incorporated into new vessels. These designs can be more complex and costly, and must be balanced against the efficiency and fuels savings achieved over time.

While advanced designs are incorporated into new vessels, many vessels are also undergoing retrofits. This is particularly the case for slow steaming vessels operating at significantly lower speeds than the vessel's design-speed. A popular option is the installation of a new bulbous bow, designed specifically for slow-steaming. This change is sometimes made in conjunction with other modifications such as a new propeller, engine modifications, and vessel modifications to increase cargo carrying capacity. Ship classification society DNV-GL reports that as of 2015, they have supported the bulbous bow optimizations of 150 containerships (DNV-GL, 2015a).

A 2000 IMO study of hull and propeller optimizations found that a fuel savings of 5 percent to 30 percent could be realized. Nevertheless, many times shipyards recycle designs from previous builds to save on design costs. There are pros and cons to the various designs and each ship needs to be designed to meet the requirements required of its duty cycle/design speed and draft.

Hull and Propeller Optimization

Hull and propeller optimization generally involves a procedure evaluating the wetted hull surface and propeller, and as noted earlier, is often applied to new ship designs in order to achieve reduction of drag (resistance). Advances in computer design technology also allow for more elaborate hull designs to increase fuel efficiency. Additionally, ship designers are beginning to optimize their designs for irregular wave conditions rather than still water conditions, which is a more realistic design approach that vessels will experience on the open ocean (IMO, 2009).

The percentage of new designs that are subjected to systematic optimization of the hull and of the propeller compared to the percentage of designs that are built merely on the basis of existing experience is currently unknown. However, in general, it is believed that a greater proportion of new designs today are going through some systematic form of optimization of hull and propeller design, focusing on drag reduction and increased propulsive efficiency. Because optimization requires a high level of expertise, it is possible that many of the optimization procedures performed do not provide the optimum design for all of a ship's operational modes. Because of this, it is difficult to quantify the emission reduction potential, on a world fleet basis, of systematically applying hull and propeller optimizing procedures (IMO, 2009).

The IMO's 2009 GHG study listed the following details about energy efficient propeller systems and hull designs. The following Table III-5 lists technology descriptions, estimated fuel savings, and applicability associated with each system.

Table III-5: Unconventional Propulsion Systems

Propulsion System	Description	Power Consumption Reduction	Applicability
Coaxial contra-rotating propeller	The coaxial contra-rotating propeller is an obvious device for recovering some of the rotational energy. To avoid problems with cavitation, the aft propeller usually has a smaller diameter than the front propeller.	Reported reductions in power consumption range from 6 percent to 20 percent.	Beneficial for relatively heavily loaded propellers, and the best results (in the form of power consumption) are found in fast cargo vessels, RO–RO vessels and container vessels.
Free rotating vane wheel	The vane wheel (Grim wheel) is a freely rotating propeller, installed behind the main propeller. The vane wheel has a larger diameter than the main propeller. The part that is directly behind the main propeller is turned by the swirl from that propeller and acts like a turbine, driving the part of the vane wheel that is outside the diameter of the main propeller.	Improvements in power consumption are reported around 10 percent.	The vane wheel should be a suitable potential improvement for cargo ships.
Ducted propeller	The ducted propeller consists of a propeller mounted centrally in a ring foil. Compared to the conventional propeller of the same diameter and thrust, this arrangement allows a larger mass of water to be supplied to the propeller, improving the operating conditions around the propeller and the ideal efficiency.	The potential for reduced power consumption on relevant ships is reported to be in the range 5 percent to 20 percent, with perhaps 10 percent being a good average value.	Ducted propellers are therefore suited for ships operating at high propeller loadings, such as tankers, bulk carriers, tugs and different offshore supply and service vessels.

(IMO, 2009)

Table III-5 (Cont.): Unconventional Propulsion Systems

Propulsion System	Description	Power Consumption Reduction	Applicability
Pre-swirl devices	These are devices that aim to provide a favorable pre-rotation of the flow of water in front of the propeller. They include radial reaction fins in front of the propeller and an asymmetric stern.	Radial reaction fins, a reduction in power consumption of 3 percent to 8 percent was reported, while asymmetric sterns show improvements of 1 percent to 9 percent.	Radial reaction fins or an asymmetric stern should be applicable to all single-screw ships.
Post-swirl device	The most important among these devices may be additional thrusting fins at the rudder, rudder bulb systems with fins, fins on the propeller fairwater (boss cap fins) and an asymmetric rudder.	From full-scale measurements, a gain of 8 percent to 9 percent was measured for additional thrusting fins at the rudder, while 4 percent has been reported for boss cap fins.	Post-swirl devices should be applicable to all new ships.
Integrated propeller and rudder units	As the name implies, the propeller and rudder are designed as an integrated unit, part of the design being a bulb behind the propeller that is fitted into the rudder.	An improvement of 5 percent in power consumption may be taken as typical.	The units are applicable to general cargo vessels, Ro-Pax vessels and container vessels operating at relatively high speed.

(IMO, 2009)

2. System/Network Suitability and Operational/Infrastructure Needs

These hull and propeller designs are matched to the vessel expected duty cycles/design speed and draft. A complex analysis is done in the initial design stage to determine what propulsion system and hull design can optimize fuel savings that will also meet the duty requirements and shipping routes expected for the vessel. If a vessel operates at a significantly different speed, these designs will not achieve the expected efficiency and retrofits would be needed to again achieve optimal efficiency. There may be some designs that are difficult for some shipyard to construct. There can also be limitations in these designs due to the use of the vessel in harbors and canals.

3. Technology Readiness

Many of these systems are already demonstrated on various ships and are achieving fuel savings. Cost and payback time are key drivers in incorporation of these technologies. If the numbers work to the operator's advantage, these systems will be incorporated into the new vessel design.

One barrier to the widespread usage of such improvements of design is that designs may be owned by specific shipyards. Also, as previously mentioned, performance in waves is not always part of the standard test conditions, and assessing the performance of ships at sea is challenging; it may not be easy to see the improvement that results from such optimization.

Many of these optimization technologies can also be retrofitted on existing vessels. Ship owner E.R. Schiffahrt modified several of their vessels, incorporating new bulbous bows, energy efficient propellers, engine modifications and boosted cargo capacity (DNV-GL, 2015a). Shipping line CMA CGM reports retrofitting bulbous bows on 15 of their vessels, with intention to optimize 10 more vessels (CMA CGM, 2014). Maersk has also similarly modified their vessels to optimize the bulbous bows for slow-steaming (Spilman, 2013).

4. Economics

Hull and propeller systems can cost upwards of 20 percent to 30 percent of a new ship build. IMO estimates that optimization of the hull could add $50,000 to $200,000 to the design cost of the vessel. Additional material and labor costs could be added due to more complex shapes and time required to build the systems. Regarding vessel retrofits, the popular bulbous bow changeover for slow steaming is reportedly around $600,000, and payback periods around 1 to 2 years were estimated in some cases (DNV-GL, 2015b; Hand, 2013).

5. Emissions Reductions

The total range of GHG reductions for propeller improvements is 5 percent to 10 percent. Combined with the optimization of the hull, fuel consumption could decrease approximately 5 percent to 30 percent (IMO, 2009).

6. Next Steps to Demonstrate and Deploy Technology

Many of these propulsion systems are established and demonstrated. Major drivers to include this technology will be the cost, reduced fuel consumption, and IMO's requirements. IMO EEDI regulations require shipbuilders to increase new vessel efficiency in steps up to 30 percent more efficient by 2025. The design efficiency starts at a 10 percent increase in 2015 and ramps up 10 percent every 5 years. To meet this goal, many of these designs will be incorporated into new builds. Incentive programs could also be developed to encourage vessel operators to consider retrofits to improve the efficiency of the existing fleet.

Vessel Speed Reduction/Slow Steaming

1. Technology Description

Vessel speed reduction (VSR) is the practice of slow steaming, which is an operational practice of reducing OGVs speeds from typical cruising speeds to lower speeds. Slowing down throughout an entire voyage or part of a voyage can reduce emissions of diesel PM, SOx, NO_X, CO_2, and provide fuel cost savings. While reducing the speed also results in more time to travel a given distance, the overall vessel emissions (from main and auxiliary engines) are lower because the emissions associated with the increased travel time are less significant (linear with ship speed) than the decreased main engine power requirements. The main engine power is approximately proportional to the ship speed, cubed, so reductions in vessel speed result in dramatic reductions in main engine power and associated emissions.

2. System/Network Suitability and Operational/Infrastructure Needs

Overall, reducing speed is a viable approach for reducing fuel and thereby reducing emissions; however, there are some issues to be considered, especially for reducing speeds for an entire voyage.

Scheduling

Many vessel operators, primarily cruise and container ship operators, expressed concern over scheduling issues due to slowing to 12 knots in the voluntary VSR zones established by some ports in California. Before the introduction of VSR zones, container vessels typically cruised around 22 to 23 knots.[2] The primary concern is that vessels are on tight timelines due to labor contracts and fixed schedules. Some vessel types carry special cargo, like bananas which must meet fixed arrival and discharge ports to preserve the integrity of the produce. As a result, some companies will add an additional ship to maintain the company's operational schedule -- but this can still net overall fuel savings. AP Moller-Maersk reports that regular steaming for 8 vessels traveling at 22 knots would consume 9,500 metric tons (mt) of bunkers and emit 30,000 mt of CO_2, whereas at slow steaming speeds along the same route, 9 vessels travelling at 20 knots would consume 8,000 mt and emit 25,000 mt of CO_2 (Maersk, 2009). Several other large companies also report engaging in slow steaming to curb emissions and to cut fuel costs.

Cruise ships are unique in that they are on a fixed schedule due to itineraries, time in ports, excursions, etc. Many cruise vessel operators have indicated that they would do

[2] Recent speed data shows that vessels cruise on average 10 to 14 knots transiting within 40 nm of California's major ports.

whatever is necessary to maintain their schedule due to the cost and other ramifications associated with missing a targeted berthing time. As such, regular slow steaming may not be an ideal emissions reduction method for cruise vessels.

Engine and Maintenance Issues

Some vessel operators express concern with engine operation and maintenance issues when operating ships at low loads for long periods of time (i.e., below their prescribed operating parameters). Some of the issues include: increase in exhaust gas economizer fires due to build-up of soot, piston rings sticking in top landings due to over lubrication of cylinder oil, and increased cleaning of scavenge air manifold (Lloyd's Register, 2008). Also, some engines are optimized to run at certain speeds (for example, 15 knots to 16 knots and if sailing below that speed, the engine performance will suffer. This must be considered when designing any VSR zone.

Cruise ships

Many modern cruise lines are designed with a diesel electric energy plant instead of direct drive diesel propulsion plant found on most commercial cargo vessels. These vessels are equipped with diesel engines coupled to diesel generators which produce the required amount of electricity to supply the many different energy requirements on-board, from the air conditioning for passengers and crew, to the electric propulsion motors that drive the propeller shafts. Some cruise line companies determined that operating their vessels at 12 knots was not as efficient in saving fuel and subsequently reducing pollutant emissions. The ports worked with several cruise ship lines and concluded that the cruise vessel engines ran efficiently and achieved emission reductions while traveling at vessel speeds of 15 knots in a VSR zone. Based on this information, the ports of Los Angeles and Long Beach and San Diego allow cruise ships to travel at 15 knots in their VSR zones.

Rerouting and Traffic Patterns

Traffic separation schemes are established by the Commandant of the USCG under the Ports and Waterways Safety Act and in accordance with international agreements. Traffic separation schemes are lanes used to promote vessel safety by regulating the flow of traffic in busy or congested waterways. A mandatory VSR zone could have an impact of vessel traffic patterns. Vessels may try to alter their traffic patterns to avoid a VSR zone, thereby causing a higher potential for vessel collisions.

3. Technology Readiness

VSR is an operational methodology that is already in use at multiple ports and has well-known benefits. Many operators are voluntarily reducing speeds to reduce fuel costs; in California, POLA, POLB, San Francisco Bay, and the port of San Diego all have (or have trialed) successful voluntary VSR programs.

POLB designed a Green Flag Program, a voluntary vessel speed reduction program that rewards vessel operators for slowing down to 12 knots or less within 40 nm of the harbor. OGVs that achieve a 90 percent compliance rate within 40 nm of the harbor in a calendar year can earn a 25 percent reduction in dockage fees. OGVs slowing from 20 nm of the harbor can earn a 15 percent reduction in dockage fees. Additionally, 90 percent participation at either 20 nm or 40 nm from harbor will earn the vessel a Green Flag achievement award. For 2016, the compliance rate was over 95 percent for 20 nm and close to 90 percent for 40 nm (POLB, 2016b). 2017 saw slightly increased percentages, with 97 percent compliance for 20nm and 92 percent compliance with the 40nm speed zone (POLB, 2018).

Similarly, POLA created a voluntary vessel speed reduction incentive program at 20 nm and 40 nm from harbor which also provides reduced dockage fees for OGVs that comply with the reduced speed limits for 90 percent of the time. For 2016, the compliance rate was over 90 percent for 20 nm and close to 85 percent for 40nm (POLA, 2016b).

A trial VSR program began in the Santa Barbara Channel in 2014, with second and third trials completed in 2016 and 2017. This program, developed and implemented by the Santa Barbara County Air Pollution Control District (SBCAPCD), Channel Islands National Marine Sanctuary (CINMS), Environmental Defense Center (EDC), Ventura County Air Pollution Control District (VCAPCD), and the National Marine Sanctuary Foundation (NMSF), is modeled after the successful speed reduction programs at POLA/POLB. The program incentivizes container ships to slow down to speed at or below 12 knots by offering a monetary amount to participants, reducing air pollution and the frequency of fatal ship strikes to endangered whales in and around the Santa Barbara Channel. Automatic Identification System (AIS) data is used to track vessels to verify their speed for participation in the program (SBCAPCD, 2014).

The initial 2014 VSR trial resulted in 27 vessels from seven different shipping lines slowing in the Santa Barbara Channel, preventing an estimated 12 tons of NOx and 500 tons of GHG from being emitted in direct relation to lower fuel consumption. To incentive participation, payments of $2,500 were paid to shipping companies per transit for participation in the trial (SBCAPCD, 2015). Increased participation was seen in 2016, with 50 slow speed transits funded, nearly double the number funded in 2015, with incentives ranging from $1,500 to $2,500 (SBCAPCD, 2017). The 2017 program saw additional partnership with 3 air districts and 4 national marine sanctuaries along the California coast, while funding incentives for 143 transits, nearly 3 times number of transits as 2016 (SBCAPCD, 2018).

A unique approach was also trialed by Santa Barbara in 2016 and 2017, with additional incentives up to $1,250 were offered for vessels reducing speeds to 10 knots or less while reporting detailed whale sightings. To receive this additional incentive, operators must prove that they adjusted a vessel's schedule to prevent the need for speeding up elsewhere along the vessel's route. This is an important factor to consider when implementing a VSR zone as the emission reductions achieved from slowing down through the VSR zone may be mitigated if vessels have to speed up outside the VSR zone to meet a tight schedule (SBCAPCD, 2017).

4. Economics

For a vessel operator, several types of costs could be associated with a VSR program. Costs to vessel operators could include things such as onshore labor, crew supplies, maintenance, on-board labor, schedule adjustments, and general overhead. However, cost-benefits can occur for vessels if a voluntary program administered by a port or other local agency offers financial incentive. Cost savings can also be accrued due to overall fuel savings. Companies who have adopted slow steaming policies had fuel savings of 22 percent in 2010 (Joregensen, 2012). Additionally, according to Maersk, for a 6,310 nm voyage from Hong Kong to Long Beach there was a potential savings on fuel of $250,000 (White, 2010). In general, a 1 percent reduction in vessel speed can result in approximately 2 percent reduction in fuel costs (Lloyd's Register, 2008). Administrative costs for ports or other agencies that adopt a voluntary VSR program could range from $50,000 to $200,000 (including staffing, speed data, monitoring equipment, non-financial incentives.). Costs could also be accrued for financial incentives, such as reduced dockage fees or other incentive monies.

Researchers at Taiwan's National Cheng Kung University conducted a thorough assessment of available operating strategies to identify the approach to speed reduction that is best able to minimize costs and reduce the impact of shipping on the environment. The researchers acknowledged that the significant cost advantages of speed reduction could improve the competitiveness of ship operators; however, the study's results indicate that optimum speed reduction is a dynamic process depending largely on charter rates and fuel prices (Chang, 2014).

5. Emissions Reductions

VSR can reduce emissions of diesel PM, SOx, NOx, and CO_2 via the reduction in fuel use. As mentioned earlier, there is a decrease in emissions from main engines due to the reduced power needed to transit at lower speeds. Emission reductions from slowing vessel speeds primarily depend on how fast vessels transit at cruising speeds. Prior to about 2008, container vessels tended to maintain faster cruising speeds, typically around 21 knots to 24 knots. In this scenario, slowing a vessel from 24 knots to 12 knots would result in emission reductions of about 75 percent. Current speed data shows that vessels cruise at about 10 knots to 14 knots within a 40 nm radius of most major ports. Vessels reducing their speeds from 14 knots to 12 knots would reduce emissions from the main engines by about 25 percent.

CARB and UCR conducted VSR testing on two container vessels. Emission measurements were made from two different types of vessels for three voyages. The main objective of this research was to measure emission benefits on reducing vessel speed from cruise (about 23-24 knots) to 15 knots or less. VSR to 12 knots or less resulted in approximately 61 percent and 56 percent reduction in CO_2 and NOx emissions (kg/nm), respectively. Note that the reductions in emissions are attributed to change in both speed and fuel (switching from HFO to MGO). Switching from HFO to MGO would not change CO_2 emissions significantly, whereas NOx emissions are expected to reduce by about 6 percent to 10 percent due to the lower nitrogen content in MGO. The mass emission rate (kg/nmi) of $PM_{2.5}$ was reduced by 69 percent with VSR at 12 knots alone and by about 97 percent when coupled with the use of MGO. Approximately 75 percent, 70 percent and 53 percent reductions in hydrated sulfate, organic carbon, and elemental carbon were observed when reducing vessel speed from cruise to 12 knots, respectively. These reductions increased to 99.8 percent, 87 percent, and 74 percent, when fuel was switched to MGO and vessel speed was reduced to 11 knots in VSR zone. Therefore, based on three measurements from two ships, reducing vessel speed in VSR zone would result in significant reduction of criteria pollutants (NOx and $PM_{2.5}$) and CO_2. It is important to note that vessels speeding up to make up for the slower speeds in the VSR zone could generate an overall increase in CO_2 emissions (Miller, 2012).

6. Next Steps to Demonstrate and Deploy Technology

This technology is already being deployed via the voluntary programs at the ports of Los Angeles/Long Beach, San Diego, and in the Santa Barbara Channel. As discussed earlier, these programs have high compliance rates and vessels have made the necessary adjustments in scheduling and any maintenance issues to address their concerns. Most emission reductions from this technology are already being achieved around the ports due to the successful voluntary programs. The Ports of San Francisco and Oakland currently have speed restrictions in the Bay, and maneuverability requirements outside of the Golden Gate Bridge require vessels to slow down before coming into port.

Voyage Optimization

1. Technology Description

Voyage optimization is the optimization of the ships schedule, route, and other shipping constraints. Examples of this optimization include: just-in-time shipping, minimal speed or power variation, routing for weather concerns and tides, and optimum ballast and trim levels.

Weather routing is an optimization strategy that may allow vessel operators to save fuel and reduce overall voyage costs. Weather routing involves the analysis of forecasted weather patterns, global currents, and climatological trends, along with current fuel prices, to optimize the best route for a vessel considering port rotation, vessel specifics, and numerous other factors. In many cases, depending on the time of year, the shortest route between arrival and destination port may not be the most fuel/cost efficient if multiple storm systems are expected along the route. While sailing through heavy weather, a ship will have to run at higher engine loads to maintain required speed, thus burning extra fuel. This can eliminate the fuel efficiency advantage of sailing a shorter distance route. Weather routing is often purchased through a third party; weather routing providers can also offer optimum speed or power suggestions (main engine load or speed) for additional cost savings, including suggesting optimal speed to sail outside and inside the ECA in order to meet a vessel's schedule while minimizing fuel consumption. This reduces the risk of a vessel sailing at a higher than necessary speed and burning extra fuel for a prolonged period of time, and helps vessels to meet Required Time of Arrival (RTA) to prevent prolonged anchorage periods prior to berthing.

Just-in-time (JIT) shipping coordinates the end user with the shipping services, where the vessel arrives at berth at a specific pre-arranged time. When coordinated with shore-side services, this can create a moving line of freight that arrives when needed rather than storing a product for months in a warehouse. It helps to reduce the idling time of ships while they wait to unload their cargo, thus saving fuel and reducing emissions at-berth by decreasing the amount of time a ship must sit at berth.

Speed or power variation during a voyage, as compared to steady running of the ship's engine, will typically increase the fuel consumption. Steady conditions during a voyage are more favorable and will normally be the simplest and most economical option to implement. Steady power tends to keep fuel consumption to a minimum (IMO, 2000).

Optimal or minimal ballast is a strategy which involves decreasing the ballast and extra bunker to a minimum. When implementing this strategy, propulsion efficiency and weather and stress dependent ship safety must also be considered (IMO, 2000).

Trim optimization is another potential operational measure that can reduce fuel use. Sailing at optimum trim to keep ship resistance at a minimum can reduce fuel consumption. If weight is added either behind or ahead of the mid-ship area, but within the center line partition of the ship then the vessel would get tilted either forward or aft. This tilting is known as trim. Optimal trim must be determined by ship model tank tests for full-scale measurements on board the ship (IMO, 2000).

Several of these voyage optimization technologies can be monitored through the use of a vessel performance management system. Computer based systems/monitors can provide vessel operators with the tools to monitor these voyage optimization practices. These systems provide on-going streams of critical data to the bridge.

2. System/Network Suitability and Operational/Infrastructure Needs

Vessel operators may need a relatively small number of instruments (e.g., flow meters, anemometers, temperature sensors, ballast level indicators) and additional ship external data (e.g., pertinent current data, weather data) installed to provide input to an on-board dedicated computer that uses specific software to calculate and make suitable recommendations to the bridge (SkySails, 2014).

Weather routing systems are available and on the market. The systems combine vessel information and weather forecast with the planned departure and position of the arrival port. Main parameters for choice of a route are safety, avoidance of cargo damage, comfort of crew and passengers, limitation on time of arrival, maintenance work and economy. Weather routing decision support systems can only take into acccount a limited amount of these factors, however (IMO, 2000). In addition to the procurement of systems to monitor vessel performance, crew training in procedures and safety may be required to implement many of these strategies.

3. Technology Readiness

As companies are looking for additional cost-effective ways to reduce emissions, voyage optimization is gaining more interest. Several companies developed and released vessel performance monitoring systems that incorporate several of the methods discussed in this section, and many are widely used by vessel fleets today. Additional development is expected as vessel owners and operators work with third party technology companies to advance and bring new products to the market.

4. Economics

The costs associated with many of these optimization measures are widespread and variable, as they are associated with the specific vessel performance management system or the individual components, such as a weather system. The SkySails performance manager basic Skysails PM system costs approximately $15,000 installed (SkySails, 2014). The vessel specific selected add-on sensors and instruments determine the overall cost of the system. There are numerous firms all across the globe that offer vessel performance management systems. Prices can vary for vessel operators who only wanted certain components of vessel optimization. The main cost of applying a weather routing system is related to the purchase of these services (IMO, 2000).

Trim tests can provide substantial savings and a return on investment between one and six months, depending on vessel type, operation, and number of vessels in the series (Greentech, 2011).

5. Emissions Reductions

Emission reduction estimates for different voyage optimization technologies vary depending on the study. Listed below are IMO estimates of fuel and GHG emission reductions that could potentially be achieved for several types of operational measures (IMO, 2000).

- Just in time shipping: 1 percent to 5 percent
- Minimal speed and power variation: 1 percent to 2 percent
- Weather routing: 2 percent to 4 percent
- Minimal ballast: up to 1 percent

- Optimal trim: up to 1 percent

Although individually these may not seem significant, combining these could lead to the potential for up to a 13 percent reduction in fuel use and GHG emissions.

Optimal trim studies conducted at Force Technologies showed that even small trim changes can have an impact on vessel performance. Reductions of 2 percent to 4 percent are anticipated for many ship owners (Greentech, 2011).

6. Next Step to Demonstrate and Deploy Technology

As companies are looking for additional cost effective ways to reduce emissions, voyage optimization is gaining more interest. Several companies now have vessel performance monitoring systems that can be installed on board a vessel; this technology can be coupled up with shore side weather routing companies to provide further optimization of a vessel's voyage. To implement many of these strategies, propulsion efficiency, weather, ship safety, cargo, and vessel schedule must all be considered. Additional improved procedures have to be implemented for practical utilization of this strategy, including crew training to ensure crew members understand the procedures involved with each type of operational measure.

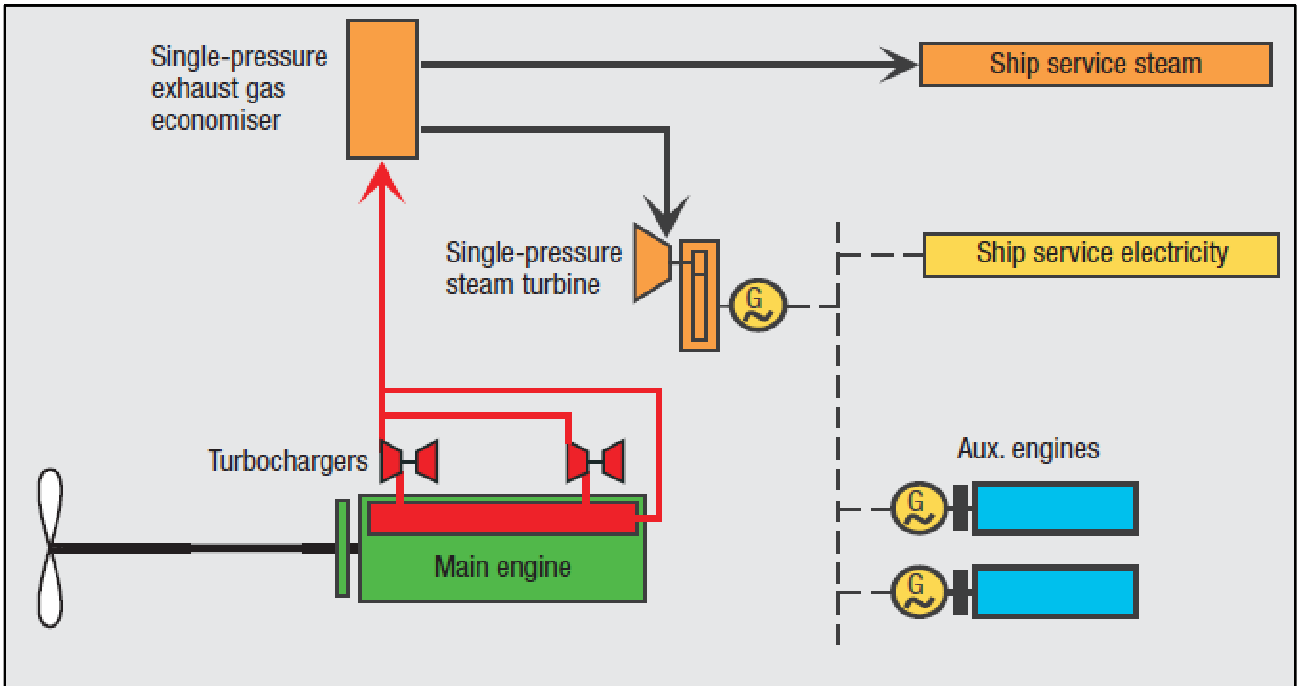
Waste Heat Recovery Systems

1. Technology Description

Waste heat recovery (WHR) systems offer a way to use the waste heat from the engine combustion to create electricity for the rest of the ship. The exhaust gas would otherwise be wasted and vented off. Use of the exhaust gas in this manner was shown to increase efficiency up to 10 percent (MDT, 2010). The exhaust gas can be used in two different ways: a steam turbine and a power turbine.

For a steam turbine, the engine exhaust is routed through a heat exchanger or exhaust gas boiler to create high pressure steam. Once the steam is created, it is sent through a steam turbine to extract the energy from the steam and create electrical power used to run the electrical grid on-board the vessel. After all the energy is extracted from the steam, the residual heat can be used on-board to heat water or fuel to maximize the efficiency of the steam loop. This is shown in Figure III-.

Figure III-14: Example of Steam Turbine Waste Heat Recovery Schematic



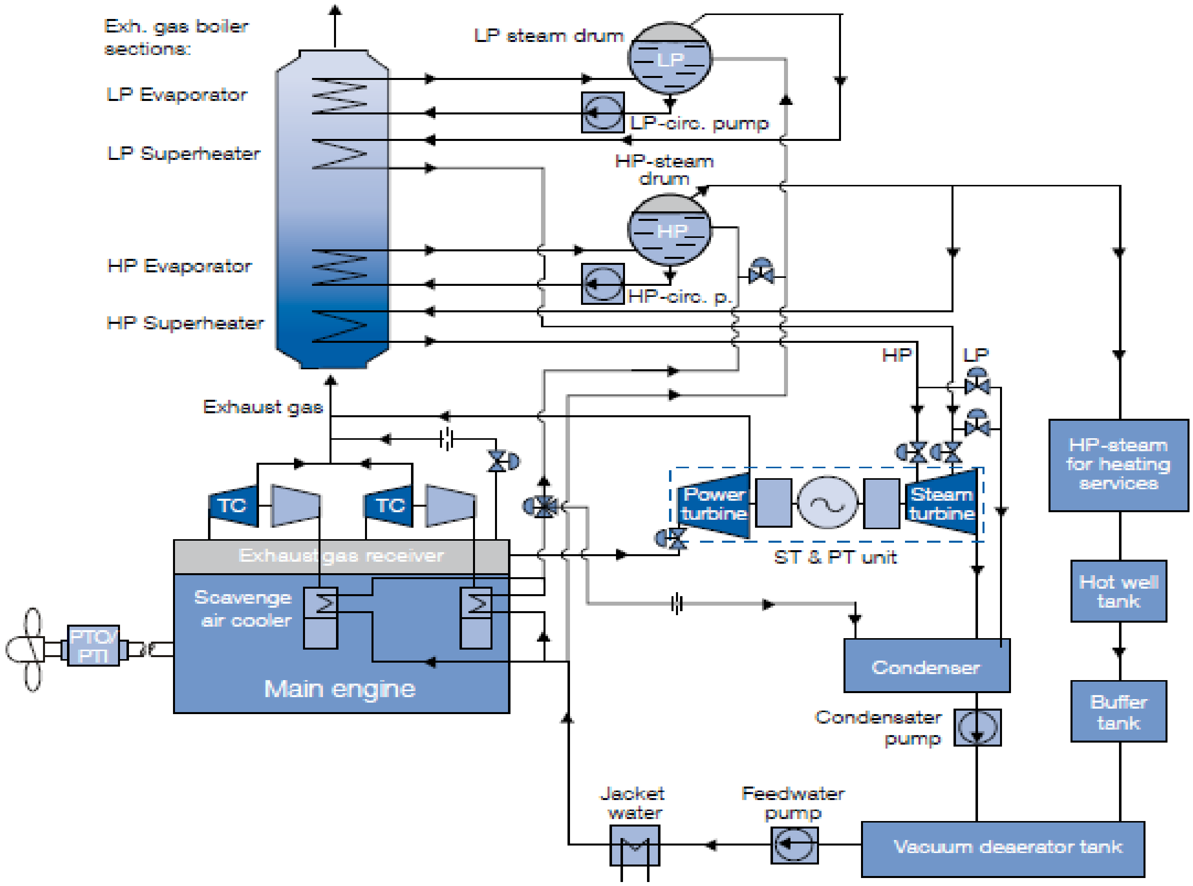
Schematic of a simplified high-efficiency WHR plant as might be employed with a Wärtsilä 7RT-flex84T-D engine for a large tanker with the turbogenerator supplying all ship's service electricity while the ship is at sea.

(Vankeirsbilck, 2011)

The second way to produce electricity from the exhaust gas is to use to a power turbine. The power turbine is the easiest and cheapest system to install as the exhaust gas is routed directly through a turbine which is connected to a generator to produce electricity. Figure III- shows both a steam turbine and power turbine.

A power turbine can also be used in conjunction with the steam turbine. The power turbine uses a part of the exhaust gas stream (about 10 percent) from the diesel engine to generate shaft power which can be added to the steam turbine driving the generator (Wärtsilä, 2004). MDT recommends a power turbine and steam turbine system for engines larger than 25,000 kW. For engines less than 25,000 kW, they recommend a power turbine or steam turbine (MDT, 2012e).

Figure III-15: Example Steam Turbine and Power Turbine WHR System



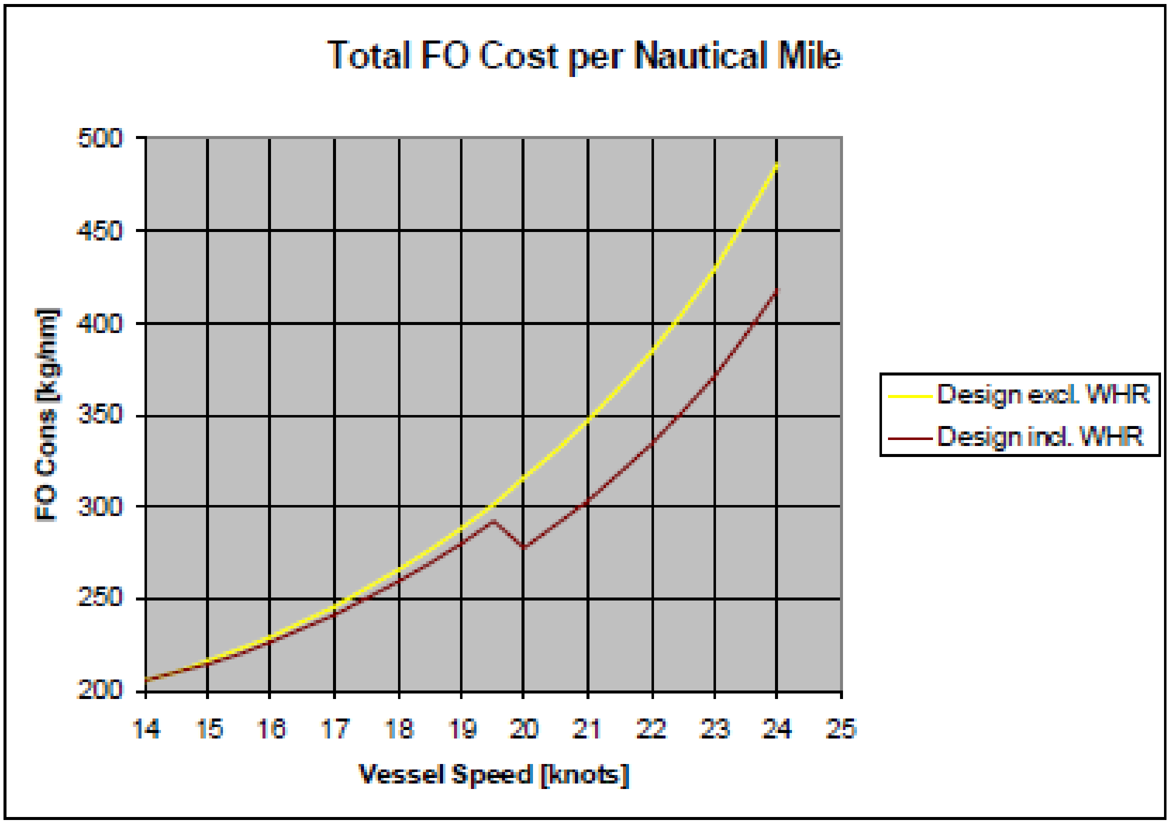
(MDT, 2012e)

2. System/Network Suitability and Operational/Infrastructure Needs

Heat recovery systems can be very large. There are heat exchangers, turbines, and piping that all require space in the engine room. For this reason, WHR systems are most likely to be installed on new vessels, where the vessel and engine room can be designed to accommodate the system. Retrofits will be very difficult to retrofit a WHR system into an existing vessel (MDT, 2012e); the exhaust boiler alone can be as large as a main engine.

Another important consideration is the operational speed of the vessel. The vessel must reach an optimal operating speed to reach a temperature for the WHR system to work. At lower speeds, the engine does not put out enough heat to operate the system. **Figure III-** shows the difference in fuel consumption between a vessel designed with a WHR system and one without. As shown, the vessel starts to conserve fuel at around 19 to 20 knots.

Figure III-16: Fuel Consumption with a Waste Heat Recovery System



Total FO = Total Fuel Oil

3. Technology Readiness

Exhaust recovery systems are demonstrated to work and reduce fuel consumption. Specifically, demonstrations show engine efficiencies up to 55 percent (MDT, 2010). There are commercially available systems from a number of manufacturers including Aalborg, MDT, and Wärtsilä.

A partnership of three companies LR Marine, APV, and DESMI produced a product for tankers that takes the exhaust heat and routes it through a heat exchanger to heat water. This heated water is then used to heat the fuel on a tanker to reduce emissions from a boiler. As a result, the boiler only needs to run while the main engine is not running. Testing of this system initially indicates a 20 percent reduction in fuel consumption, along with an emission reduction of CO_2, NO_x, and SO_x around 20 percent. Calculations indicate that utilizing this product for a 75,000 dead weight ton (DWT) tanker would save around eight tons of oil per day, which equates to around 24 tons less of CO_2 for every eight tons of oil. This system can fit in an existing tanker with an estimated construction time of two weeks to install the system (Green Ship, undated).

4. Economics

LR Marine estimates that their heat recovery system would take approximately two weeks to install on a 75,000 DWT tanker vessel, which equates to about a two year payback period basis calculated savings of eight tons of oil per day (Green Ship, undated).

Wärtsilä estimates that their heat recovery system could cost approximately $10 million to install. In their report, they estimate a payback period of approximately four years with an estimated fuel savings of $1.2 million, and a total net savings of $4.6 million over the lifetime of the vessel (Wärtsilä, 2004).

5. Emissions Reductions

Marine diesel engines are already very efficient engines. Efficiency levels vary but they hover around 50 percent. With the incorporation of a WHR system, the efficiency of the engine could increase by 10 percent to 20 percent, reducing fuel consumption and CO_2 emissions by the same percentage (Schmid, 2004; MAN, 2010).

6. Next Steps to Demonstrate and Deploy Technology

New builds will likely be the target for these WHR systems. As stated for other categories, IMO's EEDI will likely be a driving force for the installation of fuel efficient technologies. WHR systems are commercially available now and have a reasonable payback period of approximately four years. This makes it a viable technology that will very likely be incorporated into new vessels in the coming years.

Air Lubrication Systems

1. Technology Description

This is an emerging technology that involves injecting air bubbles along the underside of a vessel or into an air pocket underneath the vessel to glide along on a thin layer of air. This reduces the friction between the vessel and water and reduces the fuel consumption. In general, these air lubrication systems are built into new vessels; however, Mitsubishi is developing retrofit kits that could be adapted to existing vessels. Flat vessel hulls are preferable in order for this technology to work properly.

Air Cavity System

Developed by the DK Group, the technology was originally applied to custom new builds, where a cavity is designed along the length of the hull into which compressed air is pumped. A retrofit version has recently become available (Fathom, 2014).

Micro-Bubbles

In this variant, a stream of bubbles (rather than a single air cushion) is injected below the hull. While there is significant progress around the technology in recent years, challenges remain, such as how to ensure the air remains under the hull when the ship is rolling or pitching. Energy is also required to power the air pumps, which will offset the energy savings to some extent. The Institute for Marine Engineering, Science, and Technology (IMarEST) estimates this additional energy requirement to be in the order of 0.3 tons to 0.5 tons of fuel per day, but other academic studies have put the energy penalty much higher; in one study of a microbubble system it reduced the savings from lower friction by 42 percent. IMarEST also put the cost of including an air lubrication system at an extra 2 percent to 3 percent of the price of a new build ship, although DK Group put the figure at 1 percent (Fathom, 2014).

2. System/Network Suitability and Operational/Infrastructure Needs

Air lubrication systems will likely be installed in new vessels because the hull of the vessel must be compatible with the system. Based on the current designs, this includes an area for an air pocket to collect or a flat hull bottom for the bubble to collect under as the vessel is moving. These systems are likely to be installed primarily on new vessels, as the vessel must have a compatible hull design, although Mitsubishi has developed an MALS retrofit product which can be installed at dry dock to reduce emissions from the existing fleet.

3. Technology Readiness

Two major demonstrations were conducted to demonstrate the effectiveness of two different air lubrication systems. The first is from the DK Group and the second is from the Monohakobi Technology Institute (MTI).

The Danish-Dutch DK Group patented the Air Cavity System (ACS) technology and estimates that ACS reduces a ship's hull friction by approximately 10 percent. This results in fuel savings of ten to 15 percent for bulk carriers and tankers, and just under 10 percent for container ships. Other benefits include: improved safety by shortening emergency stopping distance by 50 percent, improved maneuverability, payload increase, and speed increase. The DK Group built a ship demonstrator and concluded full scale sea trials on a 2,550 deadweight, 83-metre multi-purpose vessel, which completed a first set of trials in Norwegian waters in 2008. The trials were conducted in association with Germanischer Lloyd, FORCE Technology, and Lyngs Marine (SKEMA, 2009).

Nippon Yusen Kaisha and two NYK Group companies, MTI and NYK-Hinode Line Ltd., completed two years of experiments on the Mitsubishi air-lubrication systems (MALS) installed on two of the group's module carriers, Yamato and Yamatai, and resultantly confirmed an average 6 percent reduction in CO_2 emissions during actual sea passage. The air-lubrication system effectively reduces the frictional resistance between a vessel's bottom and the seawater by means of bubbles generated by supplying air to the vessel's bottom. The system was installed on the two vessels when they were built, and the experiments were conducted during actual sea passage (NYK, 2012).

4. Economics

Fathom Maritime Intelligence estimates that the cost to add on an air lubrication system is approximately 1 percent to 3 percent of the cost of the vessel, with an estimated payback period of 1 to 2 years, depending on the price of fuel and the vessel type. It is estimated that up to a 10 percent reduction of fuel usage could be realized with these systems, which is an annual cost savings to the ship operator.

5. Emissions Reductions

Demonstrations show approximately 6 percent to 10 percent reduction in fuel use could be realized, along with a 10 percent to 15 percent reduction in CO_2 (Kantharia, 2017).

6. Next Steps to Demonstrate and Deploy Technology

Additional demonstrations of air lubrication systems need to be done. While the savings could be significant, only a limited amount of vessels have been tested with the systems installed. More testing and documented savings could create much more interest in air lubrication systems. Once again, the IMO 30 percent efficiency improvement requirement could create interest in these types of emission technologies to reduce the fuel consumption of these vessels.

H. Marine Boilers

Most of the focus of this Technology Assessment is on diesel engines; however, boilers on OGVs are also a significant source of emissions. These emissions occur primarily while vessels are dockside, closest to port communities. For this reason, some preliminary observations and emission reduction options are presented below.

Most OGVs have boilers that are used for a variety of purposes such as: (1) heating residual fuel, (2) production of hot water and space heating for passengers or crew, (3) distillation of seawater to generate fresh water, and (4) driving steam turbine pumps to offload crude oil or other petroleum products carried by tankers. Boilers can also be used to drive steam turbines for propulsion on steamships. Since very few steamships remain in operation or visit California ports, this discussion will focus on auxiliary boilers used for purposes other than propulsion.

For many vessels, the boilers are primarily operated at or near port. This is because the exhaust heat generated by the main engine at cruising speeds is sufficient for heat exchangers (economizers) to provide the uses mentioned (except driving steam turbines). Tankers are a special case, in that they may have small boilers for heating crude and other uses, and very large boilers used only at dockside to offload crude or other petroleum products.

Table III-6 provides 2014 emissions estimates for auxiliary boilers, and compares these emissions to main and auxiliary diesel engines. The emissions in Table III-6 are shown within Regulated California Waters (24 nm zone) because boilers operate primarily at dockside or close to port. Tanker boilers are also shown separately as they represent the majority of auxiliary engine boilers. As shown, auxiliary boiler emissions are comparable to or higher than auxiliary diesel engines for some pollutants. However, their NOx emissions are much lower because fuel combustion in boilers produces significantly less NOx. The auxiliary boilers on tankers account for the majority of the total auxiliary boiler emissions due to the large loads when tankers offload crude.

Table III-6: 2014 OGV Emissions* Breakdown

Engine or Boiler	Fuel (gpdx10^6)	CO_2 (tpd)	SOx (tpd)	NOx (tpd)	$PM_{2.5}$ (tpd)	ROG (tpd)
Main Engine	136	4,989	3	131	2.1	6.5
Auxiliary Engine	36	1,382	0.7	20	0.47	0.9
Auxiliary Boiler	48	1,768	2.9	4	0.25	0.21
Tanker Boiler	*37*	*1,362*	*2.2*	*3*	*0.19*	*0.16*
Non-Tanker Boiler	*11*	*406*	*0.7*	*1*	*0.06*	*0.05*
Grand Total	221	8,139	6.6	155	2.8	7.6

* Based on 2014 CARB Emissions Inventory. Emissions expressed in tons per day, and fuel use in millions of gallons per day. Updates to the emissions inventory are expected to result in reduced emissions estimates from boilers, and tanker boilers in particular.

Auxiliary boilers are not presently subject to CARB's At-Berth Regulation since they provide steam rather than electrical power. However, they are subject to the low sulfur fuel requirements in both CARB's OGV Clean Fuel Regulation and the federal ECA. These fuel requirements significantly reduce their PM and SOx emissions, and their NOx emissions are already low compared to diesel engines. Additional reductions may also be possible in the future by utilizing new control technologies. One possible control strategy is the use of a barge or land-based bonnet capture and control emissions control technologies discussed in Section III.E. Bonnet capture and control systems are designed to control auxiliary diesel engines, but could potentially also be used to capture and control tanker boiler emissions. Current designs may not be suitable to control the large exhaust volumes from tanker boilers offloading petroleum products, but if the current designs prove to be effective in controlling emissions from smaller emissions sources, it may be possible that they could be scaled up to handle the larger exhaust volumes from tanker boilers.

Other potential emission control options include the use of new low-NOx burner designs, the use of natural gas-fired boilers in LNG carriers or dual-fueled vessels, SCR systems, and scrubbers, as described in Section III.D.

As noted, the large boilers on tankers account for the majority of OGV boiler emissions, and they represent a special case amenable to some different control strategies. A couple of control options specific to tanker boilers are: (1) greater use of land-based electric motors to assist in the pumping of crude oil from the vessel, and (2) for new vessels, onboard electrically driven pumps that can accept shore-power. Landside electric motors cannot be used to completely offload crude from tankers due to physical and technical limitations. However, they can be used to assist in the offloading of crude, significantly reducing tanker boiler loads and emissions. This option could be used in new or modified terminals where it is possible to install crude storage tanks closer to dock, where the tanker boilers would only need to pump the crude to the nearby tanks, and then landside electric motors would pump the crude the remaining distance to the refinery.

Another approach, for new-build vessels, is a tanker design that incorporates onboard diesel-electric motors designed to offload crude, rather than the more common boiler-driven steam turbine pumps. For example, Alaska Tanker Company (ATC) operates four diesel-electric tankers using this configuration (Alaska Legend, Alaska Frontier, Alaska Explorer, and Alaska Navigator). These four vessels use diesel engines that drive generators for power that is used both to propel the vessels and drive the crude oil pumps (General Dynamics, undated). This type of configuration would provide the possibility that the vessel could connect to shore-side power if the vessel and terminal were properly equipped. In fact, two of the ATC tankers mentioned (Alaska Frontier and Alaska Navigator) are shore-power equipped and plug-in at POLB to reduce their port emissions through a voluntary agreement between POLB and BP America (POLB, 2009). But very few tankers use this type of pumping system, and according to one marine engineering firm, the use of electric pumping would likely be limited to shuttle tankers, or tankers on relatively shorter routes (e.g., Alaska trade) for various economic reasons (Herbert Engineering, 2004).

I. Significant Current Research Efforts

While significant efforts are being made to reduce vessel emissions, there are still knowledge gaps where additional research and work is needed. Some of these areas include:

- Determining how to assist in the implementation of a robust fueling infrastructure for alternative fuels like LNG (e.g., funding, permit assistance, and site location),
- Investigating the most effective approaches to encourage vessel operators to retrofit older vessels and purchase the cleanest new vessels exceeding regulatory requirements,
- Evaluating approaches to bring the cleanest vessels to California ports and to ensure that the cleanest and most efficient vessels are being designed and built,
- Validating of the emission control effectiveness and economics of emerging technologies, and
- Testing the long-term durability of technologies not yet proven in a marine environment.

There are a number of ongoing research projects targeted towards research and development efforts for improving efficiency and reducing harmful emissions from ship engines.

Hercules

The HERCULES project started in 2002 as a long-term research and development program for marine engines. HERCULES is an acronym for Higher Efficiency, Reduced Emissions, Increased Reliability and Lifetime Engines for Ships. The project is led by the two engine manufacturer groups MDT and Wärtsilä, which together have about 90 percent of the marine engine market. The HERCULES program explores every angle for improving the marine engine, but does not explore alternatives like renewable fuels or other propulsion technologies.

Phase 1 of HERCULES, called I.P. HERCULES, lasted from 2004 to 2007. It had a budget equivalent to around $35.1 million, and funded 54 subprojects covering the gambit of research categories including: engines, combustion, turbocharging, energy recovery, emission reductions, exhaust after-treatment, friction, and controls. Phase 1 showed a path forward to exceeding the project's 2007 emission and reliability targets.

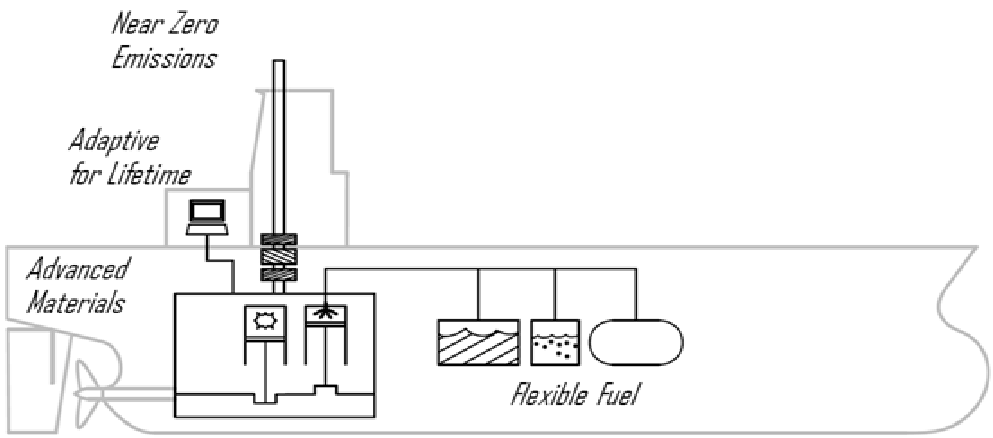
Phase 2 of HERCULES, called HERCULES-B, lasted from 2008 to 2011. It had a budget of equivalent to about $27.7 million, and funded 56 subprojects, continuing on the efforts of Phase 1. Phase 2 targets were based on 2020 emission targets and a path to Tier III IMO standards. Many of the projects in Phase 2 led to new products including high efficiency and low emission turbocharging, exhaust emission reduction through exhaust gas recirculation and after-treatment, advanced materials optimization, and advanced sensing and reliable adaptive control.

Phase 3 of HERCULES, called HERCULES-C, started in 2012 and finished in 2015. It had a budget of around $18.1 million, and funded 47 subprojects. The focus on Phase 3 was for continued improvements through new advancements and integrating new and existing technologies. For fuel consumption, the target was a 5 percent improvement by 2020 over best available technology in service in 2010. For emission reductions, the target was a 95 percent reduction over IMO Tier I by 2020. Lastly, the operational lifetime target was to maintain the technical performance of engines with a maximum of 5 percent divergence from as-new (Kyrtatos, 2012).

The emission reduction target in Phase 3 represents a significant improvement over Tier III's 80 percent reduction over Tier I. A 95 percent reduction over Tier I results in a maximum NOx emission rate between 0.5 and 0.85 g/kWh depending on the marine engine RPM speed. HERCULES-C aimed to reach this target through developments in combustion, and integrating the best technologies from HERCULES Phase 1 and Phase 2. For example, work package six of HERCULES-C has the objective of reaching toward zero NOx emissions by combining exhaust gas recirculation and water emulsified fuel (HERCULES-C, 2013).

In 2016, work started on HERCULES-2, which is the fourth phase of the HERCULES project. Figure III- depicts the three main areas of focus for HERCULES-2. This next phase of research and development is set to run for 3 years, and will include 34 subprojects focusing on flexible fuel marine engines in four areas: 1) alternative fuels and improving the technology that allows vessels to successfully switch back and forth between fuel types, 2) development of new materials to support high temperature components, 3) lifetime engine performance optimization methodologies, 4) achievement of near-zero emissions utilizing exhaust gas treatments. (HERCULES-2, 2015).

Figure III-17: HERCULES 2 Conceptual Diagram



(HERCULES-2, 2015)

Through more than 10 years of research, the HERCULES program shows the possibility for marine engines to continually have substantial improvements to efficiency and air quality.

Greenship

Greenship of the Future is an open private-public partnership of the Danish maritime community and other partners dedicated to investigating and developing technical solutions for cleaner, more efficient vessels and operations. The Greenship group includes over 40 companies and organizations, including ship owners, class societies, suppliers, consultants, governmental organizations, universities, and maritime organizations. Greenship's main focus is on vessel design, machinery, propulsion, and operation/logistics (Green Ship, 2015).

The Greenship partnership already completed a number of studies discussing technologies that can lower emissions and improve vessel efficiency. These studies include the following:

- Low Emission Container Vessel Study,
- Low Emission Bulk Carrier Study,
- ECA Retrofit Study, and
- Low Emission Ferry Study.

As an example, the Low Emission Container Vessel Study began with the goal of reducing NOx and SOx emissions by 90 percent, and CO_2 by 30 percent. The study investigated the use of the following technologies:

- Water-in-fuel systems,
- Exhaust gas recirculation,
- Waste heat recovery,
- Power and steam turbine technology, and
- Exhaust gas scrubbers.

The study found that using the above technologies, they could meet their SOx reduction target, achieve an 80 percent NOx reduction, and an 11 percent to 14 percent CO_2 reduction, with a modest 10 percent increase in the cost of the vessel over a standard ship. The study partners also identified potential technologies for further research to achieve the 30 percent CO_2 reduction, including the use of alternative fuels (LNG, biofuels), optimized vessel hull design, alternative means of propulsion (wind, solar, fuel cells), more efficient engines, and optimized operation (slow steaming, weather routing).

Vessels for the Future

The European maritime industry launched the research association Vessels for the Future in November 2014. The initiative is a public private partnership composed of 50 companies, research institutes, academic organizations, and interested associations. The group is focusing on shipping safety, sustainability, and competitiveness. The group established ambitious 2050 emissions targets, including: (1) an 80 percent reduction in CO_2, and (2) a 100 percent reduction in NOx and SOx. To achieve these targets, the effort is expected to focus on the following technology areas:

- Energy management and novel design concepts,
- Hull/water interaction,
- Information and communication technology,
- Materials, design, and production, and
- Fuels and propulsion systems.

The organization also plans to reach out a European vessel demonstrator to test new technologies at ship level (DNVGL, 2015).

LeanShips

LeanShips project is a combined effort of largely European industries seeking to explore innovative efforts for ship efficiency using on board demonstrations. The project began in 2015 and will run through 2019, and focuses on eight on-board case studies (primarily on small/mid-size cargo vessels and passenger vessels):

- CNG powered RSD ship-handling tug – Testing of a high speed tug boat that operates on compressed natural gas and utilizing fewer crew for operational cost savings.
- The potential of methanol as alternative fuel - Study will compare emissions reductions and cost comparisons between methanol and diesel engines using a converted dual fuel high speed marine engine.
- Efficient LNG Carrier – Goal is a 25 percent reduction in fuel consumption by optimizing the engine, hull/coating, propeller configuration, and energy management of the vessel.
- SECA Refit Strategy – This project seeks to test which methods of retrofit are feasible for the fleet of general cargo vessels operating primarily in the SECA, and uses a mathematical formula to determine most cost effective strategy for each ship. Once the vessels are retrofit, results are to be fed back into the mathematical formula for improvements and future implementation.
- Expanding the application of ESDs to ships with CPP - Focuses on energy saving devices (ESDs) designed by Wärtsilä and MARIN for vessel designed with controllable pitch propellers (CPP).
- Large Diameter Propeller for General Cargo Vessel – Study of propeller design on ship efficiency; in this case, an ice-class vessel to be retrofitted with a larger diameter propeller will be demonstrated to see if the design results in improved propulsion efficiency.
- Decision Support System for ship energy efficiency - Explores non-mechanical changes to a passenger vessel and evaluates cost effectiveness, market availability, and compliance with existing regulations; includes study of ship layout, energy management, hull and propeller characteristics.

- Energy efficient systems for leisure/passenger ship – Addresses ways to reduce emissions from passenger vessels by enhancing on board waste treatment systems, heat based energy production systems, energy storage system, and solutions for emission reduction.

While generally geared towards smaller vessels, the eight case studies still represent a step forward in the direction of exploring alternative fuel and ship design efficiency for the reduction of emissions for OGVs (LeanShips, 2016).

PERFECt Project

The Piston Engine Room Free Efficient Containership Project is a joint effort between Gaztransport & Technigaz (GTT), CMA CGM and subsidiary ships, and DNV-GL to study the technical and economic feasibility of an electrically driven ultra large container vessel (ULCV) powered by LNG and a combination gas and steam turbine system (COGAS), which generates steam from heat using gas turbines. The goal of the PERFECt Project is to develop a more efficient and cleaner way to power ULCVs, while remaining economically competitive with a standard 20,000 TEU ULCV using two-stroke diesel engines operating on HFO. This system has been used on cruise vessels but never on a container ship (Würsig, 2015).

The initial phase of the project involved modeling a PERFECt vessel as compared to a traditional HFO-powered vessel. The vessel design included two 10,960 m^3 LNG tanks, enough for a round trip voyage from Europe to Asia. This was compared to a comparable HFO-powered vessel on the same trade route. The base design was modeled off CMA CGM's vessel Marco Polo (Marine Log, 2015).

The COGAS system is expected to be more flexible in design with increased cargo capacity, and is related directly to the engine room design. Traditional design for an HFO piston engine design positions the engine room aft of the ship, with the associated exhaust funnel taking up cargo space at the back of the ship; this reduces the amount of containers placed aft. But by utilizing electric drive, the main propulsion unit can be separated from the power generation units (Figure III-18, label 'A'), eliminating the need for a traditional engine room. The gas turbines can be placed above the LNG tanks below the Deck House (Figure III-18, label 'B'), with the exhaust funnel (Figure III-18, label 'C'), shifted to the wheelhouse. This compensates for the fact that LNG tanks take up more space on than diesel fuel tanks due to LNG's lower energy density. The conceptual PERFECt design indicates the potential for an additional 300 containers on board the vessel as compared to a standard 20,000 TEU container vessel (Würsig, 2015). Figure III-18 shows the conceptual design.

Figure III-18: PERFECt Project Conceptual Design

(Würsig, 2015)

There are some structural challenges with this conceptual design. The removal of the reinforced engine room would result in a weaker overall structure, leaving the vessel more susceptible to damage from bending and torsion, particularly in the rear of the ship. Some minor changes to the ship's structure, such as adding thickness to certain areas of the ship's hull, will need to be explored to make the design viable (Moore, 2016).

According to the study, additional costs for the PERFECt ship (versus traditional HFO ULCV) include:

- Gas and steam turbines,
- Membrane tanks,
- Fuel gas handling, and
- Structural reinforcements (needed as there is no aft engine casing).

But costs that could be eliminated or reduced in compared to the two-stroke engine system include:

- Scrubber, which is eliminated,
- Cooling system capacity, which is reduced and the system simplified, and
- HFO treatment or tank heating (not needed for LNG).

At this time, capital costs are around 20 percent to 24 percent higher for a PERFECt vessel compared to a traditional diesel ULCV. Operating costs will depend heavily on the price difference between HFO and LNG along with how much additional revenue can be gained from additional container slots. Enough technical and economic viability was seen to justify further study by project members. Phase 2 of the project will study optimization potential to gain additional efficiency from the PERFECt design (Würsig, 2015, Moore, 2016).

IV. SUMMARY AND CONCLUSIONS

As OGV technologies continue to advance, significant additional emission reductions are possible. Technologies are available that will move vessels and associated infrastructure at dockside toward our long-term goal of zero and near-zero emissions. New build vessels in particular will be able to benefit from many of these technological advancements.

Existing regulations at the state, federal, and international level will achieve significant progress in the next five to ten years. The international Tier III NOx standard for new 2016 vessels is expected to reduce NOx emissions by 80 percent within the North American ECA when compared to 2012 baseline vessels. International vessel efficiency rules are also expected to result in an estimated 30 percent reduction in GHG emissions from most vessels by 2025. Vessels at dockside in California are now increasingly turning off their diesel generators and plugging in to shore-side electrical power and/or utilizing alternative methods to reduce their at-berth emissions.

As illustrated in this technology assessment, there are many technologies available and coming soon that will continue to make vessels and vessel operations cleaner. To accelerate the implementation of these technologies, CARB staff is planning to develop the following near-term measures in the next few years:

- Advocating with national and international partners for new IMO Tier IV NOx and PM engine standards,
- Exploring more aggressive GHG emissions reductions targets above and beyond existing IMO goals,
- Defining criteria for a Low Emission Ship Visit and develop seaport incentive programs to encourage these vessels to visit California ports, and
- Proposing amendments to the At-Berth Regulation to expand the use of shore-side power and other technologies to include other vessel fleets and types of vessels.

Support for research and demonstration programs to evaluate emerging technologies can help identify the technologies with the most promise to reduce emissions. These efforts may include:

- Support NOx retrofit technology demonstrations for in-use vessels not subject to IMO Tier III NOx standards,
- Evaluate the effectiveness of emission control technologies and other innovative on-board technologies on black carbon, NOx, SOx, PM, GHGs, and
- Seek federal funds from the U.S. Department of Transportation’s Maritime Administration (MARAD) and the U.S. Department of Energy for technology and fuel demonstration projects.

Finally, CARB regulations and incentive programs can require or provide the impetus for vessel operators to pursue the cleanest available technologies. These instruments may include the following:

- Develop an OGV renewable biofuels market through proposal of an amendment allowing the option to include these fuels in the Low Carbon Fuel Standard if it is adopted, or inclusion in the Cap-and-Trade Regulation,
- Define criteria for a Low Emission Ship Visit and achieving early implementation of clean technologies via incentive programs,
- Support existing and develop new incentive programs to help offset the costs of existing and emerging technologies (both shore side and vessel based), and
- Amend CARB’s At-Berth Regulation to include other technologies and vessel types to achieve additional emission reductions.

Reducing emissions from the shipping industry is necessary not only to help California achieve its emissions reduction and climate goals, but also to improve the air quality and lessen impacts of climate change globally. Many of the technologies discussed in this technology assessment are commercially available and can be used to achieve reductions from OGVs in the near-term. Without stricter NOx and PM standards and more ambitious GHG emissions reductions targets from the global shipping industry, it may not be possible for California or other international entities to reach air quality and climate goals. Continued advocacy and collaboration at the international level will be crucial to the development of new technologies, enhanced ship designs and operational strategies, and regulatory efforts that can reduce the global impact of shipping.

V. REFERENCES (By Section)

Executive Summary

(DNV-GL, 2012): *Fuel Cells for Ships*, *Research and Innovation, Position paper 13-2012,* Det Norske Veritas-Germanischer Lloyd, June, 2012.

(Hercules, 2017): *HERCULES-C (HIGHER EFFICIENCY, REDUCED EMISSIONS, INCREASED RELIABILITY AND LIFETIME, ENGINES FOR SHIPS)*, HERCULES Project, http://www.hercules-c.com/index.php/about/project-overview. Accessed on January 19, 2017.

(Schuler, 2017) Schuler, M. *OOCL Hong Kong Breaks 21,000 TEU Mark, Becoming 'World's Largest Containership,* gCaptain, May 15, 2017, http://gcaptain.com/oocl-hong-kong-breaks-21000-teu-mark.

(Zhang, 2016) Zhang, B. *This $1 billion monster is the largest cruise ship ever built — and it just set sail*, Business Insider, May 17, 2016. http://www.businessinsider.com/harmony-of-the-seas-royal-caribbean-2016-5. Accessed February 28, 2018.

Section II – Overview of Ocean-Going Vessels

(CARB, 2008): California Air Resources Board, *Staff Report: Initial Statement of Reasons (ISOR) Proposed Regulations for Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline*, June, 2008.

(CARB, 2016) *Advisory to Owners and Operators of Ocean-Going Vessels Visiting California Ports,* CARB Marine Notice 2016-1, April 2016, https://www.arb.ca.gov/ports/marinevess/documents/marinenote2016_1.pdf

(Engineering-Marine, 2010) *What is a Marine Boiler?* Marine Engineering Blog, November 26, 2010, http://engineering-marine.blogspot.com/2010/11/what-is-marine-boiler.html

(EPA, 2011) *Adoption of an Energy Efficiency Design Index for International Shipping*, United Stated Environmental Protection Agency, Office of Transportation and Air Quality, EPA-420-F-11-025, July 2011.

(gCaptain, 2018) *Here is the IMO's Full Briefing on Its Strategy to Reduce Greenhouse Gas Emissions from Ships*, gCaptain, April 13, 2018, http://gcaptain.com/here-is-the-imos-full-briefing-on-its-strategy-to-reduce-greenhouse-gas-emissions-from-ships/

(Hand, 2018) *Marshall Islands says the IMO faces 'moment of truth' on Greenhouse Gas emissions*, Seatrade Maritime News, April 9, 2018, http://www.seatrade-maritime.com/news/europe/marshall-islands-says-the-imo-faces-moment-of-truth-on-greenhouse-gas-emissions.html

(ICCT, 2011) *The Energy Efficiency Design Index (EEDI) for New Ships*, The International Council on Clean Transportation (ICCT), October 3, 2011.

(IMO, 2014) *Energy Efficiency Measures,* International Maritime Organization (IMO), *http://www.imo.org/en/ourwork/environment/pollutionprevention/airpollution/pages/technical-and-operational-measures.aspx*. Accessed January 19, 2017.

(IMO, 2018) *UN body adopts climate change strategy for shipping*, International Maritime Organization, April 13, 2018, http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

(Johnson, 2013) Johnson, K., et. al, *Black Carbon Emissions from an Ocean Going Vessel Equipped with a Scrubber*, University of California, Riverside - College of Engineering-Center for Environmental Research and Technology, Final Report prepared for California Air Resources Board, December, 2013, https://www.arb.ca.gov/ports/marinevess/documents/emissiontest/bc_scrubber.pdf

(Jordan, 2018) Jordan, J. and Watson, F. *IMO greenhouse gas cuts present unprecedented challenge for shipping,* April 13, 2018, https://www.platts.com/latest-news/shipping/london/imo-greenhouse-gas-cuts-present-unprecedented-21790483

(Maersk, 2014) *Building the World's Biggest Ship,* Maersk, May 30, 2014. http://www.maersk.com/innovation/leadingthroughinnovation/pages/buildingtheworldsbiggestship.aspx. Accessed January 19, 2017.

(NY Daily News, 2018) *UN holds meeting on curbing greenhouse emissions from ships*, NY Daily News, April 9, 2018, http://www.nydailynews.com/newswires/news/business/holds-meeting-curbing-greenhouse-emissions-ships-article-1.3923463

(Oakland, 2005) *Port of Oakland 2005 Seaport Air Emissions Inventory,* Port of Oakland, 2005. *http://www.portofoakland.com/files/pdf/environment/airEmissions_Inventory.pdf*

(Oakland, 2015): *Operating Statistics,* Port of Oakland, 2015 *http://www.portofoakland.com/port/seaport/operations/*

(POLA, 2008) *Low-Sulfur Marine Fuel Availability Study*, Port of Los Angeles and Port of Long Beach, April 14, 2008. http://www.portoflosangeles.org/DOC/REPORT_Fuel_Availability_Study_Final_041408.pdf

(POLA, 2014) *Environmental Ship Index Program,* Port of Los Angeles, 2014. http://www.portoflosangeles.org/environment/ogv.asp

(POLA, 2016a) *Inventory of Air Emissions For Calendar Year 2016,* Port of Los Angeles, July 2017. https://www.portoflosangeles.org/pdf/2016_Air_Emissions_Inventory.pdf

(POLB, 2016a) *2016 Air Emissions Inventory,* Port of Long Beach, July 2017. http://www.polb.com/civica/filebank/blobdload.asp?BlobID=14109

(Royal Caribbean, 2014) *Our Fleet,* Royal Caribbean, 2014, http://www.royalcaribbean.com/findacruise/ships/class/ship/home.do?shipCode=AL

(Saul, 2018) Saul, J. and Chestney, N. *IMO Reaches Deal to Cut CO2 Emissions from Ships,* Reuters, April 13, 2018, http://gcaptain.com/imo-reaches-deal-to-cut-co2-emissions-from-ships/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+Gcaptain+%28gCaptain.com%29&goal=0_f50174ef03-ce37d4b777-139827965&mc_cid=ce37d4b777&mc_eid=4bc5f2004f

(Stefanini, 2018) Stefanini, S. *Countries inch towards 'bare minimum' climate target for shipping*, businessGreen, Climate Home News, April 11, 2018, https://www.businessgreen.com/bg/news/3029947/countries-inch-towards-bare-minimum-climate-target-for-shipping

(UNFCCC, 2017) *The Paris Agreement*, United Nations Climate Change, April 20, 2018, https://unfccc.int/process/the-paris-agreement/what-is-the-paris-agreement

Section III – Assessment of Ocean-Going Vessel Emission Reduction Technologies

(ABB, 2014) *Turbocharging in Switzerland – A history*, ABB Group, Undated, https://library.e.abb.com/public/79f13790333970d9c1257c8c00396458/Turbocharging%20in%20Switzerland%20-%20A%20history.pdf

(Alfa Laval, 2014) *Front-running NOx abatement technology approaches 3500 hours of real-world operation at sea*, Product News, Alfa Laval, May 28, 2014, http://www.alfalaval.com/media/news/2014/front-running-nox-abatement-technology-approaches-3500-hours-of-real-world-operation-at-sea/

(Ashworth, 2015), Ashworth, J. *LNG: A Trans-Atlantic Divide,* The Maritime Executive, March 2015, http://www.maritime-executive.com/features/lng-a-trans-atlantic-divide.

(Azzara, 2014) Azzara, A.,et al, *Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction*, Working Paper, The International Council on Clean Transportation, March, 2014.

(Bluefield, 2013) *Evaluation of the Emission Reduction Performance of a Hamworthy/Krystallon Exhaust Gas Cleaning Scrubber*, Final Report, Bluefield Holdings, May, 2013, http://www.cleanairactionplan.org/documents/evaluation-emission-reduction-performance-hamworthykrystallon-exhaust-gas-cleaning-scrubber.pdf

(Bonney, 2016) Bonney, J. *Matson orders two container/ro-ro ships for Hawaii trade,* Journal of Commerce, August 2016, http://www.joc.com/maritime-news/container-lines/matson/matson-spend-511-million-two-ships-hawaii-trade_20160826.html

(Bureau Veritas, 2014). *Exhaust Scrubbers - What you need to know*, Bureau Veritas, March, 2014, https://www.bureauveritas.com/wps/wcm/connect/fef2970d-288d-413b-8555-e5fb70ca13b0/ExhaustScrubbers_LD.pdf?MOD=AJPERES

(CARB, 2007) *Initial Statement of Reasons (ISOR) Including Proposed Regulation Order,* Staff Report, Appendix E: *Cost-Effectiveness Methodology*, California Air Resources board, https://www.arb.ca.gov/regact/2007/shorepwr07/appe.pdf

(CARB, 2008) *2007 Ocean-Going Ship Survey Summary of Results*, Staff Survey, California Air Resources Board, https://www.arb.ca.gov/regact/2008/fuelogv08/appcfuel.pdf

(Chang, 2014). Chang, C. and Wang, C., *Study evaluates the effects of speed reduction*, National Cheng Kung University, Oct 1, 2014

(Chiotopoulos, 2017) Chiotopoulos, Ioannis*, Ship owners should start planning for the 2020 sulphur cap, as time frame is closing rapidly says DNV GL*, Interview by Nikos Roussanoglou, Hellenic Shipping News Worldwide, January 30, 2017, http://www.hellenicshippingnews.com/ship-owners-should-start-planning-for-the-2020-sulphur-cap-as-time-frame-is-closing-rapidly-says-dnv-gl/, Accessed January 30, 2017.

(Christensen, 2010) Christensen, O., *Cylinder lubrication of two-stroke crosshead marine diesel engines*, Wärtsilä Technical Journal, February, 2010, http://www.pattakon.com/tempman/Wartsila_technical_journal_02_2010.pdf

(Chryssakis, 2014) Prepared by Chryssakis C., Balland O., Tvete, H.A., Brandsæter, A., *Alternative Fuels for Shipping,* Position Paper 17-2014, DNV-GL, January, 2014.

(CMA CGM, 2014*) CMA CGM continues its fleet's energy and consumption optimizations by retrofitting 10 of its vessels' bulbous bows*, CMA CGM Group, October, 30, 2014, https://www.cma-cgm.com/news/640/cma-cgm-continues-its-fleet-s-energy-and-consumption-optimizations-by-retrofitting-10-of-its-vessels-bulbous-bows

(Corbett, 2014) Corbett, J., et al. *Natural Gas for Waterborne Freight Transport: A Life Cycle Emissions Assessment with Case Studies*, University of Delaware, June 6, 2014.

(Corbett, 2015) Corbett, J., et al. *Methane Emissions from Natural Gas Bunkering Operations in the Marine Sector: A Total Fuel Cycle Approach*, Prepared for U.S. Department of Transportation Maritime Administration, November 21, 2015.

(Diesel Facts, 2013) *US Oil Major Places Order for Ultra-Efficient Tier III-Compliant Engines,* Diesel Facts - A Technical Customer Magazine of MAN Diesel & Turbo, January, 2013.

(Diesel Facts, 2014) *Introducing a State-of-the-Art Combustion Concept*, Diesel Facts - A Technical Customer Magazine of MAN Diesel & Turbo, February, 2014.

(DME, 2012) *Economic Impact Assessment of a NOx Emission Control Area in the North Sea,* Danish Ministry of the Environment, Incentive Partners & Litehauz, 2012

(DNV-GL, 2012) *Fuel Cells for Ships*, Det Norske Veritas-Germanischer Lloyd, Research and Innovation, Position paper 13-2012, June, 2012.

(DNV-GL, 2013). *SOx Reduction, Class Involvement*, PowerPoint presentation, Det Norske Veritas-Germanischer Lloyd January 28, 2013.

(DNV-GL, 2015a) *Retrofitting: Where the Savings Are*, Det Norske Veritas-Germanischer Lloyd, June 4, 2015, https://www.dnvgl.com/maritime/energy-efficiency/article/retrofitting.html

(DNV-GL, 2015b). *Vessels for the Future – New Research Association to Spur Maritime transport's competitiveness*, Det Norske Veritas-Germanischer Lloyd, March, 2015. http://www.dnv.nl/nieuws_events/nieuws/2015/vessels_for_the_future.asp

(DNV-GL, 2016), *Developing a Roadmap for Green Coastal Shipping,* Det Norske Veritas-Germanischer Lloyd, September 2016 *https://www.dnvgl.com/news/developing-a-roadmap-for-green-coastal-shipping-75090*

(Doosan, 2007) *Retrofit for Alpha Lubricator,* Slide Presentation, Doosan Engine Company, http://www.bosung.com/upload/[221]20071120173954.pdf

(Eagle LNG, 2018) *Projects in Progress - Jacksonville, FL,* Eagle LNG, http://eaglelng.com/projects/jacksonville-fl, Accessed March 19, 2018.

(Enercon, 2013) *Rotor sail ship, "E-Ship 1" saves up to 25% fuel*, Press Release, ENERCON 7/29/2013.

(EPA, 2009) *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Category 3 Marine Diesel Engines*, U. S. Environmental Protection Agency, December 2009, https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1005ZGH.TXT.

(Fairplay, 2015) *First IMO Tier III compliant Wartsilla X72 engine with pre-turbocharger SCR passed shop test*, Press Release, IHS Fairplay, May 10, 2016, http://fairplay.ihs.com/commerce/first-imo-tier-iii-compliant-w%C3%A4rtsil%C3%A4-x72-engine-with-pre-turbocharger-scr-passed-shop-test_20160510, Accessed June 2017.

(Fathom, 2014) *Air Lubrication (Section 1.2.7), Technology (Section 1.2), Chapter 1. Ship Design*, In Ship Design: The Guide. Fathom Maritime, Accessed October 17, 2014.

(Fournier, 2006) Fournier, A., *Controlling Air Emissions from Marine Vessels: Problems and Opportunities*, Donald Bren School of Environmental Science and Management, University of California Santa Barbara, February 2006, http://www2.bren.ucsb.edu/~kolstad/temporary/Marine_Emissions__2-11-06_.pdf.

(gCaptain, 2018), *LNG-Powered Viking Grace Now Using Rotor Sail for Wind-Assisted Propulsion*, gCaptain, May 1, 2018, http://gcaptain.com/lng-powered-viking-grace-now-using-rotor-sail-for-wind-assisted-propulsion/

(General Dynamics, undated) *BP Tanker Fact Sheet*, General Dynamics, NASSCO, undated, http://nassco.com/products/construction/commercial-construction/commercial-ship-portfolio/bp-tanker-fact-sheet/.

(Green Ship, 2015). Green Ship of the Future Project Homepage, Accessed May 26, 2015, http://www.greenship.org.

(Green Ship, undated) *System Integration and Waste Heat Utilization,* Green Ship Magazine, Accessed October 2016.

(Greentech, 2011) *Understanding the Physics of Trim,* Special Greentech, Ship & Offshore - The international publication for Offshore & Marine Technology, 2011 edition, pages 36-38.

(GWADF, 2013) *In-Water Hull Cleaning System Cost & Cost Benefit Analysis*, Government of Western Australian Department of Fisheries, July 2013, http://www.fish.wa.gov.au/Documents/occasional_publications/fop115.pdf

(Hand, 2013) Hand, M., *Bulbous bow pays off in a year*, Seatrade Maritime News, June 6, 2013, http://www.seatrade-maritime.com/news/asia/bulbous-bow-pays-off-in-a-year.html

(Hellenic Shipping News, 2016) *Singapore sets out new measures to shape bunkering for the future,* Hellenic Shipping News, October 2016, http://www.hellenicshippingnews.com/singapore-sets-out-new-measures-to-shape-bunkering-for-the-future/

(Herbert Engineering, 2004) *Cargo Pumping Systems for Large Crude Oil Tankers*, Herbert Engineering & Aspland Consultants, 2004.

(HERCULES-C, 2013) *Overview,* HERCULES-C Project, Undated, http://hercules-c.com/index.php/work-structure/work-structure-overview

(HERCULES-2, 2015), *EU-Funded Project Hercules-2 Launched,* HERCULES-2 Project, September 2015 http://www.hercules-2.com/ // http://www.hercules-2.com/sites/default/files/pub/13_Diesel%20%26%20Gas%20Turbine%20Worldwide%20-%20August%202015.pdf

(Hydrex, 2011) *Ship Hull Coating Systems Simplified,* White Paper, Hydrex LLC. April 2011, http://www.boudvanrompay.com/upload/author/files/d773e8c64281e311bbb75462b9ef5124.pdf.

(ICAC, 1997) White Paper: *Selective Catalytic Reduction (SCR) Control of NOx Emissions*, Institute of Clean Air Companies, Inc., 1997.

(ICCT, 2013) *Assessment of the Fuel Cycle Impact of Liquefied Natural Gas as Used in International Shipping*, White Paper, The International Council on Clean Transportation, May, 2013.

(IGU, 2016) *2016 World LNG Report LNG - 18 Conference & Exhibition Edition*, International Gas Union, http://www.igu.org/publications/2016-world-lng-report.

(IMO, 2000) *Study of Greenhouse Gas Emissions from Ships, Final report to the IMO*, International Maritime Organization, Issue no. 2-31, March 2000.

(IMO, 2009) *Second IMO Greenhouse Gas Study 2009*, International Maritime Organization, 2009.

(IMO, 2014) *Nitrogen Oxides (NOx) – Regulation 13*, International Maritime Organization, Undated, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf

(IPCC, 2007) *Climate Change 2007 – Synthesis Report.* A Report of the Intergovernmtal Pannel on Climate Change (IPPC). 2008. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

(Jallal, 2016), Jallal, C. *The Value of the Jones Act Fleet: $4.6 Billion*, Maritime Executive, March 21, 2016, http://maritime-executive.com/editorials/the-value-of-the-jones-act-fleet-46-billion.

(Jayaram, 2009) *Effect of Selective Catalytic Reduction Unit on Emissions from an Auxiliary Engine on an Ocean-Going Vessel*, Jayaram, V., et. al, University of California - Riverside College of Engineering-Center for Environmental Research and Technology, Final Report prepared for California Air Resources Board, April 2009.

(Johnson, 2013) Johnson, K., et. al, *Black Carbon Emissions from an Ocean Going Vessel Equipped with a Scrubber*, University of California, Riverside - College of Engineering-Center for Environmental Research and Technology, Final Report prepared for California Air Resources Board, December, 2013, https://www.arb.ca.gov/ports/marinevess/documents/emissiontest/bc_scrubber.pdf

(Joregensen, 2012) Joregensen, R., *Slow Steaming – the Full Story,* A.P. Moller-Maersk Group, Printed 2012.

(Juliussen, 2011) Juliussen, L., et al., *MAN B&W ME-GI Engines - Recent Research and Results*, Proceedings of the International Symposium of Marine Engineering, MAN Diesel &Turbo, October 17-21, 2011.

(Kantharia, 2017), Kantharia, R., *How Air Lubrication System for Ships Works?* Marine Insight, https://www.marineinsight.com/green-shipping/how-air-lubrication-system-for-ships-work. January 13, 2017.

(Kristenen, 2012) Kristensen, H.O., *Energy Demand and Exhaust Gas Emissions of Marine Engines*, Technical University of Denmark, September, 2012.

(Kristenen, 2015) Kristensen, H.O., *Energy Demand and Exhaust Gas Emissions of Marine Engines*, Technical University of Denmark, September, 2015.

(Kyrtatos, 2012) Kyrtatos, N. *HERCULES A-B-C, A 10-Year, EC funded Major R&D Effort Towards the Next Generation Large Marine Diesel Engine*, HERCULES Project, Published 2012.

(Lloyd's Register, 2008), *Container Ship Speed Matters*, Lloyd's Register Marine Services, September 2008.

(LNG World News, 2015) *DNV GL to class China's first LNG-ready containership,* LNG World News, December 2015, http://www.lngworldnews.com/dnv-gl-to-class-chinas-first-lng-ready-containership/

(LNG World News, 2018) *Hyundai Mipo delivers world's first LNG-fuelled bulk carrier to Ilshin*, LNG World News, February 21, 2018, https://www.lngworldnews.com/hyundai-mipo-delivers-worlds-first-lng-fuelled-bulk-carrier-to-ilshin/

(Lövblad, 2006) Lövblad, G. and Fridell, E., *Experiences from use of some techniques to reduce emissions from* ship, May 8, 2006, http://www.profu.se/pdf/experiences

(Maersk, 2009) *Efficiency Optimization - Brief Summary of the A.P. Møller-Mærsk Energy Efficiency Initiatives*, Presentation by Ole Graa Jakobsen, Senior General Manager Head of Machinery Section, Ship Engineering – Maersk Maritime Technology, September 18, 2009. http://www.ship-efficiency.org/onTEAM/pdf/AP_Moller_Maersk.pdf

(Maio, 2014) Maio, P., *Ports to power a new kind of cleaning crew*, Orange County Register, April 21, 2014, http://www.ocregister.com/articles/long-610755-garcia-beach.html

(Marine Log, 2013a) *MAN PrimeServ retrofits 20,000th slide fuel-valve,* Marine Log, June 7, 2013, http://www.marinelog.com/index.php?option=com_k2&view=item&id=4165:man-primeserv-retrofits-20000th-slide-fuel-valve&Itemid=227, Accessed January 2017.

(Marine Log, 2013b) *Turbocharger retrofit yields slow steaming fuel savings*, October 2, 2013, http://www.marinelog.com/index.php?option=com_k2&view=item&id=5269:turbocharger-retrofit-yields-slow-steaming-fuel-savings&Itemid=231

(Marine Log, 2014) *More Shipowners opt for exhaust gas scrubbers*, MarineLog.com, March 31, 2014, http://www.marinelog.com/index.php?option=com_k2&view=item&id=6467:more-shipowners-opt-for-exhaust-gas-scrubbers&Itemid=227,

(Marine Log, 2015), *Concept LNG fueled mega box ship would be COGAS electric*, MarineLog.com, October 28, 2015, Accessed January 30, 2017, http://www.marinelog.com/index.php?option=com_k2&view=item&id=9974:concept-lng-fueled-mega-box-ship-would-be-cogas-electric&Itemid=230

(Matson, 2015) *Matson Begins Production on New "Aloha Class" Ships for Hawaii,* Matson Shipping, October, 2015, http://investor.matson.com/releasedetail.cfm?ReleaseID=934776

(MDT, 2006) Presentation at *Faster Freight Cleaner Air* Conference, MAN B&W Diesel Research & Development, Long Beach, CA, January 30, 2006.
(MDT, 2009) *Improved Efficiency and Reduced* CO_2, MAN Diesel & Turbo, May 2009. http://marine.man.eu/docs/librariesprovider6/technical-papers/5510-0068-01ppr_low12553af0bf5969569b45ff0400499204.pdf?sfvrsn=8

(MDT, 2010) *How to Influence* CO_2, MAN Diesel & Turbo, Released 2010, http://marine.man.eu/docs/librariesprovider6/technical-papers/how-to-influence-co2.pdf?sfvrsn=18

(MDT, 2011a). *Common Rail Medium Speed Diesel Engines-Less Consumption, Less Soot and Less NO,* Product Brochure. MAN Diesel & Turbo, Released 2011.

(MDT, 2011b), *Alpha Lubricator, PrimeServ Retrofitting,* MAN Diesel & Turbo - PrimeServ Copenhagen, June 2011, http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/alpha-lubricator.pdf?sfvrsn=6

(MDT, 2012a), *ME-GI Dual Fuel MAN B&W Engines, A Technical, Operational, and Cost-Effective Solutions for Ships Fueled by Gas,* MAN Diesel &Turbo, March 2012, http://marine.man.eu/docs/librariesprovider6/technical-papers/me-gi-dual-fuel-man-b-amp-w-engines433833f0bf5969569b45ff0400499204.pdf?sfvrsn=18

(MDT, 2012b) *Costs and Benefits of LNG as Ship Fuel for Container Vessels*, MAN Diesel & Turbo, May 2012, http://marine.man.eu/docs/librariesprovider6/technical-papers/costs-and-benefits-of-lng.pdf?sfvrsn=10

(MDT, 2012c) *Tier III Two-Stroke Technology*, MAN Diesel & Turbo, August 2012, http://marine.man.eu/two-stroke/low-speed-technology

(MDT, 2012d) *Alpha Lubricator Upgrade – Slow Steaming Kit*, MAN Diesel &Turbo - PrimeServ Copenhagen, May, 2012, http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/alpha-lubricator-upgrade.pdf?sfvrsn=10

(MDT, 2012e) *Waste Heat Recovery System for Reduction of Fuel Consumption, Emissions, and EEDI*, MAN Diesel & Turbo, 2012, http://marine.man.eu/docs/librariesprovider6/technical-papers/waste-heat-recovery-system.pdf?sfvrsn=10

(MDT, 2013a) *Two-stroke Marine Engines - Emission Project Guide*, MAN Diesel & Turbo - B&W, 2013, http://marine.man.eu/two-stroke/project-guides

(MDT, 2013b) , *Derating, Change of Engine SMCR*, MAN Diesel & Turbo, PrimeServ Copenhagen, January 2013, http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/de-rating.pdf?sfvrsn=2

(MDT, 2014a) , *Marine Engine, IMO Tier II, Programme 2nd Edition 2014,* September, 2014, MAN Diesel &Turbo, http://marine.man.eu/docs/librariesprovider6/marine-engine-programmes/marine-engine-programme-2015.pdf?sfvrsn=6

(MDT, 2014b) *Slide Fuel-Valves Pass Noteworthy Milestone*, MAN Diesel & Turbo, June 7, 2013, http://dieselturbo.man.eu/press-media/news-overview/details/2014/06/05/Slide-Fuel-Valves-Pass-Noteworthy-Milestone, (MDT, 2014c) *Slide Fuel Valve - Retrofit Solution*, MAN Diesel & Turbo – PrimeServ Copenhagen 2014, http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/slide-fuel-valve.pdf?sfvrsn=2

(MDT, 2014d) *New Generation of Turbochargers Announced*, MAN Diesel & Turbo, September 15, 2014, http://dieselturbo.man.eu/press-media/news-overview/details/2014/09/15/New-Generation-of-Turbochargers-Announced, Additional details accessible at http://www.marinelink.com/news/turbochargers-generation377175, (Accessed January 2017).

(MDT, 2014e) MAN Turbocharger Homepage, Man Diesel & Turbo. http://www.corporate.man.eu/en/products-and-services/power-engineering/turbocharger/Turbocharger.html

(MEPC, 2014) *Consideration and Adoption of Amendments to Mandatory Instruments, Revisions to the NOx Technical Code with respect to the use of dual-fuel engines as a Tier III NOx control Strategy,* Marine Environment Protection Committee MEPC 67/7/6, International Maritime Organization, August 8, 2014.

(Miller, 2012) Miller, J.W., et.al, *In-Use Emissions Test Program at VSR Speeds for Oceangoing Container Ship,* University of California, Riverside - College of Engineering-Center for Environmental Research and Technology, Final Report prepared for California Air Resources Board, June 2012, https://www.arb.ca.gov/ports/marinevess/vsr/docs/vsr.pdf

(MOL, 2012) *World's First Hybrid Car Carrier Emerald Ace Completed*, Mitsui O.S.K. Lines, June 29, 2012, http://www.mol.co.jp/en/pr/2012/12035.html, Accessed September 22, 2014.

(Moore, 2016) Moore, R. *PERFECt LNG-fueled box ship moves into second phase*, LNG World Shipping News, November 21, 2016, http://www.lngworldshipping.com/news/view,perfect-lngfuelled-box-ship-moves-into-second-phase_45510.htm, Accessed January 30, 2017.

(Motorship, 2011) *Ultra low-speed engines for VLCCs make economic sense*, Motorship.com, April 29, 2011, http://www.motorship.com/news101/engines-and-propulsion/ultra-low-speed-engines-for-vlccs-make-economic-sense

(Motorship, 2016), *Early progress for fuel cell demonstrators*, Motorship.com http://www.motorship.com/news101/fuels-and-oils/early-progress-for-fuel-cell-demonstrators, September 2016

(Navigator, 2016) *Finnish Battery-powered Ferry Due for 2017 Delivery*, Navigator News, September 2016, http://navigatormagazine.fi/finnish-battery-powered-ferry-due-for-2017-delivery/

(Northstar, 2016) *JAX LNG Executes Engineering Contracts to Begin Construction of Jacksonville LNG Facility*, Northstar Midstream, October 11, 2016, http://northstarmidstream.com/news/jax-lng-executes-engineering-contracts/

(NYK, 2012) *Air-lubrication System on Two Module Carriers Reduces CO_2 Emissions by 6 percent,* NYK Line Press Release, Accessed September 25, 2014, http://www.nyk.com/english/release/1964/NE_120711.html

(NYK Line, 2016) *World's First LNG-fueled Pure Car and Truck Carrier (PCTC) Delivered,* NYK Line September 30, 2016, *http://www.nyk.com/english/release/4208/004443.html*

(Parsons, 2009), Parsons, S., *World's First Cargo Ship Propelled by Solar Panels,* July 6, 2009, Accessed September 22, 2014, http://inhabitat.com/auriga-leader-cargo-ship-gets-power-from-solar-panels

(PennEnergy, 2016) *Carnival signs agreement with Shell to fuel world's first LNG-powered cruise ships*, PennEnergy, October 2016 http://www.pennenergy.com/articles/pennenergy/2016/10/carnival-signs-agreement-with-shell-to- fuel-world-s-first-lng-powered-cruise-ships.html

(POLA, 2014) *Ports of Los Angeles and Shanghai launch 'Ecopartnership'*, Port of Los Angeles, July 10, 2014, https://www.portoflosangeles.org/newsroom/2014_releases/news_071014_ecopartnership.asp

(POLA, 2016b), *Vessel Speed Reduction Program Operator Summary Report,* Port of Los Angeles, 2016, https://www.portoflosangeles.org/compliance/2016_VSR_Counts_POLA.pdf

(POLB, 2009) *Port and BP Dedicate Plug-In Power for Clean Air*, Press Release, Port of Long Beach, June 3, 2009, http://www.polb.com/news/displaynews.asp?NewsID=560

(POLB, 2016b) *Participate in the Green Flag Program – Reduce Your Dockage Rates and Help the Environment,* Fact Sheet, Green Flag Incentive Program, Port of Long Beach, 2016, http://www.polb.com/civica/filebank/blobdload.asp?BlobID=6963

(POLB, 2018) *Green Flag Program – Operator Compliance Report 1/1/2017 - 12/31/*2017, Green Flag Incentive Program, Port of Long Beach, March 7, 2018, http://www.polb.com/civica/filebank/blobdload.asp?BlobID=14364

(Pospiech, 2014), Pospiech, P.*, Is Internal Combustion Engine Methane Slip Harmful to the Environment?*, Maritime Reporter & Engineering News, pg.32, April 2014.

(Pratt, 2013) Pratt, J.W. and Harris, A.P., *Vessel Cold-Ironing Using a Barge Mounted PEM Fuel Cell: Project Scoping and Feasibility*., Sandia National Laboratories, February 2013, https://energy.gov/sites/prod/files/2014/03/f12/sand2013-0501_barge_mounted_pemfc.pdf

(Pratt, 2016), Pratt, J.W. and Klebanoff, L.E., *Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry*, Sandia National Laboratories, September 2016, https://www.marad.dot.gov/wp-content/uploads/pdf/SF-BREEZE-Ferry-Feasibility-Study-Report-by-Sandia-National-Laboratory-2.pdf

(RCL, 2016) *RCL announces two new ships powered by LNG and fuel cell,* Royal Caribbean Cruises LTD., October 2016, http://www.rclcorporate.com/rcl-announces-two-new-ships-powered-by-lng-and-fuel-cells/

(Reuters, 2010) *Shipping faces turbulent ride on carbon cutting quest*, Reuters, May 18, 2010, Accessed September 25, 2014. http://news.cnet.com/8301-11128_3-20005347-54.html

(Reuters, 2013) *Analysis – In U.S., natgas struggles as a transport fuel despite low cost*, Reuters, December 13, 2013, http://in.reuters.com/article/usa-natgas-transport-idINL1N0JQ1DN20131213.

(Rolle, 2011) Rolle, S. and Wiesmann, A., *Combustion Control and Monitoring of two-stroke engines*, Wärtsilä Technical Journal, February, 2011, http://cdn.wartsila.com/docs/default-source/Service-catalogue-files/Engine-Services---2-stroke/combustion-control-and-monitoring-of-two-stroke-engines114e7e4a7f0f601bb10cff00002d2314.pdf?sfvrsn=4

(Royal Belgian Institute, 2008) *From the Front Lines - Slide Valves: Small Things that Mean a Lot*, Royal Belgian Institute of Marine Engineers, Fall 2008. http://www.gallois.be/ggmagazine_2009/gg_04_07_2009_166.pdf

(Royal Belgian Institute, 2013), *EGR application to meet future emissions requirements*, Royal Belgian Institute of Marine Engineers, January 2013, http://www.gallois.be/ggmagazine_2013/gg_01_01_2013_26.pdf.

(SBCAPCD, 2014), *Vessel Speed Reduction Incentive Trial Program Factsheet*. Santa Barbara County Air Pollution Control District, 2014, http://www.sbcapcd.org/itg/VSR-Trial-Factsheet.pdf.

(SBCAPCD, 2015), *Report on the 2014 Vessel Speed Reduction Incentive Trial in the Santa Barbara Channel Factsheet,* Santa Barbara County Air Pollution Control District, March 2015 (Revised April 2016), https://www.ourair.org/wp-content/uploads/Brochure-VSR-Executive-Summary-revApril2016.pdf

(SBCAPCD, 2017), *Ten Companies Slowed Ships in Santa Barbara Channel Region 2016 Program to Protect Blue Whales and Blue Skies - Program Cuts Over 27 Tons of*

Smog-Forming Emissions, Press Release, Santa Barbara County Air Pollution Control District, January 23, 2017, https://www.ourair.org/012317-news/

(SBCAPCD, 2018), *Eleven global shipping companies slowed transits in 2017 program to protect blue whales and blue skies*, Press Release, Santa Barbara Air Pollution Control District, March 1, 2018. . https://www.ourair.org/wp-content/uploads/030118newsrel-VSR.pdf

(Schmid, 2004): Schmid, H., *Less Emissions Through Waste Heat Recovery,* Wärtsilä Corporation, April 2004.

(Schuler, 2017) Schuler, M. *Maersk Tanker to Be Fitted with Flettner Rotor Sails,* gCaptain, March 14, 2017, http://gcaptain.com/maersk-tanker-fitted-flettner-rotor-sails/

(Schuler, 2018a), Schuler, M. *TOTE Maritime Completes 'Phase 1' of Orca-class LNG Conversions*, gCaptain, February 26, 2018, http://gcaptain.com/tote-maritime-completes-phase-1-of-orca-class-lng-conversions/

(Schuler, 2018b), Schuler, M. *Carnival Returns to Meyer Werft for Third LNG-Powered Cruise Ship for AIDA*, gCaptain, February 27, 2018 *http://gcaptain.com/carnival-returns-to-meyer-werft-for-third-lng-powered-cruise-ship-for-aida/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+Gcaptain+%28gCaptain.com%29&goal=0_f50174ef03-5ab653e9c9-139827965&mc_cid=5ab653e9c9&mc_eid=4bc5f2004f*

(SEA-LNG, 2018), *LNG Bunkering in the Port of Jacksonville*, JAX LNG http://jaxlng.com/lng-bunkering-in-the-port-of-jacksonville/, Accessed March 19, 2018

(Ship & Bunker, 2016a) *First North American LNG Bunkering Terminal Opens*, Ship & Bunker News and Intelligence for the Marine Fuels Industry, February 16, 2016, http://shipandbunker.com/news/am/843978-first-north-american-lng-bunkering-terminal-opens

(Ship Efficiency Review, 2016) *World's Largest LNG-Powered Bulk Carrier Ordered,* Ship Efficiency Review, July 28, 2016, http://www.shipefficiencyreview.com/worlds-largest-lng-powered-bulk-carrier-ordered/

(SkySails, 2014) Email communication from Alex Spataru, ADEPT Group, Inc. September 29, 2014.

(SOCP, 2011) *Exhaust Gas Cleaning Systems Selection Guide*, Page 28. Prepared by The Glosten Associates for Ship Operations Cooperative Program, February 22, 2011, http://www.procal.com/docs/Exhaust_Gas_Cleaning_Systems_Guide.pdf

(SPBP, 2012). *San Pedro Bay Ports Clean Air Action Plan Guide to OGV Emission Control Strategies.* Port of Los Angeles, Port of Long Beach, January 2012.

(Spilman, 2013) Spilman, R, *Container Ship Nose Jobs – Maersk Retrofits Bulbous Bows for Slow Steaming,* Oldsaltblog.com, March 17, 2013, http://www.oldsaltblog.com/2013/03/container-ship-nose-jobs-maersk-retrofits-bulbous-bows-for-slow-steaming

(Starcrest, 2013) *MAN Slide Valve Low Load Emissions Test Final Report*, Starcrest Consulting Group, Mitsui Engineering & Shipbuilding Co., LTD, and MAN Diesel & Turbo A/S, Prepared for The Port of Long Beach and the Port of Los Angeles, June, 2013, http://www.cleanairactionplan.org/documents/man-slide-valve-low-load-emissions-test.pdf

(TAP, 2012) *OGV Slide Valve Low-Load Emissions Evaluation,* Section 2.1.1*,* Pg. 9, Chapter 2.1 - *Ocean-Going Vessels (OGVs),* San Pedro Bay Ports Clean Air Action Plan Technology Advancement Program, http://www.cleanairactionplan.org/documents/2012-tap-annual-report.pdf

(Transport Canada, 2014) *Liquefied Natural Gas: A Marine Fuel for Canada's West Coast,* Condensed version of Transport Canada's report, TP 15248 E - *Canadian Marine Liquefied Natural Gas (LNG) Supply Chain Project, Phase 1 – West Coast*, April 2014, http://www.cngva.org/media/35832/04-2014_-_liquefied_natural_gas_-_a_marine_fuel_for_canada_s_west_coast__en_.pdf

(Trauthwein, 2016) Trauthwein, G., *NYK Steams Ahead,* Marine Link, October 2016, http://www.marinelink.com/news/steams-ahead-nyk416335

(Tregurtha, 2015), Tregurtha, L. *The MARAD Gives Over $1M to Technology Forerunners,* The Maritime Executive, October 2015, http://www.maritime-executive.com/article/marad-gives-over-1m-to-technology-forerunners.

(USS-POSCO, undated) *UPI Culture*, USS POSCO webpage, http://www.ussposco.com/culture.php, Accessed June 2017

(Vankeirsbilck, 2011) Vankeirsbilck, I., Vanslambrouck, B., Gusev, S., & De Paepe, M., *Organic Rankine Cycle As Efficient Alternative To Steam Cycle For Small Scale Power Generation*, Presented at 8th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, 2011

(Vesterager, 2013) Vesterager, J., *MAN shipping consultancy pays off in orders*, Shipping Watch, July 22, 2013, http://shippingwatch.com/suppliers/article5742592.ece

(Wärtsilä, 2004) *Less Emissions Through Waste Heat Recovery,* Wärtsilä, http://marineengineering.co.za/technical-information/waste-heat-recovery.pdf, April 2004.

(Wärtsilä, 2007a) *Wärtsilä Common Rail, A Super-Efficient Fuel Injection System*, Wärtsilä Technical Journal, Wärtsilä Coorporation, February, 2007.

(Wärtsilä, 2007b) *SOx Scrubbing of Marine Exhaust Gases*, February, 2007.

(Wärtsilä, 2008) *Derating: a solution for high fuel savings and lower emissions*, Wärtsilä Coorporation, June, 2008.

(Wärtsilä, 2012a) *Why dual fuel is the best answer for gas-fueled ships*, Wärtsilä Corporation, May 23, 2012.

(Wärtsilä, 2012b) *Dual Fuel Engines – Wärtsilä 20DF, Wärtsilä 34DF and Wärtsilä 50 DF*, Wärtsilä Corporation, 2012, http://cdn.wartsila.com/docs/default-source/product-files/engines/df-engine/brochure-o-e-df-engines-2015.pdf?sfvrsn=6

(Wärtsilä, 2013) *Twice as Good, Dual-Fuel Two-Stroke*, Wärtsilä Corporation, April, 2013.

(Wärtsilä, 2014) *Retrofit Pulse Lubricating System*, Wärtsilä Services and Support, 2014, http://cdn.wartsila.com/docs/default-source/Service-catalogue-files/Engine-Services---2-stroke/retrofit-pulse-lubricating-system-rta-rt-flex.pdf?sfvrsn=2

(Wärtsilä, 2015) *First Wärtsilä two-stroke engine with Tier III compliant high pressure SCR produced in China introduced,* Press Release, Wärtsilä, March 16, 2015, http://www.wartsila.com/media/news/16-03-2015-first-wartsila-two-stroke-engine-with-tier-iii-compliant-high-pressure-scr-produced-in-china-introduced, Accessed June 2017

(White, 2010) White, R. *Ocean shipping lines cut speed to save fuel costs*, Los Angeles Times, July 31, 2010, http://articles.latimes.com/2010/jul/31/business/la-fi-slow-sailing-20100731.

(WPCI, 2016) World Ports Climate Initiative, *LNG Fueled Vessels,* 2016. http://www.lngbunkering.org/lng/environment/benefits-of-LNG, Accessed October 2016.

(Würsig, 2015) Würsig, G.M., Adams, S.D., *Power without pistons: GTT, CMA CGM and DNV GL present LNG-fueled, turbine-powered mega box ship study*, DNV-GL, October 28, 2015, https://www.dnvgl.com/news/power-without-pistons-gtt-cma-cgm-and-dnv-gl-present-lng-fuelled-turbine-powered-mega-box-ship-study-45289. Accessed January 30, 2017.

APPENDIX A:

Assumptions Used in Well to Propeller Greenhouse Gas Emissions Estimates

Fuel Production and Distribution Assumptions:

- Fuel Carbon intensities based on April 2015 proposed updates to CARB's Low Carbon Fuel Standard, with methane leakage rate of 1.15 percent.
- North American NG to LNG, CH_4 leakage rate of 1.15 percent (LCFS April 3, 2015 workshop http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040315presentation.pdf).

Vessel Assumptions:

Containership Power and Speed

Typical Containership	Power (kW)	Load Factor	Cruising Power (kW)
Main Engine Power (kW)	40,000	0.8	32,000
Auxiliary Engine Power (kW)	8,000	0.13	1,040
Cruising Speed (knots)	20	-	-

**Note: Estimates based on 2008 Ocean-Going Vessel Fuel Staff Report, Appendix D, with rounding.*

Engine Efficiency Estimates:

Estimated OGV New Engine Efficiency (g/kW-hr)

Typical Engines	2012 (Baseline) Diesel Vessel	2016 Diesel Vessel	2016 Dual-Fuel LNG Vessel in Gas Mode
Slow-speed two-stroke main engine - transiting	177	170	136
Medium Speed four-stroke Auxiliary engine	192	185	154

**Note: 2016 diesel and LNG fuel consumption estimates based on current product literature from engine manufacturers MAN Diesel and Wärtsilä. 2012 fuel consumption estimates increased by four percent (one percent per year) from 2016. Note that 2025 vessel emissions estimates use 2016 fuel efficiency figures since it is difficult to project out to 2025.*

Engine Emission Factors:

Estimated OGV New Main Engine GHG Emission Factors (g/kW-hr)

Slow-speed two-stroke Main-Transiting	2012 (Baseline) Diesel Vessel	2016 Diesel Vessel	2016 LNG Vessel
CO_2	588	577	446
CH_4	-	-	0.2
GHG (CO_2E)	588	577	451

**Note: 2012 CO_2 emission factor estimated from 2008 OGV Fuel Staff Report App. D, assuming the use of distillate fuel. 2016 diesel and LNG CO_2 emission factors based on test data from MAN Diesel, per August 1, 2014 email communication with CARB staff. LNG CO_2 emission factor based on slow-speed, diesel-cycle (high pressure) dual-fuel engine operating in gas mode, since MAN Diesel manufactures this type of LNG dual-fuel engine and MAN Diesel makes the majority of propulsion engines in large OGVs. Methane emissions factor based on Juliussen, Lars, et al., Proceedings of the International Symposium of Marine Engineering. "MAN B&W ME-GI Engines. Recent Research and Results." October 17-21, 2011.*

Estimated OGV New Auxiliary Engine GHG Emission Factors (g/kW-hr)

Medium Speed four-stroke Auxiliary Engine	2012 (Baseline) Diesel Vessel	2016 Diesel Vessel	2016 LNG Vessel
CO_2	645	633	506
CH_4	-	-	6
GHG(CO_2E)	645	633	656

**Note: 2012 CO_2 emission factor estimated from 2008 OGV Fuel Staff Report App. D, assuming the use of distillate fuel. 2016 diesel CO_2 emission factors based on 2012 emfac adjusted using ratio of 2016 to 2012 main engine CO_2 emissions. 2016 LNG CO_2 emission factor estimated at 80 percent of the diesel CO_2 emfac based on lower carbon content of natural gas compared to diesel fuel. LNG emission factor based on medium speed Otto-cycle (low pressure) dual-fuel engine operating in gas mode, since virtually all of the auxiliary engines are Otto-cycle. Methane emissions factor based on Juliussen, Lars, et al., Proceedings of the International Symposium of Marine Engineering. "MAN B&W ME-GI Engines. Recent Research and Results." October 17-21, 2011.*