Ocean-going Vessels
Technology Assessment

September 9, 2014

Diamond Bar, California

California Environmental Protection Agency

Air Resources Board

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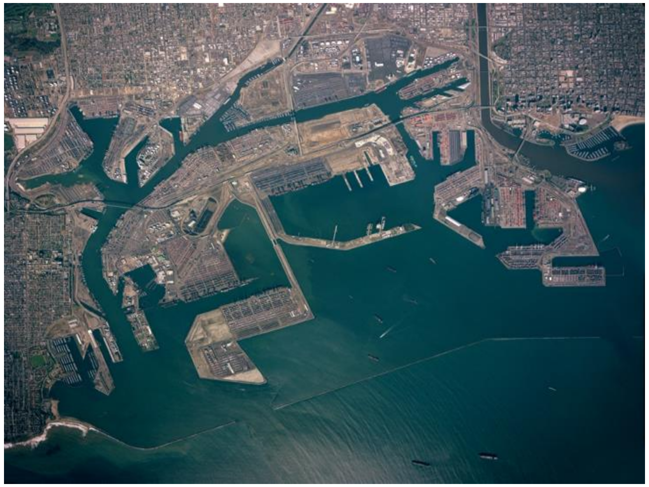
Background
Ocean-going Vessels (OGVs)

- Large vessels designed for deep water navigation

- Travel internationally
- 16 California maritime ports
  - Over 9,000 ship visits per year

Emissions from OGVs Impact Public Health and Air Quality

- PM, NOx, and SOx emissions
- Emissions concentrated near population centers
- Localized & regional impacts
- Contributes to:
  - Cancer risk & PM mortality
  - Ambient levels & other GHGs



Adopted Regulatory Programs

- International (IMO)
  - Annex VI new engine NOx standards & fuel sulfur limits
  - Provision for Emission Control Areas (ECAs)
  - Vessel Efficiency Requirements
- Federal Regulations
  - North American ECA
  - New engine NOx standards that mirror IMO Requirements
- California Regulations
  - Vessel Low Sulfur Fuel Rule
  - At-Berth (Shore-side) Power Rule

Summary of Regulatory Limits NOx Standards

IMO Annex VI New Engine NOx Limits in grams/kW-hr (g/hp-hr)[1]				
Date	Tier	$n<130$	$130 \leq n < 2000$	$n \geq 2000$
2000[2]	I	17 (12.7)	$45 * n^{-0.2}$	9.8 (7.3)
2011	II	14.4 (10.7)	$44 * n^{-0.23}$	7.7 (5.7)
2016[3]	III	3.4 (2.5)	$9 * n^{-0.2}$	1.96 (1.5)

1. Standards based on engine speed, "n." $N<130$ includes most main engines. $N<2000$ includes most auxiliary engines.
2. Tier I standards become applicable to existing engines installed on ships built between January 1, 1990 to December 31, 1999, with a displacement $\geq$ 90 liters per cylinder and rated output $\geq$ 5000 kW, subject to availability of approved engine upgrade kit.
3. Tier III applies in NOx ECAs, Tier II applies outside ECAs.

Summary of Regulatory Limits Fuel Sulfur Content

Fuel Sulfur Limits (% by weight)		
Date	California (24 nm)[1]	Federal ECA (200 nm)
August 2012		
January 2014	0.1% Sulfur Distillate[4]	

1. Applies within 24 nm of the California shoreline, including islands.
2. Marine gas oil up to 1.5% sulfur, or marine diesel oil up to 1%.
3. Fuel does not have to be distillate grades.
4. Marine gas oil or marine diesel oil up to 0.1% sulfur. Exemptions available for nondistillate fuels meeting 0.1% sulfur.

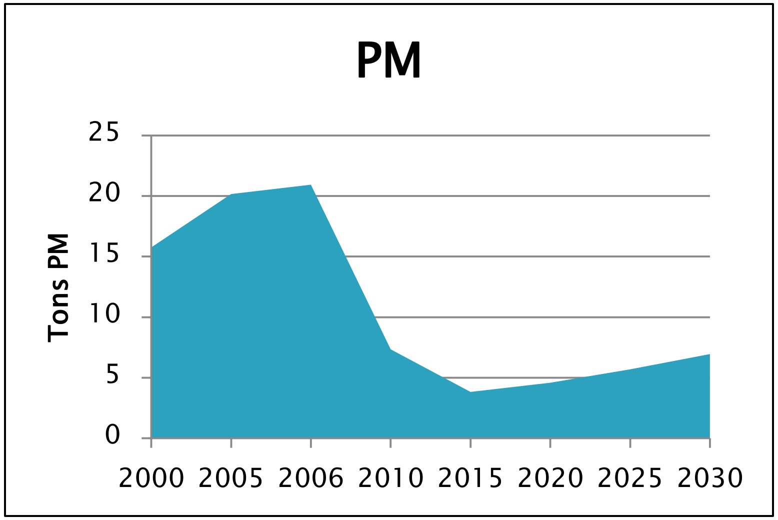
Voluntary/Incentive/Ports Programs

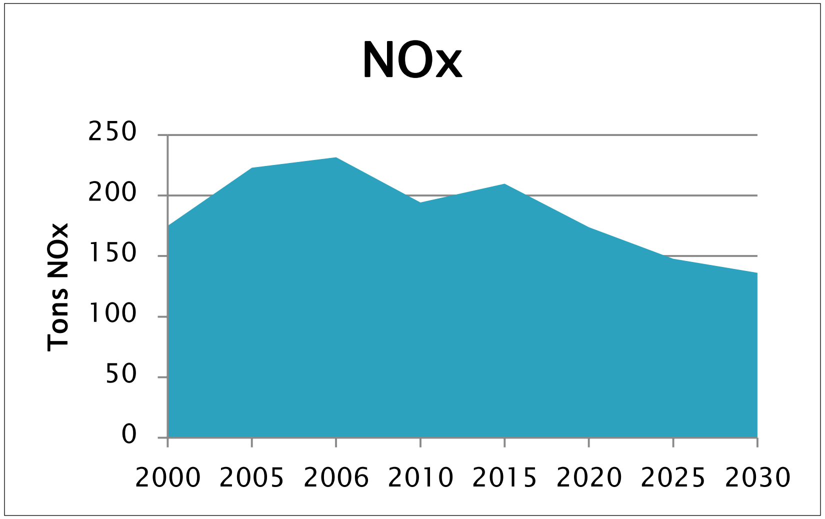
- Vessel Speed Reduction Program
- Port Clean Air Plans/Programs
- Incentive programs for cleaner equipment
  - Prop 1B, Carl Moyer
- State/Local district funded demonstration projects

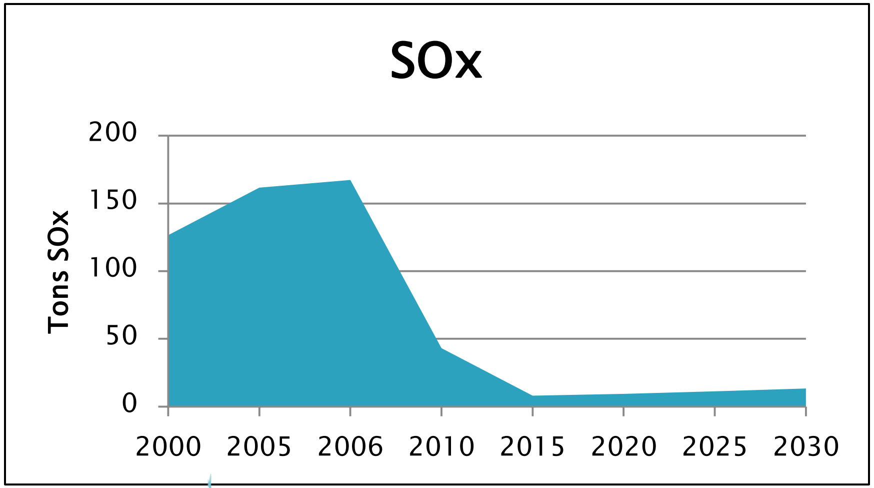
Existing Programs Effective in Reducing Emissions

- Significant PM and SOx reductions due to California Clean Fuel Regulation
- Moderate NOx reductions from new engine standards
  - Slow vessel turnover & inability to retrofit existing vessels result in slow penetration of lower NOx engines

Statewide OGV Emission Trends 2000-2030







Types of OGVs

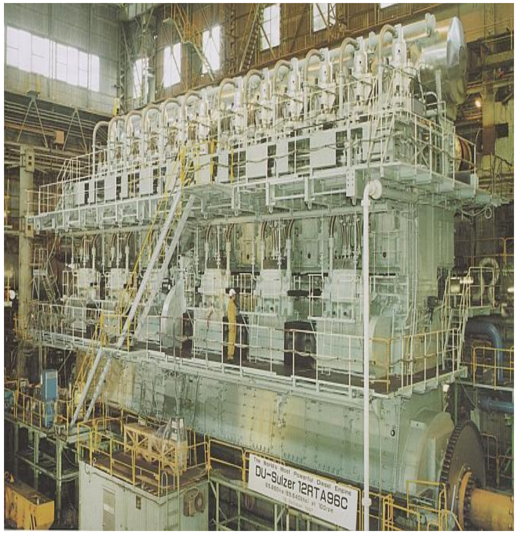
- Auto Carriers
- Bulk Cargo
- Container
- Cruise Ships
- Refers
- Ro-Ros
- Tankers

Engines and Boilers on OGVs

Main Engines

Used for propulsion.

Power up to 80+ MW

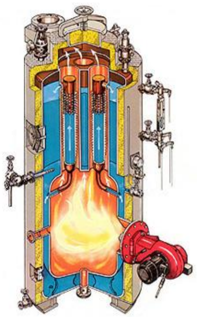


Auxiliary Engines

Used for electricity.
Diesel electric for both propulsion & electricity on cruise ships.
Power <1 to 10+ MW

Boilers

Used for steam, and heating of heavy fuel oil and water. Large boilers used for propulsion on steamships



Challenges

- International Fleet
  - Most visitors are foreign-flagged
  - Many one-time visitors, vessel routes change frequently
- Costly asset with slow vessel turnover
- Subject to international/national/state/local regulations
- Fuel is largest operating expense
- Unique safety concerns

Alternative Fuels

Alternative Fuels

- Potential Alternative Fuels
  - Natural Gas (CNG, LNG)
  - Biodiesel
  - Dimethyl Ether (DME)
  - Methanol
  - Many others
- LNG appears to be most promising option for widespread deployment

Liquefied Natural Gas (LNG)- Technology and Suitability

- Natural gas (mostly methane) cooled/liquefied to minus 160º C (-260º F)
- LNG demonstrated for full range of vessel types and applications
  - Mostly dual-fuel engines to allow for diesel operation
- Lack of bunkering infrastructure biggest obstacle to greater use of LNG

Liquefied Natural Gas-
Cost and Implementation

- Favorable economics in SOx ECA zones
  - Price predicted to be comparable to standard heavy fuel oil
  - LNG tanks are a significant added cost
- Lower emissions compared to diesel engines
  - LNG low sulfur levels result in low SOx emissions
  - NOx emissions can be lower than comparable diesel engines
  - Significantly reduced PM emissions expected, but robust testing data needed to quantify benefits

Liquefied Natural Gas-
Cost and Implementation

- Potential for GHG emission reductions
  - CO_2 engine emissions reduced by ~25%
  - “Methane slip” may be significant with Otto cycle engines, but minimal with diesel cycle engines
- Bunkering infrastructure needed to expand LNG use
- Implementation expected to phase in over many years due to time needed to build bunkering infrastructure and LNG vessels

LNG Readiness and Deployment

- Full spectrum of LNG dual fuel engines available
- About 40 LNG ships in operation worldwide*
- Over 20 new or retrofitted LNG vessels planned between 2015 and 2018** in North America
- California LNG vessel projects

LNG Vessels Planned for Routes including California Ports				
Operator	**Type**	**New or Retrofit**	**Year Planned**	**Route**
Matson	Container	New	2018	Hawaii Trade
Matson	Container	New	2018	Hawaii Trade
Horizon	Container	Conversion	2015	Hawaii Trade
Horizon	Container	Conversion	2016	Hawaii Trade

* DNV GL, not counting LNG carriers ** Zeus Intelligence Services (excludes harbor craft)

Engine Technologies

Advanced Fuel Injection

Technology and Suitability

- Improvements including common rail, electronic controls, slide valves, and advanced orifice design
  - Common rail and electronic controls provide better control of spray pattern at all loads
  - Slide valves prevent “dribbling” of fuel after injection
- Standard feature of new engines for OGVs
  - Many technologies can be retrofitted to older engines

Cost and Implementation

- Many of these technologies are mature
  - Common rail & slide valves available for over a decade
- Economics are case-specific
- Reduces fuel consumption, PM and HC emissions
  - Greater benefits at low loads, reductions vary with technology

Electronically Controlled Cylinder Lubrication Systems

Technology and Suitability

- Minimize consumption by precision electronic control that adjusts for engine operating conditions
  - MAN Diesel “Alpha” & Wärtsilä “Pulse” lubrication systems
- Standard on new slow speed two-stroke engines and retrofit option for older engines

Cost and Implementation

- Retrofits reduce lube oil consumption along with associated cost savings
  - Manufacturer estimates lube consumption and cost reduced by 30-50%; 2 year payback period
- Reduces PM emissions

Automated Engine Monitoring

Technology and Suitability

- Electronic monitoring and control of multiple engine parameters
  - Cylinder pressure, fuel injection timing, exhaust valve timing, lube oil control
  - Standard feature on new slow speed two-stroke engines, retrofit option for older engines

Cost and Implementation

- Cost savings due to reduced fuel and oil consumption, and engine wear
- Emission reductions due to lower fuel/lube use
  - Can operate in Low-NOx mode in special areas

Ultra Slow Speed Engines

Technology and Suitability

- Slower speed (rpm) engines with higher “stroke to bore” ratio reduces fuel consumption & emissions
- Suitable for new build vessels, not retrofit
- Commercially available option for many main engine models

Cost and Implementation

- Economics are case specific
- Significant fuel savings
- Fuel consumption and CO_2 reductions estimated at up to 4%

Engine De-rating

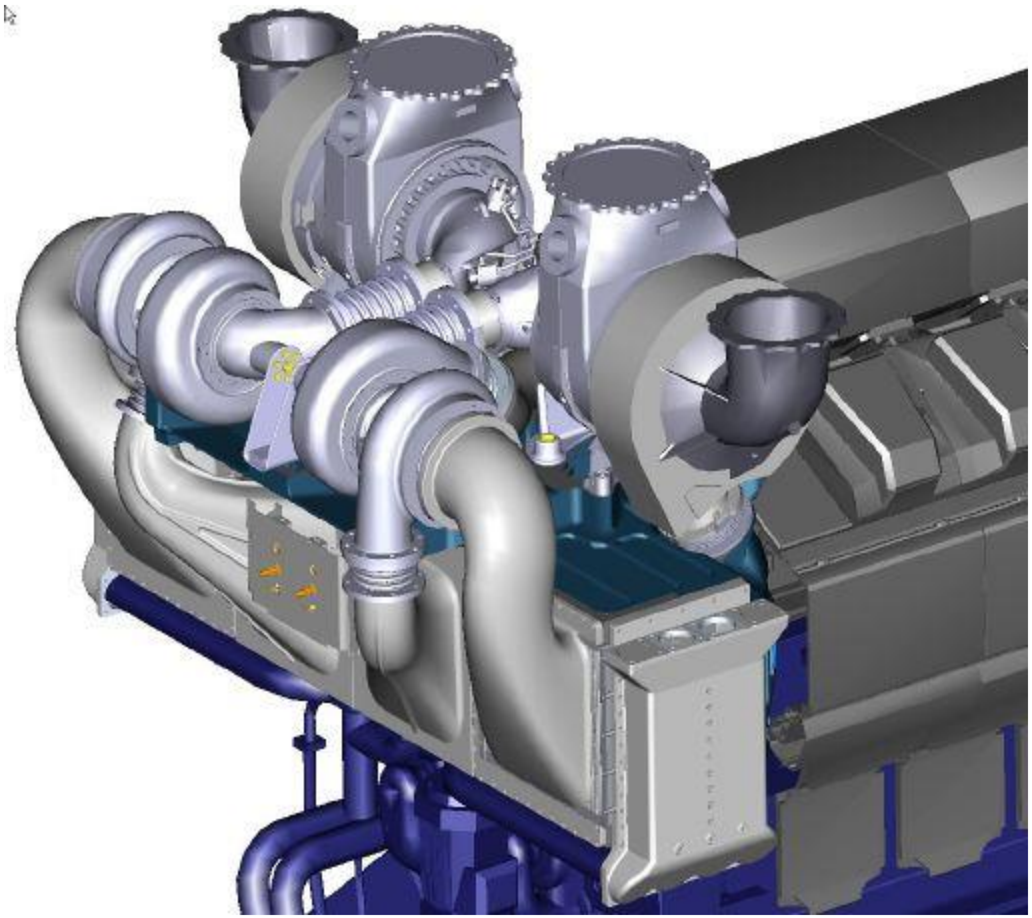
Technology and Suitability

- Modified engine setup (e.g. fuel injection) for greater fuel efficiency/less maximum power output
- Best accomplished at time of purchase
- Retrofit of an existing engine can be accomplished if a de-rated engine has adequate power, but other changes may be needed

Cost and Implementation

- Economics are case-specific
  - Payback periods of 3-7 years with larger de-rated engines with an extra cylinder
- Reductions in fuel consumption and associated CO_2 emissions vary (in some cases 2-3% lower)
- Commercially available for decades

Engine Support Technologies



Exhaust Gas Recirculation-
Technology and Suitability

- Portion of exhaust gas cleaned and rerouted into the combustion chamber via air intake
  - Reduces the formation of NOx
- Suitable for new engines, challenge to retrofit
  - Commercially available on new engines
  - Limited demonstration as retrofit
    - Alexander Maersk

Exhaust Gas Recirculation-
Cost and Implementation

- New vessels - cost ~15% higher for a Tier 3 compared to comparable Tier 2 engine
- EGR may increase fuel consumption and increase PM
- NOx reductions on the order of 65% when combined with engine tuning to meet IMO Tier 3 standard
- Tier 3 requirements will drive market penetration beginning in 2016 for new vessels

Water in Fuel Technologies-
Technology and Suitability

- Water added into combustion process
  - Reduces NOx and PM
- Multiple ways to introduce water
  - Emulsified fuel, in-cylinder water injection, water injection into the intake air
- Suitable for new engines or as retrofit
- Few Demonstrations
  - Lower than expected reductions and system issues
  - Technology not sufficiently mature for marine applications

Water in Fuel Technologies-
Cost and Implementation

- Cost data unavailable
- Emission reductions variable
  - APL demo showed varied results from 6% decrease to a 12% increase in NOx (14-27% water in fuel), depending on engine load and percent water content
- Technology needs to advance from prototype phase to reliable product phase to be viable strategy

Turbocharging-
Technology and Suitability

- Increased pressure of engine intake air, providing more oxygen during combustion, resulting in either:
  - Higher power output with the same fuel consumption or
  - Same power output with reduced fuel consumption and emissions
- Two stage turbocharging with valve timing modifications under development
  - Reduces NOx emissions without reducing fuel consumption or increasing PM emissions
- Suitable for new builds, challenging to retrofit

Turbocharging-
Cost and Implementation

- Cost information not available
- NOx reductions of over 30%
- Up to 4% reduction in fuel consumption
- 15% increase in specific power output
- Implementation dependent on IMO NOx standards, IMO efficiency reduction guidelines or incentive programs

After-Treatment (Exhaust) Controls

Selective Catalytic Reduction-
Technology and Suitability

- Exhaust gas treated with ammonia or urea and fed through a catalyst at high temperature
  - Chemical reaction occurs that breaks down the NOx into nitrogen & water
- Suitable for new engines-main and auxiliary, challenge to retrofit
  - Commercially available on new engines
  - Challenge to retrofit, equipment requires large space
  - Low exhaust temperature in two stroke engines or at low engine load presents challenge
  - May require use of very low sulfur fuel, systems being developed for higher sulfur fuels

Selective Catalytic Reduction- Cost and Implementation

- MAN estimates $95/kW, about $4.4M for average sized container vessel
- Urea/Ammonia consumption costs, increased maintenance and training may be needed to operate SCR
- NOx reductions on the order of 80-95%
- Tier 3 requirements will drive market penetration beginning in 2016 for new vessels only*

*Tier 3 required in 2016 for new vessels only in regions such as US/Canada with an established Emission Control Area (ECA)

Exhaust Gas Scrubbers- Technology and Suitability

- Exhaust gas scrubbers are exhaust aftertreatment equipment that remove SOx and PM from the exhaust
  - Wet scrubbers use fresh or sea water to remove and neutralize the sulfur compounds
  - Closed loop systems do not discharge waste. Open loop systems discharge waste
  - Dry scrubbers use a dry chemical to remove SOx
- Suitable for new engines, main and auxiliary, and can be a retrofit option in many applications
  - Some systems have large space requirements
  - Demonstrations on smaller vessels or on OGV auxiliary engines, very few demonstrations on large OGV propulsion engines. A number of projects in design/build phase to comply with 2015 requirements

Exhaust Gas Scrubbers-
Cost and Implementation

- Cost estimate ~$120/kW
  - $5.5M for an average size container vessel*
- Emissions reductions reported by manufacturers of up to 99% SOx and 80% PM.
- North American ECA** 2015 requirements for 0.1% sulfur fuel will drive market penetration
- Strict requirements covering overboard wastewater discharge may present operational challenges

*Total installed power, main engine 40,400 kW plus 3 1900 kW auxiliary engine
**0.1% S fuel or equivalent required for all OGVs operating in regions such as US/Canada with an established Emission Control Area (ECA)

Shore-side Technologies

Connecting to Shore Power

Technology and Suitability

- Vessel connects to shore-side electricity and turns off auxiliary engines
  - Equipment required on vessel as well as shore
    - Suitable for retrofit & new build; higher cost for retrofit.

Cost and Implementation

- Costs about $0.5 – 2M per vessel, $1 – 7 M per berth
- Local emissions eliminated when using shore power
- Challenges - labor to connect to shore power, shore-side compatibility and availability, and electricity rate structure

Barge Based Emission Controls

Technology and Suitability

- Exhaust is treated through barge based system
  - NOx and PM are treated with SCR and Scrubbers
  - Manufacturers expect reduction efficiency greater than 90%
- Little to no retrofit is required by vessel

Cost and Implementation

- About $10M per system capable of handling a 2 MW load
- Technology has potential to control both auxiliary engine emissions and boiler emissions
- System testing is underway for use with At-Berth Regulation

Alternative Supplemental Power

Fuel Cells

Technology and Suitability

- Fuel cell power pack consists of fuel and gas processing system and a stack of fuel cells that convert the chemical energy of the fuel to electric power through electrochemical reactions
- Possible use as supplemental power system
  - Possible for new builds and possibly retrofit if the space on the vessel is available
- DNV demonstration on Viking Lady with 330 kW fuel cell unit
  - Electric efficiency ranged from 44.5% to 55% with a heat exchanger
    - No detectable NOx, SOx, or PM emissions from fuel cell

Fuel cell type	Temperature (°C)	Electric efficiency (%)
Proton Exchange Membrane (PEM)	30-100	35-40
High Temperature PEM (HT-PEM)	160-200	~45
Molten Carbonate (MCFC)	~650	45-50
Solid Oxide (SOFC)	500-1100	45-50

-DNV Fuel cells for ships 2012

Fuel Cells
Cost and Implementation

- High capital cost of fuel cell system ($3,000+/kW)
- Reduced fuel costs once operational
  - Eliminate SOx, NOx and PM emissions from fuel cell
  - Long term demonstrations needed to prove durability
  - Cost of fuel cell technologies needs to come down before wide adoption
    - DNV estimates a target of $1,500/kW to garner more attention

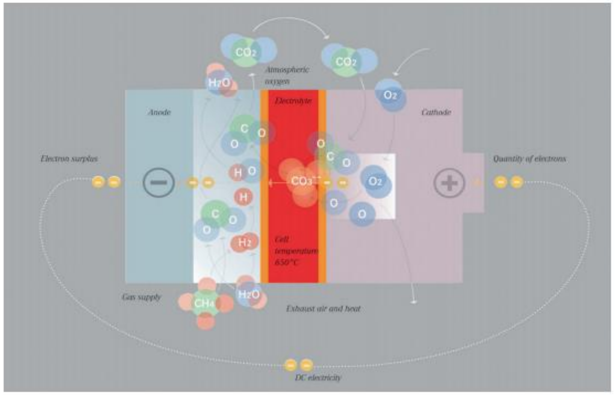


Figure 4: Chemical processes inside an MCFC (courtesy of MTU Onsite Energy)

–DNV Fuel cells for ships 2012

Wind/Sails
Technology and Suitability

- Multiple Types of Wind Applications
  - Kite, Rotors
- Sails can take significant space on deck
  - Possible for new and retrofit if space is available
- Multiple projects are currently in testing phase

Wind/Sails
Cost and Implementation

- SkySail estimated to cost $6.7 million
  - Payoff time of 4-5 years
- Emissions demonstrations ongoing
  - Current emission demonstrations show fuel savings from 5% to about 20% with fuel savings the greatest at higher speeds
- Testing needs to show significant fuel reductions and simple operation to incentivize deployment in vessels
  - Deployment likely limited to vessels that have deck space (ie. tankers)
  - Prevailing wind direction and vessel routing key factor to determine if vessel can take advantage of this technology

Battery Electric and Solar Technology and Suitability

- Solar to supply supplemental power in testing phase
- Solar panels take up significant space on the deck of vessels
- Marine atmosphere can cause corrosion and degradation of panels
- Backup power needed

Battery Electric and Solar
Cost and Implementation

- Cost data unavailable
- Emissions reductions depend on the amount of solar panels installed
  - Testing has shown ~10% of auxiliary power needs reduced
- Demonstrations needed to demonstrate technology is durable and cost effective on vessels

Vessel Efficiency Improvements

Efficient Hull & Propeller Design

Technology and Suitability

- New fuel efficient designs for hulls and propellers
  - Improvements to propeller designs include number of blades, blade pitch, hub design, counter rotating propellers, etc.
  - Improvements to hull design include a bulbous bow, reduction of weight
- Generally new shipbuilding will be the main driver for these technologies, however, some limited retrofits could be possible

Cost and Implementation

- Hull costs 20-30% of new ship costs
- Efficient hull and propeller designs could reduce fuel consumption by 5-30%
- IMO requires 30% increase in efficiency by 2025
  - Hull and propeller design will assist in meeting requirement

Hull Coatings –
Technology and Suitability

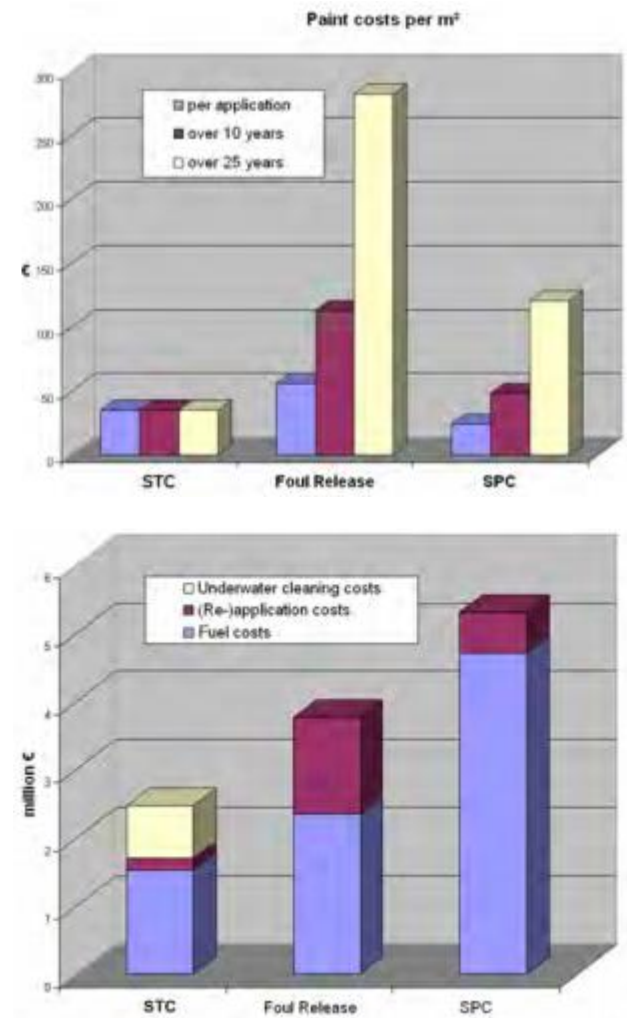
- Modern hull coatings are low-copper or copper free, lead free, tributyl-tin free and come in one of the following categories:
  - ablative antifouling (SPC)
  - foul release (FR)
  - surface treated coatings (STC)
- Reduce marine organism attachment and friction

	Protection and longevity	Fuel saving properties and conditions
Typical AF coating system(SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. 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 2-4% fuel penalty. Usually sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/ reapplication. Full recoating required 1-3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups.
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% or more on fuel compared to AF or FR coating.

–The Hydrex Group

Hull Coatings –
Cost and Implementation

- Applicable to new and existing ships
- $2-$5 million/vessel depending on the type of hull coating deployed
- Up to 10% fuel savings
- IMO requires 30% increase in efficiency by 2025, hull coatings could contribute to this requirement



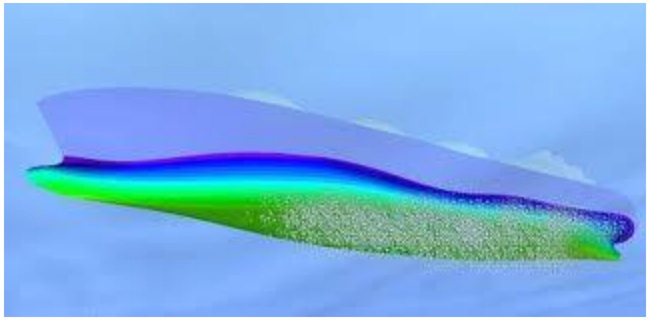
Estimated costs of a 1000-TEU container vessel over 25 years. -The Hydrex Group

Air Lubrication Systems - Technology and Suitability

- Air bubbles injected on the hull of the vessel
  - Reduces fuel usage
- Generally requires new builds with special hull design
  - Retrofit kits being developed
- Products developed and are in testing phase
  - Mitsubishi Air Lubrication System installed on 3 bulk carriers

Air Lubrication Systems-
Cost and Implementation

- Payback ~1-2 years
- Up to 10% reduction fuel usage
- Additional testing and durability testing of the product could create more interest in the shipping community
- IMO requires 30% increase in efficiency by 2025, air lubrication systems could contribute to this requirement



Exhaust Heat Recovery

Technology and Suitability

- Use exhaust heat from main engine to power a steam turbine
- Commercially available
- Available from Aalborg, MAN, Wärtsilä

Cost and Implementation

- ~$10 million cost in new build
  - Payback ~ 3-4 years depending on fuel costs
- Emissions reduced up to 15%
- IMO requires 30% increase in efficiency by 2025, EHR could contribute to this requirement

Voyage Optimization

Technology and Suitability

- Optimization of ships schedule, route, and other shipping parameters for fuel efficiency
- Applicable to all vessels

Cost and Implementation

- Additional time may need to be added on to the voyage to optimize each trip
- 1% to 5% reduction in fuel usage
- Fuel cost savings need to be greater than time lost to incentivize use of these techniques

Vessel Speed Reduction-
Technology and Suitability

- Practice of slowing vessel speeds typically from cruising speeds to 12 knots
  - Potential for reductions of diesel PM, SOx, and NOx
  - Reductions in CO_2 may be offset due to ships increasing speed to make up for lost time
  - Potential benefit to marine mammals
  - Recent speed data shows vessel average of 10 to 14 knots within 40 nautical miles of major California ports

- Suitability for OGVs and operational/infrastructure needs
  - Successful voluntary programs currently exist
  - Some concern over maintenance issues, scheduling, and costs of delivering goods

Vessel Speed Reduction- Cost and Implementation

- Cost/Economics
  - Potential increased costs for onboard labor, crew supplies, maintenance, scheduling changes, and potentially increased fuel costs outside VSR zone
  - Costs for ports voluntary programs or other enforcing agencies include: administrative, vessel monitoring, financial incentives, enforcement

- Emissions reductions, fuel savings, efficiency improvements
  - Slowing from 14 to12 knots can reduce emissions by about 27 percent
  - Maersk slow steaming study showed 22 percent fuel savings

- Deployment challenges:
  - Vessels altering routes outside of shipping lanes
  - Speeding up outside the VSR zone to maintain their schedule which could lead to an overall increase in CO_2 emissions

Enhanced Maintenance

Enhanced Hull & Propeller Cleanings

Technology and Suitability

- Marine organisms attach to vessels, increasing frictional drag which increases fuel consumption
- More frequent hull cleaning can reduce fuel use and associated emissions
- Cleanings can be done at dry dock or in-water

Cost and Implementation

- Dry dock: $65,000 to $1,300,000; in-water: $20,000 to $300,000
- Up to 35% reduction in fuel consumption (Not actual savings but represent a return to baseline emissions from vessel)
- Fuel savings weighted against total cost to clean hull and propeller

Summary

- Numerous technologies available to reduce emissions from new ocean-going vessels
  - Many incorporated into manufacturer new engine programs
  - Others with uncertain benefits or feasibility
- Key technologies to achieve emission reductions in new vessels
  - LNG fueled engines
  - Selective Catalytic Reduction
  - Exhaust heat recovery
  - Advanced hull and propeller design

Hypothetical "Clean Vessel" Reductions*

- Vessel using engines meeting IMO Tier III NOx standard, LNG fuel, & 20% vessel efficiency improvements
  - Reductions from current baseline (Tier II) vessel on low sulfur diesel
    - NOx ↓ 80%
    - PM ↓ 70%
    - SOx ↓ 20+%
    - CO_2 ↓ 40%

* Tank to hull (not full life-cycle) analysis of typical container vessel in transit mode.

Summary (cont'd)

- "In-use" programs may be key for achieving emission reductions from existing fleet
  - Bring cleaner vessels (e.g., Tier III) to California
  - Vessel speed reduction
  - Expand use of shore-side power or other "at-berth" technologies
  - Propeller and hull maintenance
- Unique challenges for this sector
  - OGVs are "visitors" that travel internationally
  - Very slow turnover
  - Coordination with international and federal regulations necessary

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