Independent Statistics & Analysis
U.S. Energy Information Administration

Marine Fuel Choice for Ocean-Going Vessels within Emissions Control Areas

June 2015

Independent Statistics & Analysis
www.eia.gov

U.S. Department of Energy
Washington, DC 20585

Introduction

The U.S. Energy Information Administration (EIA) contracted with Leidos Corporation to analyze the impact on ocean-going vessel fuel usage of the International Convention for the Prevention of Pollution from Ships (MARPOL) emissions control areas in North America and the Caribbean.

Leidos developed a new methodology for calculating fuel consumption by ocean-going maritime vessels in the United States within emission control areas by:

- Establishing a fuel usage methodology baseline for ocean-going vessels by U.S. Census Division and Puerto Rico for several ship types and energy and non-energy commodities
- Discussing relevant MARPOL and associated U.S. Environmental Protection Agency emissions regulations and major emissions compliance strategies, including exhaust scrubber controls, fuel switching to liquefied natural gas, and engine-based controls
- Creating a methodology for projecting ocean-going vessel travel demand by commodity and ship type, ship efficiency, and fuel choice by various compliance choices

In addition, Leidos recommended study of additional issues for future model improvements as more data become available. These include:

- Expanding the scope of the marine fuel estimates to include travel beyond North American and Caribbean emission control areas and Great Lakes and inland waterway transit
- Expanding the scope to include fuel usage estimates tied to U.S. ports for tugs, barges, and lightering vessels, fishing vessels, cruise ships, and other commercial vessels
- Fractioning the fuel purchases made in the United States versus abroad
- Improving the future projections of fuel usage, including slow steaming and auxiliary power needs, and technology adoption

EIA plans to update the upcoming *Annual Energy Outlook 2016* to include a new methodology for calculating the amount of fuel consumption by ocean-going vessels traveling though North American and Caribbean emissions control areas, including the impact of compliance strategies. Further, EIA plans to update the methodology for calculating ocean going vessel energy demand to include estimation of fuel consumption by ship type and commodity moved. The new methodology will also estimate energy consumption within and outside emission control areas. In addition, EIA will explore the interplay between refinery operation, refined product slates, and marine fuels in light of the impact of emission regulations.

Appendix A

Marine Fuel Choice for Ocean Going Vessels within Emission Control Areas

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EIA Task 7965, Subtask 17

Prepared for:
Energy Information Administration
Office of Energy Analysis
Office of Energy Consumption and Efficiency Analysis

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FINAL REPORT

April 2015

Disclaimer

Certain statements included in this report constitute forward-looking statements. The achievement of certain results or other expectations contained in such forward-looking statements involve known and unknown risks, uncertainties and other factors which may cause actual results, performance or achievements described in the report to be materially different from any future results, performance or achievements expressed or implied by such forward-looking statements. We do not plan to issue any updates or revisions to the forward-looking statements if or when our expectations or events, conditions, or circumstances on which such statements are based occur.

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List of Abbreviations and Acronyms

ACOE	Army Corps of Engineers
AEO	Annual Energy Outlook
Btu	British thermal units
CWA	U.S. Clean Water Act
CO_2	carbon dioxide
dwt	dead weight tonnage
C1, C2, & C3	Category 1, 2, and 3 (marine diesel engines)
dm^3	cubic decimeter (liter)
DNV	Det Norske Veritas
ECA	Emission Control Area
EEZ	exclusive economic zone
EGCS	exhaust gas cleaning system
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EU	European Union
GHG	greenhouse gas
GWh	Gigawatt-hours
HAM	humid air motor
HFO	heavy fuel oil
hp	horsepower
ICCT	International Council on Clean Transportation
IFO	intermediate fuel oil
IMO	International Maritime Organization
kg	kilograms
kWh	kilowatt-hours
LNG	liquefied natural gas
LPG	liquefied propane gas
LSFO	low sulfur fuel oil
m^3	cubic meters
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	maximum continuous rating
MDE	marine diesel engine
MDO	marine diesel oil
MEPC	Marine Environment Protection Committee
MGO	marine gas oil
MSAR SFO	Multiphase Superfine Atomized Residue Synthetic Fuel Oil
MT	million metric tons (million tonnes)
Mtpa	million tons per annum
MWh	Megawatt-hours
NEMS	National Energy Modeling System
nm	nautical miles
NO_x	oxides of nitrogen

NO_2	nitrogen dioxide
NPDES	National Pollutant Discharge Elimination System
NPV	net present value
ODS	ozone depleting substances
OGV	ocean going vessel
O&M	operating and maintenance
PAH	polycyclic aromatic hydrocarbons
RFO	residual fuel oil
R&D	research and development
rpm	revolutions per minute
SCR	Selective catalytic reduction
SO_x	oxides of sulfur
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSD	slow speed diesel
TDM	Transportation Demand Module
TEU	twenty-foot equivalent unit
U.S.	United States
VLCC	very large crude carrier
VSR	vessel speed reduction

Executive Summary

The National Energy Modeling System (NEMS) is the primary analysis tool for projections of domestic energy markets by the United States (U.S.) Energy Information Administration (EIA). The NEMS model can be used to understand the impacts that current energy and environmental issues and policies may have on energy markets. This particular study focuses on how a treaty/policy issue might affect the waterborne freight component of the Freight Transportation Submodule within the Transportation Demand Module (TDM) of NEMS.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships. Committees of the International Maritime Organization (IMO) meet periodically to consider and adopt revisions to the various annexes of MARPOL and related treaties. Annex VI (Prevention of Air Pollution from Ships) entered into force on May 19, 2005. Annex VI sets limits on sulfur oxides (SO_x) and oxides of nitrogen (NO_x) emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances (ODS).

Annex VI also designated emission control areas (ECAs), which set more stringent standards for SO_x, NO_x, and particulate matter emissions. The IMO has designated waters along the U.S. and Canadian shorelines as the North American ECA for the emissions of NO_x and SO_x (enforceable from August 2012) and waters surrounding Puerto Rico and the U.S. Virgin Islands as the U.S. Caribbean ECA for NO_x and SO_x (enforceable from 2014).[1] The ECAs ensure that foreign flagged vessels comply with IMO Tier III NO_x limits while in U.S. waters. Tier III NO_x limits will apply to all ships constructed on or after January 1, 2016, with engines over 130 kW that operate inside a NO_x ECA area.

The North American ECAs generally extend 200 nautical miles (nm) from the U.S. and Canadian ports (50 nm for the U.S. Caribbean ECA), and their requirements went into effect on January 1, 2015. The new requirements mandate that existing ships either burn fuel containing a maximum of 0.1% sulfur or use scrubbers to remove the sulfur emissions. New ships will be built with engines and controls to handle alternative fuels and meet the ECA limits.

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[1] The North American ECA does not include the Pacific U.S. territories, smaller Hawaiian Islands, the Aleutian Islands and Western Alaska, and the U.S. and Canadian Arctic waters. The U.S. Caribbean ECA includes the waters adjacent to the Commonwealth of Puerto Rico and the U.S. Virgin Islands out to approximately fifty nautical miles from the coastline.

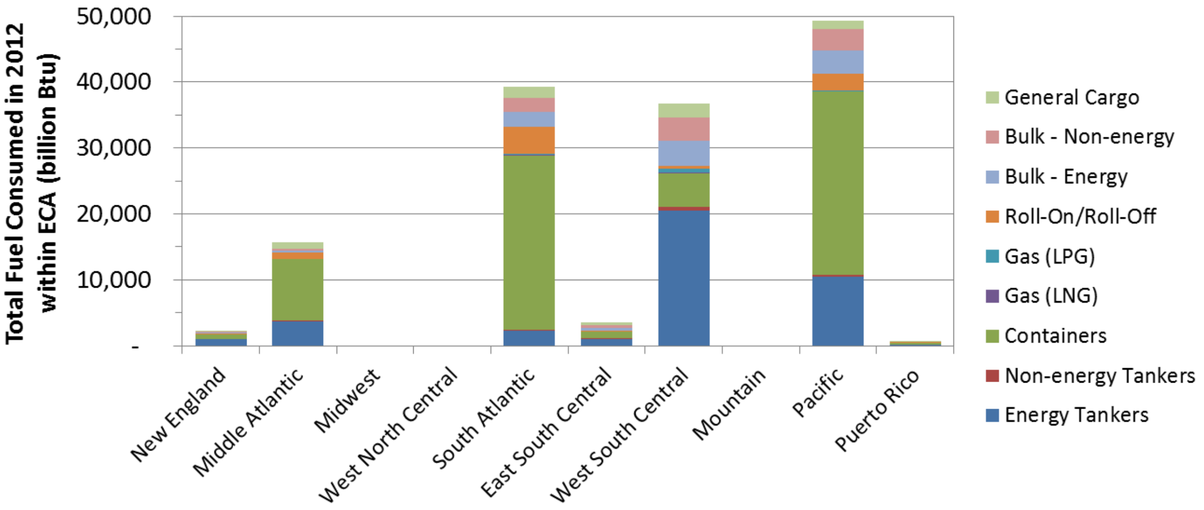

Figure ES- 1. Total 2012 Fuel Consumed by OGVs within ECAs by U.S. Census Divisions Based on Vessel Type

This report begins with an assessment of the 2012 fuel usage of ocean going vessels within the ECAs based on data about 2012 port calls in the U.S. The nautical miles traveled that year are calculated for each U.S. Census Division, and the average dead weight tonnages are used to compute the number of ton-miles traveled in ECA Waters. The ship weights determine the likely engine sizes and design speeds. Because slow steaming practices indicate significant fuel savings, 2012 estimates were used to compute the transit times and fuel requirements. Auxiliary fuel consumption was based on estimates for both the transit time and time in ports. Figure ES- 1 shows the estimate for total fuel consumed within the ECAs in the U.S. Census Divisions based on the ocean-going vessel (OGV) type.[2]

Compliance options associated with travel in the ECAs for new vessels include using exhaust controls (e.g., scrubbers and selective catalytic reduction), changing fuels to marine gas oil (MGO) or liquefied natural gas (LNG), or installing engine-based controls (e.g., exhaust gas recirculation). Other technologies (e.g., biofuels and water injection) are also under development but have not yet reached wide-scale adoption.

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[2] Note that the total fuel consumed per voyage will be much greater. The ECA represents only 3.5 percent of the distance between Shanghai, China and Los Angeles and 5.9 percent of the distance between Rotterdam, NL and New York/New Jersey. Some general assumptions about speeds and times in port show that a voyage from Shanghai to Los Angeles would spend 12 to 15 percent of the time in an ECA, and a voyage from Rotterdam to New York would spend 36 to 41 percent of the time in ECAs.

Ship efficiency improvements, shipping demand changes, and fuel price fluctuations will also drive future fuel consumption predictions within the North American and U.S. Caribbean ECAs. Using the 2012 estimates as a basis and the reference case for the Annual Energy Outlook 2014 as growth projections, the fuel consumption was estimated for future years. A sample chart in Figure ES- shows that residual fuel oil consumption in the ECAs drops precipitously in 2015 when the ECA provisions begin but rises again when scrubbers are installed on the new fleet of ships.[3] Distillate fuel oil is used to cover the gap until emission controls and fuel switching systems are installed aboard ships. Implementation of the recommendations in Section 5 (e.g., quantification of emission control installation rates for retrofits) might improve the estimates.

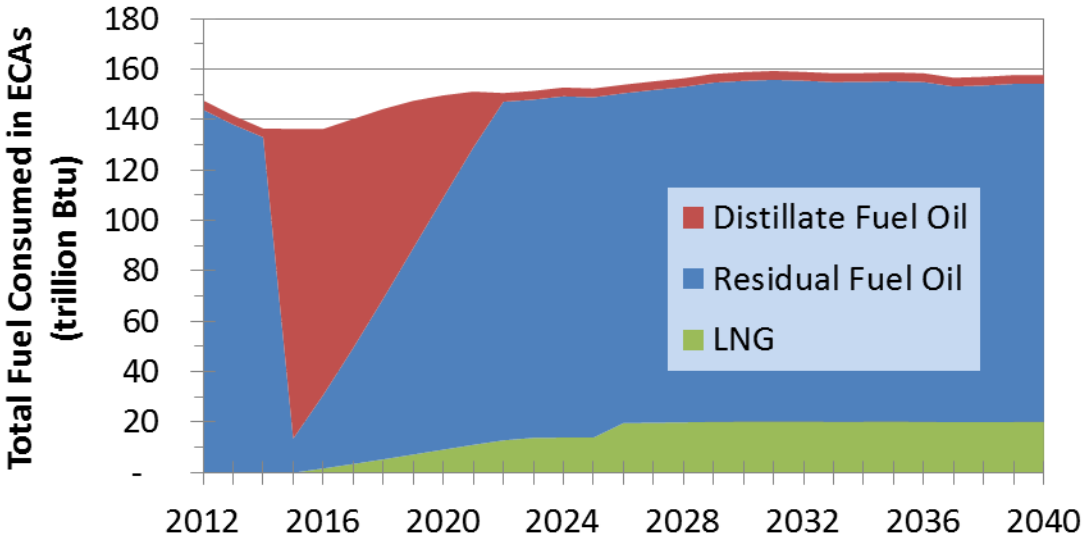

Figure ES- 2. Sample Projections of Fuel Consumed Within North American and U.S. Caribbean ECAs by NEMS Fuel Type

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[3] Figure ES-2 shows a large increase in distillate fuel oil for the coastal ECA activity. However, readers should understand that other vessels at U.S. ports already operate with distillate fuel oil blends (e.g., barges and tugs on inland waterways). According to U.S. Army Corps of Engineers statistics for 2013 (http://www.navigationdatacenter.us/factcard/factcard14.pdf), U.S. coastal and inland waterborne activities were responsible for 240 and 252 billion ton-miles of transport, respectively, and inland vessels operate on distillate. Therefore, the substantial increase in distillate fuel oil shown in Figure ES-2 should not give readers the impression that a sudden demand for distillate fuels would be created in 2015.

1 Introduction

The National Energy Modeling System (NEMS) is the primary analysis tool for projections of domestic energy markets by the U.S. Energy Information Administration (EIA). The NEMS model can be used to understand impacts that current energy and environmental issues and policies have on energy markets. This particular study focuses on how a treaty/policy issue might affect the waterborne freight component of the Freight Transportation Submodule within the Transportation Demand Module (TDM) of NEMS.

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Annex VI also designated emission control areas (ECAs) which set more stringent standards for SO_x, NO_x, and particulate matter emissions. The IMO has designated waters along the U.S. and Canadian shorelines as the North American ECA for the emissions of NO_x and SO_x (enforceable from August 2012) and waters surrounding Puerto Rico and the U.S. Virgin Islands as the U.S. Caribbean ECA for NO_x and SO_x (enforceable from 2014). The ECAs ensure that foreign flagged vessels comply with IMO Tier III NO_x limits while in US waters. Tier III NO_x limits will apply to all ships constructed on or after January 1, 2016, with engines over 130 kW that operate inside a NO_x ECA area.

The North American ECAs generally extend 200 nautical miles (nm) from the U.S. and Canadian ports (50 nm for the U.S. Caribbean ECA), and their requirements went into effect on 1 January 2015. The new requirements mandate that existing ships either burn fuel containing a maximum of 0.1% sulfur or to use scrubbers to remove the sulfur emissions. New ships will be built with engines and controls to handle alternative fuels and meet the ECA limits.

This report focuses on how the introduction of North American and U.S. Caribbean ECAs will affect fuel usage by ocean going vessels (OGVs). Because fuel usage from ships is not generally reported, Chapter 2 addresses the estimates to establish a 2012 baseline of fuel consumption (by billion British thermal units [Btus]) for ships traveling in each of the U.S. Census Divisions and Puerto Rico. Section 3 discusses MARPOL Annex VI and the associated U.S. Environmental Protection Agency (EPA) regulations associated with waterborne vessels, as well as discussion about compliance options. Section 4 focuses on how future projections can be made that account for ship efficiency improvements, shipping demand changes, and fuel price fluctuations. Section 5 gives recommendations for future model improvements as more data become available.

2 Baseline Current Estimates

The methodology used to calculate the baseline for energy consumption by ships calling on the U.S. ports that traveled through the North American and U.S. Caribbean ECAs is explained in this Section. Even though the ECAs were not in effect in 2012, the numbers, types and sizes of the vessels used in the baseline were based on the ships calling on the U.S. ports during the year 2012. The most recent year for which these data are published by the U.S. Maritime Administration (MARAD) is 2012. These data are contained in the MARAD '2012 Total Vessel Calls - U.S. Ports, Terminals and Lightering Areas Report.' Based on these data, the typical engine size and design speed of each ship type can be determined. Studies conducted by the IMO and collaborated by other sources have established fuel consumption rates based on engine output and have also documented the average speed (as a percentage of ship design speeds) that was used by each type and size ship during 2012.

The ship types in the MARAD report are:

- Tanker (both petroleum and chemical tankers),
- Container (container carriers and refrigerated container carriers),
- Gas (liquefied natural gas [LNG], liquefied petroleum gas [LPG] and LNG/LPG carriers),
- Dry Bulk (bulk vessels, bulk container ships, cement carriers, ore carriers, and wood-chip carriers),
- Roll-On/Roll-Off (roll-on/roll-off vessels, roll-on/roll-off container ships, and vehicle carriers), and
- General Cargo (general cargo carriers, partial container ships, refrigerated ships, barge carriers, and livestock carriers).

Through the use of U.S. Army Corps of Engineer's Waterborne Commerce of the United States, Calendar Year 2012, Part 5– National Summaries and MARAD's Vessel Calls Snapshot-2011 (Revised: November 2013), the number of Tanker and Dry Bulk ships transporting energy products and the number of Gas ships transporting Liquid Natural Gas (LNG) were determined. The 2012 fuel consumption baseline yields fuel consumption by Census Divisions and ship types (Figure 2-1).[4]

This section discusses the calculations and assumptions used in developing the energy consumption baselines, considerations of issues that can induce error into the final calculations, and recommendations for refining the model over time.

The baseline current estimates are not envisioned to be calculated directly within NEMS modules, so this Section does not directly refer to programming variables and matrices. However, there may be a need to update the baseline with new information as the protocols are implemented. Therefore, Appendix A shares how matrix-based variables might be related to computation of these baseline estimates.

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[4] The MARAD report showed no vessels with DWT over 10,000 tons calling on seaports in the Midwest (IL, IN, MI, OH, and WI), West North Central (IA, KS, MN, MO, NE, ND, and SD), or Mountain (AZ, CO, ID, MT, NV, NM, UT, and WY) Census Divisions, so the tables and figures in this chapter do not include these Census Divisions.

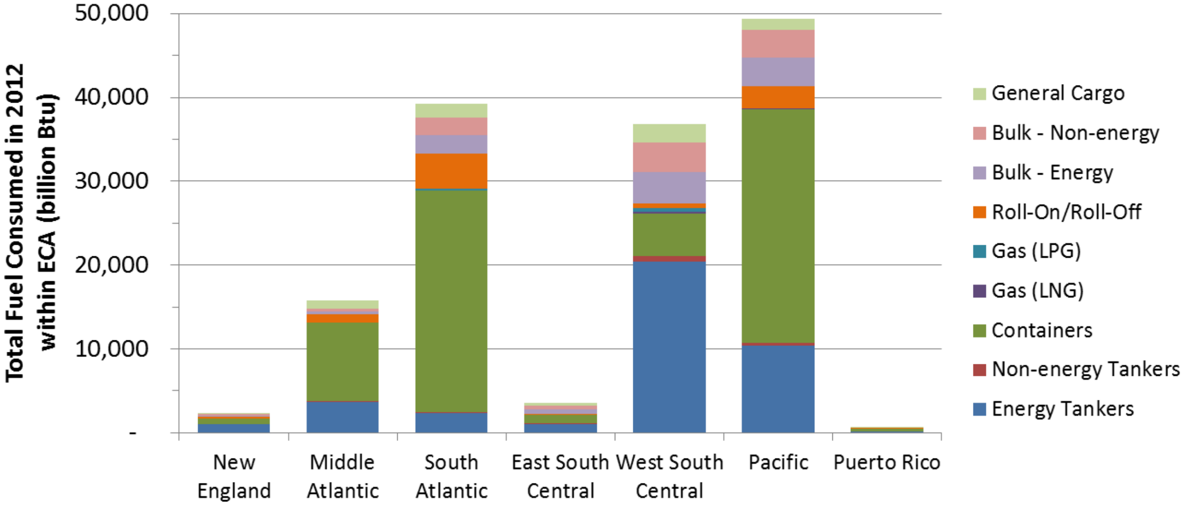

Figure 2-1. Total Fuel Consumed in 2012 by Ship Type in Census Divisions That Have Seaports

2.1 Grouping the Ships

The average dead weight tonnage (dwt) of each vessel type making port calls to deepwater ports in the U.S. was derived from data in the U.S. Maritime Administration (MARAD) 2012 Total Vessel Calls - U.S. Ports, Terminals and Lightering Areas Report – for vessels over 10,000 dwt.[5] The MARAD data provides the total number of port calls and total dwt (listed under capacity) for each ship type by port. For example, Table 2-1 lists the ports in the Pacific Census Division and tanker ship calls. Figure 2-2 provides the results of the calculations of this process that were repeated for each Census Division and type of ship.

Table 2-1. Estimating Average DWT of Tanker Ships Operating in the Pacific Census Division

Port	State	ECA distance (nautical miles/call)	Tankers	
			Calls	Capacity
Anacortes	WA	586	-	-
Anchorage	AK	764	9	476,000
Cherry Point Refinery	WA	616	248	26,138,862
Columbia River	OR	572	104	4,403,989
Coos Bay	OR	400	-	-
Drift River Terminal	AK	400	7	324,358
Dutch Harbor	AK	400	11	490,752
El Segundo Offshore Oil Terminal	CA	400	304	30,487,664
Everett	WA	624	-	-
Ferndale	WA	610	80	10,846,865
Grays Harbor	WA	400	1	27,000

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[5] U.S. Department of Transportation Maritime Administration. 2012 Total Vessel Calls - U.S. Ports, Terminals and Lightering Areas Report. Last accessed from http://www.marad.dot.gov/library_landing_page/data_and_statistics/Data_and_Statistics.htm on January 22, 2015.

Port	State	ECA distance (nautical miles/call)	Tankers	
			Calls	Capacity
Hilo	HI	400	-	-
Honolulu	HI	400	118	10,612,636
Kahului	HI	400	-	-
Kalaeloa (Barbers Point)	HI	400	120	12,487,384
Kenai	AK	616	6	277,416
Kodiak	AK	400	-	-
Long Beach	CA	400	965	102,829,099
Los Angeles	CA	400	222	11,280,721
Manchester	WA	648	21	1,219,033
March Point	WA	618	276	25,738,712
Nikiski	AK	616	76	3,918,520
Olympia	WA	732	-	-
Point Wells	WA	618	13	606,295
Port Angeles	WA	512	271	31,707,930
Port Hueneme	CA	400	14	653,866
Red Dog Mine	AK	400	2	128,159
San Diego	CA	100	3	98,285
San Francisco Bay Area	CA	400	1,601	110,513,536
Seattle	WA	640	27	1,137,244
Tacoma	WA	680	37	4,376,035
Valdez	AK	400	260	33,378,365
		TOTAL	**4,796**	**424,158,726**
			AVERAGE DWT PER CALL	**88,440**

Considerations in the calculations:

1. The classification of 10,000 dwt (and above) will essentially capture all international and coastal ship commerce and nearly all barge operations to Puerto Rico, Hawaii, and Alaska from the continental United States.
2. The size of an LNG ship normally is stated as the ship's obtainable volumetric capacity of liquid natural gas in cubic meters (m^3). Multiplying the dwt by a factor between 1.8 and 2.1 (depending on the ship size and tank configuration) will provide a rough approximation of the volumetric LNG capacity in m^3 of the LNG ship.
3. Waterborne commerce on the inland rivers is generally excluded from these data reports, but the following deep water ports on rivers are included in this analysis:
    a. Albany, New York located on Hudson River
    b. Philadelphia, Pennsylvania located on Delaware River
    c. Baton Rouge, Louisiana located on Mississippi River
    d. Portland, Oregon located on the Columbia River

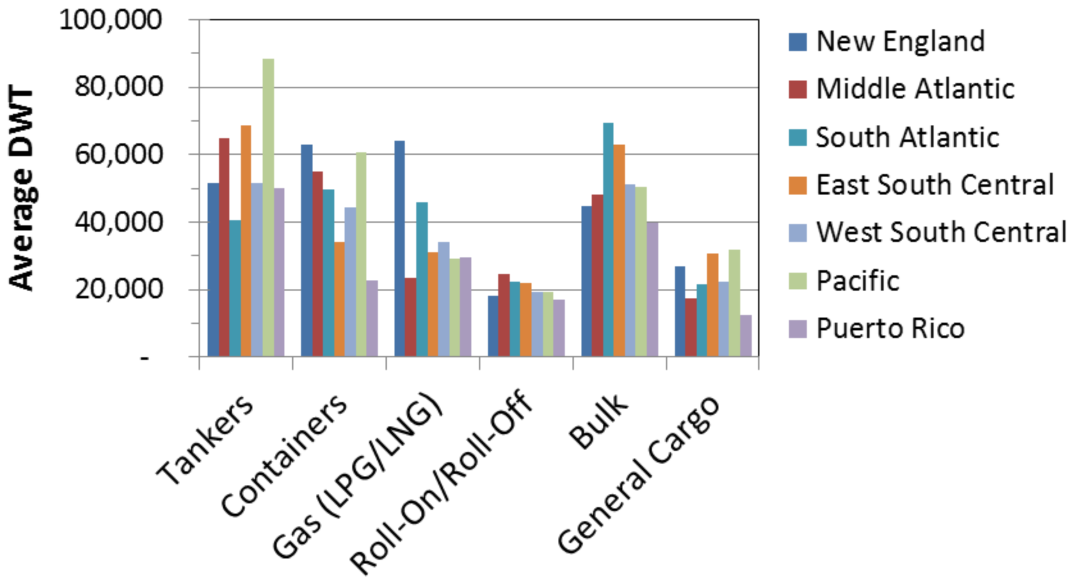

Figure 2-2. Average DWT of Each Vessel Type by Census Division

4. The waterborne commerce on the inland rivers (other than the deep water ports listed) generally operates outside the ECA.
5. Tug (tow) boats involved in barge operations to/from Puerto Rico, Hawaii, and Alaska from continental United States are not captured in these data. However, those barges are generally over 10,000 dwt and therefore the shipments are captured in the data. Generally barges designed for ocean service are at least 330 feet in length and at least 10,000 dwt.
6. Vessels operating on the Great Lakes are not operating in the designated North American ECA and are not included in these data.
7. Cruise ships, fishing vessels, offshore supply boats, and harbor tug boats are not considered in the model because they are not generally involved in the commerce of coastal or international transport of goods within the scope of this project.
8. The four lightering areas off the coasts of California, Louisiana, and Texas were not included in this study because the tanker vessels traveling from the lightering areas to the ports are already counted in the port data.

2.2 Determining Engine Size and Design Speed of Each Ship Grouping

The speed at which a ship will be operated is contingent on many factors, including the type of service (e.g., container, tanker or other) the ship will operate, customer expectations, daily operating/bunker costs, and economic climate. "Fuel consumption for a ship can be approximated by a cubic function of the ship's speed."[6] Generally tanker and dry bulk ships operate at slower speeds than container ships. Roll-on/Roll-off, gas, and general cargo ships

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[6] 'Ship Speed Optimisation with Time-Varying Draft Restrictions', by Elena Kelareva, Philip Kilby, Sylvie Thiébaux, http://www.nicta.com.au/pub?doc=6886

operate at speeds faster than tankers and slower than container ships. General guidelines matching vessel types to engine output by dwt are published by MAN Diesel & Turbo[7] and other major engine manufacturers. In addition, detailed analyses have been published by Gdynia Maritime University[8] and others.

The size of the engine required for each ship profile (Table 2-2) and their design speeds (Table 2-3) used in the model were derived from data published by Gdynia Maritime University and MAN Diesel & Turbo. The design speed is a trend based on assumptions by the industry of the maximum sustained speed that ships of a certain size and vessel type should be capable of operating at under normal economic and physical conditions. During normal economic conditions (those upon which the trends were developed), ships were expected to operate at or near their design speeds.[9] However, the considerations below discuss the common practice of slow steaming.

Table 2-2. Ship Engine Output (kW) for Each Ship Profile

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	9,400	42,000	8,000	10,000	8,400	12,000
Middle Atlantic	10,500	37,600	8,000	12,000	8,700	8,000
South Atlantic	8,500	33,600	12,000	10,000	10,000	10,000
East South Central	10,800	21,700	8,000	10,000	9,700	14,000
West South Central	9,400	30,100	8,000	10,000	9,000	10,000
Pacific	12,500	41,500	8,000	10,000	8,900	14,000
Puerto Rico	9,400	14,000	8,000	8,000	7,200	7,000

Table 2-3. Ship Design Speed (Knots) for Each Ship Profile

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	15.0	24.7	17.5	18.0	14.5	18.0
Middle Atlantic	15.0	24.2	15.0	18.0	14.5	18.0
South Atlantic	15.0	23.8	17.0	18.0	14.5	18.0
East South Central	15.0	22.0	15.0	18.0	14.5	18.0
West South Central	15.0	23.0	15.0	18.0	14.5	18.0
Pacific	15.0	24.6	15.0	18.0	14.5	18.0
Puerto Rico	15.0	20.0	15.0	18.0	14.5	18.0

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[7] Propulsion Trends' in LNG Carriers, container, bulk Two-stroke Engines series published by MAN Diesel & Turbo, Teglholmsgade 41, 2450 Copenhagen SV, Denmark; info-cph@mandieselturbo.com; www.mandieselturbo.com

[8] 'Analysis of Trends In Energy Demand For Main Propulsion, Electric Power And Auxiliary Boilers Capacity Of General Cargo And Container Ships,' Zygmunt Górski, Mariusz Giernalczyk, Gdynia Maritime University 83 Morska Street, 81-225 Gdynia, Poland, e-mail: magier@am.gdynia.pl, zyga@am.gdynia.pl

[9] Collected data indicates that ships have not been operating near design speeds for the last six years.

Considerations in the calculations and variations from design speeds:

1. Minor changes in ship speed can impact ship engine output requirements significantly.

> *Reducing the nominal ship speed from 27 to 22 knots (-19%) will reduce the engine power to 42% of its nominal output. This results in an hourly main engine fuel oil savings of approximately 58%.*
>
> *A further reduction down to 18 knots could save 75% of the fuel. The reduced speed however results in a longer voyage time; therefore the fuel savings per roundtrip (for example AsiaEurope-Asia) are reduced by 45% at 22 knots, or 59% at 18 knots. These are calculated values, and the actual values depend also on a number of external factors, such as the loaded cargo, vessel trim, weather conditions, and so on.”*[1]
>
> **An example of the results of slow speed steaming provided by Wärtsilä**

2. The optimal load range of the two-stroke engine lies between 70 and 85 percent of its design load.[10] Engine loads below 60 percent are generally considered to be slow steaming.[11] The IMO reported that the average ratio of operating speed to design speed was 0.85 in 2007 and 0.75 in 2012.[12] This ratio (expressed as a percentage) for each vessel type in 2012 is provided in Table 2-4.
3. Table 2-5 provides the percentage of engine output/load that each vessel type was operating at during 2012.

Table 2-4. Slow Speed Steaming Reduction in Ship Speed by Vessel Type (Percentage of Design Speed)

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	80%	68%	68%	73%	82%	82%
Middle Atlantic	81%	68%	73%	73%	82%	82%
South Atlantic	80%	68%	68%	73%	83%	82%
East South Central	81%	70%	70%	73%	83%	82%
West South Central	80%	68%	70%	73%	82%	82%
Pacific	78%	68%	70%	73%	82%	82%
Puerto Rico	80%	73%	70%	73%	82%	82%

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[10] Slow steaming – a viable long-term option?; Andreas Wiesmann; Wärtsilä Technical Journal; February 2010. www.wartsila.com

[11] There is some variation in the definitions used to define slow steaming. Some definitions link slow steaming to speeds below a certain nautical miles per hour (knots) while others link it to a percentage of engine output/load. Engine load is used in the calculations in this model.

[12] International Maritime Organization, Marine Environment Protection Committee. Reduction of GHG Emissions from Ships: Third IMO GHG Study 2014 – Final Report. 67th session Agenda item 6, MEPC 67/INF.3, July 25, 2014.

Table 2-5. Slow Speed Steaming Reduction in Ship Power Output by Vessel Type (Percentage of Design Power)

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	55%	36%	36%	45%	58%	59%
Middle Atlantic	57%	36%	45%	45%	58%	59%
South Atlantic	55%	36%	36%	45%	60%	59%
East South Central	57%	39%	39%	45%	60%	59%
West South Central	55%	36%	39%	45%	58%	59%
Pacific	51%	36%	39%	45%	58%	59%
Puerto Rico	55%	45%	39%	45%	58%	59%

4. A rule of thumb calculation indicates that a 10 percent decrease in speed will result in a 19 percent reduction in engine power (on a tonne-mile basis).[13] The rule of thumb is valid for most engine loads that exceed 25 percent of the maximum continuous rating (MCR), so it should be appropriate in these calculations.

2.3 Calculating Fuel Oil Consumption

Fuel oil consumption rates (Table 2-6) for ship main propulsion engines (commonly called the marine diesel engine [MDE]) were based on IMO data[12] and assume:

1. MDEs are two-cycle engines that burn IFO (Figure 2-3),
2. MDEs are slow speed diesel (SSD) engines,
3. Ships have one engine with one propeller and are direct drive (no transmission), and
4. Engines were built after 2001.

Table 2-6. Fuel Oil Consumption Rates for Slow, Medium and High Speed Diesel Engines (kg/kWh)[12]

Engine Age	Slow speed diesel	Medium speed diesel	High speed diesel
Before 1983	0.205	0.215	0.225
1984-2000	0.185	0.195	0.205
After 2001	0.175	0.185	0.195

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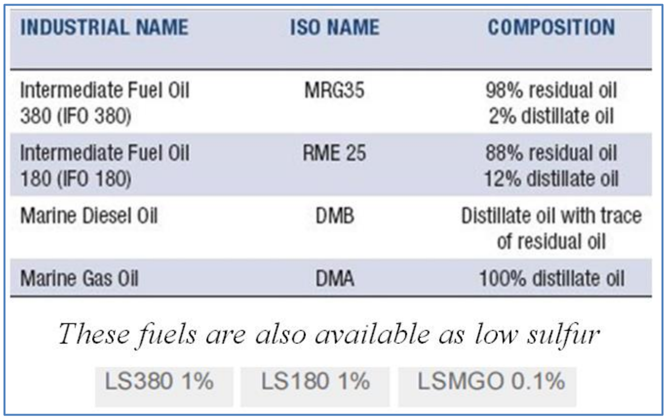
[13] Faber, J., M. Kőpke, and D. Nelissen. Going Slow to Reduce Emissions: Can the current surplus of maritime transport capacity be turned into an opportunity to reduce GHG emissions?; January 2010; Seas At Risk, Copyright © 2010; The production of the report was supported by the Dutch Ministry for Environment, Spatial Planning and Housing (VROM) and the European Commission (DG Environment). Last accessed from http://www.seas-at-risk.org/1mages/GoingSlowToReduceEmissions_1.pdf on January 22, 2015.



INDUSTRIAL NAME	ISO NAME	COMPOSITION
Intermediate Fuel Oil 380 (IFO 380)	MRG35	98% residual oil 2% distillate oil
Intermediate Fuel Oil 180 (IFO 180)	RME 25	88% residual oil 12% distillate oil
Marine Diesel Oil	DMB	Distillate oil with trace of residual oil
Marine Gas Oil	DMA	100% distillate oil

These fuels are also available as low sulfur

LS380 1% LS180 1% LSMGO 0.1%

Figure 2-3. Most Common Ship Bunker Fuels

To calculate fuel oil consumption (kg) for the MDEs, the slow steaming engine output (kW) was multiplied by 0.175 kg/kWh and the time operating in the ECA (hours).

Considerations in the calculations:

1. The fuel oil consumption rates (0.175 kg/kWh) for the MDEs matched those in the IMO studies, but the IMO reports a range of observed rates from 0.165 to 0.185 kg/kWh.
2. The heating values of ship bunker fuels are not set by standards and vary by supplier. The heating value is generally agreed upon in the purchase agreement between the buyer and seller, so the kilogram basis is only a placeholder for a later conversion on a Btu basis.
3. Ships used to transport LNG generally are equipped with one of three engine configurations options. The older ships use forced natural gas boil-off from the cargo tanks in steam boilers to produce steam for steam turbines. Although the conventional steam propulsion system has a low efficiency of about 28% compared to the approximately 50% for a conventional slow speed diesel engine, this option had the advantage of simplicity (no additional fuel tanks, or equipment to convert a SSD to run on LNG). As the selling price of natural gas began to rise, some ships were built to utilize the naturally occurring boil-off gas in a dual fuel (heavy fuel and compressed natural gas) diesel engine for main propulsion. In some of the largest LNG ships, an SSD engine for ordinary heavy fuel oil was used for main propulsion. Because few LNG port calls occurred in 2012, the difficulty of determining the engine option being used in each port call, and the acknowledgement that the introduced error would be insignificant in the national and Census Division totals, the increased fuel consumption required for forced gas boil-off/boilers/steam turbine propulsion was not calculated.

2.3.1 Time ship will be operating in the ECA

The computed hours of operation in the ECA are found by multiplying the number of port calls by the distance traveled and vessel travel speed. The U.S. Caribbean ECA waters extend 50 nautical miles (nm) from the shoreline, so the ECA distance traveled to the four Puerto Rican ports was assumed to be 100 nm (50 nm reaching and 50 nm leaving the port). The North

American ECA waters generally extend 200 nm from the shoreline, so the traveled distance is assumed to be 400 nm for other ports.[14]

The vessel travel speeds are computed by multiplying the design speeds (Table 2-3) by the slow steaming reductions (Table 2-4). Figure 2-4 shows the travel times for the fleets by vessel type for each Census Division. The largest bar (time for tanker calls in the West South Central Census Division) in Figure 2-4 is much larger than other bars because 20 percent of the nation’s 2012 port calls were by tankers to Texas and Louisiana ports.

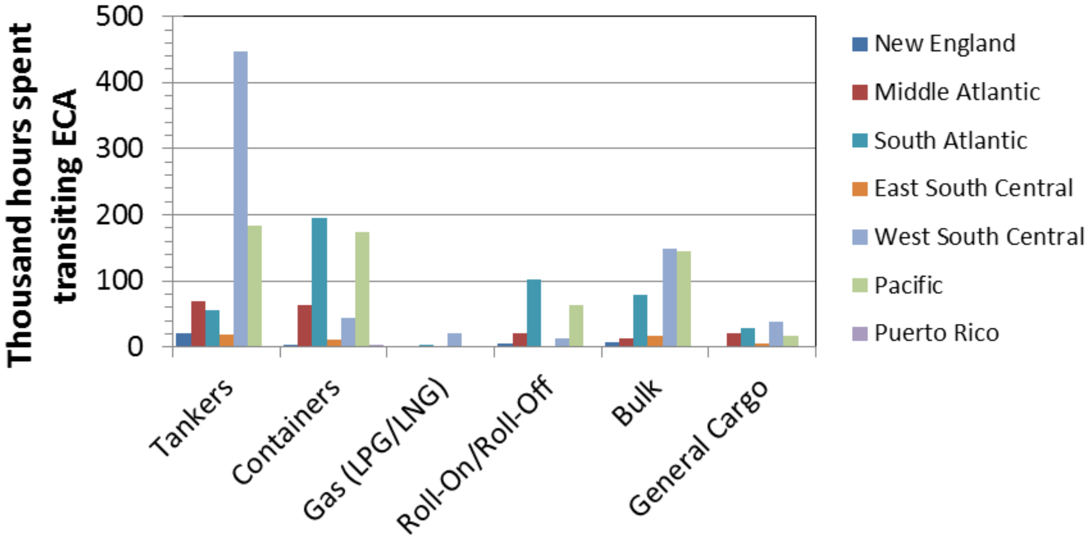


Figure 2-4. Time (in Thousands of Hours) Each Vessel Type Operated in the ECA Waters in 2012

Considerations in the calculations:

1. The following ports can be accessed by avoiding part of the ECA (Appendix B):

Port	Reason ECA is Abridged	Total Effective ECA
San Diego, CA	Proximity to Mexican waters (Figure B-1)	10 nm
Brownsville, TX	Proximity to Mexican waters (Figure B-1)	7 nm
Miami, FL	Proximity to Bahamian waters (Figure B-2)	25 nm
Port Everglades, FL	Proximity to Bahamian waters (Figure B-2)	25 nm
Palm Beach, FL	Proximity to Bahamian waters (Figure B-2)	25 nm

2. Some ports have longer effective ECAs as a result of their placements significantly inland of the shore baseline. Waterways that link the oceans to these deepwater ports would be considered to be U.S. navigable waters.[15] The EPA regulations used to implement the ECA requirements also apply to U.S.-flagged vessels wherever located and to foreign-flagged vessels operating in the U.S. navigable waters or the U.S. Exclusive Economic Zone (EEZ). These situations occurred in the following regions: Cook Inlet in Alaska, Puget Sound in Washington, Columbia River in Oregon,

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[14] Several exceptions with different travel distances are discussed in the Considerations section.

[15] This is not an exclusive definition of navigable waters; there are many other waterways that are also considered to be navigable waters.

Mississippi River in Louisiana, Chesapeake Bay in Maryland, Delaware River for Delaware and Pennsylvania, and the Hudson River in New York.

3. Some ships that call on more than one U.S. port may opt to transit from one port to another without leaving the ECA. This might introduce error into the model, but the introduced errors are expected to be mostly insignificant because:
    a. Most major port areas in the U.S. are spaced apart by more than 200 nm, so travel outside the ECA would often be economical.
    b. Using a ship to move goods short distances is generally not cost effective due to added port fees and terminal fees. Transport of cargo across short distances is usually conducted by truck, rail, or pipelines.
4. Ships may choose to operate at speeds slower than their slow steaming speed for many reasons, including: regulatory speed limits, ship traffic, weather/sea conditions, navigational requirements, or to take on a tugboat assist. Such ship speed reductions would inflate estimated consumption totals but only near the ports.

2.3.2 Power consumption in propelling the ships through the ECA

Table 2-7 estimates the energy in GWh used to propel ships through the ECA and was calculated by multiplying the total time (by vessel type) that the ships operated in the ECA by the engine slow steaming output for each vessel type.

Table 2-7. Power Spent for Propulsion Through the ECA (GWh)

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	110	56	4.1	21	33	7.7
Middle Atlantic	420	850	6.0	110	70	100
South Atlantic	260	2,400	17	460	470	170
East South Central	120	97	3.7	11	100	41
West South Central	2,300	480	62	61	770	220
Pacific	1,200	2,600	6.2	287	750	140
Puerto Rico	13	21	0.6	5.4	2.1	3.7
Nationwide	**4,400**	**6,500**	**99**	**950**	**2,200**	**680**

2.3.3 Auxiliary power consumption

In addition to fuel consumed by the MDE, ships are generally operating auxiliary power units that provide ship electricity, running water, and warm the IFO so that it burns efficiently. In this model the auxiliary power required was assumed to be equal to 5 percent of the MDE design output.[16] Auxiliary power systems operate when the MDEs are operating and while ships are in port or at anchor. This model initially assumed that the ship would be in port and/or at anchor for

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[16] Same assumption used in footnote 12. The 5 percent assumption is also supported by Table 1 of the California regulation calling for airborne toxic control measures from ocean-going vessels; the default auxiliary power requirements listed in that table (4000-4999 TEUs) closely match 5 percent of the propulsion engine estimates for average vessels in New England, Middle Atlantic, and Pacific Census Divisions (representing more than half of the 2012 container vessel capacity).

72 hours (3 days) for each port call, but Appendix D describes how the estimates were refined based on available data indicating that port times are mandated to be short:

- 1.8 days for container ships
- 1.5 days for tanker vessels
- 2.6 days for general cargo vessels
- 0.88 days for roll-on/roll-off vessels
- 1.5 days for gas vessels
- 2.0 days for bulk vessels

The auxiliary power spent in an ECA was calculated by multiplying the hourly auxiliary power times the sum of the number of transit hours in the ECA and the port time.

Table 2-8 lists the auxiliary power estimates by Census Division for each vessel type. The large number of container ship port calls into Hampton Roads, Virginia and Savannah, Georgia yield the highest numbers for the South Atlantic Census Division.

Table 2-8. Auxiliary Power Spent in ECA and Port (GWh)

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo
New England	21	22	1.2	3.9	7.0	2.1
Middle Atlantic	71	320	1.1	20	13	23
South Atlantic	49	950	4.7	82	90	45
East South Central	22	33	0.9	2.1	21	11
West South Central	420	170	15	12	150	59
Pacific	220	920	1.4	51	140	34
Puerto Rico	6	17	0.4	1.2	1.2	3.2
Nationwide	**820**	**2,400**	**25**	**170**	**420**	**180**

Fuel consumption rates for auxiliary power are assumed to be 0.225 kg/kWh (based on Table 2-9). This number is used to convert the power spent into fuel consumption.

Table 2-9. Fuel Oil Consumption Rates (grams/kWh) for Auxiliary Power[12]

Engine Type	RFO	MDO/MGO
Gas turbine	305	300
Steam boiler	305	300
Auxiliary engine	225	225

Considerations for calculations:

1. Auxiliary power fuel consumption remains less documented than consumption rates by the MDE. While this study and the IMO are basing the size of the auxiliary power units as 5 percent of the MDE size, some reports have indicated auxiliary power may be up to 10 percent or higher of the size of the MDE. Auxiliary power warms the IFO prior to injection into an engine and provides the ships with electricity, hot water, and heat.

Container ships and ships with large refrigeration systems will consume more electricity than comparably sized dry bulk and tank ships.

2. Auxiliary power fuel consumption will exceed 5 percent of the total fuel consumption of the 2012 baseline totals because:
   a. MDEs are operated below design loads;
   b. Auxiliary power has a higher fuel consumption rate per kW than the MDE; and
   c. Auxiliary power continues operation while the ship is in port or at anchor.
3. Ships with waste heat capture units may greatly reduce the amount of fuel consumed by auxiliary power. Future IMO studies will probably study auxiliary power in more detail, and these baseline estimates should be revised if the IMO changes its estimates for auxiliary power.

2.3.4 Fuel consumed in 2012

The 2012 fuel consumption numbers for transiting the ECA were calculated by multiplying the spent power for propulsion (GWh) by the fuel consumption rate of 0.175 kg/kWh and the conversion of 42,195 Btu/kg (based on the NEMS heating value for residual oil[17]). The 2012 fuel consumption numbers for auxiliary engines are calculated in a similar manner using a fuel consumption rate of 0.225 kg/kWh. Both sets of data are presented in Figure 2-5.

To obtain the total fuel oil consumption used in each of the Census Divisions by vessel type, the fuel consumption values used for transiting the ECA were added to those used for auxiliary power. Table 2-10 displays the combined totals by Census Divisions, nationally, and by vessel type.

Table 2-10. Total Fuel Consumed in 2012 for Transit and Auxiliary Power (Billion Btus)

Census Division	Tankers	Containers	Gas (LPG/LNG)	Roll-On/ Roll-Off	Bulk	General Cargo	Total
New England	1,000	620	41	190	310	77	**2,300**
Middle Atlantic	3,800	9,300	55	980	640	980	**16,000**
South Atlantic	2,400	26,000	170	4,200	4,400	1,700	**39,000**
East South Central	1,100	1,000	36	100	940	410	**3,600**
West South Central	21,000	5,100	610	560	7,200	2,200	**37,000**
Pacific	11,000	28,000	60	2,600	6,800	1,300	**49,000**
Puerto Rico	150	320	8	60	27	57	**630**
Nationwide	**40,000**	**71,000**	**980**	**8,700**	**20,000**	**6,700**	**150,000**

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[17] Energy Information Administration. "Conversion Tables" from Annual Energy Outlook 2014. Last accessed from http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2014&subject=0-AEO2014&table=20-AEO2014&region=0-0&cases=ref2014-d102413a on January 16, 2015.

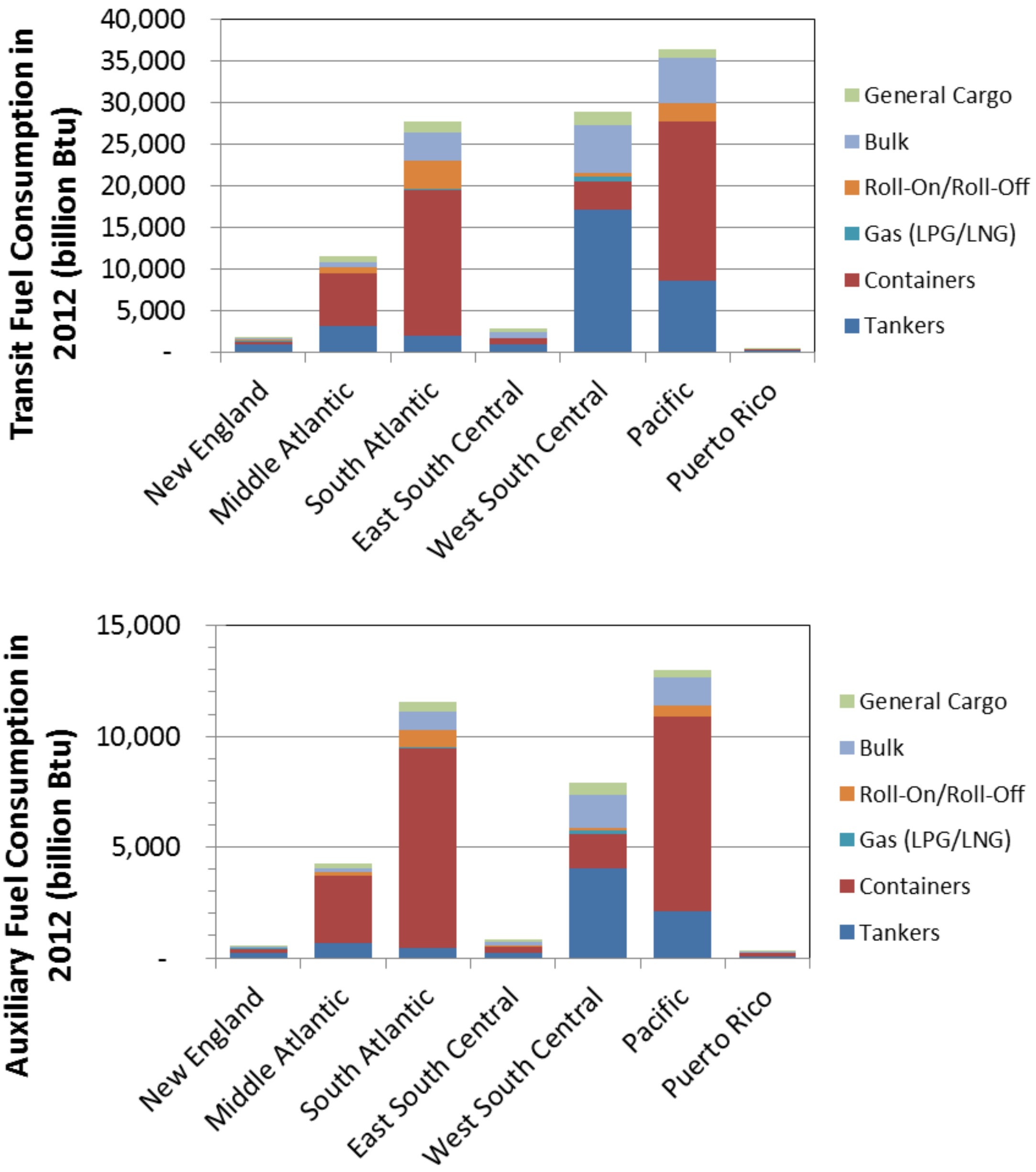

Figure 2-5. Fuel Consumption in ECA Waters in 2012

2.4 Distribution Between Energy and Non-Energy Products

The NEMS model tracks energy product demands, imports, and exports in modules related to specific fuels (e.g., Coal Market Module and Liquid Fuels Market Module). Therefore, future projections of energy product imports and exports may be aligned directly with annual demands within the appropriate NEMS modules. Therefore, this section discusses the allocation of the 2012 numbers between energy and non-energy products. Tankers, gas, and bulk ships will be divided into vessel subtypes.

2.4.1 Determining percentage of tankers and dry bulk ships transporting energy products

Tankers and dry bulk ships transport both energy and non-energy products. To determine the number of tankers and dry bulk ships that transported energy products in 2012, the U.S. Army Corps of Engineer (ACOE) Waterborne Commerce of the United States, Calendar Year 2012, Part 5– National Summaries[18] was reviewed and the total tonnage of products that are generally[19] transported on tanker and on dry bulk ships was compared to the total tonnage of energy products transported (foreign inbound, foreign outbound, or in coastal trade) as freight.

Table 2-11 lists the products and tons shipped and illustrates that 97 percent of the tankers and 51 percent of the dry bulk ships involved with U.S. port calls were transporting energy products. The total port calls by tankers and dry bulk ships were multiplied by these percentages to allocate the energy consumption within the ECAs between energy and non-energy products.

Considerations in calculations:

1. The ACOE statistics list products transported by commodity code, but not by the type of ship being used to transport the commodity. Relatively small amounts of these commodities may be shipped in drums or packages on container, roll-on/roll-off, or general cargo vessels. Likewise, shipment of commodities not normally shipped on dry bulk ships may be loaded onto a dry bulk ship under certain conditions. Tankers generally are certificated to transport specific products and are less likely to be used for other commodities.
2. The list of products used in this section may be revised over time as the issue is studied further.

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[18] U.S. Army Corps of Engineers. Waterborne Commerce of the United States: Calendar Year 2012 Part 5—National Summaries. Last accessed from http://www.navigationdatacenter.us/wcsc/pdf/wcusnatl12.pdf on January 22, 2015.

[19] Based on professional opinion.

Table 2-11. Percentage of Product Moved on Tank Ships That Are Energy Products (Top). Percentage of Product Moved on Dry Bulk Ships That Are Energy Products (Bottom).

Product	Non-energy (thousand short tons)			Energy (thousand short tons)		
	Import	Export	Coastal	Import	Export	Coastal
Crude oil	--	--	--	361,000	80	34,700
Gasoil	--	--	--	39,200	27,700	40,500
Kerosene	--	--	--	924	479	177
Distillate	--	--	--	64,000	71,200	20,500
Residual	--	--	--	5,310	5,580	9,880
Naphtha	1,270	2,540	1,140	--	--	--
Benzene	1,950	178	99	--	--	--
Sulfuric acid	503	47	3	--	--	--
Alcohols	8,800	4,140	3,000	--	--	--
Subtotal	**12,500**	**6,900**	**4,250**	**471,000**	**105,000**	**106,000**
Total	**23,700**			**682,000**		
Percentage	**3%**			**97%**		

Product	Non-energy (thousand short tons)			Energy (thousand short tons)		
	Import	Export	Coastal	Import	Export	Coastal
Petroleum coke	--	--	--	2,530	36,200	751
Coal	--	--	--	9,210	120,000	4,510
Wood chips	2	1,480	259	--	--	--
Gypsum	3,580	66	232	--	--	--
Sand/gravel	8,140	689	2,960	--	--	--
Iron ore	7,530	9,870	--	--	--	--
Copper ore	14	546	4	--	--	--
Aluminum ore	16,400	1,760	406	--	--	--
Magnesium ore	479	4	--	--	--	--
Other ore	945	344	--	--	--	--
Grains	2,610	58,200	--	--	--	--
Oil seed	588	52,200	--	--	--	--
Subtotal	**40,300**	**125,000**	**3,863**	**11,700**	**156,000**	**5,260**
Total	**169,000**			**173,000**		
Percentage	**49%**			**51%**		

2.4.2 Determining number of gas carriers (ships) that are transporting LNG and LPG

LNG terminals are located in each of the Census Divisions except the Middle Atlantic (New York, New Jersey, and Pennsylvania). The ACOE statistics assign the same commodity code (2640) to LNG and LPG and the 2012 Total Vessel Calls Report does not separate LNG and

LPG. However, a periodic report[20] does provide annual totals for gas carriers (LNG and LPG) and breaks out LNG carriers for the years from 2006 to 2011. The total port calls for gas carriers were subtracted from this total and the average number of 'total gas carrier' port calls was computed and compared to the LNG carrier port calls. During this period it appears that LNG carriers accounted for 26 percent of the 'total gas carrier' port calls outside of the Middle Atlantic District (Table 2-12).

Table 2-12. LNG Carriers as a Percentage of Total Gas Carriers

Year	Total Gas Carriers	LNG Carriers	Percentage of LNG Vessels
2006	875	213	
2007	804	202	
2008	703	171	
2009	640	201	
2010	670	202	
2011	779	157	
Average	**745**	**191**	**26±4%**

In 2012 there were 747 total gas carrier port calls outside of the Middle Atlantic District and this equates to an estimated 194 LNG carrier port calls nationally. The total fuel consumption for gas ships in each Census Division (except the Middle Atlantic) were multiplied by 26 percent to allocate fuel consumption for LNG shipments, and the remainders were allocated to LPG shipments.

Considerations:

1. LNG ships tend to be larger than LPG ships, but this should not impact overall model projections. Gas ships are only responsible for less than 1 percent of the total fuel consumed in Table 2-10.
2. The computed percentage of LNG carriers as part of the larger total gas carrier numbers may be subject to rapid change due to fluctuations in both oil and natural gas pricing.

Table 2-13 shows the calculated 2012 fuel consumption numbers by vessel type and subtype (for tankers, gas ships, and bulk ships) among the Census Divisions. Nationally container ships represented almost half of the fuel consumed.

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[20] Vessel Calls Snapshot, 2011, Released: March 2013, Revised: November 2013, Office of Policy and Plans, Maritime Administration, U.S. Department of Transportation, www.marad.dot.gov/data_statistics.

Table 2-13. Total Fuel Consumed (Billion Btu) in 2012 by Vessel Type and Subtype (by Product Type)

Census Division	Energy Tankers	Non-energy Tankers	Containers	Gas (LNG)	Gas (LPG)	Roll-On/ Roll-Off	Bulk - Energy	Bulk - Non-energy	General Cargo	**Total**
New England	1,000	31	620	11	30	190	160	150	77	**2,300**
Middle Atlantic	3,700	110	9,300	-	55	980	330	310	980	**16,000**
South Atlantic	2,300	72	26,000	43	120	4,200	2,200	2,100	1,700	**39,000**
East South Central	1,000	32	1,000	9	27	100	480	460	410	**3,600**
West South Central	20,000	630	5,100	160	450	560	3,700	3,500	2,200	**37,000**
Pacific	10,000	320	28,000	15	44	2,600	3,500	3,300	1,300	**49,000**
Puerto Rico	150	5	320	2	6	60	14	13	57	**630**
Nationwide	**39,000**	**1,200**	**71,000**	**240**	**740**	**8,700**	**10,000**	**10,000**	**6,700**	**150,000**
Fraction	26%	0.8%	48%	0.2%	0.5%	6%	7%	7%	5%	--

3 Compliance Strategies

Marine vessels are significant sources of air pollutant and greenhouse gas (GHG) emissions. The regulations governing vessel emissions in the North American and U.S. Caribbean ECAs will alter the ship fuels consumed in the future as well as alter the control devices operating on board the ships. This section details some of the provisions within the regulatory framework and also presents the most likely compliance strategies.

3.1 Regulatory Framework

This section describes both the U.S. EPA regulations and the IMO protocols.

3.1.1 U.S. EPA regulations

The U.S. emissions from compression-ignition MDEs have been regulated through a number of U.S. EPA regulations, the first of which was issued in 1999. Marine engine regulations overlap those for mobile, land-based non-road engines, but marine engines have no emission control requirements for particulate matter (smoke).

Marine engines are divided into three categories in EPA regulations based on their displacement per cylinder, as shown in Table 3-1. Category 1 and Category 2 marine diesel engines typically range in size from about 500 to 8,000 kW (700 to 11,000 hp). Categories 1 and 2 (C1 and C2) are further divided into subcategories, depending on displacement and net power output. These engines are used to provide propulsion power on many kinds of vessels including tugboats, pushboats, supply vessels, fishing vessels, and other commercial vessels in and around ports. They are also used as stand-alone generators for auxiliary electrical power for many vessel types. Category 3 (C3) MDEs are very large and used for propulsion power on OGVs such as container ships, oil tankers, bulk carriers, and cruise ships. Category 3 engines typically range in size from 2,500 to 70,000 kW (3,000 to 100,000 hp).

Table 3-1. Marine Engine Categories

	Displacement per Cylinder (D)		
Category	Tier 1-2 Emission Standards	Tier 3-4 Emission Standards	Engine Technology Basis
1	$D < 5\ dm^3$ and power ≥ 37 kW	$D < 7\ dm^3$	Land-based non-road diesel engines
2	$5\ dm^3 \leq D < 30\ dm^3$	$7\ dm^3 \leq D < 30\ dm^3$	Locomotive engines
3	$D \geq 30\ dm^3$		Unique marine engine design

The 1999 Marine Engine Rule adopted Tier 2 standards for C1 and C2 engines that are based on the standard for land-based non-road engines. At that time the largest C3 engines were expected to comply with IMO's MARPOL Annex VI Tier I standards set in 1997 but were not required to meet standards by the rule. In 2003, EPA introduced the C3 Engine Rule "Control of Emissions From New Marine Compression-Ignition Engines at or Above 30 Liters Per Cylinder" [40 CFR Part 9 and 94][68 FR 9745-9789, 28 Feb 2003]. The rule established Tier 1 emission standards for marine engines that were virtually equivalent to the IMO MARPOL Annex VI limits.

In 2008 EPA finalized a three-part program that further reduced emissions from MDEs with per-cylinder displacements below 30 liters. This rule addressed marine propulsion engines used on vessels from recreational and small fishing boats to towboats, tugboats and Great Lake freighters, and marine auxiliary engines ranging from small generator sets to large generator sets on OGVs. The rule included the first-ever national emission standards for existing commercial MDEs, applying to engines larger than 600 kW when they are remanufactured. The rule also set Tier 3 emissions standards for newly built engines that were phased in beginning in 2009. Finally, the rule established Tier 4 standards for newly built commercial marine diesel engines above 600 kW, phasing in beginning in 2014. The Tier 4 emission standards were modeled after the 2007/2010 highway engine program and the Tier 4 non-road rule, with an emphasis on the use of exhaust control technology.

To enable catalytic aftertreatment methods, EPA established a sulfur cap in marine fuels (as part of the non-road Tier 4 rule). The sulfur limit of 500 ppm became effective in June 2007, and the sulfur limit of 15 ppm replaced that in June 2012 (these sulfur limits are not applicable to residual fuels).

EPA's 2009 Category 3 Engine Rule (published April 30, 2010) revised the standards that apply to C3 engines installed on U.S. vessels and to marine diesel fuels produced and distributed in the U.S. The rule added two new tiers of engine standards for C3 engines: Tier 2 standards that were enforceable in 2011 and Tier 3 standards that begin in 2016. Under this regulation, both U.S.-flagged and foreign-flagged ships which are subject to the engine and fuel standards of MARPOL Annex VI (shown in Table 3-2) must comply with the applicable Annex VI engine and fuel sulfur limits provisions when they enter U.S. ports or operate in most internal U.S. waters, including the Great Lakes.

Table 3-2. MARPOL Annex VI NO_x Emission Standards

		NO_x Emission Limit (g/kWh)		
Tier	Effective Date	RPM (n < 130)	RPM (130 ≤ n < 2000)	RPM (n ≥ 2000)
I	2004	17.0	$45 \cdot n^{-0.2}$	9.8
II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	2016 *	3.4	$9 \cdot n^{-0.2}$	1.96

* In NO_x ECAs only (Tier II standards apply outside of ECAs).

The 2009 Category 3 Engine rule also revised EPA's diesel fuel program to allow for the production and sale of diesel fuel with up to 1,000 ppm sulfur for use in C3 marine vessels, phasing in by 2015. Vessels were allowed to use other methods to achieve SO_x emissions reductions equivalent to those obtained by using the lower 1,000 ppm sulfur fuel. In the final action, EPA provided an exclusion of the application of the ECA-level fuel sulfur standards in MARPOL Annex VI to existing steamships operating on the Great Lakes and Saint Lawrence Seaway. An additional economic hardship relief provision was included in the regulation for vessels with diesel engines operating on the Great Lakes and Saint Lawrence Seaway. This option provides temporary relief from the 2015 ECA-level fuel sulfur standards upon demonstration that the burden of compliance costs would cause serious economic hardship.

In 2012, EPA revised the large marine engine regulation by adding a provision to provide an incentive to repower Great Lakes steamships with new, more efficient diesel engines. This consisted of an automatic, time-limited fuel waiver that allows the use of residual fuel in the replacement diesel engines that exceeds the global and ECA sulfur limits that otherwise apply to the fuel used in ships operating on the U.S. portions of the Great Lakes. This automatic Great Lakes steamship repower fuel waiver is valid through December 31, 2025. After that date, repowered steamships will be required to comply with the Great Lakes ECA fuel sulfur limits for diesel engines. This automatic fuel waiver is available only to steamships that operate exclusively on the Great Lakes, that were in service on October 30, 2009, and that are repowered with a Tier 2 or better diesel engine.

3.1.2 IMO protocols

On the international front, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) is the United Nations agency concerned with the prevention of marine pollution from ships. The EPA participates on the U.S. delegation to the IMO and submits position papers to the IMO's MEPC suggesting measures to reduce air pollution and GHG emissions from ships.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering pollution prevention of the marine environment by ships. The MARPOL Convention was adopted on November 2, 1973 at IMO. Committees of the IMO meet periodically to consider and adopt revisions to the various annexes of MARPOL and related treaties. Annex VI (Prevention of Air Pollution from Ships) entered into force on May 19, 2005. Annex VI sets limits on sulfur oxides (SO_x) and oxides of nitrogen (NO_x) emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances (ODS).

The IMO emission standards are commonly referred to as Tiers I through III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments adopted in 2008. Annex VI applies retroactively to new engines greater than 130 kW installed on vessels constructed on or after January 1, 2000, or which undergo a major conversion after that date. In anticipation of the Annex VI ratification, most marine engine manufacturers had been building engines compliant with Tier I standards since 2000. Annex VI amendments were adopted in October 2008 and ratified by 53 countries (including the U.S.), representing 81.88 percent of the tonnage. The amendments became enforceable on 1 July 2010. They introduced:

- New fuel quality requirements beginning from July 2010,
- Tier II and Tier III NO_x emission standards for new engines, and
- Tier I NO_x requirements for existing pre-2000 engines.

Annex VI also designated ECAs, which set more stringent standards for SO_x, NO_x, and particulate matter emissions. The IMO has designated waters along the U.S. and Canadian shorelines as the North American ECA for the emissions of NO_x and SO_x (enforceable from August 2012) and waters surrounding Puerto Rico and the U.S. Virgin Islands as the U.S. Caribbean ECA for NO_x and SO_x (enforceable from 2014). The ECAs ensure that foreign flagged vessels comply with IMO Tier III NO_x limits while in U.S. waters. Tier I and Tier II limits are global standards, while the Tier III standards apply only in NO_x ECAs. Tier III NO_x limits will apply to all ships operating within a NO_x ECA area constructed on or after 1 January

2016 with engines over 130 kW. Table 3-2 shows the Annex VI adopted NO_x emissions standards, which are set based on the engine's maximum operating speed (number of rpm).

The ECA also triggers IMO and US EPA low sulfur fuel requirements for vessels in U.S. waters. Table 3-3 shows the fuel sulfur content limits.

Table 3-3. MARPOL Annex VI Fuel Sulfur Limits Globally and Within a SO_x ECA

Global		Within SO_x ECA	
Effective Date	Sulfur Fuel Limits	Effective Date	Sulfur Fuel Limits
2004	45,000 ppm	2005	15,000 ppm
2012	35,000 ppm	2010	10,000 ppm
2020*	5,000 ppm *	2015	1,000 ppm

* Subject to a feasibility review in 2018; may be delayed to 2025.

IMO has developed guidelines for the use of exhaust gas cleaning systems (EGCS), such as SO_x scrubbers, as an alternative to operating on lower sulfur fuel. These guidelines include a table of sulfur dioxide (SO_2) limits intended to correspond with various fuel sulfur levels. For existing ECAs, the corresponding limit is 0.4 g SO_2/kW-hr for a 1,000 ppm fuel sulfur limit. This limit is based on an assumed fuel consumption rate of 200 g/kW-hr and the assumption that all sulfur in the fuel is converted to SO_2 in the exhaust. The IMO guidelines also allow for an alternative approach of basing the limit on a ratio of SO_2 to CO_2. This has the advantage of being easier to measure during in-use monitoring. In addition, this ratio holds more constant at lower loads than a brake-specific limit, which would approach infinity as power approaches zero. For the existing 15,000 ppm fuel sulfur limit in ECAs, an SO_2 (ppm)/CO_2 (%) limit of 65 was developed. The equivalent limit for a 1,000 ppm fuel sulfur level is 4.0 SO_2 (ppm)/CO_2 (%).

In summary, a 0.1 percent low sulfur fuel requirement applies to all ships entering an ECA after January 1, 2015. Prior to this date and since 2010, ships were required to use a fuel with no more than 1 percent sulfur content. Additionally Tier III NO_x emission standards that apply only to new ship constructions (and major engine rebuilds) will become effective in 2016.

3.2 Major Compliance Strategies

This section details some of the major compliance strategies available for the OGVs traveling within the North American and U.S. Caribbean ECAs. The following section mentions some additional technologies that are not expected to have significant early market penetration.

3.2.1 Strategy A – Exhaust Controls

Emission control technologies that can be used on C3 MDEs are limited. In addition to using distillate fuel to meet the fuel sulfur content limit in the ECA, one available option is to use a SO_x scrubber. For meeting the NO_x emission limits required in the North American ECA, selective catalytic reduction (SCR) was the control technology that EPA envisioned would be used to meet the Tier 4 emission standards. The following discussion describes these two control technologies.

3.2.1.1 Compliance with sulfur limits

Currently most OGVs use residual fuel as the main component in their main propulsion engines because this fuel is relatively inexpensive and has a good energy density. Residual fuels typically are composed of heavy and very heavy hydrocarbons and can contain contaminants such as heavy metals and sulfur compounds. If the vessel does not employ a control technology, such as a sulfur scrubber, it will most likely operate using a marine distillate fuel while in an ECA in order to meet the sulfur emission requirements.

The SO_x scrubbers are capable of removing up to 95 percent of SO_x from ship exhaust using the available seawater to absorb SO_x. The SO_x scrubbers have been widely used in stationary source applications for SO_x reduction. In the stationary source applications, lime or caustic soda are typically used to neutralize the sulfuric acid in the water. While SO_x scrubbers are not widely used on OGVs, there have been prototype installations to demonstrate their viability (e.g., the Krystallon systems installed on the P&O ferry Pride of Kent and the Holland America Line cruise ship the ms Zaandam). These demonstrations have shown scrubbers can replace and fit into the space occupied by the exhaust silencer units and can work well in marine applications.

There are two main scrubber technologies for OGVs. The first is an open-loop design, which uses seawater as exhaust washwater and discharges the treated washwater back to the sea. Such open loop designs are also referred to as seawater scrubbers. In a seawater scrubber, the exhaust gases are brought into contact with seawater, either through spraying seawater into the exhaust stream or routing the exhaust gases through a water bath. The SO_2 in the exhaust reacts with oxygen to produce sulfur trioxide (SO_3) which then reacts with water to form sulfuric acid. The aqueous sulfuric acid then reacts with carbonate and other salts in the seawater to form solid sulfates which may be removed from the exhaust. The washwater is then treated to remove solids and raise the pH prior to its discharge back to the sea. The solids are collected as sludge and held for proper disposal ashore.

A second type of SO_x scrubber uses a closed-loop design and is also feasible for use on marine vessels. In a closed-loop system, fresh water is used as washwater, and caustic soda is injected into the washwater to neutralize the sulfur in the exhaust. A small portion of the washwater is bled off and treated to remove sludge, which is held and disposed of at port, as with the open-loop design. The treated effluent is held onboard or discharged at open sea. Additional fresh water is added to the system as needed. While this design is not completely closed-loop, it can be operated in zero discharge mode for periods of time.

Water-soluble components of the exhaust gas, such as SO_2, SO_3, and NO_2, form sulfates and nitrates that are dissolved into the discharge water. Scrubber washwater also includes suspended solids, heavy metals, hydrocarbons and polycyclic aromatic hydrocarbons (PAH). Before the scrubber water is discharged, several approaches are available to process the scrubber water to remove solid particles. Heavier particles may be trapped in a settling or sludge tank for disposal. The removal process may include cyclone technology similar to that used to separate water from residual fuel prior to delivery to the engine. Sludge separated from the scrubber water would be stored on board until it is disposed of at proper facilities. The IMO guidelines for the use of exhaust gas cleaning devices such as SO_x scrubbers recommended monitoring and water discharge practices. The washwater should be continuously monitored for pH, PAHs, and turbidity. Further, the IMO guidance includes limits for these same measurements, as well as nitrate content when washwater is discharged in ports, harbors or estuaries. Finally, the IMO guidance recommends that washwater residue (sludge) be delivered ashore to adequate reception facilities and not discharged to the sea or burned on board. Any discharges directly into U.S. waters may be subject to Clean Water Act (CWA) or other U.S. regulation. To the extent that the air pollution control technology results in a wastewater discharge, such discharge will require a permit under the CWA's National Pollutant Discharge Elimination System (NPDES) permit program.

Achieving a reduction of sulfur by using a wet scrubber means increasing power usage significantly due to the use of pumped water, which indirectly results in an increase in other pollutant emissions associated with power production (e.g., GHGs).

3.2.1.2 Compliance with Tier 3 emission standards – SCR system

Among presently available after-treatment technologies, the urea-based Selective Catalytic Reduction (SCR) system represents the most mature and available solution to meet the marine engine Tier 3 NO_x emissions standards. An SCR uses a catalyst to chemically reduce NO_x to nitrogen using urea as a reagent in the presence of high-temperature exhaust gases. The SCR technology is compatible with higher sulfur fuels and may be equipped with a soot blower to remove particulate matter. The SCR systems require intermediate inspections approximately every 2.5 years and full inspections every five years. Because heavy metals deposit on the catalysts over time, the catalyst disposal process has created an industry to regenerate spent catalysts and reintroduce them into the supply chain. The useful life of a marine SCR catalyst can be five to six years, and manufacturers typically guarantee catalysts for up to 16,000 hours of service.[21] For vessels operating only part of the time within ECAs, the catalyst lifetime may be extended, in particular where 0.1% sulfur fuel is available.

Like many pollution control systems, the operation of SCR can be sensitive to *engine exhaust temperature*. Common practices of slow steaming could potentially contribute to SCR operational issues with low-load operation. Marine SCR applications have been designed to operate over a range of exhaust temperatures depending on fuel type, engine and catalyst design, and operating conditions. General minimum operating temperature ranges are between 260°C and 340°C, but systems may operate at lower temperatures for limited times. For marine engines, a variety of strategies are under development to expand the range of operating load conditions under which the SCR system functions normally. Exhaust gas temperatures can be boosted by several means, including:

- Reducing the amount of air and using a system to preheat the exhaust before entry into the SCR system;
- Adjusting injection timing;
- Bypassing part of the exhaust through a heated hydrolysis catalyst which allows urea to be injected at exhaust gas temperatures as low as 150°C;
- Heating the urea dosing system prior to injection to maximize efficiency; and,

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[21] Wärtsilä, "IMO Tier III Solutions for Wärtsilä 2-Stroke, Engines—Selective Catalytic Reduction (SCR)," 2011.

- For ships with multiple engines, shutting down one or more engines and running fewer engines at higher power.

In another approach, at low loads, a portion of the catalyst can be bypassed by condensing the exhaust gas volume and forcing it through a smaller catalyst volume, maintaining turbulent flow and high catalyst temperature. Hitachi Zosen and MAN Diesel recently completed a successful sea trial with SCR systems in use to operate at a 10 percent engine load.[22]

Engine architecture may allow specific strategies. For four-stroke engines, the SCR catalyst can be mounted after the turbocharger. Four-stroke engines have also been developed which allow SCR operation down to a 10–15 percent load. For two-stroke engines, the catalyst is mounted before the turbocharger inlet where the exhaust gas temperatures and pressures are higher. This has the added benefit of allowing the system to be operated using a smaller reactor. For two-stroke engines, the placement of the SCR catalysts upstream of the exhaust turbine can ensure effective NO_x reduction down to at least a 25-percent load. The "pre-turbocharger" SCR approach has been used successfully for over a decade on vessels equipped with slow-speed engines that required NO_x control when operating at low loads near coastal areas. Recently, Hitachi Zosen certified an engine design utilizing a compact, high-pressure, high-temperature SCR system that meets Tier III standards while producing minimal additional CO_2 emissions down to a 10-percent engine load.[22]

Overall, demand for urea for marine SCR applications is expected to be modest compared to other applications. The EPA estimates that urea use in the North American NO_x ECA will total approximately 454,000 tons in 2020 (which would constitute less than 10 percent of the 2015 on-road consumption levels and an even smaller fraction of projected 2020 use).[23] Because road transport is expected to consume no more than 5 percent of 2020 worldwide urea production, this suggests that marine urea consumption in 2020 will be significantly less than 1 percent of the worldwide total. Because the IMO regulation applies to new builds only (and to new engines installed on existing vessels), there should be adequate time for a urea supply chain to develop further in the future as marine SCR application slowly grows in step with the global vessel new-building program.

In October 2013, Caterpillar Marine announced that their C280 and 3516C models will meet EPA Tier 4 using SCR after-treatment systems.[24] Cummins Marine already uses SCR and indicates their planned use for higher horsepower marine engines to achieve EPA's Tier 4 standards. Other engine manufacturers have also indicated SCR as their planned approach to compliance.

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[22] Hitachi Zosen Corporation. "First ever marine vessel equipped with Pre-Turbo SCR system achieves compliance with Tier III NO_x emission standards certified by Nippon Kaiji Kyokai." 6 December 2011. Last accessed from http://www.hitachizosen.co.jp/english/news/2011/12/000568.html on January 22, 2015.

[23] U.S. Environmental Protection Agency. Proposal to designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides, and Particulate Matter: Technical Support Document. EPA-420-R-09-007. Last accessed from http://www.epa.gov/nonroad/marine/ci/420r09007-chap5.pdf on January 19, 2015.

[24] Marine Log. "Cat unveils Tier 4 marine engines." 8 October 2013. Last accessed from http://www.marinelog.com/index.php?option=com_k2&view=item&id=5236:cat-unveils-tier-4-marine-engines&Itemid=231 on January 22, 2015.

3.2.2 Strategy B – LNG-fueled vessels

As the shipping industry considers alternatives to HFO, part of the market will shift toward marine gas oil (MGO) and part toward LNG or other alternative fuels. Marine vessels equipped with scrubbers will retain the advantage of using lower-priced HFO. Shipping that takes place outside ECA areas might choose HFO or low-sulfur fuel oil (LSFO) depending on future global regulations. Ships operating partly in ECA areas will likely choose MGO as a compliance fuel. Heavy shipping within ECA areas, however, might provide enough incentive for a complete shift to LNG.

LNG-fueled engines burn cleaner and do not require after-treatment or specialized NO_x abatement measures to meet EPA Tier 4 (IMO Tier III). The potential lack of emission controls, in conjunction with its significantly lower fuel cost, makes LNG an attractive option for compliance. The only large ships currently using LNG as a fuel on international voyages are LNG cargo carriers. For LNG to become an attractive fuel for the majority of ships, a global network of LNG bunkering terminals must be established. If not, LNG-fueled ships will be limited to coastal trades where LNG bunkering networks are established.

The ability of LNG engines to meet Tier III NO_x requirements depends on the engine technology. While all LNG engine manufacturers do not yet have Tier III-compliant offerings, they are all likely to have introduced Tier III compliant engines within a few years.[25] The marine LNG engines currently available are almost exclusively dual-fuel engines that use a pilot fuel (MDO) to provide an ignition source for natural gas in the engine's cylinders. The amount of pilot fuel required varies based on engine technology, engine load, and pilot fuel quality. While some engines need a load of at least 30 percent before they can burn natural gas,[26] one of the most recent engine introductions can burn gas at any load, with pilot fuel energy consumption that is around 2 percent of the primary fuel energy consumption.[27] For the purposes of fuel demand modeling, it is reasonable to assume that virtually all LNG new-builds operating in an ECA will use dual-fuel engine designs that are equivalent to the current most advanced designs that meet Tier III without the addition of SCR, are able to burn natural gas at all engine loads, and have pilot fuel use equivalent to 2 percent of the total engine energy use.

When LNG is considered with its storage and support systems, the volumetric energy density of LNG can be up to three times higher than diesel fuels. This space penalty can be too large to

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[25] The most recent dual-fuel LNG marine engines introductions by both Wärtsilä and MAN meet Tier III without SCR:
Hagedorn, M. "LNG Engines: Specifications and Economics." Presented at LNG shipping Rostock. October 13, 2014. Last accessed from http://www.golng.eu/files/Main/20141017/Rostock/LNG%20Shipping%20Session%20II%20-%20LNG%20Engines-Specifications%20and%20Economics-%20W%C3%A4rtsil%C3%A4,Ship%20Power%20-%20Hagedorn.pdf on January 22, 2015.
The Motorship. "MAN goes for Tier III compliance." 30 October 2014. Last accessed from http://www.motorship.com/news101/engines-and-propulsion/man-goes-for-tier-iii-compliance on 22 January 2015.

[26] MAN Diesel. "ME-GI Dual Fuel MAN B&W Engines: A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas." Last accessed from http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Bunkering%20operations%20and%20ship%20propulsion/ME-GI%20Dual%20Fuel%20MAN%20Engines.pdf on 22 January 2015.

[27] Stiefel, R. "Wärtsilä awarded milestone order to supply 2-stroke dual-fuel engines for large LNG carriers." Press release on 9 September 2014. Last accessed from http://www.wartsila.com/en/press-releases/wartsila-awarded-milestone-order-to-supply-2-stroke-dual-fuel-engines-for-large-lng-carriers on 22 January 2015.

overcome for many vessels. If technically feasible, a total ownership cost analysis is needed to evaluate whether this approach would result in a low enough payback period to justify the higher investment cost.

It has been suggested that about half the commercial fleet of marine vessels could be converted to LNG. However, these conversions would not involve the largest vessels and likely not OGVs. Thus, in terms of amount of converted fuel use, the percentage would be much lower than half the fleet. One estimate on marine LNG consumption in 2020 is 2.4 megatonnes (MT) of LNG in 2020. [28]

A report from the IEA Advanced Motor Fuels Implementation Agreement[29] stated:

> “A major concern with LNG is the possibility for de-bunkering (or emptying the fuel tanks). This step is necessary when a ship is to be anchored for an extended period of time. Unless special LNG de-bunkering facilities are available in the port, the gas would boil off, causing huge methane losses to the atmosphere. In the case of grounding accidents, a technique for de-bunkering would also be necessary. Another concern is the pressure increase when consumption occurs below the natural boil-off rate, which will happen if there is no re-liquefaction plan available onboard. Re-liquefaction of boil-off gas requires about 0.8 kWh/kg gas. One large LNG carrier, such as Qatar Q-max, requires 5–6 MW of re-liquefaction power, corresponding to a boil-off rate of 8 tons/hour.
>
> “A third concern that needs to be addressed with LNG conversions is methane slip from larger marine engines burning the gas. Methane slip will occur, especially on four-stroke, dual-fuel engines (Figure 13 *[not shown]*), partly from the scavenging process in the cylinder and partly from the ventilation from the crank case, which is being led to the atmosphere. In addition, there is some uncertainty as to whether future regulations will allow LNG tanks to be situated directly below the outfitting/accommodation of the ship. If not, this constraint could cause difficulties in retrofitting certain ships.”

3.2.3 Strategy C – Engine-based controls

Engine modifications to meet Tier III emission levels will most likely include a higher percentage of common rail fuel injection systems coupled with the use of two-stage turbocharging and electronic valving. Engine manufacturers estimate that practically all slow-speed engines and 80 percent of medium-speed engines will use common rail fuel injection. Two stage turbocharging will probably be installed on at least 70 percent of all engines produced to meet Tier III emission levels. Electronically (hydraulically) actuated intake and exhaust valves for medium-speed engines and electronically actuated exhaust valves for slow-speed engines are necessary to accommodate two-stage turbocharging.[30]

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[28] “North European LNG Infrastructure Project,” Danish Maritime Authority, accessed at the following link: http://www.dma.dk/themes/LNGinfrastructureproject/Sider/Papersandpresentations.aspx

[29] “Alternative Fuels for Marine Applications,” A report from the IEA Advanced Motor Fuels Implementation Agreement, May 2013. Last accessed from http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_41.pdf on January 18, 2015.

[30] U.S. Environmental Protection Agency, Costs of Emission Reduction Technologies for Category 3 Marine Engines. Final Report EPA-420-R-09-008. May 2009.

The on-engine approach requires the addition of an Exhaust Gas Recirculation (EGR) system. EGR is a mature technology that has widely been used for on-road engines. By using EGR, a portion of the exhaust gas is recirculated back to the engine cylinders. The recirculated gases lower the oxygen content at the engine intake resulting in lower combustion temperatures and less thermal NO_x production. A heat exchanger is used to cool the recirculated exhaust air before entering the air intakes. The net of effect of this recirculated air is a less efficient combustion process due to the lower combustion pressure. Consequently EGR usage presents a fuel consumption penalty. To offset the lower combustion pressure, manufacturers are implementing improved engine designs such as new generation common rail direct fuel injection systems with higher pressures (15,000-40,000 pounds per square inch). The common rail allows finer electronic control over the fuel injection to provide multiple controlled injections per stroke. The fuel is further atomized to allow improved combustion. EGR allows the engine user to avoid the use of a urea-based SCR system, but it adds weight and complexity on the engine. In addition, EGR requires higher quality fuel with lower sulfur content for proper operation. Though not an issue in the U.S., this fuel requirement could create complications for vessels operating abroad where low sulfur diesel may not be available.

3.3 Other Compliance Options Considered

Alternative fuels are being developed as replacements to marine oil to help with compliance with the low sulfur fuel standard and to reduce operating costs in the long run. Quadrise Canada has developed a low-cost alternative to heavy fuel oil called Multiphase Superfine Atomized Residue Synthetic Fuel Oil (MSAR® SFO™).[31] The MSAR® SFO™ fuel technology renders heavy hydrocarbons easier to use by producing a low-viscosity fuel oil using water instead of expensive oil-based diluents, and also produces a superior fuel with enhanced combustion features. The process involves injecting smaller fuel droplets in a stable water-based emulsion into the cylinder, resulting in a complete combustion that produces lower NO_x and particulate exhaust gas emissions. MSAR® SFO™ can be air-atomized into 80-micron drops that contain thousands of small 5-micron fuel droplets that have seventeen times more surface area than a standard steam atomized drop. This property provides a much larger surface for contacting the combustion air with the fuel, leading to the need for low excess oxygen, quicker and more complete combustion, and less char formation (lower particulate emissions). In addition, since the fuel contains liquid water, the combustion temperature is lower, leading to lower NO_x formation.

Biofuels are one of the options to lower carbon intensity in the propulsion of ships and to reduce the effect of emissions to local air quality. However, the shipping sector is still in a very early stage of orientation towards biofuels. Currently no significant consumption of biofuels for shipping is taking place. However, there are R&D initiatives[32] in Europe that are investigating the possibilities. For example, under the TEN-T Priority Project 21: Motorways of the Seas,[33]

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[31] Quadrise Canada Corporation. "Low Cost Alternative Fuel (MSAR ® SFO™)." Last accessed from http://www.quadrisecanada.com/fcs-low-cost.php on January 22, 2015.

[32] European Biofuels Technology Platform. "Use of Biofuels in Shipping." Last accessed from http://www.biofuelstp.eu/shipping-biofuels.html#proj on January 22, 2015.

[33] Innovation and Networks Executive Agency, European Commission. "Priority Project 21: Motorways of the Sea." Last accessed from http://inea.ec.europa.eu/en/ten-t/ten-t_projects/30_priority_projects/priority_project_21/priority_project_21.htm on January 22, 2015.

pilot tests on methanol as a marine fuel of the future[34] are currently being carried out. Biomethanol potentially could be used as well as methanol from fossil sources. These potential solutions should be followed in the future as they may become viable options.

Other potential NO_x emission reduction techniques that may have some merit include water injection, which could consist of the introduction of water into the combustion chamber either through fumigation or as fuel emulsions, or direct water injection. Another alternative is to use EGR and a Humid Air Motor (HAM) system, a combination that resulted in NO_x emission reductions approaching those for SCR.[35]

3.4 Compliance Cost Issues

As discussed in the preceding sections, as of January 2015, vessels operating in designated ECAs and in regions with ECA-equivalent regulations are required to use fuels with sulfur levels that do not exceed 0.1% or use exhaust treatment technologies (i.e., scrubbers) to remove SO_x. Options for meeting these regulations include the use of low-sulfur MDO, the use of HFO with scrubbers, or the use of LNG (a naturally low-sulfur fuel). Beginning in 2016, new-build vessels operating in the North American ECA will additionally need to meet stringent IMO Tier III (or EPA Tier 4) NO_x regulations which require use of after-treatment technologies (i.e., SCR or EGR) for MDO and HFO combustion. It is assumed that the 2016 new-build LNG engines will be able to meet Tier III without the use of SCR.

Compliance with these new emission requirements will raise operating costs for ship owners and operators in the North American ECA as they upgrade their aging shipping fleet with new ships. The new ships will have more complicated fuel systems, potentially post-treatment control equipment, and more expensive low sulfur fuels. Existing ships that do not have dual tanks may require retrofits with dual fossil fuel systems to allow fuel switching when they enter an ECA.

In general, the costs to ship owners for complying with the 2015 sulfur fuel limits are substantially greater (e.g., at least ten-fold) than the additional costs for implementation of strategies to comply with the lower NO_x limits dictated by IMO's Tier III standards (equivalent to EPA Tier 4 NO_x standards). It should be noted that the confidence that can be placed in economic feasibility comparisons of marine compliance strategies at the present time is substantially limited by the immaturity of the technologies associated with some of the key strategies that were identified in the previous section.

The low sulfur fuel ECA requirement applies to all ships entering an ECA after January 1, 2015, but the Tier III NO_x emission standards only apply to new ship builds (and major engine rebuilds) that are initiated starting in 2016. Consequently some studies assessing compliance strategies have assumed that fuel selections will essentially be determined based on sulfur compliance strategies (i.e., low sulfur MDO, scrubbers, or LNG).[36]

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[34] Innovation and Networks Executive Agency, European Commission. "2012-EU-21017-S Methanol: The marine fuel of the future." Last accessed from http://inea.ec.europa.eu/en/ten-t/ten-t_projects/ten-t_projects_by_country/multi_country/2012-eu-21017-s.htm on January 22, 2015.

[35] Presentation of Ulf Hagstrom, Marine Superintendent, Technical sector, Viking Line Apb, "Humid Air Motor (HAM) and Selective Catalytic Reduction (SCR) Viking Line," at Swedish Maritime Administration Symposium/Workshop on Air Pollution from Ships (May 24-26, 2005)

[36] Danish Ministry of the Environment, 2012. "Economic Impact Assessment of a NO_x Emission Control Area in the North Sea." http://www2.mst.dk/Udgiv/publications/2012/06/978-87-92903-20-4.pdf

Appendix C briefly describes current (i.e., 2014/2015) perspectives on compliance strategy selection, provides summary results of studies that examine and estimate future adoption of scrubbers and LNG technologies, and concludes with a summary of recently published cost analyses of the compliance strategies. Some costing information was available for smaller ships (engine sizes around 10,000 kW), but more information (and possibly vendor quotes) would be necessary to understand the costs to ships as large as the average container ships (engine sizes around 36,000 kW in Table 2-2). Because some technologies are still relatively new, the costs are expected to decrease with market penetration.

4 Projections to Future Years

Section 2 discussed the method for determining fuel consumed by OGVs traveling in the North American ECA based on port calls in 2012. However, the IMO protocol requirements for ships traveling in the North American ECA did not take effect until January 1, 2015. In addition, shipping patterns change with time, and newer vessels will be more efficient than older ones. This section explores a method that NEMS model developers could use to estimate future fuel usage within the North American and U.S. Caribbean ECAs.

Because the average age of ships calling on the U.S. between 2006 and 2011 was 10.5 years based on MARAD data,[37] the fleet turnover rate of 9.5 percent each year was considered rapid. Older ships have been routed to non-U.S. ports after the service life to the U.S. ended; the world fleet's average age in 2014 was 20.2 years.[38] Ships built for use in the North American ECA after 2015 must meet at least one of the compliance options, but older ships without scrubbers were assumed to opt against retrofit technologies in favor of either operation with MGO fuel or operation elsewhere in the world outside the North American ECA.[39] This assumption may result in higher MGO and lower IFO fuel use from 2015 to 2025 than would an approach that considers retrofitted units as a significant fraction of the fleet.

4.1 Increased Efficiency of New Vessels

As mentioned in the preceding paragraph, the fleet turnover (*FLEETTO*) variable (default value of 9.5 percent per year) was computed from MARAD data to represent the rate of introduction of new vessels into the fleet moving through the North American ECA. The new vessels are assumed to be more efficient than their predecessors.

Some technologies that the International Council on Clean Transportation (ICCT) suggests will reduce fuel use (and CO_2 emissions)[40] appear in Table 4-1. Under the implementation of the mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI, it is expected that ship efficiency will result in an average 1 percent increase in ship operating efficiency each year above a 2000-2010 reference case.[41]

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[37] Vessel Calls Snapshot, 2011, Released: March 2013, Revised: November 2013, Office of Policy and Plans, Maritime Administration, U.S. Department of Transportation, www.marad.dot.gov/data_statistics

[38] United Nations Conference on Trade and Development. Review of Maritime Transport 2014. ISBN 978-92-1-112878-9. Last accessed from http://unctad.org/en/PublicationsLibrary/rmt2014_en.pdf on March 5, 2015.

[39] Ships built on or before 1 August 2011 that are powered by propulsion boilers that were not originally designed for continued operation on marine distillate fuel or natural gas are exempted from the ECA regulations until 1 January 2020 (according to IMO -RESOLUTION MEPC.202(62)- Adopted on 15 July 2011). In addition, conditional waivers granting additional time to comply with the ECA regulations have been issued by the U.S. EPA and U.S. Coast Guard to Totem Ocean Trailer Express and to Horizon Lines (Horizon Lines is being divided for sale to Matson and to Pasha Group). Totem, Horizon Lines and Matson represent a majority of the U.S. container ship fleet.

[40] Wang, H. and N. Lutsey. "Long-term potential for increased shipping efficiency through the adoption of industry-leading practices." 2013 International Council on Clean Transportation. www.theicct.org

[41] International Maritime Organization. "Technical and Operational Measures." Last accessed from http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx on January 22, 2015.

Table 4-1. ICCT List of Potential Fuel Reduction Technologies

Area	Technology	Potential CO_2 and Fuel Use Reduction
Engine Efficiency	Engine controls	0-1%
	Engine common rail	0-1%
	Waste heat recovery	6-8%
	Design speed reduction	10-30%
Thrust efficiency	Propeller polishing	3-8%
	Propeller upgrade	1-3%
	Rudder	2-6%
Hydrodynamics	Hull cleaning	1-10%
	Hull coating	1-5%
	Water flow optimization	1-4%
Aerodynamics	Air lubrication	5-15%
	Wind engine	3-12%
	Kite	2-10%
Auxiliary power	Auxiliary engine efficiency	1-2%
	Efficient pumps, fans	0-1%
	Efficient lighting	0-1%
	Solar panels	0-3%
Operational	Weather routing	1-4%
	Autopilot upgrade	1-3%
	Operational speed reduction	10-30%

This improved efficiency was translated in the computations to be expressed in new fleet vessels by calculating the 1 percent improvement per year for the average age of a vessel since the 2012 baseline. The *EFFINC* variable (default of 1 percent per year) can be used with the constant *FLEETTO* variable to compute the fuel consumption associated with a new fleet for a different year (*YR*):

$$FUELCONS'_{YR,class,CD} = \text{fuel by 2012 fleet} + \text{fuel by post-2012 fleet}$$

$$\begin{aligned} FUELCONS'_{YR,class,CD} &= FUELCONS_{2012,class,CD} \times maximum[0,1\text{-}(YR\text{-}2012)*FLEETTO] \\ &+ FUELCONS_{2012,class,CD} \times \{1\text{- } maximum[0,1\text{-}(YR\text{-}2012)*FLEETTO]\} \\ &\times [1\text{-}EFFINC]\text{^}[(YR\text{-}2012)/2] \end{aligned}$$

4.2 Changes in Shipping Demands

The variable $FUELCONS'_{YR,class,CD}$ in the previous section included an apostrophe because a second step to predicting the future fleet demands for total fuel consumption by a class is accounting for changes in market growth. The NEMS market growth numbers on imports and exports might vary by U.S. Census Division but are more easily collected on a national basis. Table 4-2 shares some baseline 2012 estimates from the ACOE about shipments to indicate whether the larger markets are by imports or exports.

Table 4-2. Weight (Million Short Tons) Transported in 2012 Through U.S. Waters Now under the North American ECA[42]

Commodity	Foreign Inbound	Foreign Outbound	Domestic Coastwise	Associated Vessel Class
Total petroleum and petroleum products	***482***	151	110	Energy tankers
Other chemicals and related products	35	***54***	9	Non-energy tankers
Total all manufactured equipment, machinery and products + total primary manufactured goods - vehicles and parts	***128***	41	16	Containers
Hydrocarbon and petrol gases, liquefied and gaseous	5.7	***6.3***	0.06	Gas (LNG)
Hydrocarbon and petrol gases, liquefied and gaseous	5.7	***6.3***	0.06	Gas (LPG)
Vehicles and parts	***12***	6	0.8	Roll-on/roll-off
Total coal + petroleum coke	12	***156***	5	Bulk - Energy
Total food and farm products	41	***155***	4	Bulk – Non-energy
Total all manufactured equipment, machinery and products + total primary manufactured goods - Vehicles and parts	***128***	41	16	General cargo

Examination of Table 4-2 indicates that imports might represent the larger ECA activity for energy tankers, container ships, roll-on/roll-off vessels, and general cargo. Fuel usage from these four vessel classes represents 85 percent of the 2012 energy profile from Section 2.

NEMS predicts imports and exports of the Table 4-2 commodities to change at different rates for future years, so the recommended approach is to distinguish these commodities using some parameters associated with NEMS. For energy commodities, the growth rates for the market imports/exports will change based on the AEO scenarios. Table 4-3 shows how the AEO 2014 reference case predicts that energy commodities might change with time.

Table 4-3. Energy Commodity Changes in the AEO 2014 Reference Case

Year	Crude Oil Gross Imports (million bbl per day)	LNG Exports (trillion cf)	Steam Coal Export (million short tons)
2012	8.49	0.03	55.9

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[42] Table 2-1 in "Waterborne Commerce of the United States: Calendar Year 2012 Part 5—National Summaries." U.S. Army Corps of Engineers. Last downloaded from http://www.navigationdatacenter.us/wcsc/pdf/wcusnatl12.pdf on January 14, 2015.

Year	Crude Oil Gross Imports (million bbl per day)	LNG Exports (trillion cf)	Steam Coal Export (million short tons)
2013	7.48	0.01	49.6
2014	6.59	0.01	45
2015	6.31	0.11	47
2016	5.92	0.31	48.9
2017	5.97	0.76	51.1
2018	5.96	1.26	53.4
2019	5.91	1.77	53.4
2020	5.94	2.08	55.2
2021	6.04	2.32	55.4
2022	6.08	2.32	57
2023	6.11	2.52	58.8
2024	6.17	2.72	60.5
2025	6.18	2.72	62.3
2026	6.32	2.92	63.7
2027	6.46	3.12	63.6
2028	6.58	3.32	63.5
2029	6.7	3.5	67.4
2030	6.77	3.52	73.6
2031	6.91	3.52	77.3
2032	6.99	3.52	77.9
2033	7.02	3.52	78.5
2034	7.12	3.52	81.4
2035	7.27	3.52	83.8
2036	7.43	3.52	82.6
2037	7.53	3.52	74.2
2038	7.74	3.52	76.1
2039	7.79	3.52	83.7
2040	7.87	3.52	86.9

Therefore, the fuel consumption from the various vessel classes may be directly related to AEO 2014 scenario outputs. As an example, the calculations for energy tankers could be based on the projections of petroleum imports:

$$FUELCONS_{YR,energy\ tankers,CD} = FUELCONS'_{YR,energy\ tankers,CD} \times [MGPETR_{YR} / MGPETR_{2012}]$$

where $MGPETR_{YR}$ represents the imports of "Petroleum and Products" in the Macroeconomic Activity Module. A list of NEMS variables that might be associated with the different vessel types is presented in Table 4-4.

Another option for the non-energy vessel classes would be to base growth rates on population growth rates within the U.S. Census Divisions. The U.S. Census last predicted national growth to rise from 321 million in 2015 up to 380 million by 2040.[43]

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[43] U.S. Census Bureau. "Population Projections: 2014 National Population Projections: Summary Tables." Last accessed from http://www.census.gov/population/projections/data/national/2014/summarytables.html on January 14, 2015.

Table 4-4. Potential NEMS Variables That Could Indicate Fleet Growth in Future Years

Vessel Class	Parameter	Module	Parameter Description
Energy tankers	MGPETR	Macroeconomic Activity Module	Real Imports of "Petroleum and Products"[44]
Non-energy tankers	XGINR	Macroeconomic Activity Module	Real Exports of "Industrial materials and supplies"
Containers	MGCR	Macroeconomic Activity Module	Real Imports of "Consumer goods except motor vehicles"
Gas (LNG)	NGLEXP	Liquid Fuels Market Module	Natural Gas Liquid export
Gas (LPG)	NGLEXP	Liquid Fuels Market Module	Propane export
Roll-on/roll-off	MGAUTOR	Macroeconomic Activity Module	Real imports of "Motor vehicles & parts"
Bulk - Energy	--	Coal distribution submodule in Coal Market Module	"CEXPRT" generates reports from the export portion of the linear program (plus petroleum coke exports)
Bulk – Non-energy	XGFFBR	Macroeconomic Activity Module	Real exports of "Foods, feeds and beverages"
General cargo	MGKR	Macroeconomic Activity Module	Real imports of "Capital goods except motor vehicles"

4.3 Compliance Choices

The final element in the determination of fuel projections is the allocation of energy consumption among the different fuel choices. Before describing the resultant profiles, several assumptions about the projections are discussed below:

1. Protocol takes effect:
    a. The North American ECA went into effect on January 1, 2015. It requires existing ships to either burn fuel containing a maximum of 0.1% sulfur or to use scrubbers to remove the sulfur emissions.
    b. On January 1, 2020 the IMO will require the sulfur content of fuel used outside of the ECA to be reduced to 0.5% (a possible five-year delay is possible and would be based on a 2018 re-evaluation).
2. Technology Introduction Year to Fleet
    a. EPA Tier 3: On January 1, 2016 all new build ship engines used in the ECA are required to be EPA Tier 3 compliant.
    b. LNG Vessels enter U.S. Fleet: In 2015 the first LNG-fueled container ship is due to become operational.

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[44] NEMS also tracks ethanol and biodiesel imports and exports. These variables could be added to the petroleum values to track total activity projections of energy tankers.

   c. Scrubber: While the exact date that emission scrubber technology was installed on commercial freight ships was not reported, DNV[45] estimated in a 2012 report that 30-40 percent of all new builds will have emission scrubber technology installed by 2016. After 2016, all new ships that consume fuel oil and will operate within the ECA are required to have scrubber and other emission control technologies installed.

3. Conventional engine using IFO: Prior to 2015 ships calling on the U.S. could operate on fuel used internationally and their ships did not require scrubbers to remove sulfur emissions. Nearly all large OGVs were powered by slow speed diesel engines that burned IFO 380 or IFO 180. IFO is 88-98 percent residual fuel oil with 2-12 percent distillate added to achieve proper viscosity. IFO for use outside an ECA has a maximum sulfur content of 3.5%.
4. Conventional engine using MGO: Existing ships can continue to operate in the ECA without scrubbers if they use MGO as their fuel oil.
5. Conventional engine with operating scrubber using IFO: Ships in existence before 2016 can continue to use a conventional engine and burn IFO within the ECA if the ship has installed sulfur scrubbers. Ships that enter service after January 1, 2016 must be equipped with sulfur scrubbers and NO_x controls technology.

The projection that new ships built after 2015 would install and operate scrubbers instead of burning MGO in the ECAs is based on a BIMCO study that presented the investment function for scrubbers versus MGO.[46] Calculations conducted for this project show that container ships from Asia and Europe would spend 16-21 percent and 43-49 percent of their operating time on voyages within ECAs.[47] The AEO 2014 reference case, high oil price case, and low oil price cases all showed high spreads between HFO and MGO prices after 2015 (over $600/metric ton), and the BIMCO summary indicated that such voyages and price spreads would justify the investment in scrubber technologies for new ships.[48]

These assumptions were used to build fleet profiles for the activity of OGVs within the North American ECA. The profiles appear in Table 4-5 for three scenarios developed by DNV.[49] The first scenario estimated that, if the price if LNG was 10 percent above the price of HFO, that 7.5 to 9 percent of new builds would use LNG as their fuel. The second scenario estimated that, if the price of LNG was 30 percent below the price of HFO, that 13 percent of new builds would use LNG as their fuel. The third scenario estimated that, if LNG was 70 percent below the price of HFO, that 30 percent of new builds would use LNG as their fuel. All three scenarios assume that any subsidies for a particular fuel or technology have already been incorporated into the cost comparison.

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[45] DNV, Report of Shipping 2020: http://www.dnv.nl/binaries/shipping%202020%20-%20final%20report_tcm141-530559.pdf; last accessed on January 20, 2015.

[46] “Business Case: Marine Gas Oil or Scrubbers When Operating in an ECA?” BIMCO. Published on April 25, 2013. Last accessed from https://www.bimco.org/Reports/Market_Analysis/2013/0424_ECAStory.aspx on January 22, 2015.

[47] Calculations done for voyages from Shanghai to Los Angeles and from Rotterdam to New York/New Jersey.

[48] Note that the BIMCO study reflects tanker ships, but similar curves could be derived for container ships.

[49] DNV report shipping 2020; Det Norske Veritas; NO-1322 høvik, Norway; www.dnv.com

Table 4-5. Fleet Profiles of Compliance Strategies under Three Scenarios

Year	Conventional engine using IFO (includes vessels with non-operating scrubbers)	Conventional engine using MGO	LNG Price 10% above HFO Price		LNG Price 30% below HFO Price		LNG Price 70% below HFO Price	
			Conventional engine with operating scrubber using IFO	LNG engine	Conventional engine with operating scrubber using IFO	LNG engine	Conventional engine with operating scrubber using IFO	LNG engine
2012	100%	--	--	--	--	--	--	--
2013	100%	--	--	--	--	--	--	--
2014	100%	--	--	--	--	--	--	--
2015	--	90%	10%	--	10%	--	10%	--
2016	--	77%	22%	1%	22%	1%	20%	3%
2017	--	64%	34%	1%	33%	2%	30%	6%
2018	--	51%	46%	2%	45%	4%	40%	9%
2019	--	39%	59%	3%	56%	5%	50%	11%
2020	--	26%	71%	4%	68%	6%	60%	14%
2021	--	13%	83%	4%	80%	7%	70%	17%
2022	--	--	95%	5%	91%	9%	80%	20%
2023	--	--	95%	5%	91%	9%	79%	21%
2024	--	--	95%	5%	91%	9%	79%	21%
2025	--	--	95%	5%	91%	9%	79%	21%
2026 and beyond	--	--	93%	8%	87%	13%	70%	30%

Table 4-5 shows that engines with scrubbers are more prevalent in the fleets in 2022 through 2025 than they are in years beyond that point. These high percentages occur because scrubbers were introduced to the new fleet before LNG vessels.

Scrubbers and other control devices do require energy, as do fuel chillers associated with the use of MGO. The model has been constructed to impose energy penalties for the use of MGO, LNG, and scrubbers. Such an energy penalty might also take the form of a decreased *cargo* footprint aboard vessels with the alternate fuels and control technologies. However, the energy penalties have not yet been well characterized and reported in the published literature. The energy penalties have been initially set to zero, except the penalty for scrubbers is set to 2 percent.[50,51] Designs are changing very rapidly with the introduction of these technologies aboard larger ships, so EIA should consider energy penalties for these systems that decrease over time.

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[50] ABS. Exhaust Gas Scrubber Systems: Status and Guidance. Last accessed from https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/References/Capability%20Brochures/ExhaustScrubbers on January 22, 2015.

[51] "EffShip Project Final Seminar." Published on 21 March 2013. Last downloaded from http://www.effship.com/PublicPresentations/Final_Seminar_2013-03-21/09_EffShip-Handout.pdf on January 16, 2015.

An energy penalty for older LNG gas ships could be approximated because they use a forced natural gas boil-off from the cargo tanks in steam boilers to produce steam for steam turbines. A steam turbine propulsion system has an energy efficiency of about 28 percent compared to the approximately 50 percent for a conventional slow-speed diesel engine. However, the number of LNG ships calling on U.S. ports is very small compared to total vessel calls and quantifying the declining number of older LNG gas ships using steam turbine propulsion systems would not significantly impact the overall report projections.

4.4 Fuel Estimates

Total fuel consumptions in each Census Division were multiplied by the fleet profiles and energy penalty corrections to determine the amount of each fuel consumed (as billion Btu) within the North American and U.S. Caribbean ECAs for each Census Division:

$$MARFUEL_{YR,CD,MFtype} = FLTPROF_{YR,MFtype} \times \left(1 + ENPEN_{MFtype}\right) \times \sum_{class=energy\ tankers}^{general\ cargo} FUELCONS_{YR,class,CD}$$

where $MARFUEL_{YR,CD,MFtype}$ = marine fuel consumed in ECA transit using *MFtype* fuel in year *YR* across Census Division *CD*

$FLTPROF_{YR,MFtype}$ = fraction of the fleet using *MFtype* fuel in year *YR*

$ENPEN_{MFType}$ = energy penalty associated with *MFtype* fuel[52]

Using the scenario where the LNG price is 30 percent below the HFO price, Table 4-6 shows the marine fuels consumed in the North American and U.S. Caribbean ECAs in 2021. That year is the last one in which MGO fuel is likely to be used (Table 4-5).

Table 4-6. Total Fuel Consumed (Billion Btu) in North American and U.S. Caribbean ECAs in 2021 by Marine Fuel Type

Census Division	IFO	LNG	MGO	Total
New England	2,200	200	350	**2,700**
Middle Atlantic	12,000	1,100	1,800	**14,000**
Midwest	-	-	-	**-**
West North Central	-	-	-	**-**
South Atlantic	33,000	3,000	5,200	**41,000**
East South Central	3,100	290	500	**3,900**
West South Central	34,000	3,100	5,300	**42,000**
Mountain	-	-	-	**-**
Pacific	37,000	3,400	5,900	**46,000**
Puerto Rico	590	53	90	**730**
Nationwide	**120,000**	**11,000**	**19,000**	**150,000**

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[52] The previous section discusses that the energy penalties were initially assigned as zero percent for LNG and MGO options.

The numbers in Table 4-6 were converted to the fuel types tracked in NEMS: residual fuel oil, distillate fuel oil, and LNG. Based on global estimates of marine fuel use,[53] the assumption was that low-sulfur IFO would be used in 2021 but that it would be composed of 10 parts IFO500 (0% distillate), 60 parts IFO 380 (2% distillate), and 6 parts IFO 180 (12% distillate). The results for 2021 using the scenario where the LNG price is 30 percent below the HFO price appear in Table 4-7.

Table 4-7. Total Fuel Consumed (Billion Btu) in North American and U.S. Caribbean ECAs in 2021 by NEMS Fuel Type

Census Division	Residual Fuel Oil	Distillate Fuel Oil	LNG	Total
New England	2,100	400	200	**2,700**
Middle Atlantic	11,000	2,100	1,100	**14,000**
Midwest	-	-	-	**-**
West North Central	-	-	-	**-**
South Atlantic	32,000	6,000	3,000	**41,000**
East South Central	3,100	570	290	**3,900**
West South Central	33,000	6,200	3,100	**42,000**
Mountain	-	-	-	**-**
Pacific	36,000	6,800	3,400	**46,000**
Puerto Rico	570	110	50	**730**
Nationwide	**120,000**	**22,000**	**11,000**	**150,000**

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[53] IEA-AMF Organization. A Report from the IEA Advanced Motor Fuels Implementing Agreement- Alternative Fuels for Marine Applications. May 2013. Last accessed from http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_41.pdf on March 31, 2015.

5 Recommendations

The recommendations for EIA's path forward include expanding the scope of the marine fuel estimates, fractionating the fuel purchases made in the U.S. versus abroad, and improving the future projections of fuel usage. An initial recommendation would be to consider a sensitivity analysis and determine the factors (e.g., slow steaming reductions and auxiliary power needs) that would most affect the fuel consumption estimates. A sensitivity analysis would help determine the factors for later investigations and also the best ways to relate the model to EIA's model scenarios.

The expansion of the scope would likely center on improving EIA's estimates of fuel usage in waters beyond the North American and U.S. Caribbean ECAs:

1. Remainder of ocean voyages beyond the ECAs
2. Great Lakes transit[54]
3. Inland waters transit

The expanded scope might also include fuel usage estimates for additional ships that may be more tied to U.S. ports for fuels:

1. Tugs, barges, and lightering vessels
2. Fishing vessels (most operate with C1 engines)
3. Cruise ships
4. Other commercial vessels

While the number of ships that operate full-time or nearly full-time in the North American ECA is small, they may exert a disproportionate influence on total energy consumption within the ECA due to the time that they spend in the ECA. Many of these will be U.S.-flagged vessels and include non-cargo vessels such as port tugboats and ferries. Their fuel consumption would be calculated with different assumptions about time spent within the ECA.

The U.S. commercial deep draft fleet and the U.S.-flagged oceangoing tug and barge operations to Alaska, Hawaii, Puerto Rico, and the Virgin Islands were considered very small and likely captured as port calls by the larger ships in the MARAD data.

A future study might examine fuel purchasing to better understand what fraction of the fuel consumed within the ECAs was purchased at U.S. ports.

Many factors affect the total fuel consumption estimates (e.g., transit time, engine efficiency, loads, and auxiliary power usage). The recommendations below address changes that could be made to baseline fuel consumption estimates (and those through 2014/2015):

1. Update the estimates to give consideration to active vessel speed reduction (VSR) programs which are currently required at a number of ports, which are mostly on the west

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[54] These vessels and the inland fleet were excluded from this current model. The inland fleet (about 3,000 towboats) is using generally using domestically procured diesel oil for fuels, while the large Great Lake ships (about 76 North American ships full-time and 800 foreign port calls/year from Europe) are using IFO. The U.S. EPA has allowed some alterations to the ECA regulations in the Great Lakes.

coast (including Ports of Long Beach, Los Angeles, and San Diego), and by the Port Authority of New York and New Jersey. VSR has also been evaluated at the Ports of Seattle and Tacoma, as well as the Port of Houston Authority. These speed reductions would be applied on a port-by-port basis and not scaled directly to the entire U.S. Census Division.

2. Update the estimates to give consideration to the expanding use of on-shore power (cold ironing). The Ships at Berth Regulation (California Air Resource Board) began requiring use of on-shore power by OGVs by 50 percent of the fleet visits to California ports starting in 2014. Fleets affected by this regulation include container vessels, passenger vessels, and refrigerated cargo vessels.
3. Give future consideration in the model to congestion issues and delays at sea or at berth due to local infrastructure constraints or labor issues.

Other investigations might yield better estimates of the fuel types consumed in the baseline estimates. Worldwide numbers might be distributed to North America and the U.S. using the resources of BIMCO, IMO, and United Nations Conference on Trade and Development. An appropriate fraction of those numbers could be applied to the North American and U.S. Caribbean ECAs.[55]

Additionally some recommendations would apply to estimates in the future projections:

1. According to the baseline estimates in this study, 26 percent of the energy used for port calls was for auxiliary power. Auxiliary power requirements are the least documented on an international scale, but there is sufficient documentation available on a ship-by-ship basis to create typical auxiliary power needs by ship class. In addition, auxiliary power requirements can be greatly reduced by implementing new practices such as waste heat reclamation, cold ironing, solar panels, and switching to distillate fuels that do not require preheating.
2. Fully analyze the BIMCO report that chooses between using scrubbers versus burning MGO in ECAs.[56] Perform a similar set of cost calculations for container ships because they represent almost half of the fuel consumption within ECAs in 2012.
3. Ship design speeds and engine sizes: A new study might predict potential cost savings or energy efficiencies based on multiple changes to ship design trends (e.g., ship speed, ship size, engine types, new technologies, adoption of best practices, and new environmental safeguards), their installation/operational costs, and confidence in the technologies involved (expressed as a probability of expected performance). This new study with an economics basis would allow for gaming potential changes and be based on the highest levels of expected return.

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[55] A 2008 report prepared for the U.S. EPA (Global Trade and Fuels Assessment—Future Trends and Effects of Requiring Clean Fuels in the Marine Sector, EPA420-R-08-021, November 2008) stated that Houston's heavy fuel oil for marine activities was mostly imported from refineries in Venezuela, Mexico, and Aruba, so an understanding of U.S. imports for marine fuel might also be important.

[56] BIMCO. "Business Case: Marine Gas Oil or Scrubbers When Operating in an ECA?" Published on 25 April 2013. Last accessed from https://www.bimco.org/Reports/Market_Analysis/2013/0424_ECAStory.aspx on January 22, 2015.

4. Add a Technology Adoption Model (TAM) to project the selection of strategies and associated fuel type for meeting marine environmental regulations. The primary TAM outputs would be marine demand for HFO, MDO, and LNG. The model would enable analyses of the effects of fuel prices, capital cost changes, and policy measures on the proportionate use of the different marine fuels. Model inputs and availability of these inputs are summarized in the Table 5-1. The TAM would also consider fuel incentives and low emissions shipping incentives.

Table 5-1. Model Inputs for a Possible Technology Adoption Model for Fuel Use Projections

Model Input	Data Availability
Number of vessels by census region and ECA/non-ECA trade partner	Readily available at national level – assumptions would likely be needed for regional level
Number of vessels by type and size class for tankers and container ships	Readily available at national level – regional level is available with additional effort
Number of vessels by age class	Readily available at national level – assumptions would likely be needed for regional level
Total marine energy demand by region	An input from the output of the current project
Inland and coastal vessel energy demand by fuel type	An input variable as manual entry or from a separate coastal/inland technology adoption model
Fuel prices	An input from NEMS
Average engine efficiency	Available – some assumptions would be needed for applying to each vessel type and size class
Strategy capital costs	Available – some assumptions would be needed for applying to each vessel type and size class
Strategy operating costs	Available – some assumptions would be needed for applying to each vessel type and size class
Representative industry discount rate	Available

Appendix A. Matrix-Based Derivations of Baseline Estimates

A.1 Notation

Class = Tanker, Container, Gas (LPG/LNG), Roll-on/Roll-off, Bulk, or General Cargo

CD = 9 U.S. Census Divisions and Puerto Rico

Year = 2012

A.2 Formulas

For the total nautical miles traveled:

$TOTNMI_{2012,class,CD} = \sum_{all\ ports\ in\ CD} CALLS_{2012,class,port} \times ECADISTPERCALL_{port}$

where

$CALLS_{2012,class,port}$ = number of calls to MARAD-tracked port in 2012 (by class and port)

$ECADISTPERCALL_{port}$ = distance traveled across ECA for port entry and exit (nautical miles)

For the average dead weight tonnage:

$AVGDWT_{2012,class,CD} = TOTALDWT_{2012,class,CD} / CALLS_{2012,class,CD}$

where

$CALLS_{2012,class,CD}$ = number of calls to all MARAD-tracked ports in 2012 (by class and CD)

$TOTALDWT_{2012,class,CD}$ = total dead weight tonnage for all MARAD-tracked ports in 2012 (by class and CD)

For the total work associated with transit (ton-miles):

$ECATRANSITWORK_{2012,class,CD} = TOTNMI_{2012,class,CD} \times AVGDWT_{2012,class,CD}$

For the time transiting the ECA (hours):

$TIMETRANSITINGECA_{2012,class,CD} = TOTNMI_{2012,class,CD} / [ENGDESSPD_{class} \times SLOWSTMSPDRED_{class,CD}]$

where

$ENGDESSPD_{class}$ = engine design speed (knots)

$SLOWSTMSPDRED_{class,CD}$ = percentage of engine design speed achieved during slow steaming

For the engine sizes (kW):

$ENGINESIZE_{2012,Class,CD}$ is a function of $AVGDWT_{2012,class,CD}$ and read from MAN tables

For the energy spent during transit (kWh):

$$TRANSITENERGY_{2012,class,CD} = ENGINESIZE_{2012,Class,CD} \times SLOWSTMPWRRED_{class,CD} \times TIMETRANSITINGECA_{2012,class,CD}$$

where

$SLOWSTMPWRRED_{class,CD}$ = percentage of engine power reduction achieved during slow steaming

The transit fuel consumption is computed by multiplying the transit energy by the specific fuel oil consumption for transit (e.g., 0.175 kg/kWh for post-2001 slow-speed diesel engines):

$$TRANSITFUELCONS_{2012,class,CD} = TRANSITENERGY_{2012,class,CD} \times SFOC_{transit}$$

where

$SFOC_{transit}$ = specific fuel oil consumption for main propulsion engines

The auxiliary power usage of ships is generally reported as a percentage of the power used for transit under design conditions (e.g., 5%). The auxiliary power is assumed to continue operating while in port or at anchor within the ECA (e.g., 21 to 62 hours for loading/unloading in port). Therefore, the auxiliary power spent while in the ECA can be calculated with the formula:

$$AUXENERGY_{2012,class,CD} = [ENGINESIZE_{2012,class,CD} \times PCTAUX] \times [TIMETRANSITINGECA_{2012,class,CD} + PORTTIME_{class} \times CALLS_{2012,class,CD}]$$

where

$PCTAUX$ = percentage of the power used for transit under design conditions

$PORTTIME_{class}$ = average time spent in port or at anchor by a specific vessel class

The auxiliary fuel consumption is computed by multiplying the auxiliary energy by the specific fuel oil consumption for auxiliary engines (e.g., 0.225 kg/kWh):

$$AUXFUELCONS_{2012,class,CD} = AUXENERGY_{2012,class,CD} \times SFOC_{aux}$$

where

$SFOC_{aux}$ = specific fuel oil consumption for auxiliary engines

For the total fuel consumption while in the ECA (Btu):

$$FUELCONS_{2012,class,CD} = TRANSITFUELCONS_{2012,class,CD} + AUXFUELCONS_{2012,class,CD}$$

Appendix B. Ship Routes to Avoid Significant Travel in North American ECA

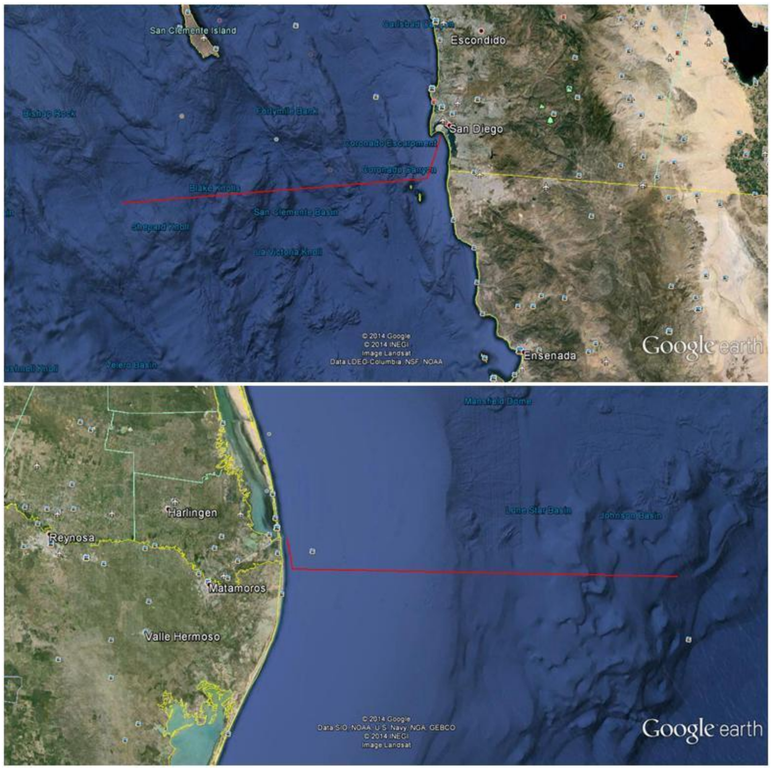

Figure B-1. Ship routes (to San Diego- top and Brownsville- bottom) that would avoid most of the North American ECA by staying south of the ECA until jogging north to cross from Mexican into U.S. waters (shown as red lines)

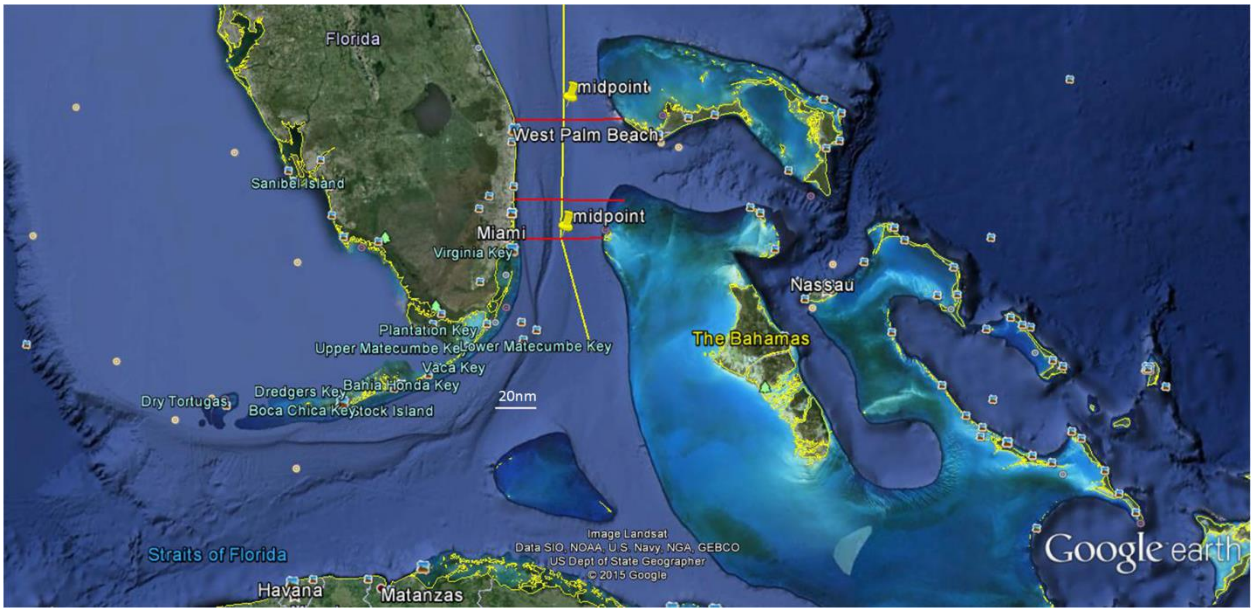

Figure B-2. Approximate boundary (yellow) of North American ECA as a result of proximity to the Bahamas. White line shows a 20-nautical mile scale.

Appendix C. Adoption of Compliance Strategies by Ship Industry

C.1 Strategy Selection: Current Status

A typical economic evaluation for the selection of emissions compliance strategies includes standard economic measures of the capital and operating and maintenance (O&M) costs, savings associated with the use of cheaper fuels (i.e., HFO or LNG), and summary measures of payback and net present value (NPV). However, the confidence that can be placed in economic feasibility comparisons of marine compliance strategies at the present time is substantially limited by the immaturity of the technologies associated with two of the key strategies: exhaust scrubbers and LNG propulsion systems. While these strategies have been applied to land-based systems for decades, they have only been applied to relatively few ships within the last few years. The harsh marine environment (e.g., corrosive seawater), tight space limitations, and a high degree of design customization on marine vessels are significant factors to which manufacturers must adapt their products. Marine sulfur scrubbers and SCR systems and LNG propulsion systems can be described as being in the demonstration phase of development. Although multiple products are on the market for these strategies, it is estimated that there were fewer than 100 ships with LNG propulsion systems in 2013.[57] With respect to scrubbers, according to the Exhaust Gas Cleaning Systems Association, as of November 2014, there are around 300 scrubber systems installed or on order, with greatest growth among ferries, cruise ships, and roll-on/roll-offs that spend a substantial portion of their time in ECAs.[58] Experience with SCR on marine vessels is more substantial – it has been applied to marine vessels for about 25 years, primarily as a retrofit. In 2013, there were 519 vessels operating with SCR worldwide.[59] With a longer history of marine applications, and installation costs that are roughly one-tenth the costs for scrubbers, SCR represents a much lower financial risk than sulfur scrubbers or LNG, and is only needed for new builds beginning in 2016.

The tight profit margins associated with the highly competitive shipping industry mean the risks associated with adoption of a multi-million-dollar new technology can make or break a shipping company. With this understanding, a cautious adoption of scrubbers and LNG propulsion systems is expected, and most shippers will “test” one or both of these new technologies on a few of their vessels before making firm decisions regarding adoption for the remainder of their fleet. Further, since sulfur scrubbers and LNG substitution are strategies that comply with the 0.1% fuel sulfur requirements for both existing and new-build vessels operating in ECAs, retrofits are viewed as a key near-term developing market for these strategies in addition to new-builds. While some new builds on order incorporate sulfur scrubbers or LNG propulsion systems, others are being dubbed as “LNG conversion-ready” and “scrubber-ready,” thereby postponing the determination of an optimal compliance strategy.[60]

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[57] Shaw, Jim, May 1, 2013. “Propulsion: Is LNG the Future?” Pacific Maritime Magazine, http://www.pacmar.com/story/2013/05/01/features/propulsion-is-lng-the-future/152.html

[58] The Maritime Executive, November 30, 2014. “Scrubber Sales Accelerate.” http://www.maritime-executive.com/article/Scrubber-Sales-Accelerate-2014-11-30

[59] Alyson Azzara, Dan Rutherford, Haifeng Wang, March 2014. “Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction,” ICCT Working Paper 2014-4, http://www.theicct.org/sites/default/files/publications/ICCT_MarineSCR_Mar2014.pdf

[60] Ship & Bunker, September 17, 2014. “Construction Underway for "LNG-Conversion-Ready" Eco-Tankers,” http://shipandbunker.com/news/am/519431-construction-underway-for-lng-conversion-ready-eco-tankers

Common reasons for postponing selection of LNG and scrubber strategies include the lack of technology maturity for both of these strategies; uncertainty in regulations for LNG bunkering as well as for scrubber waste handling and disposal;[61] the availability of trained crews (for both LNG and scrubbers); LNG fuel availability; and uncertainty in fuel price.[62] While the general difference in HFO and MDO fuel prices is typically viewed as likely to continue, the magnitude of this difference is more uncertain, and there is yet more uncertainty in the relative price of LNG both over time and among global regions. The recent introduction of new financial instruments that shift fuel price risk from ship owners (or charterers) to financiers who pay for LNG or scrubber capital costs and collect the fuel savings as borrowers pay for the MDO that would have been burned[63] may help to reduce the current avoidance of strategy selections that promise long-term savings.

Many analysts are suggesting that the optimal compliance strategy will vary by individual ship depending on typical routes, proportion of time traveling in an ECA, frequency of use on other routes, engine design (i.e., ease of conversion to LNG), vessel design and balance,[64] and vessel age. With respect to routes, the availability of fuel and maintenance services will influence strategy selections, and percent time in an ECA will substantially affect the magnitude of potential fuel savings and associated payback for both scrubbers and LNG.

While it will take years for adoption of strategies using currently immature technologies to become a significant portion of the OGV fleet, the technology options suggest the possibility that the marine transportation sector may ultimately demand three primary fuel types: distillate fuel, residual fuel, and LNG.

C.2 Projections of LNG and Scrubber Adoptions

Both scrubbers and LNG strategies are thought to be at the beginning of the traditional technology adoption “S-curve.” Several studies have projected that the adoption of scrubbers and LNG will initially be greatest among inland and coastal fleets that spend most of their time in ECAs or in regions with ECA-equivalent regulations (i.e., inland US waterways) where it would be easiest to build out the LNG bunkering. Regional liners with fixed routes are among the key targets for LNG. Some analysts suggest that scrubbers will be more prevalent in the regional European Union (EU) fleet than in the U.S., where LNG prices are expected to be more favorable.[62,63] The more expensive closed-loop or hybrid scrubbers associated with low alkalinity (fresh) water supplies will also facilitate LNG competitiveness in inland waters.

A number of groups have developed models for examining compliance strategy economics with regard to LNG market penetration, and some of these extend their analyses to project strategy

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[61] Maritime Denmark, November 12, 2014. “Shipowners want information on scrubbers.” http://www.maritimedenmark.dk/?Id=18087

[62] Semolinos, Pablo, et al., 2013. LNG as marine fuel: Challenges to be overcome. 17th International Conference and Exhibition on Liquefied Natural Gas (LNG17), Houston, TX, April 16-19, 2013. http://www.gastechnology.org/Training/Documents/LNG17-proceedings/7-2-Pablo_Semolinos.pdf

[63] Ship & Bunker, June 26, 2014, "Industry Insight: Financing the Cost of ECA Compliance," http://shipandbunker.com/news/features/industry-insight/263088-industry-insight-financing-the-cost-of-eca-compliance

[64] Some vessels may become unstable with the additional weight of a scrubber(s) at the top of the exhaust stack, others may not have enough space in the funnel casing for a scrubber system, and still others do not have the space to accommodate the larger footprint needed for LNG.

adoption over time. These collective results are summarized below for the next five years and then the subsequent ten years (2020 to 2030).

2015 to 2020 -- Inland ships and short sea ships (coastal shipping) with fixed routes are expected to be the first significant adopters of scrubber and LNG strategies due to the more rapid payback for vessels that operate almost entirely in regions with ECA-equivalent regulations.[62,65,66] There will be a preference for LNG among vessels that are unable to install scrubbers due to design and stability issues (i.e., more common among ferries, roll-on/roll-offs, and product tankers).[62] Other analysts have identified ferries and offshore supply vessels as prime candidates for the initial phase of LNG adoption in the U.S.[67]

A study by DNV that considers global LNG bunker demand for new-build OGVs estimates that in 2020, LNG demand will be in the range of 8 to 33 million tons per annum (Mtpa), or 400 to 1,700 TBtu/yr. Corresponding HFO demand is estimated to be 80 to 110 million tons (13,000 to 20,000 ships with scrubbers) assuming the global sulfur rule begins in 2020. Other analyses that consider a wider range of vessel types suggest more favorable economics for LNG among small and mid-size ships versus large and very large ships.[62,65] The expected proportion of new-builds versus retrofits is expected to vary among vessel types and will likely be determined by both fuel price spreads and early reports of experiences with both scrubbers and LNG. A study by Angola LNG and Total that considers vessel types and adoption behaviors estimates that by 2020, bunker LNG demand will be in the range of 3 to 5 Mtpa (150 to 250 TBtu/yr) in North America and 5 to 8 Mtpa in Europe.[62] While these total LNG demand estimates are similar to DNV's 2020 low-end LNG demand estimates, the critical distinction is where the demand is located. In the view of the Angola LNG and Total paper, smaller ports will gradually develop sufficient LNG demand to invest in larger LNG bunkering operations that will facilitate LNG adoption among deep-sea liners in the next decade.

2020 to 2030 -- After LNG becomes available in several ports in a region (i.e., North America, Europe and Asia), some short sea ships without fixed routes may begin to convert as well as some deep sea liners (intercontinental shipping). The latter, in particular, are expected to be primarily new or recently built vessels designed to be "conversion-ready." Major container-ship operators will begin ordering a few LNG ships to test this strategy, and if the tests prove positive, will likely diversify their fuel and technological risks by switching part of their fleet to LNG.[62] However, the need for route flexibility limits the use of LNG among deep sea very large crude carriers (VLCCs) and bulk carriers, suggesting a higher rate of scrubber use among these categories.

A study by Marine and Energy Consulting has projected that globally about 6,000 marine scrubber systems will operate on ships by 2025, consuming 28 million metric tons of HFO per year (a slower adoption rate than the low end of 80 million tons estimated by DNV for 2020). The Marine and Energy Consulting study also suggests that in 2025, about 1,700 smaller vessels

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[65] Andersen, Mads Lyder *et al*., 2011. "Costs and benefits of LNG as ship fuel for container vessels: Key results from a GL and MAN joint study." http://www.gl-group.com/pdf/GL_MAN_LNG_study_web.pdf

[66] Zeus Intelligence, May 27, 2014. "LNG Ready: The Key to Deep-Sea LNG Fuel?" http://member.zeusintel.com/ZLFMR/news_details.aspx?

[67] Zeus Intelligence, July 23, 2013. "Economic Analysis of LNG Vessel Costs in North America," http://member.zeusintel.com/ZLFMR/news_details.aspx?newsid=30096

will consume 8 Mtpa (400 TBtu/yr) of LNG, representing about 11% of total bunkers.[68] In contrast, the study by Angola LNG and Total estimates that by 2030, global bunker LNG demand will be considerably higher, in the range of 20 to 30 Mtpa (1 to 1.5 QBtu/yr).[62]

C.3 Compliance Strategy Cost Estimation

The three Tier III compliance strategies could employ a total of four technologies: LNG propulsion systems, exhaust scrubbers, MDO adaptations, and SCR (the latter of which is used in conjunction with the previous two technologies). The additional uncertainties that surround the use of immature technologies for scrubbers and LNG compliance strategies limit the confidence in cost estimates for these strategies. Technology improvements in production and installation of engines and fuel systems are expected to largely decrease the installation costs for LNG and scrubbers, reducing the payback period for projects. The costs provided in this section do not attempt to adjust for anticipated cost-reductions as these technologies mature. Costs associated with each of the four technologies are briefly discussed below followed by a summary table of “typical” costs for the technology (Table C- 1).

MDO Adaptation **--** Most OGV are designed to operate on HFO, but can burn MDO with the addition of a fuel cooler or chiller and associated piping prior to the fuel pump to decrease fuel viscosity.[69] This retrofit typically requires about fourteen days in the shipyard.[70] The cost of modification for a medium range tanker (38,500 dwt, 9,4800 kW MCR) to use MDO has been estimated to be around $800,000, including the fuel cooler, piping, shipyard services, etc.[70] This cost will vary with vessel size and design, and the ability to include this conversion during regularly scheduled shipyard visits. MDO is already available in ports and there are no problems regarding regulations, logistics or operations. However, if demand for MDO rises significantly, infrastructure expansions would be needed, and refining balances in some regions may be disrupted with resulting price impacts until new equilibriums are established.[71] This increases the fuel price risk for operating with MDO.

SCR **--** The costs of SCR are driven by capital costs, which vary with engine design. In general, the larger the engine, the less expensive the installation costs per kW. SCR operating expenses are dominated by the cost of the reducing agent (urea). Additional operational costs are incurred for catalyst replacement (typically every five or six years) and for the additional fuel consumption associated with SCR use.[72]

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[68] Ship & Bunker, April 7, 2014. “$15 billion in Scrubber Sales Predicted by 2025,” http://shipandbunker.com/news/world/707962-15-billion-in-scrubber-sales-predicted-by-2025

[69] The International Council on Combustion Engines (CIMAC), 2013. “Guideline for the operation of marine engines on low sulfur diesel,” http://www.cimac.com/cms/upload/workinggroups/WG7/CIMAC_SG1_Guideline_Low_Sulphur_Diesel.pdf

[70] Kotakis, Nikolaos K. 2012, “Cost Comparative Assessment Study between Different Retrofit Technologies applied on Model Ship to Conform to IMO MARPOL 73/78, Annex VI, Reg. 14,” Masters Thesis, University of Greenwich. https://www.academia.edu/8507275/Cost_Comparative_Assessment_Study_between_Different_Retrofit_Technologies_applied_on_Model_Ship_to_Conform_to_IMO_MARPOL_73_78_Annex_VI_Reg._14

[71] It should be noted that refining balance issues are more commonly cited as a concern for Europe than for North America.

[72] IACCSEA, 2012. “White Paper: The Technological and Economic Viability of Selective Catalytic Reduction for Ships”, http://www.iaccsea.com/fileadmin/user_upload/pdf/iaccsea_white_paper.pdf .

In a study of the North Sea fleet adoption of NO_x strategies, technologies considered include SCR, EGR, and LNG.[36] The analysis did not require application of the same technology to both the main and auxiliary engines. It was found that for 2-stroke engines, annual total (i.e., levelized) costs of EGR were only 68% of the SCR costs (on average), while SCR costs for 4-stroke engines were 83% of EGR costs.[73] Levelized costs of the most cost-efficient NO_x strategy were found to vary greatly by both ship size and type. In the North Sea Fleet analysis, the fleet's total compliance costs were estimated for comparison to total benefit costs, and compliance capital costs were linked to the number of new ships projected to be built from 2016 to 2030, with consideration of efficiency changes and slow steaming. Throughout the analysis timeframe, fuel and capital costs represented 12-14% and 58-59% of the total costs, and the non-fuel operating costs ranged from 27-30%. This distribution suggests that fuel price changes over time are a relatively minor cost component for NO_x compliance.

With respect to capital costs for SCR installation on 2-stroke, slow speed engines, the following linear relationship to engine size has been found (using Euros): €/kW = -0.71a + 59.5 where "a" is the engine size (kW).[36] This relationship suggests a relative reduction in SCR cost with engine size.

Sulfur Scrubbers -- The capital costs of scrubber installation vary significantly with vessel design. Scrubbers may treat one or more engines. Scrubber retrofit costs are increased when there is a need for major modification of the ship's exhaust funnel to accommodate the scrubber system. Advances in both scrubber size reduction and multi-streaming configurations that enable the use of one scrubber unit for multiple engines[74] and varying loads are promising developments for capital cost reductions. Furthermore, new scrubber designs that are lighter and lower the system's center of gravity enable compatibility of scrubber systems on a wider range of existing vessels.

The retrofit of a typical vessel with a 10-MW engine includes around 25 days in the shipyard, with roughly half of the installation costs associated with the scrubber system equipment, and the remainder for the shipyard account, certifications, inspections, etc.[70,75] Initial scrubber purchases were dominated by open-loop designs, but hybrid scrubbers are becoming more common to provide the greatest flexibility in routes by enabling travel in ECA coastal and inland waters with low alkalinity. Recognizing this trend, the cost summary table below (Table C- 1) assumes a hybrid scrubber, which typically costs around 20% more than an open loop scrubber.[76]

In addition to capital costs, the use of scrubbers has incrementally higher operating costs due to the added logistics and maintenance for water treatment products and sludge management, and

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[73] In general, 2-stroke engines are more common for the main engines of larger vessels, while 4-stroke engines are more common for auxiliary engines and smaller vessel main engines.

[74] Exhaust Gas Cleaning Systems Association (EGCSA), November 18, 2014. "CR Ocean Industries Scrubber – Lighter, Smaller, More Efficient," http://www.egcsa.com/another-egcsa-member-cr-ocean-engineering-llc/

[75] Nielsen, Christian Klimt and Christian Schack, 2012. "Vessel Emission Study: Comparison of Various Abatement Technologies to Meet Emission Levels for ECA's", 9th annual Green Ship Technology Conference, Copenhagen 2012. http://www.greenship.org/fpublic/greenship/dokumenter/Downloads%20-%20maga/ECA%20study/GSF%20ECA%20paper.pdf

[76] Aminoff, Tomas, 2014. "A glance at CapEx and OpEx for compliance with forthcoming environmental regulations," 16th Annual Marine Money Greek Forum, October 15, 2014, http://www.marinemoney.com/sites/all/themes/marinemoney/forums/GR14/presentations/1220%20Tomas%20Aminoff.pdf

fuel consumption increases of 1 to 3%. Over the years, new-generation scrubbers with more efficient operation resulting in less frequent catalyst replacement and a lower fuel penalty may gradually reduce these costs.[77] As scrubber technology for marine applications matures, both the capital and operating costs of this compliance strategy are expected to decrease in terms of real dollars.

Achieving a reduction of sulfur by using a wet scrubber means increasing power usage significantly to pump water.

***LNG* --** The capital costs of new-build LNG vessels are currently estimated to be about 20% more than conventional vessels.[76] Approximately one sixth of the incremental capital costs for LNG relate to the vessel engines, while the remainder is for the LNG storage tanks, safety systems, and other ship modifications.[78] Vessel retrofits to use LNG typically take around 45 days, but this will likely be reduced for the new "conversion-ready" vessels. The immaturity of LNG technology for marine applications substantially limits the confidence in current engine and storage costs to be representative of capital costs several years in the future. For example, one engine manufacturer has claimed that their recently introduced LNG engine provides a 15 to 20% reduction in capital costs as a result of design improvements.[27]

The lower energy density of LNG compared to MDO and HFO means the fuel tank has a larger footprint. As such, conversion of existing vessels to LNG requires a higher threshold of fuel savings to compensate for greater cargo losses with LNG, which are of greatest concern for container ships and bulk carriers. The medium-sized container vessels (4,600 TEU to 8,500 TEU) are estimated to have the largest proportionate cargo losses, equivalent to as much as 3% of cargo capacity.[65] Cargo losses are reduced for new-builds that are designed for LNG use, and the ongoing development of membrane fuel tanks that conform to the ship's hull can further reduce cargo losses.[62] For retrofits, some types of tankers and roll-on/roll-offs are thought to be able to relatively easily install type C LNG storage tanks on the deck with no or minimal cargo losses.[62]

Maintenance costs for the LNG propulsion system are general estimated to be around 15% lower than those costs for conventional vessels,[76] but experience with these vessels has not been extensive enough to provide substantial field confirmation of the magnitude of this expected benefit. Other non-fuel operation costs such as crew and spare parts have been estimated to be 10% higher than for MDO.[65] Additional costs associated with the learning curve for use of a cryogenic fuel are also not well established.

LNG bunker costs include the regional LNG fuel price and port logistics costs. For ports with small LNG bunkering operations, these costs are estimated to be in the range of \$2 to \$3.5/MMBtu. Unit costs can be lower for larger ports but initial investment is higher, and the risk of overinvestment is viewed as particularly high when the market supplied is less than 0.25 Mtpa. An incremental growth in port capabilities for LNG bunkering is viewed as a means to control these risks, with initial bunker operations supplied by trucks. Investment in port infrastructure for LNG buffer storage, LNG bunker vessels, and port-side liquefaction becomes more appealing as LNG bunker demand approaches and exceeds 1 Mtpa.[62]

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[77] Exhaust Gas Cleaning Systems Association (EGCSA), November 18, 2014. "CR Ocean Industries Scrubber – Lighter, Smaller, More Efficient," http://www.egcsa.com/another-egcsa-member-cr-ocean-engineering-llc/

[78] American Clean Skies Foundations (ACSF), 2012, Natural Gas for Marine Vessels, US Market Opportunities," http://www.arcticgas.gov/sites/default/files/documents/2012-clean-skies-lng-marine-fuel.pdf .

The table below provides typical costs for each of the discussed compliance strategies for an average vessel with a 10-MW main engine. The point costs shown in this table are an average of the referenced sources, which are for engines within 20% of the target size (i.e., 10 MW).

Table C- 1. Typical Preliminary Cost Estimates for an "Average" Ship with a 10,000 kW Engine

Control Option	**Capital Costs**		**Incremental Operating Costs** *(non-fuel, 100% time in ECA)*	
	$ millions	*Source*	$ millions/ year	*Source*
MDO *(i.e., fuel chiller and piping)*	0.8	*a*	*minimal*	
Scrubber (hybrid)	6.5	*a, b, c, e*	0.1 *(sludge handling)* 0.1 *(catalyst, levelized cost)* 0.2 *(caustic soda)*	*c, e*
LNG	9.3	*a, b, c*	*15% maintenance reduction*	*e*
SCR	0.5	*d*	0.2 *(urea)*	*c, d*

a. Kotakis, Nikolaos K., 2012. "Cost Comparative Assessment Study between Different Retrofit Technologies applied on Model Ship to Conform to IMO MARPOL 73/78, Annex VI, Reg. 14," Masters Thesis, University of Greenwich. https://www.academia.edu/8507275/Cost_Comparative_Assessment_Study_between_Different_Retrofit_Technologies_applied_on_Model_Ship_to_Conform_to_IMO_MARPOL_73_78_Annex_VI_Reg._14

b. Nielsen, Christian Klimt and Christian Schack, 2012. "Vessel Emission Study: Comparison of Various Abatement Technologies to Meet Emission Levels for ECA's", 9th Annual Green Ship Technology Conference, Copenhagen 2012. http://www.greenship.org/fpublic/greenship/dokumenter/Downloads%20-%20maga/ECA%20study/GSF%20ECA%20paper.pdf

c. Hagedorn, Matthias, 2014. "LNG Engines, Specifications, and Economics", Rostock LNG Value Chain Seminar, Klaipeda 2014. http://www.golng.eu/files/Main/20141017/Rostock/LNG%20Shipping%20Session%20II%20-%20LNG%20Engines-Specifications%20and%20Economics-%20W%C3%A4rtsil%C3%A4,Ship%20Power%20-%20Hagedorn.pdf

d. International Association for Catalytic Control of Ship Emissions to Air (IACCSEA), Marine SCR – Cost Benefit Analysis. http://www.iaccsea.com/fileadmin/user_upload/pdf/SCR_cost_calculation_model2_v1.pdf

e. Aminoff, Tomas, 2014. "A glance at CapEx and OpEx for compliance with forthcoming environmental regulations," 16th Annual Marine Money Greek Forum, October 15, 2014, http://www.marinemoney.com/sites/all/themes/marinemoney/forums/GR14/presentations/1220%20Tomas%20Aminoff.pdf

Appendix D. Computation of Port Times

During the time a ship is at anchor or is at berth the main propulsion engine is usually shut down, but the auxiliary power units continue to operate. Initially the combined time at anchorage and in port was assumed to be 72 hours. The time the ship spends in port is usually dependent on the time it takes to load/unload the ship and contingent on the volumes involved and the efficiency of the loading/unloading operations. Both times at anchor and times in port are impacted by peak loading periods. While port data are not available from all ports regarding these times, there are sufficient data available to better approximate these times by terminal types (i.e., large west coast container terminals, large east coast container terminals petroleum terminals, and coal loading terminals).

Ships are sometimes diverted to ship anchorages in or near the port prior to going to the terminal where they will load or unload cargo. The primary reason for going to an anchorage is that the ship berth at the destination terminal is not available (another ship is there). Other reasons include the need to wait until high tide if channel depth is not adequate, or the U.S. Coast Guard requires a ship inspection prior to the ship entering port. The first two reasons for a ship going to anchorage are schedule-related and are avoided or minimized, in most cases, by proper planning. Inspections by the Coast Guard do not normally require the ship to go to anchorage 'unless there is a compelling reason (high interest vessel, specific intelligence, or other intelligence that renders the risk of a vessel entering port to be high without a Coast Guard exam for safety and/or security); the exams will be conducted either in port or sometimes while *en route* to the facility.'[79] Because of the infrequency associated with anchorage, anchorage times are not reflected in the calculations.

D.1 Container Ships

Port times for container ships were based on berth productivity rates (container handling speed) and volume of containers moved/handled.[80] A Journal of Commence sponsored study[81] determined that berth productivity was generally based on the average ship size (capacity) being worked. MARAD data[5] was used to calculate the average ship size (in TEUs) for each of the 32 ports that were used to estimate the port times for the model. Six ports also had berth productivities listed in the white paper. By assuming two eight-hour shifts for loading/unloading, the berth productivity per day was computed by multiplying by sixteen hours per day. The time in port was computed by dividing the number of TEU handled per call by the berth productivity (TEU per day).

The number of containers moved when a ship calls on a port includes containers being offloaded, loaded, or repositioned on the ship. In theory, a port can unload and load 200 percent of a

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[79] Email from USCG headquarters on February 24, 2015; Michael.L.Blair@uscg.mil

[80] Berth arrival and departure refer to "lines down" and "lines up" — that is, the actual arrival and departure of the ship at berth. The calculation of moves per hour between these two times is referred to as unadjusted gross berth productivity.

[81] JOC Group Inc. "Berth Productivity: The Trends, Outlook and Market Forces Impacting Ship Turnaround Times," July 2014. Accessed from http://www.joc.com/whitepaper/berth-productivity-trends-outlook-and-market-forces-impacting-ship-turnaround-times-0.

vessel's capacity (100% off, 100% on) in one port call.[82] An American Association of Port Authorities (AAPA) Advisory[83] was used to determine the total number of TEUs handled at the individual container ship ports. The number of containers handled in each port divided by the daily berth rate and number of container ship port calls yielded the average port time in days for container ships.

Data on container handling at six ports (Anchorage, Honolulu, Palm Beach, San Diego, San Juan, and Wilmington Delaware) produced outcomes that did not align with normal practices, so the schedules for those ports were examined in greater detail in order to compute the true times spent in port. Explanations for their deviations from standard container ship operations revealed that those average ships had not spent an inordinate number of days in ports, and the port times were adjusted based on reported values rather than on berth productivity.

The call-weighted average port times for the 32 ports were computed to be 1.8 days for container ships.

Note that fuel usage during port times has decreased significantly in California in recent years based on regulation requiring shore power[84] at the Ports of Hueneme, Los Angeles, Long Beach, Oakland, San Diego, and San Francisco.[85] This regulation affects the corporate fleets as follows:

- From 2014 through 2016, at least fifty (50) percent of the fleet's visits to the port shall connect to shore power.
- From 2017 through 2019, at least seventy (70) percent of the fleet's visits to the port shall connect to shore power.

State regulations were not the subject of this investigation, but adjustments could be made to the calculations to account for such measures in the years beyond the baseline. Connecting to shore power, also referred to as 'cold ironing', is a fairly rare occurrence outside of container and cruise ship terminals in California. A few cruise ship terminals in Washington, Alaska, New York, and elsewhere have shore power, but there was no indication that cargo ships are using shore connection outside of California, with the exception of one cargo ship operator in Tacoma.[86]

D.2 Tanker Ships and Tank Barges

Port times were generally based on the "Allowed Laytimes" published by Exxon, Phillips 66, Shell, and APEX oil.[87] Allowed Laytimes are the lengths of time vessels may occupy berths at a

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[82] Diagnosing the Marine Transportation System – June 27, 2012 Research sponsored by USACE Institute for Water Resources & Cargo Handling Cooperative Program www.tiogagroup.com/215-557-2142

[83] "NAFTA Region Port Container Traffic 2012." May 6, 2013. Published at http://aapa.files.cms-plus.com/Statistics/NAFTA%20REGION%20PORT%20CONTAINER%20TRAFFIC%20PROFILE%202012.pdf

[84] Section 93118.3 of Title 17, Chapter 1, Subchapter 7.5 of the California Code of Regulations. *Airborne Toxic Control Measure for Auxiliary Diesel Engines Operated on Ocean-Going Vessels At-Berth in a California Port.* Last accessed from http://www.arb.ca.gov/ports/shorepower/finalregulation.pdf, on February 27, 2015.

[85] The Ports of Hueneme, Los Angeles, Long Beach, San Diego, and San Francisco represented 73 percent of the 2012 dead weight tonnage of container ships in the Pacific Census Division (based on MARAD data).

[86] TOTEM Ocean Trailer Express uses shore power for two of its ships when they are in Tacoma; http://www.portseattle.org/Environmental/Air/Seaport-Air-Quality/Documents/nw_ports_clean_air_implementation_2013.pdf

[87] Information collected from multiple online documents: http://www.apexoil.com/mp.pdf, http://www.exxonmobil.com/files/corporate/bsa_marineprovisions_and_specialprovisions.pdf,

terminal in order to conduct transfer operations without incurring additional charges. Allowed Laytimes are essentially contract terms, often listed as 'Provisions for U.S. Delivery and Loading.' The contractual terms are fairly consistent across different companies. Tank barges are allotted 12-36 hours depending on size (24 hours was used for tank barge port time). If the average tank vessel calling on a port was 27,000 DWT (about 180,000 barrels) or less, the vessels were assumed to be barges.

All ports with larger average vessels were assumed to be tanker ships. Tanker ships are normally allotted 36 hours at berth. Exceptions to the standard port times were used for:

- Valdez Alaska (crude oil loading port) where 12 hours port times are documented, [88] and
- Louisiana Offshore Oil Port where published discharge rate requirements indicated 48 hours were necessary.[89]
- Offshore lightering areas: South Sabine Point and Galveston Lightering Areas (near Texas coast), the Southwest Pass Lightering Area (near Louisiana coast), and the Southern California Lightering Area (near California coast). Offshore lightering normally takes place 20 or more miles and involves transferring oil from Very Large or Ultra Large Crude Carrier (VLCC or ULCC) tank ships that are too large to come into port to four to six smaller tank ships (80,000 DWT). Oil is transferred one ship at a time while both ships move at 4 to 6 knots.[90] The VLCC or ULCC never actually enter the port. The smaller tank ships and the crude oil from the VLCC or ULCC do enter port and are recorded as ship arrivals. The VLCC or ULCC were excluded from the calculation of port times, but their activity levels within the ECAs may be a subject for future characterization.

The call-weighted average port times for 70 ports with tankers and tank barges were computed to be 35.9 hours, or 1.5 days.

D.3 General Cargo

General Cargo ships transport many types of cargos ranging from sacks, to drums, to oversized fabricated structures, as well as trees, and steel products such as rebar. The three ports with the most General Cargo ship port calls are: Houston, Philadelphia, and New Orleans. These ports represent about 30% of the General Cargo Ship U.S. port call in 2012. The Port of Houston states on their website that "the average turnaround time for a ship at the terminal (General Cargo) is two to three days." Philadelphia does not list average turnaround times on their website, but a review of vessel AIS data[91] for ships that departed between February 27 and March 2, 2015 indicated the average turnaround time was 65 hours. The port operations

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http://www.phillips66.com/EN/products/Documents/Phillips%2066%20Crude%20Oil%20Marine%20Provisions.pdf, and http://www.shell.com/content/dam/shell-new/local/corporate/corporate/downloads/doc/shell-trading-company-domestic-marine-crude-oil-may-2013.pdf

[88] Marine Exchange of Alaska. "Valdez Harbor Information." From http://www.mxak.org/ports/southcentral/valdez/valdez_facilities.html, the transfer rates from fixed platform were 100,000 bbl/hr and from floating units were 80,000 bbl/hr.

[89] Loop LLC. "Tanker Offloading Services." From https://www.loopllc.com/Services/Tanker-Offloading, the tank ships of 170,000 DWT or greater must have a minimum average discharge rate of 43,000 bbl/hr.

[90] Center for Tankship Excellence. "CTX Glossary." From http://www.c4tx.org/ctx/gen/glossary.html

[91] MarineTraffic. "Live Map." http://www.marinetraffic.com/

manager at the Port of New Orleans stated in an email[92] that "Within the Port of New Orleans jurisdiction, most general cargo ships are container and break-bulk vessels. Container ship average 1-1.5 days, while break bulk ships average 2-3 days." Based on the ranges stated above, an average port time for General Cargo ships of 62 hours (2.6 days) was used.

D.4 Roll-On/Roll-Off Vessels

The configuration of roll-on/roll-off ships varies significantly. Some roll-on/roll-off ships are designed specifically to only transport automobiles, others are designed to transport truck trailers and intermodal containers on truck chassis, and some are designed to transport truck trailers, containers and break bulk cargo. A review of vessel tracking data[93] was conducted for the ports of Baltimore, Jacksonville, New York, Brunswick Georgia, Tacoma, Norfolk (Hampton Roads), and Portland (Columbia River). These ports accounted for 3276 of the 6247 roll-on/roll-off vessel port calls in 2012. An average port time for roll-on/roll-off vessels of 21 hours was observed. In general it appeared that roll-on/roll-off vessels moving only vehicles (cars, trucks, and trailers) were in port 12 to 16 hours and mixed use roll-on/roll-off vessels were in port 24 to 30 hours.

D.5 Gas Vessels

Gas vessels include both LPG and LNG ships. The allowed laytime for an LNG ship at the Sabine Pass Terminal is 36 hours.[94] At the Lake Charles LNG terminal the allowed laytime is 24 hours.[95] The 'Report to Cook Inlet Risk Assessment Advisory Panel, version: January 2012" reports that LNG ships calling on the ConocoPhilips LNG loading terminal in Alaska during 2010 spent 36 days in the Cook Inlet to conduct 12 port calls (average 3 days in the Cook Inlet). Since the terminal is 115 nm up the Inlet (230 nm round trip) it would take the ship about 29 hours to transit in and out of the Inlet (leaving an average of 42 hours berth time for each ship at the terminal). Based on these data, LNG ships were assumed to be in port 36 hours for each port call.

At this time LNG ships generally load at a single port and unload at another single port. On the other hand, LPG ships may carry products destined for multiple ports, but ascertaining which ships would be resource-intensive. Because little data were available for LPG ship laytimes, the port times for LPG vessels were conservatively chosen to match those for the LNG ships conducting full loading/unloading (36 hours or 1.5 days).

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[92] Email from: Paul Zimmermann [ZIMMERMANNP@portno.com] 3/2/2015 to O'Malley, Steve J. (Leidos) on Monday, March 2, 2015 1:58 PM

[93] For the period 2/26/2015 – 3/1/2015, this period included 43 port calls, http://www.marinetraffic.com/ais/details/ports/1326/USA_port:BRUNSWICK

[94] U.S. Securities and Exchange Commission. "Master Ex-Ship LNG Sales Agreement Between Cheniere Marketing, Inc. and Gaz de France International Trading S.A.S." http://www.sec.gov/Archives/edgar/data/3570/000119312507106384/dex102.htm

[95] Decker, John. Letter to Sally Kornfeld, U.S. Department of Energy. Last accessed online at http://www.fossil.energy.gov/programs/gasregulation/authorizations/2004_Applications/04-40-LNG.pdf on March 5, 2015.

D.6 Bulk Vessels

The average DWT and ship capacity (in tons) was calculated for 65 ports using the U.S. Maritime Administration's 2012 Total Vessel Calls in U.S. Ports, Terminals and Lightering Areas Report.[5] The average DWT was multiplied by 0.85 in order to estimate cargo capacity of the ships.[96] The rate at which bulk cargo would be loaded or unloaded is based on ton-per-hour (tph) rates posted by the ports[97] (assumed to be 800 tph if no information was posted). All posted rates are multiplied by 80 percent for probable efficiency unless the posted rates are actual averages. In addition, preparation times of four hours were added to the computations.[98]

The call-weighted average port times for 65 ports with bulk cargo vessels were computed to be 47.9 hours, or 2.0 days.

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[96] Agerschou, Hans. Planning and Design of Ports and Marine Terminals, 2nd Edition, 2004, Thomas Telford Publisher

[97] The web site www.worldportsource.com provided the data or provided a link to the specific port website

[98] The preparation times were already included in the calculations for the other types of vessels when reporting laytimes and berth productivity.