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Life Cycle Analysis of Conventional and Alternative Marine Fuels in GREET™

Energy Systems Division

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Life Cycle Analysis of Conventional and Alternative Marine Fuels in GREET™

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ACRONYMS AND ABBREVIATIONS

ACE	U.S. Army Corps of Engineers
AD	Anaerobic Digestion
Argonne	Argonne National Laboratory
ASTM	American Society for Testing and Materials
BSFC	Brake-Specific Fuel Consumption
BOEM	Bureau of Ocean Energy Management
C-3	Category 3
CA	California cruise
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EC	Entrances and Clearances
ECA	Emissions Control Areas
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EU	European Union
FAME	Fatty Acid Methyl Esters
FT	Fisher-Tropsch
G	Global Cruise
GHG	Greenhouse gas
GIS	Geographic Information Systems
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HRD	Hydroprocessed Renewable Diesel
HEFA	Hydroprocessed Esters and Fatty Acids
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
IRR	Inland River Record
ISO	International Organization for Standardization
LCA	Life-Cycle Analysis
LEA	Lipid-Extracted Algae
LF	Load Factor
LHV	Lower heating value
MARPOL	International Convention for the Prevention of Pollution from Ships
MD or D	Marine Distillates
NOx	Nitrogen Oxides
OGV	Ocean-Going Vessels
PM	Particulate Matter
RO or O	Residual Oil
RPM	Revolutions per Minute
RSZ or R	Reduced Speed Zone
PM_{10}	Particulate matter with diameters measuring 10 micrometers or less
PTH	Pump-to-Hull
SMED	Swedish Methodology for Environmental Data
SO_x	Sulfur Oxides
ULO	Used Lubricating Oil
UNCTAD	United Nations Conference on Trade and Development

USCG	U.S. Coast Guard
VLCC	Very Large Crude Carriers
VOC	Volatile Organic Compound
WC	Waterborne Commerce
WTH	Well-to-Hull
WTP	Well-to-Pump

UNITS OF MEASURE

g	gram(s)
gal	gallon(s)
J	joule(s)
kg	kilogram(s)
kJ	kiloJoule(s)
km	kilometer(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
m^3	cubic meter(s)
mg	milligram(s)
MJ	megajoule(s)
mL	milliliter(s)
Mmt	million metric ton(s)
nmi	Nautical mile(s)
ppm	part(s) per million
TEU	Twenty-foot equivalent unit(s)

LIFE-CYCLE ANALYSIS OF CONVENTIONAL AND ALTERNATIVE MARINE FUELS IN GREET

by

Felix Adom, Jennifer B. Dunn, Amgad Elgowainy, Jeongwoo Han, Michael Wang, Roger Chang, Heather Perez, Jennifer Sellers, Richard Billings

ABSTRACT

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by Argonne National Laboratory has been expanded to include well-to-hull (WTH) analysis of marine fuels with a GREET marine module. This report documents the key WTH stages and assumptions for marine fuels (conventional and alternative). The marine module is comprised of two key stages: well-to-pump (WTP) and pump-to-hull (PTH). The WTP component of the module analyzes the energy use and emissions associated with the production and delivery of both petroleum-based fuels and biofuels. The combustion of fuel during marine vessel operation constitutes the PTH stage. The combination of the WTP and PTH stages results in the full WTH fuel cycle.

The marine module comprises five fuel pathways: (i) petroleum-based marine fuel from crude oil, (ii) Fischer-Tropsch diesel fuel from natural gas, coal and biomass, (iii) hydroprocessed renewable diesel (also known as hydroprocessed esters and fatty acids) from soybeans, palm, rapeseed, jatropha, camelina, and algae, (iv) renewable diesel from pyrolysis of biomass, and (v) biodiesel from soybeans, palm, rapeseed, jatropha, camelina and algae.

Activity data for vessels visiting coastal and inland U.S. ports were obtained from the U.S. Army Corps of Engineers (ACE). Supplemented by other data sources such as the Inland River Record and the IHS Register of Ships (IHS 2013), the activity and characteristics (e.g., rated engine power) of different vessel types (container ships, bulk, and others) were determined. Using these data sources, we determined that large container ships, bulk vessels, and very large crude carriers (VLCC) dominated both marine distillate and residual oil consumption. These three vessel types were therefore selected for inclusion in the module. Subsequently, we analyzed ACE data to determine characteristic distances for trip segments (e.g., reduced speed zone, cruising) for each vessel type in four U.S. regions: Atlantic, Pacific, Gulf of Mexico, and the Great Lakes. Finally, we developed emission factors for key air pollutants and greenhouse gases (GHGs) for vessels burning both residual oil and marine distillate fuels. Fuel consumption and emission factors for alternative fuels are estimated in GREET as a percentage of those of conventional fuels. This report documents how these data are combined in the GREET module to calculate life-cycle energy consumption, GHG emissions, and air pollutant emissions for large container ships, bulk vessels, and VLCC.

1. INTRODUCTION

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by Argonne National Laboratory (Argonne) allows researchers to model the life-cycle energy use and emissions associated with a wide range of on-road vehicle technologies. The model also includes aviation fuel production pathways and aircraft operations, to enable researchers to investigate the energy consumption and air emissions of various alternative aviation fuels. In an effort to increase the functional capabilities and applications of the GREET model, the new model (GREET1_2013) has been expanded to examine the energy consumption and air emissions, including greenhouse gases (GHG), of marine fuels and vessel operation from a life-cycle perspective. This report documents the expansion of the GREET model to evaluate the life-cycle energy use, emissions of GHG and other key air pollutants, associated with the production of petroleum-based marine fuel and alternative marine fuels (a majority of which are bio-based) and their consumption by marine vessels.

A life-cycle analysis (LCA) evaluates all stages of a product from the extraction of raw materials through materials processing, manufacture, distribution, use, and disposal or recycling. The life cycle of marine fuels includes feedstock production and transportation, fuel production and transportation, and fuel consumption by marine vessels. The GREET marine module is comprised of two main LCA stages; (i) Well-to-Pump (WTP) and (ii) Pump-to-Hull (PTH). The WTP component of the module analyzes the energy use and emissions due to the production of marine fuels and their delivery to the pump. WTP activities for petroleum-based fuels include recovery of crude oil from wells, crude refining, and transportation of the fuel to the pump for distribution. In the case of biofuels, WTP activities include feedstock production, conversion, and transportation of the fuel to the pump. The combustion of fuel during marine vessel operation constitutes the PTH stage. The combination of the WTP and PTH stages results in the full fuel cycle from well to hull (WTH). The WTH stages for petroleum-based marine fuel and bio-based alternative marine fuel pathways in GREET are summarized in Figures 1 and 2, respectively.

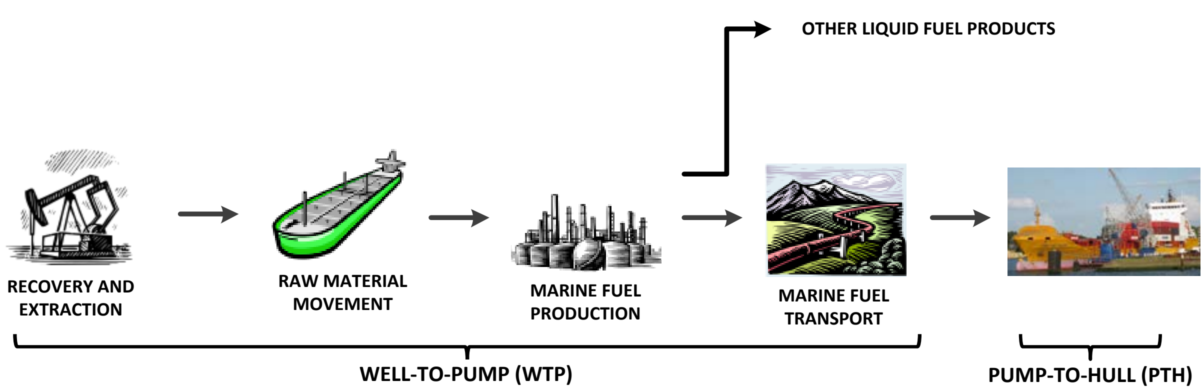

Figure 1: WTH pathway for petroleum-based marine fuels

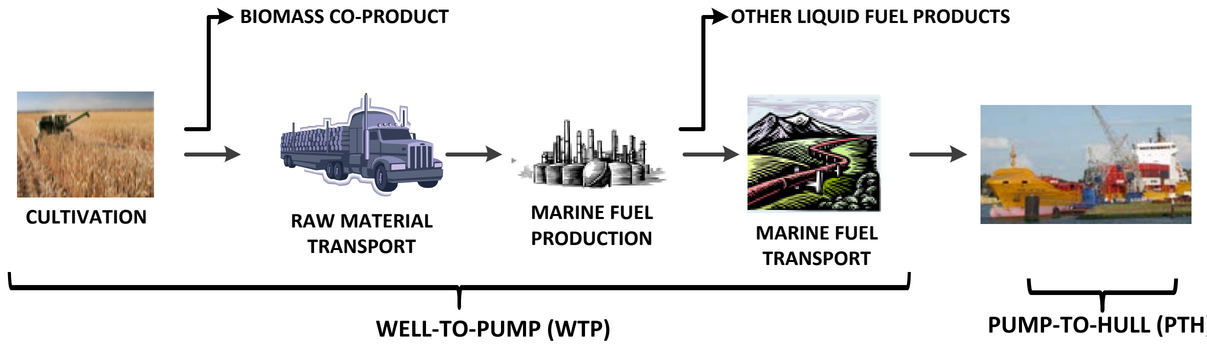

Figure 2: WTH pathway for bio-based alternative marine fuels

1.1 BACKGROUND

The maritime transportation sector, which plays a pivotal role in international trade, consumes a large amount of residual-grade oil and contributes to global warming and air pollution (Lin 2013; Righi et al. 2011). According to a 2012 United Nations Conference on Trade and Development (UNCTAD) report, ports worldwide handled 80% of global trade by volume and 70% by value (UNCTAD 2012). The International Maritime Organization (IMO) is a specialized agency of the United Nations with the mandate of ensuring safety and security of shipping and the prevention of marine pollution by ships. A study (Buhaug et al. 2009) commissioned by the IMO estimated that the shipping industry emitted 1,046 million tonnes of CO_2 in 2007, contributing 3.3% of the global CO_2 emissions in that year. 870 million tonnes of CO_2, or about 2.74% of 2007 global CO_2 emissions, was attributable to international shipping. Apart from the maritime industry, residual-grade oil is also consumed by other industries, making it difficult to estimate the actual fuel consumption by marine vessels (Irvine 2009). Eyring et al. (2005) reported total worldwide fleet fuel consumption (by civilian and all military ships) to be 289 million metric tons (Mmt) for the year 2001. Additionally, Jameson (2008) reported the world consumption of marine fuel (also known as bunker fuel) to be approximately 350 Mmt per year, with 80% (280 Mmt/yr or ~2.5 million barrels/yr) being residual fuel. Projections of marine fuel consumption in the U.S. for 2012 and 2020 are 32 Mmt and 37 Mmt per year, respectively, representing about 8.5% of the total global marine fuel consumption for 2012 (EPA 2008a).

The majority of ocean-going vessels (OGV) that transport goods are classified as Category 3 (C-3) vessels. These vessels have an engine displacement of 30 liters per cylinder or more (Cooper and Gustafsson 2004) and operate on marine fuels, which broadly fall into two major categories depending on fuel viscosity: marine distillate (MD) and residual oil (RO). MD is comparable to off-road diesel fuel (or number 2 fuel oil) in terms of chemical properties and specification limits, and can further be subcategorized into marine gas oil and marine diesel oil (Irvine 2009; Cooper and Gustafsson 2004). RO, also known as intermediate fuel oil or heavy fuel oil (HFO), is a less desirable product of the petroleum refining process. These fuels tend to be waxy and denser in structure and have relatively high viscosity and high sulfur content (Irvine 2009). See Appendix A (Tables A-1 and A-2) for detailed fuel specifications for RO and MD based on International Organization for Standardization (ISO) specification 8217 Petroleum products–Fuels (class F) – Specifications of marine fuels.

The maritime transportation sector also contributes to global emissions of key air pollutants. The most significant GHG and pollutants emitted from diesel engine-powered vessels are carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_x) and sulfur oxides (SO_x) (Lin 2013). Eyring et al. (2005) and Corbett et al. (2007) estimated that 14–31% and 4–9% of global emissions of NO_x and SO_x, respectively, are attributable to marine vessel operations. Corbett et al. (2007) reported that shipping-related PM emissions can have a significant impact on human health, especially near coastlines in Europe, East Asia, and South Asia. To regulate emissions from ships, the IMO established the International Convention for the Prevention of Pollution from Ships (MARPOL). Annex VI of MARPOL (also known as Prevention of Air Pollution from Ships) requires a progressive reduction of fuel sulfur to reduce sulfur (SO_x) emissions from marine vessels (IMO 2013; Lin 2013).

The waterborne transportation system in the U.S. shipped about 2.1 billion metric tons of goods in 2011, with 62% of this total attributable to foreign commerce (DOT 2011a). Influenced largely by economic growth, globalization, and international trade, U.S. freight tonnage of all types (i.e. exports, imports, and domestic shipments) is expected to increase by 1.4% per year between 2010 and 2040 (DOT 2011a). This growth will impact marine vessel fuel consumption and emissions.

To address some of these challenges, the U.S. Environmental Protection Agency (EPA) collaborates with and encourages U.S. ports to develop Environmental Management Systems to proactively manage the environmental footprint of a port (EPA 2007a). Also, in an attempt to harmonize the methodology for preparation of a port-related emission inventory, the EPA published a report focusing on the methodology for the development of baseline emissions inventory on mobile emission sources at ports, including OGVs (EPA 2009a). As part of the coordinated strategy to regulate emissions from C-3 vessels, EPA is adopting more stringent exhaust emissions for new marine compression-ignition engines at or above 30 L per cylinder (EPA 2009b). In March 2008, the EPA also finalized a program that further reduces emissions from marine diesel engines with per-cylinder displacement below 30 L (non C-3 vessels). The intent of these regulations is to adopt new standards to reduce PM and NO_x emissions from locomotives and marine diesel engines (EPA 2008b).

There are a number of alternatives for reducing emissions from shipping. Some have already been assessed for their efficacy and cost effectiveness. These include: speed reductions, fuel quality, engine slide valves, water-in-fuel emulsions, fuel emulsions, particulate filters, and exhaust scrubbers (Corbett et al. 2009, 2010). Speed reduction (or slow steaming) has been reported to be a viable long-term option. Apart from reducing fuel cost and CO_2 emissions with speed reduction, cylinder lubricating oil consumption by the main engine is reduced by almost the same percentages as the fuel, which also reduces particle emissions (Wiesmann 2010). In spite of these advantages, slow steaming has some disadvantages, such as increased transportation times for goods, and faces other technical issues (lower air flows, cold corrosion, etc.) (Wiesmann 2010).

It has been argued by Bengtsson et al. (2011) that alternative fuels and/or increased efficiency are needed in order to significantly reduce the contribution to global warming from the shipping industry. Biodiesel and crude vegetable oil have been reported as the most promising alternatives for ship fuels, even though pyrolysis-derived fuels and other biofuels may be potential alternatives (Opdal and Hojem 2007). Although biodiesel blends (B6 to B20) are approved per American Society for Testing and Materials (ASTM) Standards D7467 for compression-ignition engines operating on petroleum diesel (e.g. trucks, tractors), this specification is not approved for commercial marine use. Apart from the concept of using biofuels to reduce carbon emissions across the marine fuel supply chain, there are additional advantages. For example, the combustion of biodiesel does not produce polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, or SO_x (Lin 2013). As a result of these advantages, the maritime industry and government agencies are exploring the possibility of using alternative bio-based fuels for achieving their long-term sustainability goals. For example, both Maersk and the U.S. Navy tested biofuels from algal oils in 2011. Additionally, collaboration between the U.S. Coast Guard and Oak Ridge National Laboratory to test butanol blends in marine craft was announced in 2012 (European Union Biotechnology Platform 2013). Finally, Progression Industry BV recently signed a memorandum of understanding with Maersk Oil Trading to develop sustainable marine fuel using lignin as a feedstock (Green Car Congress 2013).

1.2 STUDY DESCRIPTION

Using the GREET model, we developed various alternative fuel pathways in addition to the baseline petroleum-based marine fuels to evaluate the potential GHG emissions reductions and petroleum savings offered by these alternatives. Argonne developed the marine module in GREET with support from the U.S. Department of Energy's (DOE's) Biotechnology Office within the Office of Energy Efficiency and Renewable Energy. Eastern Research Group analyzed data sets and the literature as described in Section 3 to develop activity data, fuel consumption rates, and emission factors for marine vessels. The fuel pathways considered in this analysis include petroleum-based marine fuels from crude oil; Fischer Tropsch (FT) diesel fuel from natural gas, coal, and biomass; renewable diesel fuels from fast pyrolysis of cellulosic biomass; and hydroprocessed renewable diesel (HRD) (a.k.a. hydroprocessed esters and fatty acids, or HEFA) and biodiesel fuels from vegetable and algal oils.

2. MARINE FUEL PRODUCTION (WTP) PATHWAYS

This report provides detailed information on the life-cycle stages of marine fuel production from various types of feedstock sources such as crude oil, natural gas, renewable natural gas, coal, cellulosic biomass, plants and algal oil. Feedstock/fuel pathways for the marine module examined in this report can be grouped into five main categories:

(i) Petroleum-based marine fuels from crude oil (including both conventional crude and oil sands);
(ii) FT diesel fuel from natural gas, coal and cellulosic biomass;
(iii) HEFA or HRD diesel fuel from bio-oil found in soybeans, palm, rapeseed, jatropha, camelina, and algae;
(iv) Renewable diesel from pyrolysis of cellulosic biomass; and
(v) Biodiesel or fatty acid methyl esters (FAMEs) from bio-oil found in soybeans, palm, rapeseed, jatropha, camelina and algae.

Biofuels have the potential to lower carbon emissions from propulsion engines as well as improve local air quality. Pyrolysis-derived fuels have not yet been certified for use in any marine diesel engines, although they can potentially substitute for RO, light fuel oil or natural gas in other applications such as pulp mills, stationary diesel engines, power plants, and industrial boilers (Bradley 2006).

Synthetic paraffinic middle distillate fuels such as FT diesel and HEFA (or HRD) are gradually being introduced onto the worldwide distillate fuel market. Because of their similar chemical characteristics, blends of petroleum fuel and synthetic middle distillate fuels meet specifications for some applications and are considered as "drop in" fuels (CIMAC 2013). Fuel products must meet rigorous standards irrespective of the source of fuel or blending material (ASTM 2006; DOD 2006). Mushrush et al. (2009) reported an ASTM procedure required to test storage stability of blends with petroleum diesel. The formation of 3 mg/100 mL of fuel sediments or less means the fuel will be stable in storage for up to a two-year period. The authors reported a 50/50 blend of FT diesel and petroleum middle distillate to be marginally compatible, resulting in the formation of 1.7 mg solids/100mL as sediments.

Apart from the potential replacement of RO by straight vegetable oils owing to compatibility with current marine engines, biodiesel blends (up to 20%) have been reported as the most promising from a technical integration perspective (Florentinus et al. 2012). Blends of B6 to B20 have been approved by ASTM D7467, although this specification is not currently approved for marine use. However, the U.S. government accepts commercial purchase of B20 for non-tactical applications. Also, we note that D975 is the ASTM specification for diesel fuel (Nayyar 2010).

2.1 MARINE FUEL PRODUCTION FROM PETROLEUM OIL

2.1.1 LIFE CYCLE

The combination of the WTP and PTH stages defines the full life cycle of the fuel from WTH. The key stages in the WTH pathway of petroleum-based marine fuels are: (i) petroleum extraction from oil fields, (ii) refining of petroleum to produce marine fuel, and (iii) marine fuel use in vessels. In our analysis, we took into account all transportation-related activities for movement of goods (e.g., transport of crude oil from oil fields to refineries as well as marine fuel from refineries to refueling sites). The GREET module give users the option of including environmental impacts from infrastructure-related activities (e.g., construction of oil rigs, pipelines or petroleum refineries) at the WTP-stage analysis. Figure 3 shows the LCA system boundary and key stages and activities associated with the petroleum-based marine fuel pathway.

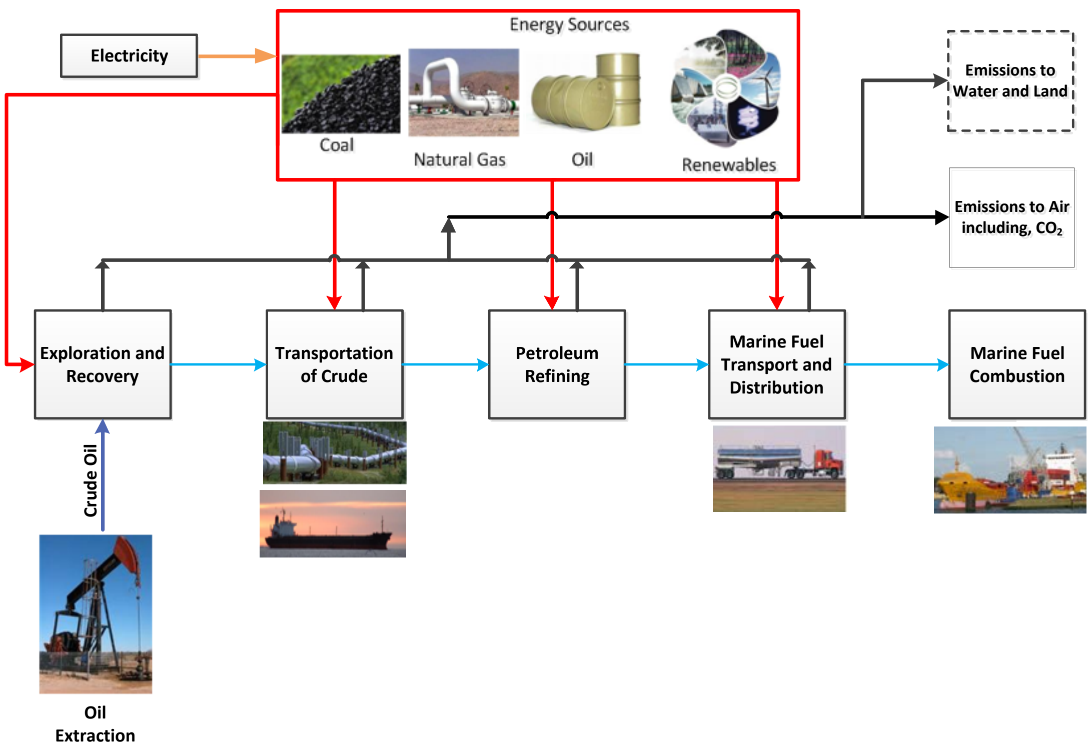

Figure 3: Key stages and activities of petroleum-based marine fuel pathways

2.1.2 CRUDE RECOVERY

The crude recovery stage of the petroleum fuel cycle include activities such as well drilling, oil extraction, and oil gathering through gathering pipes in the oil fields. Associated gas is a by-product of the crude oil recovery stage. It may be recovered as sellable natural gas, flared, or vented. For the purpose of this study, the GREET default petroleum recovery efficiency estimate of 98% (Wallace et al. 2001) was adopted. Energy consumption during the petroleum recovery stage is therefore implicitly embedded in the energy efficiency assumptions made for crude recovery. The calculated energy efficiency for petroleum recovery does not account for the energy in the flared and vented gas because this gas is not an intended energy source; however, emissions associated with gas flaring and venting are accounted for in the GREET model (Elgowainy et al. 2012). GHG emissions produced in the country of origin during crude recovery are accounted for in this study on the basis of percentage of crude imported from that country into the U.S. market. Detailed GREET assumptions for emissions associated with crude recovery are documented in another study (Burnham et al. 2012).

2.1.3 PETROLEUM REFINING

The production of petroleum products, including marine fuels, involves processes such as physical, thermal, and chemical separation and reforming of crude oil into various components. These components can undergo further processing and conversion steps to produce the target products (Irvine 2009). Refining efficiency is the amount of energy input required to produce a given amount of a refined product output. The refining efficiency values for individual fuels (e.g., marine distillate and residual oil) are required to include in the total energy and emission calculations for each fuel. Refinery efficiencies for each product are typically evaluated using linear programming-based models of internal refinery processing units (Wang et al. 2004).

Statistics on volumetric crude oil and blending stock inputs, captive hydrogen, fuel gas and process fuel consumption are published by the U.S. Energy Information Administration (EIA) annually. Overall refinery and product-specific efficiencies in GREET have been updated on the basis of an Argonne study by Cai et al. (2013), which adopts the latest data available for year 2011 (EIA, 2012a; EIA, 2012b). Refinery efficiencies of 96% for residual oil (27,000 ppm sulfur ratio by mass), 90% for MD (2,000 ppm sulfur ratio by mass) and 90% for low-sulfur MD (11 ppm sulfur ratio by mass) (Cai et al. 2013) were estimated. On the international market, these refined marine fuels are required to meet Specification 8217, Petroleum products—Fuels (class F)—Specifications of marine fuels (ISO 8217). Readers can refer to Cai et al. (2013) for more details regarding assumptions and GREET parameters for petroleum-derived fuels

2.1.4 TRANSPORTATION ACTIVITIES

Readers are referred to other studies (Cai et al. 2013; Wallace et al. 2001) for further details regarding the energy use and emissions associated with each transportation mode for conventional crude to U.S. refineries as well as the transportation and distribution of refined products to refueling stations. Energy use and emissions for marine vessel operations will be discussed in section 3 of this report.

2.2 ALTERNATIVE MARINE FUEL PRODUCTION PATHWAYS

Traditionally, the shipping industry has used heavy fuels with high sulfur content, purchased at a price lower than that of crude oil (Corbett 2004). Owing to the impacts of emissions from the shipping industry (Buhaug et al. 2009; Petzold et al. 2011; Winebrake et al. 2009), stricter regulations for fuels are being proposed and implemented by both the IMO and the EPA. For example, the IMO has officially designated waters off North American coasts as subject to stringent international emission standards for ships as of 2012 (EPA 2010). Vessels operating in these waters will need to burn lower-sulfur fuels.

A number of implicit problems regarding the use of alternative fuels such as FT diesel and biodiesel have been reported. Lower energy density, fuel injector failure, filter plugging, and lower fuel stability are but a few examples. It has also been proposed that blending alternative fuels with petroleum fuels, using high-pressure injection systems and antioxidant additives, can help address some of these technical challenges (Stamper and Lee 2008). Nonetheless, the shipping industry and the U.S. military are pursuing biofuels to improve their environmental impact and energy security, as described in Section 1.1. The next sections of this report present fuel-cycle pathways for alternative marine fuel production using different feedstocks.

2.2.1 FT DIESEL FUEL

FT diesel can be derived from a number of sources such as natural gas, coal, biomass, and co-feeding of the three. Figure 4 shows the key processing steps that constitute the FT diesel pathway. The step after feedstock cleaning and processing is the production of synthetic gas (a mixture of CO and hydrogen), which can subsequently be reacted over a catalyst in the FT synthesis process to produce hydrocarbons of varying carbon chain length. In a typical FT plant, three groups of hydrocarbons are produced: FT naphtha (C_5–C_9), FT middle distillates (C_{10}–C_{20}), and FT wax ($>C_{20}$). FT middle distillates (diesel and jet fuels) are the premium fuel components; they contain virtually no sulfur and have high cetane number properties (Elgowainy et al. 2012).

The key stages and activities for the production of FT diesel using cellulosic biomass via gasification are displayed in Figure 5. Data for the energy use and emissions for the farming and collection of biomass are based on Wang et al. (2013). Also, Xie et al. (2011) investigated fuel-cycle energy use for the production of FT diesel from coal and cellulosic biomass. Readers are referred to Elgowainy et al. (2012) for further details regarding modeling of FT diesel in GREET as applied in the marine module.

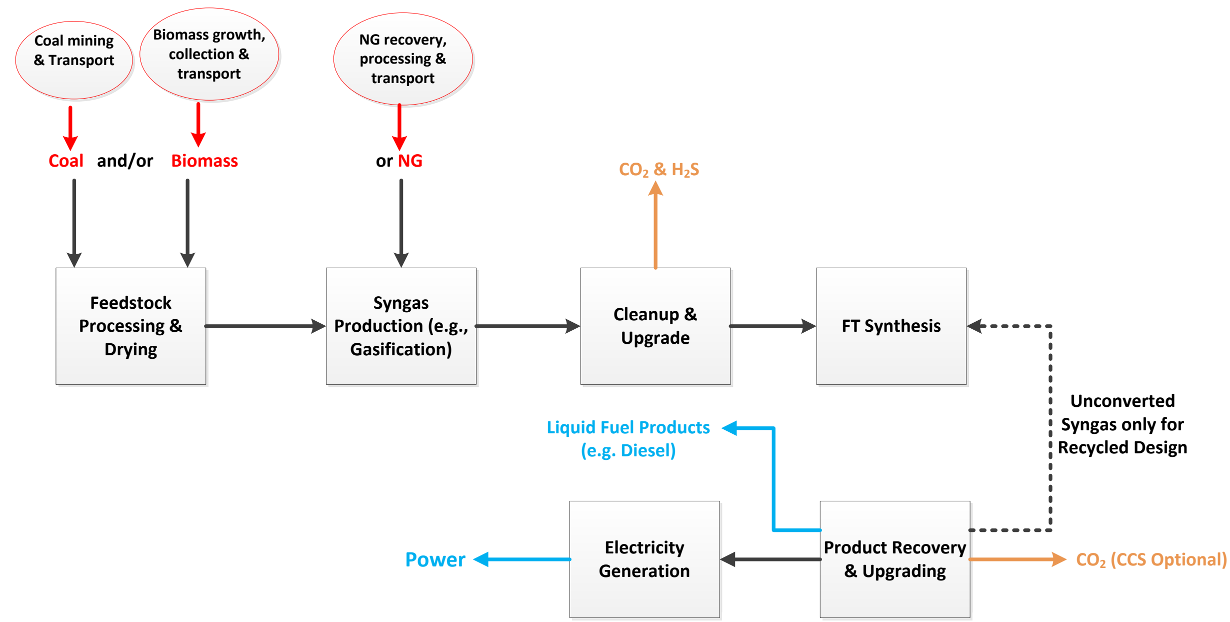

Figure 4: LCA boundary and key stages and activities of FT diesel pathways

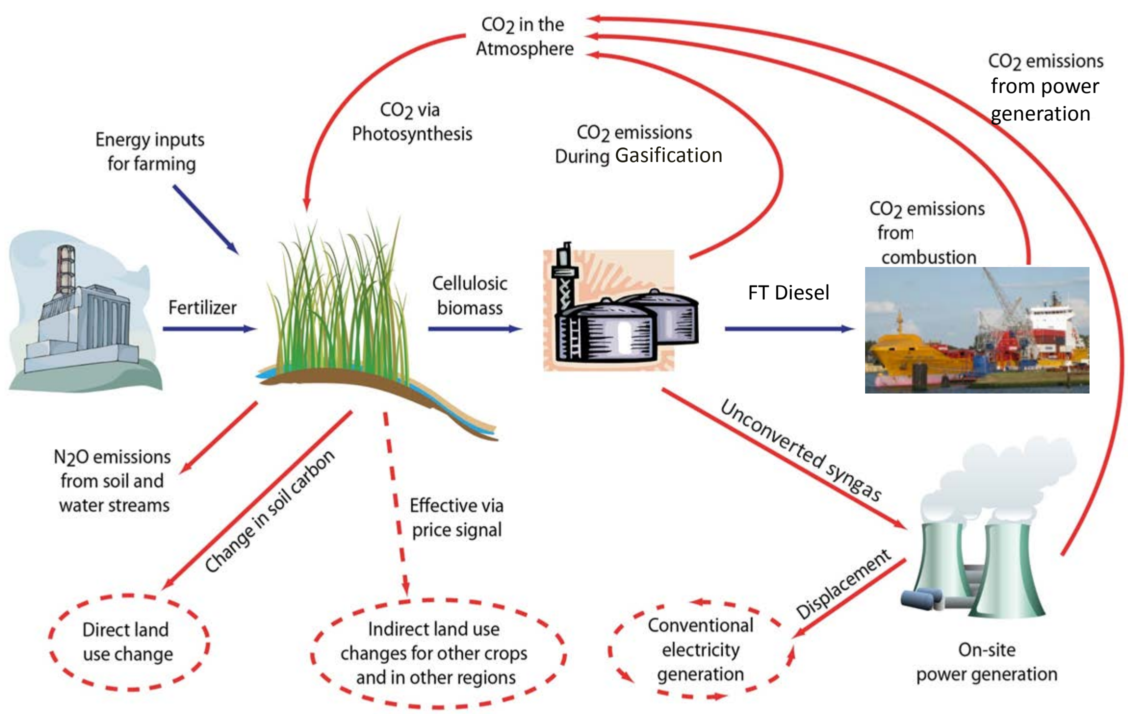

Figure 5: FT diesel production from cellulosic biomass (switchgrass shown as example), showing major co-products and carbon sources and sinks in the pathway

2.2.2 HRD OR HEFA FUELS

The marine module includes analysis of both the energy use and emissions associated with the production of HRD (or HEFA) fuels using oil extracted from soybeans, algae, palm, jatropha, rapeseed, and camelina. The general production process includes oil deoxygenation using hydrogen. The deoxygenated oil is subsequently hydrocracked over special catalysts to produce a range of hydrocarbons that fill the distillation ranges of naphtha, jet, and diesel fuels (Florentinus et al. 2012; Hileman et al. 2008). HEFA fuels are considered as "drop-in" and can be blended into fossil diesel for road transport (Florentinus et al. 2012).

Soybeans are currently the main biodiesel feedstock in the United States. Figure 6 shows the key stages and activities for the production of HRD from soybeans. Huo et al. (2008) investigated in detail the life-cycle energy use and GHG emissions of soybean-derived biodiesel and HRD fuels. GREET parameters for soybean farming (energy use, fertilizer use, and crop yields) are based on Pradhan et al. (2011). Additionally, energy input data for the extraction of oil are obtained from Omni Tech International (2010). Finally, soy meal, a co-product of the extraction process, is assumed to displace soybeans in the GREET model. On the basis of the equivalent protein content, 1 lb of soy meal can displace 1.2 lb of soybeans.

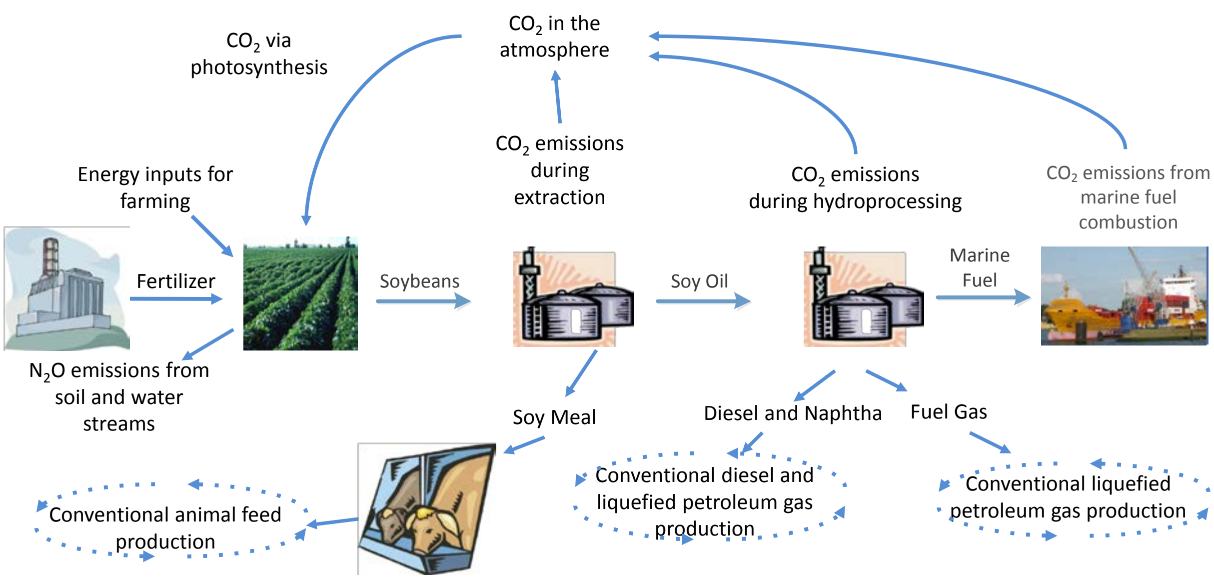

Figure 6: HRD production from soybeans, with major co-products, displaced products and carbon sources and sinks

Figure 7 shows the key stages and major co-products associated with HRD (HEFA) production from algae. Frank et al. (2011, 2012) examined in detail the energy use and GHG emissions from the growth and dewatering of algae in open ponds as well as the oil extraction and fuel production stages. Data from these studies are used within GREET for algal fuels. Allocation of energy consumption and emissions burdens between algal oil and co-products that can be produced from the lipid-extracted algae (LEA) is based on the energy content of each product.

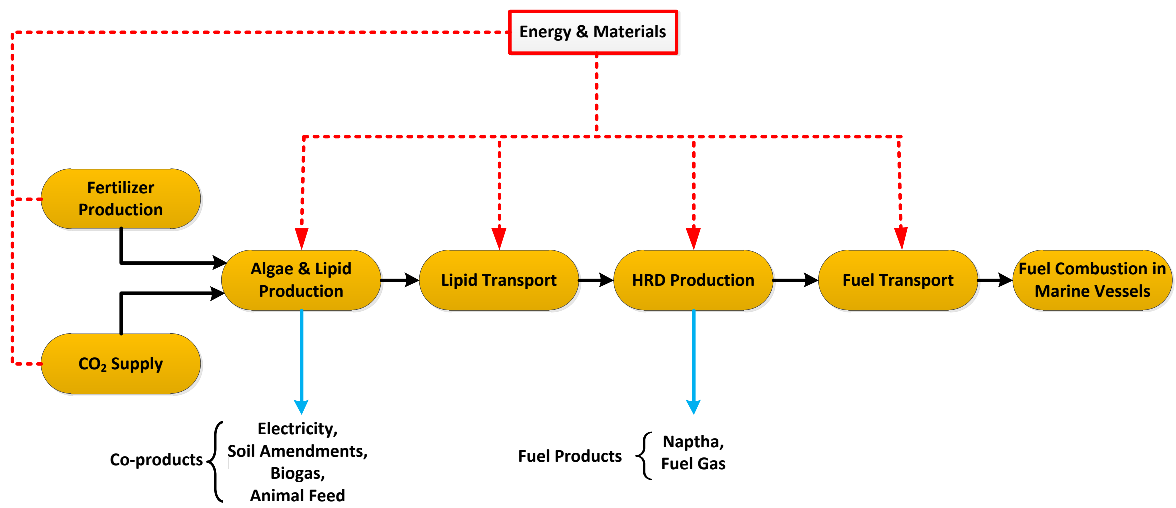

Figure 7: HRD production from algae, showing major co-products in the pathway

The LEA is a useful intermediate product in the lipid production stage, as shown in Figure 8. It can be used for CH_4 production using anaerobic digestion (AD) and/or for electric power generation. In addition, the solids remaining after AD, called the residual digestate, can be applied to soil, displacing fertilizers (see Figure 8). Interested readers are referred to Frank et al. (2012) for a detailed discussion of the impacts of different co-product treatment scenarios possible in GREET modeling of algal fuel pathways.

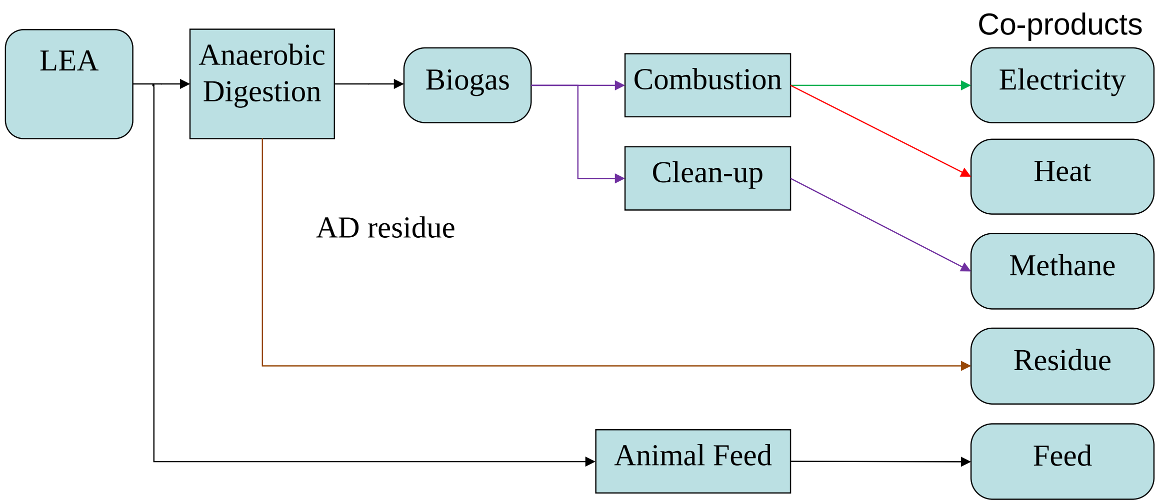

Figure 8: A variety of co-products from LEA and their potential uses

Energy use in the farming stage and oil extraction, as well as oil and co-product yields for palm, jatropha, rapeseed, and camelina, have been investigated and reported in the literature (Stratton et al. 2010, 2011; Shonnard et al. 2010). These energy input data were adopted for the marine module. Energy requirements for farming and extraction stage have been summarized in Table 3 of Elgowainy et al. (2012).

The hydrogenation process in GREET is modeled on the basis of assumptions and data provided in Pearlson et al. (2013) and Han et al. (2013). Hydrogen demand and co-product yields are adjusted for each plant oil type on the basis of its fatty acid profile as detailed in Han et al. (2013). Allocation of conversion process energy and air emissions burdens among HRD fuel and co-products (jet and naphtha co-products) was carried out with the energy allocation method. Han et al. (2013) provide a full discussion of data, methodology, and assumptions underpinning GREET modeling of HRD fuel pathways.

2.2.3 PYROLYSIS-BASED MARINE FUEL PRODUCTION PATHWAYS

GREET includes pathways for the production of pyrolysis oil and upgraded bio-oil via fast pyrolysis. The products can be further upgraded and refined to produce long-chain hydrocarbons compatible with the current transportation fuel distribution infrastructure and combustion technologies. It is believed that pyrolysis oil could substitute for HFO, light fuel oil, or liquid natural gas in a number of applications, including shipping (Bradley 2006). Figure 9 summarizes the key stages of liquid fuel production and major co-products from cellulosic biomass using fast pyrolysis in GREET.

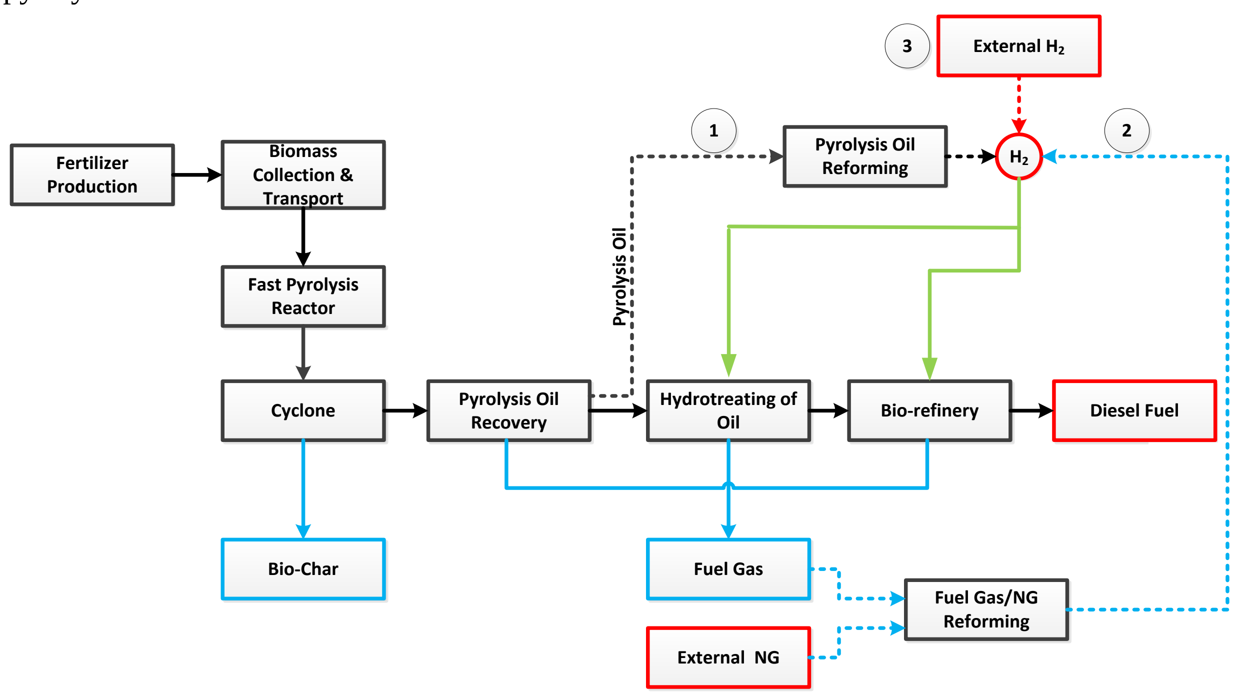

Figure 9: Liquid fuel production from cellulosic biomass via fast pyrolysis

Feedstocks are heated in the absence of oxygen around 500^{o}C for a few seconds in order to maximize pyrolysis oil yield after the collection and transportation stage. The unstable nature of the pyrolysis oil due to high oxygen and water content may result in phase separation and polymerization when the oil is stored over a long period of time. Hydrotreatment to reduce the oxygen content in the oil is essential for its stabilization, although it requires significant amounts of hydrogen. Three possible sources of hydrogen have been identified in Figure 9: (1) reforming pyrolysis oil, (2) reforming fuel gas or an external source of natural gas, and (3) external hydrogen purchased from a merchant. Hydrocracking of the stabilized pyrolysis oil is the final step to obtaining liquid fuels such as diesel, gasoline and jet fuels. This step also requires additional hydrogen use. Two key co-products are produced from pyrolysis reactions; biochar and fuel gas (a mixture of CO and CH_4). It has been reported that the heat and power requirements for biomass drying and grinding as well as bio-oil upgrading can be satisfied using these co-products (Elgowainy et al. 2012). Han et al. (2013) provide the parameters, methodology, and assumptions in the GREET pyrolysis pathways.

2.2.4 BIODIESEL OR FATTY ACID METHYL ESTERS

According to the Department of Energy's Alternative Fuel Data Center (DOE 2013), "biodiesel is a domestically produced, renewable fuel that can be manufactured from vegetable oils, animal fats, or recycled restaurant grease for use in diesel vehicles." Biodiesel blends (up to 20%) have been reported as the most promising bio-based alternative fuel for marine vessel operations from a technical integration perspective (Florentinus et al. 2012). Figure 10 shows the key stages and activities for the production of biodiesel. Bio-oil found in soybeans, palm, rapeseed, jatropha, camelina, and algae are considered in the marine module.

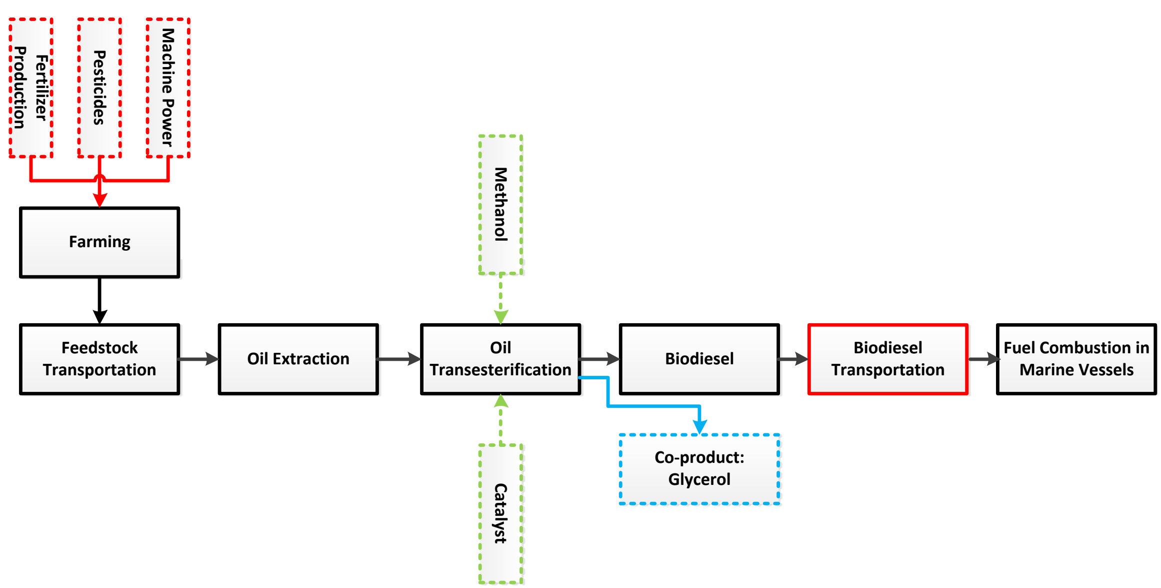

Figure 10: System boundary for life cycle of biodiesel

Briefly, biodiesel is produced via a transesterification process of the bio-oil. In the transesterification process, fat and oil derivatives from plants constituting triglycerides, which are esters of free fatty acids, are combined with alcohol (ethanol or methanol) in the presence of a catalyst to form ethyl or methyl ester (biodiesel) and glycerin as by-product. The transesterification process requires steam and electricity as energy inputs (Nayyar 2010; Huo et al. 2008).

3. PUMP-TO-HULL ENERGY USE AND EMISSIONS DURING MARINE VESSEL OPERATION

The GREET marine module aims to calculate energy consumption and air emissions from characteristic trips by the vessel types that are the primary fuel consumers in U.S. ports. In this section, we describe the data and methodology for these calculations in GREET. Section 3.1 describes how we selected vessel types to include in the GREET marine module. In Section 3.2, we explain how the GREET marine module classifies vessel trip types by U.S. region and how characteristic trip distances for each of the trip types are calculated. Vessel speed and load factors are important factors for the calculation of fuel consumption and emissions during marine vessel operation. These parameters are described in Section 3.3. Section 3.4 documents values and data sources for fuel consumption and emission factors included in marine module calculations. Finally, Section 3.5 outlines the calculation methodology in the module that estimates the fuel consumption and emissions during vessel operation for a characteristic trip.

3.1 VESSEL TYPES AND CHARACTERISTICS

Vessels visiting coastal and inland U.S. ports were identified through examination of two key data sets. The first is the Vessel Entrances and Clearances (EC) data set that is maintained by the U.S. Army Corps of Engineers (ACE) (ACE 2013a). These data are supplied by the U.S. Customs Service. The most recent release of this data set in 2013 contains data for calendar year 2011, the year chosen as the analysis year for the GREET marine module. The data set contains the following information.

- Date vessel entered or cleared a U.S. Customs port
- Vessel name
- Type of vessel (by one-digit rig type or by International Classification of Ships by Type) code
- Flag of registry
- Previous or next port
- Net and gross registered tonnage
- Vessel draft

The second data set is the Waterborne Commerce (WC) data set, also maintained by the ACE (ACE 2013b). It reports data for foreign and domestic waterborne commerce transiting U.S. waters. Data for foreign commerce are sourced from the Port Import Export Reporting Service, which is a division of the Journal of Commerce. These data are supplemented with data from the U.S. Bureau of the Census and the U.S. Customs Service. This data set includes the following: vessel type, waterway identity, and number of trips associated with unique shipping-lane segments. The GREET marine module uses WC data for calendar year 2011, released in 2013.

Unlike the EC data set, the WC data set does not contain origin-destination pairs. It includes vessel type and information about the regions through which vessels are traveling. The WC data set therefore is not used to assign distances to vessel routes. Rather, together with the Inland River Record (IRR) (Waterways Journal 2013), the WC data set is used to quantify the active vessel population and to disaggregate the vessel population into regions. Data from the IRR, including vessels' age, engines, and horsepower, are used to characterize the active fleet.

Additional data sets are used to quantify the fleet of smaller vessels and its activity. For example, fishing and research vessel data are obtained from the EPA's Engine Category 1 and 2 Census (EPA 2007b). The U.S. Coast Guard has limited data concerning its vessels. Dredger activity data are available from the ACE. The EPA's 2011 National Emissions Inventory is tapped to characterize the ferry population and its activity. Finally, our assessment used data from the Bureau of Ocean Energy Management (BOEM), which maintains some data on the activity of vessels that support offshore oil drilling.

In addition to the IRR data set, data from the IHS Register of Ships (IHS 2013) were used to characterize the vessels types in this analysis. Table 1 summarizes the different vessel types for which data are collected and the data source for both vessel activity and vessel characteristics.

Table 1: Data sources by vessel type

Vessel	Engine Category 3	Engine Category 1 and 2	Activity Source Data	Vessel Characteristics
Tankers: VLCC[a]	X	X	EC	IHS Register of Ships
Container ships	X		EC	IHS Register of Ships
Bulk carriers	X	X	EC/WC	IHS Register of Ships
Roll-on-Roll-Off	X	X	EC	IHS Register of Ships
Car carriers	X		EC	IHS Register of Ships
Chemical tankers	X	X	EC	IHS Register of Ships
Large container vessels	X	X	EC	IHS Register of Ships
Tankers: Panamax	X	X	EC	IHS Register of Ships
General cargo ships	X	X	EC/WC	IHS Register of Ships
Reefers	X	X	EC	IHS Register of Ships
Bulk lakers	X	X	EC/WC	IHS Register of Ships
Tugs/barges		X	WC	IRR WC IHS Register of Ships
Liquefied natural gas carriers	X		EC	IHS Register of Ships
Cruise/passenger vessels	X	X	EC	IHS Register of Ships
Dredgers		X	ACE	ACE
Military	X	X	USCG	USCG
Offshore support		X	BOEM	BOEM
Fishing		X	EPA 2007b	EPA 2007b
Ferries		X	EPA 2011	EPA 2011
Research vessels		X	EPA 2007b	EPA 2007b

[a]Very Large Crude Carriers

Vessel characteristics determined from the IHS Register of Ships included the following.

- Vessel identification codes
- Vessel type (e.g., tanker, container ship, cruise ship)
- Vessel flag (i.e., U.S. or foreign flagged)
- Operational design (i.e., harbor, inland waterways, lake, or deep water vessels)
- Engine type (e.g., slow speed diesel, medium speed diesel, high speed diesel, turbine, or steam)
- EPA classification and engine speed (i.e., Category 1, Category 2, Category 3 slow speed or medium speed, gas turbine, or steam turbine)
- Maximum kilowatt (kW) rating of main propulsion engine and auxiliary engines
- Freight type/payload capacity
- Vessel speed

Of the 10,227 vessels included in the EC data, approximately 95% were matched to their characteristics, as noted in Table 2. The majority of matched vessels were found within the most recent set of data from the IHS (2013). Other sources as documented in Table 2 were used to identify vessels not found in the most recent IHS Register.

Table 2: EC vessel matching summary

Grouping	**Count**	**Percent of Total**
Matched vessels	**9,679**	**94.6%**
Matched to IHS Register 2013	9,045	88.4%
Matched to IHS Register 2009	408	4.0%
Matched to internet[a]	42	0.4%
Matched to name[b]	184	1.8%
Unmatched vessels	**548**	**5.4%**
Total vessels	**10,227**	**100.0%**

[a]http://maritime-connector.com and http://www.shipspotting.com
[b]Used vessel name rather than IMO number to match to vessel characteristics in IHS Register

From these data and with the calculation methodology developed in Section 3.5, we calculated the MD and RO consumption of each of these vessel types. This analysis revealed that three commercial vessel types dominated both MD and RO consumption: large container ships, bulk vessels, and VLCC (tankers), as shown in Figure 11. These three vessel types accounted for 47% and 82% of total U.S. consumption of residual oil and marine diesel, respectively, in 2011. We therefore selected these three vessel types for analysis in the marine module. Note that offshore vessels also had high fuel consumption, which we will seek to verify before including that vessel type in the marine module.

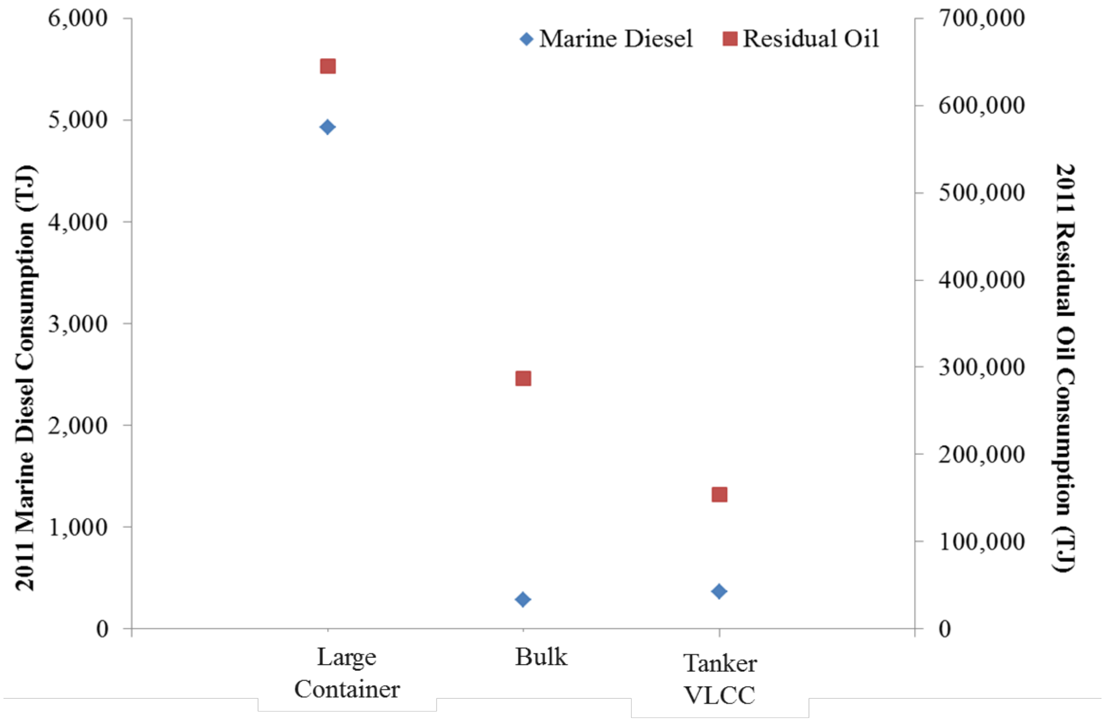

Figure 11: 2011 Marine diesel and residual oil consumption for three vessel types included in GREET

3.2 TRIP TYPES, DISTANCES, AND DOCKSIDE ACTIVITY

Trip distances were calculated after origin-destination pairs had been determined for each trip in the EC database, which contained 48,850 entrances from foreign ports and 49,625 clearances to foreign ports. There were therefore a total of 98,475 international trips. However, 858 of these trips were missing either the port of origin or destination. The remaining routes (97,617) were ranked by number of trips. The 1,587 most-traveled routes accounted for 90% of international vessel traffic. The remaining routes had five or fewer trips annually and were excluded from this analysis. To streamline the analysis, routes were defined by foreign country and the busiest port in each country was used as a surrogate port for all traffic to and from that country. Canada and Mexico, however, were treated differently. Vessels traveling between Canada and the U.S. East and West coasts were routed to St. John's and Vancouver, Canada, respectively. Vessels traveling between Mexico and the U.S. East and West coasts were routed to Tampico and Manzanillo, Mexico, respectively. Vessels traveling between the Great Lakes and Canada were routed to Hamilton, Canada. Overall, the number of foreign ports included in the analysis was 115. Route distances were obtained from the Searates.com website (Searates 2013).

The EC dataset included 58,905 trips between 394 domestic ports with 2,963 unique routes. To determine the locations of domestic ports, the domestic routes in the EC database were mapped in a Geographic Information System (GIS) using ACE port and waterway locations. The shortest path between the origin and destination ports along the ACE waterway network of navigable shipping lanes was identified with ArcGIS Network Analyst. If network analysis was not possible because port locations were slightly offset from network segments, distances were manually mapped if the route was traveled 11 or more times annually. With this approach, 96% of domestic trip activity (1,952 domestic routes, representing 56,309 trips) was accounted for in the analysis.

After determining the total trip distances, each trip was divided into segments, including transit through reduced-speed zones (RSZs), as illustrated in Figure 12. Each trip segment may have distinct fuel consumption and emission factors owing to different speeds and load factors and engine/fuel switching. At the origin and destination ports, the vessel will hotel and burn fuel dockside using mainly auxiliary engines. Some ports (for example, in California) may mandate that MD rather than RO be consumed dockside to limit sulfur and other emissions. Some ports may encourage cold ironing, or using dockside electricity to limit emissions at the port. The GREET marine module does not at this time take into account cold ironing, but does take into account dockside emissions from burning of either MD or RO in auxiliary engines, depending on the port location.

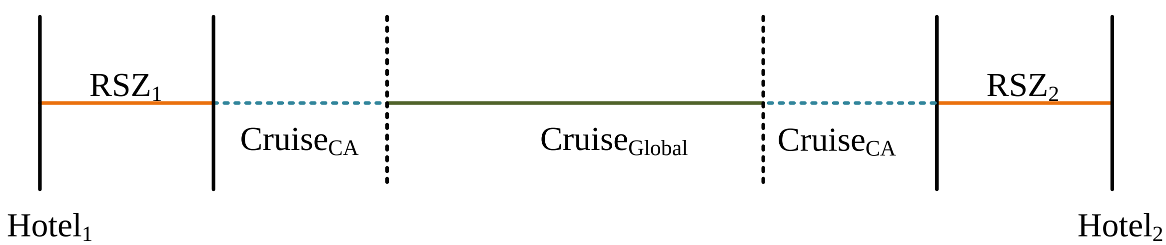

Figure 12: Trip segments: $cruise_{CA}$ segments only traveled if vessel transits California waters.

After a vessel leaves port, it travels in an RSZ, during which it uses a lower load factor and consumes less fuel, thereby emitting fewer pollutants, than when traveling at cruising speed. We note that, especially on the West coast, many vessels practice slow steaming outside RSZs to improve fuel efficiency (Wiesmann 2010). In this case, vessels may travel at the same speed while in the RSZ and cruising. In California waters, beyond the RSZ there is a zone in which vessels may operate at cruising speed, but must use MD. In global waters, we assume all vessels use RO. As the vessel nears its destination port, it may again travel through California waters with specific requirements for cruising. It will pass through an RSZ before hoteling at the port of destination.

The GREET marine module aims to model these trip segments, representatively, for different vessel types leaving or arriving at U.S. ports in different regions. After aggregating the EC data, WC data, and other data sources, we grouped U.S. ports as located in the Atlantic, Pacific, Gulf of Mexico, and the Great Lakes. This grouping corresponds to vessel grouping in the WC dataset. Then, we characterized the trips vessels might take from each of these port locations. Figure 13 diagrams these options as modeled in GREET. A key distinction in these route options is between domestic ports outside and within California. RSZs next to California ports are unique because while vessels travel through them, they are required to burn MD. Also, once the vessel exits the RSZ, it must still burn MD while it is cruising in California waters.

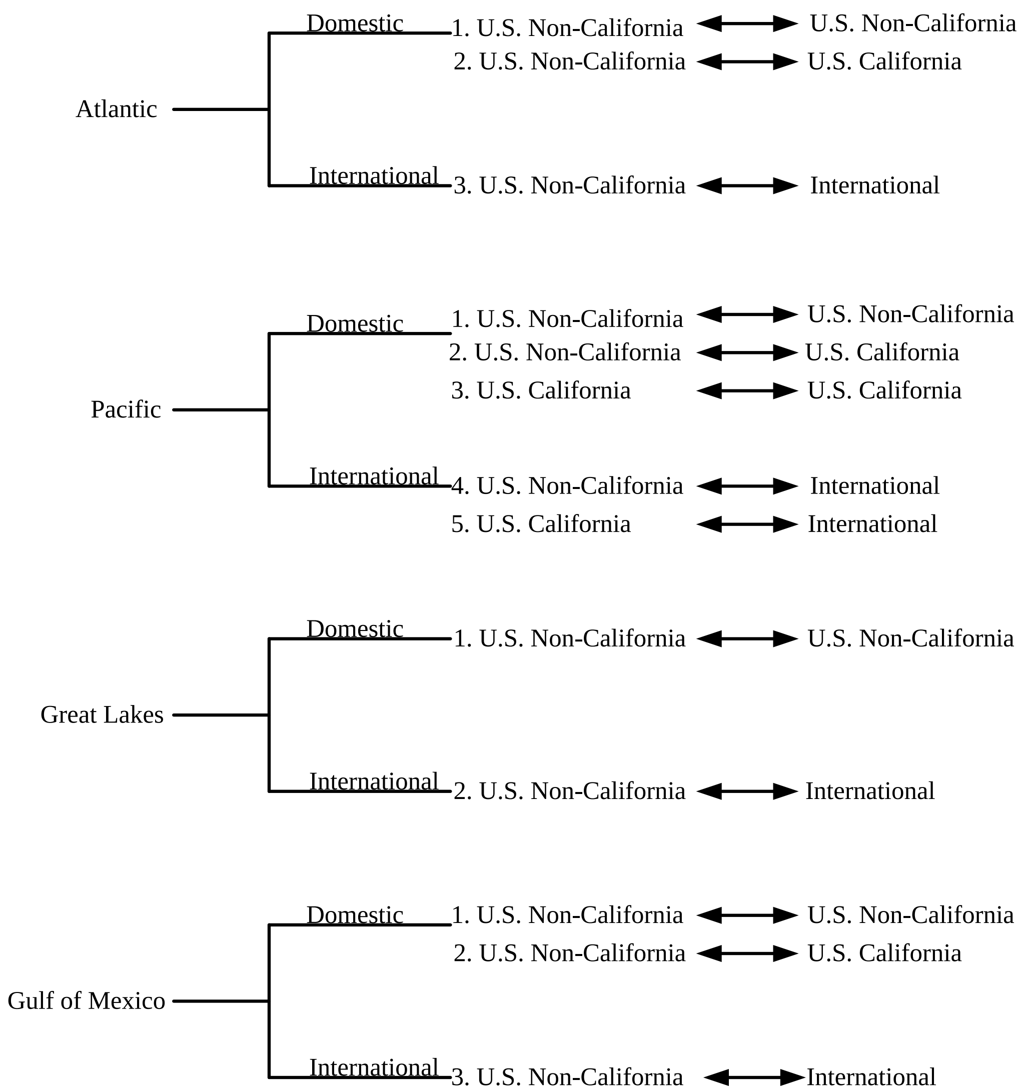

Figure 13: Route options by region included in the GREET marine module

As Section 3.5 explains, routes incorporating a California port therefore must use specific speeds, emission factors, and load factors for the leg of the trip in the California RSZ and cruise zone. Vessels cruising outside of California waters are fueled with RO. Notably, there are three trip types for vessels leaving a West coast port for a domestic destination. They may either travel between two California ports or between two non-California ports, or they may bookend their journey with both a California port and a non-California port. On the other hand, only one domestic trip option exists for vessels departing from the Great Lakes because they do not travel to California at all. International ports can be destinations for vessels leaving ports in all four of the U.S. regions we considered.

We analyzed the WC and EC data to determine characteristic distances, broken out into two RSZs, one cruise portion in global (non-California) waters, and, if applicable, one or two segments of cruise in California waters, for each of the route options in Figure 13. We assumed that the length of the RSZ for any international port was 25 nmi. For Great Lakes ports, the RSZ is set at 3 nmi, whereas for many domestic ports (including for California), we used specific values from the EPA (2009a). If data were not available for a certain port, we used 25 nmi as the RSZ length. Distances vessels traveled in cruise mode in California waters were calculated by subtracting the California RSZ from the total distance traveled in California waters, which were measured in ArcGIS using the ACE navigable-waterway network as a guide. WC and EC data were combined into a Microsoft Access© database which could then be queried by vessel and route type. For each trip in a query, to calculate a characteristic cruise distance, we first subtracted the RSZ distances (and California cruise distance(s), if applicable) from the total trip distance; then we used Equation 1 to calculate a characteristic cruise distance in global waters per trip.

$$D_C = \frac{\sum T_i d_i}{\sum T_{Ti}} \quad , \qquad [1]$$

where
D_C = characteristic distance (nmi);
d_i = distance between a unique origin and destination pair (trip i);
T_i = corresponding trips associated with each distance between a unique origin and destination pair; and
T_{Ti} = total reported trips for a particular route (e.g., U.S. Non-California ↔ International).

We followed the same approach to calculate characteristic RSZ lengths on each end of the trip and distance traveled in cruise mode in California waters if applicable. The calculated characteristic trip distances are included in the GREET marine module.

A separate analysis was conducted to determine the time each vessel type spends dockside, which influences in-port emissions from operation of auxiliary engines. Hoteling load factors, auxiliary engine power (Section 3.3), emission factors, and fuel consumption (Section 3.4) from these engines are addressed separately. In-port dwell times were determined for each vessel type from information in the EC dataset concerning the dates when each vessel arrived and departed from each port. For each vessel type, port dwell times were aggregated to the national level. Of the three vessels included in the marine module, bulk vessels have the longest dwell time, at 117 hours. Dwell times for tanker VLCC and large container vessels are 58 and 22 hours, respectively.

3.3 VESSEL SPEED, ENGINE POWER, PAYLOAD AND LOAD FACTORS

The power rating of the main and auxiliary engines of the vessels included in this release of the GREET marine module (Table 3) are the average of reported engine powers for each vessel type in the IHS Register (IHS 2013). Notably, the main engine of large container vessels is doubled that of the tanker VLCC vessels. Bulk vessels are the smallest included in the module.

Table 3: Average and range for main and auxiliary engine power of the three vessel types in the marine module

	Main engine power (kW)		**Auxiliary engine power (kW)**	
Vessel type	**Average**	**Range**	**Average**	**Range**
Large container ship	37,457	3,280–72,240	8,278	436–14,111
Tanker: VLCC	15,006	2,243–33,627	2,850	1,312–4,647
Bulk	8,698	1,140–18,673	1,852	300–8,832

Vessel speeds were determined from the IHS Register. For each type of vessel traveling in one of the four regions considered, we calculated an average maximum vessel speed. The units of vessel speed in the GREET marine module are knots, or nmi per hour. Vessel speeds were adjusted because vessels rarely travel at full speed. Tables 4 and 5 report these adjustments and load factors (the fraction of the available engine power that is used during operation) used for international and domestic trips, respectively, for different vessel types. These parameters reflect the fact that RSZs are often pertinent only to large vessels. In the module, they are only applied to large container vessels. In the RSZ, vessel speed is reduced by 5 knots and the load factor drops from 0.83 to 0.6. Bulk and tanker VLCC vessels are not subject to RSZ restrictions and operate at constant load factor and speed, although the vessels operate at 92% of maximum speed. Slow steaming is becoming common practice, especially in the Pacific, for large container ships (Wiesmann 2010). This practice conserves fuel because the vessel operates at a lower load factor and speed, and is reflected in the GREET marine module by reducing the speed for large container ships by 5 knots for large container ships in the Pacific. These speeds are not further adjusted for transiting RSZs because the vessels are already traveling at a speed that meets RSZ requirements.

For each vessel type, we also determined the average payload by region to enable calculation of WTH results on a per ton-mile functional unit. For bulk and tanker VLCC vessels, payload is equal to the deadweight. Deadweight is defined as the weight in tonnes (1000 kg) of cargo, stores, fuel, passengers and crew carried by the ship when loaded to her maximum summer draught (IHS 2013.) Deadweight data for bulk and tanker VLCC vessels in the IHS Register of Ships were averaged on a regional basis and are summarized in Table 6 along with minimum and maximum payload values.

Payload data for large container ships is typically reported on a basis of twenty-foot equivalent units (TEU). TEU is a unit of volume reflecting dimensions of 20 ft by 8.5 ft by 8 ft, or 1,260 ft^3. To determine the payload of large container ships on a mass basis, it is necessary to have information about the average density of cargo. The World Shipping Council (2010) reported that TEUs weighed on average 12 and 9 tons for export and import shipments, respectively, in the Trans-Pacific trade in 2008. The share of import and export of cargo was reported to be 34,154,885 TEU (59%) and 23,904,269 TEU (41%) in 2011 (DOT 2011), respectively. Applying the cargo capacity data from the World Shipping Council and the share of import/export, we estimated a weighted TEU average value of 10.2 tons per TEU [=9 tons per TEU (.59) + 12 tons per TEU (.41)]. This weighted average was used to estimate the corresponding weight (tonnes) of large container ships for each region. No payload data were reported for large container ships and tanker VLCCs in the Great Lakes; as a result, payload data for the Gulf of Mexico were used.

The GREET marine module includes different load factors for the auxiliary engines of each vessel type in the module. These values were adopted from ICF Consulting (2005), which indicates that the values came from ship captain, chief engineer, and pilot interviews conducted by Starcrest in developing a 2005 inventory for the Port of Los Angeles. Accordingly, the bulk carrier, tanker, and large container ship are assigned auxiliary engine load factors of 0.10, 0.26, and 0.19, respectively.

Table 4: Vessel speed adjustments and load factors for international trips

Vessel Type	All ports but CA				CA ports				Non-Pacific				Pacific, non-CA				CA			
	Leg	**LF**	**Speed**	**F**	**Leg**	**LF**	**Speed**	**F**	**Leg**	**LF**	**Speed**	**F**	**Leg**	**LF**	**Speed**	**F**	**Leg**	**LF**	**Speed**	**F**
Bulk and tanker VLCC	All	0.83	x 0.92	O	G	0.83	x 0.92	O												
					CA	0.83	x 0.92	D												
Large container ship									G	0.83	x 0.92	O	All	0.6	-5	O	G	0.6	-5	O
									R	0.6	- 5	O					CA	0.6	-5	D

LF = Load factor, F = Fuel, O = Residual oil, D = Marine distillate, G = Global cruise, CA = California cruise, R = RSZ, -5 = speed reduced by 5 knots, x 0.92 = vessel operates at 92% of maximum speed

Table 5: Vessel speed adjustments and load factors for domestic trips

Vessel Type	All Trips			
	Leg	**LF**	**Speed**	**F**
Bulk and tanker VLCC	G	0.83	x 0.92	O
	CA	0.83	x 0.92	D
Large container ship	G	0.6	-5	O
	CA	0.6	-5	D

LF = Load factor, F = Fuel, O = Residual oil, D = Marine distillate, G = Global cruise, CA = California cruise, -5 = speed reduced by 5 knots, x 0.92 = vessel operates at 92% of maximum speed. If vessel does not transit California waters, there is no CA trip leg.

Table 6. Regional average payloads and payload ranges for marine vessels

Region	Bulk (tonnes)		Large Container Ships (tonnes)		Tanker VLCCs (tonnes)	
	Average	Range	Average	Range	Average	Range
Pacific	52,200	16,200–118,500	54,500	6,700–102,600	134,500	47,900–321,300
Atlantic	68,500	11,800–208,000	40,400	6,600–93,600	116,200	6,000–318,700
Gulf of Mexico	56,800	11,800–179,000	38,000	6,400–82,000	119,200	6,600–318,701
Great Lakes	32,300	21,000–37,400	38,000	6,400–82,000	119,200	6,600–318,701

3.4 VESSEL FUEL CONSUMPTION AND EMISSION FACTORS

Vessel fuel consumption and emission factors were compiled from a number of data sources for each vessel type and for two operational modes, cruising (including in RSZs) and hoteling. It should be noted, however, that emission factors for ocean going vessels are not well understood and only a handful of data sources exist to characterize them. Emission factors depend on the engine category and engine speed as EPA defines them (Tables 7 and 8) (ICF Consulting 2005), along with the fuel consumed.

Table 7: EPA commercial marine vessel engine category definitions

Category	Displacement (L/cylinder)	Approximate Power Rating (kW)
1[a]	< 5	< 1,000
2	5–30	1,000–3000
3	≥ 30	> 3,000

[a] To be considered a commercial marine vessel, Category 1 engines must have a gross engine power greater than 37 kW.

Table 8: EPA marine engine speed designations

Category	Engine RPM[a]	Stroke Type[b]
Slow	< 130	2
Medium	130–1,400	4
High	> 1,400	4

[a] RPM = revolutions per minute
[b] A two-stroke engine finishes a power cycle in one crankshaft revolution with two strokes of the piston. A four-stroke engine uses four piston strokes for one crankshaft revolution.

Table 9 contains the emission factors that were used in GREET for vessel cruise mode; all vessels currently included in the marine module are Category 3 vessels built after 2000 and burning either RO or MD. We generated emission factors for Category 2 vessels, Category 3 vessels built prior to 2000, and steam-powered vessels. They are included in Appendix B along with black carbon emission factors.

Table 9: Cruising and RSZ emission factors (g/kWh), fuel properties, and fuel consumption for vessels with Category 3 engines built after 2000 for analysis year 2011

Fuel	**Sulfur Content (ppm)**	**Carbon Content (wt%)**	**LHV[a] (MJ/kg)**	**BSFC[b] (g/kWh)**	**NO_x**	**VOCs[c]**	**CO**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**	**CO_2**	**CH_4**	**N_2O**
RO	27,000[d]	87%	39.5	195	16	0.60	1.4	11	1.4	1.3	620	0.01	0.03
MD	2,000[e]	87%	42.8	185	15	0.60	1.4	0.74	0.22	0.19	580	0.01	0.03
Source				ICF 2005	EPA 2009a	ICF 2005	ICF 2005	S balance	EPA 2009c	EPA 2009c	C balance	SMED[f] 2004	SMED[f] 2004

[a] Lower heating value

[b] Brake-specific fuel consumption

[c] Volatile organic compounds

[d] EPA (2009d) specifies RO sulfur at 27,000 ppm for U.S. waters (excluding California, on the basis of a California Air Resources Board survey).

[e] MD is currently only used in California waters for analysis year 2011, because it is not required to be used elsewhere. California regulations capped MD fuel sulfur content at 2,000 ppm prior to 2012. From 2012 onward, the fuel sulfur content is limited to 1,000 ppm. Vessels traveling in emissions control areas (ECAs) that come into force in 2012 will also be required to use fuels with this level of sulfur or lower. Within the North American ECA, which extends 200 nmi from the U.S. coast, vessels must burn fuel with sulfur content below 1,000 ppm.

[f] Swedish Methodology for Environmental Data (Cooper and Gustafsson 2004).

One important source of emission factor data was the 2005 report from ICF (ICF Consulting, 2005). This report summarized methods for preparing mobile-source port-related emission inventories and surveyed the literature for emission factors. The values reported for BSFC, volatile organic compounds (VOCs), and CO emissions were derived from an earlier report by EnTec (2002). EnTec developed the emission factors by relying on published sources from the Swedish Environmental Research Institute and Lloyd's Register Engineering Services. They also developed an emissions inventory and characterized vessels entering the area of the European Union (EU) that was subject to their study. These inventory data were used to weight the emission factors for each vessel type (e.g., slow-speed diesel, high-speed diesel) for cruising, maneuvering, and hoteling. These values are adopted in GREET as recorded in Table 9.

PM_{10} emission factors for vessels burning RO (included in Table 9) and MD with a sulfur content of 10,000 ppm were provided to ICF Consulting (2005) by the California Air Resources Board on the basis of existing test engine data. ICF Consulting used a factor of 0.92 to convert PM_{10} emission factors to $PM_{2.5}$ emission factors, which is in line with EPA's (2009c) approach. EPA chose this value over the 0.97 used in its NONROAD model because higher-sulfur fuels combusted in medium- and slow-speed marine engines would likely produce larger particulates than higher-speed engines modeled with NONROAD that burn low-sulfur fuels. The PM_{10} and $PM_{2.5}$ emission factor for vessels burning MD with 2,000 ppm sulfur was calculated from the ICF Consulting MD emission factors (for 10,000-ppm-sulfur fuels) on the basis of the difference in fuel sulfur content, as shown in Equation 2 (EPA 2009c):

$$PM_{EF} = PM_{NOM} + [(S_{Act} - S_{Nom}) \times BSFC \times FSC \times MWR \times 0.0001], \qquad [2]$$

where
PM_{EF} = PM emission factor adjusted for fuel sulfur;
PM_{Nom} = PM emissions at a nominal fuel sulfur level (0.45 g/kWh);
S_{Act} = Actual fuel sulfur level (0.2 wt%);
S_{Nom} = Nominal fuel sulfur level (1.0 wt%);
BSFC = Brake-specific fuel consumption (g/kWh) (as in Table 9);
FSC = Percentage of sulfur in fuel that is converted to direct sulfate PM (2.247%) (EPA 2009c); and
MWR = Molecular weight ratio of sulfate PM to sulfur (224/32 = 7) (EPA 2009c).

NO_x emission factors in Table 9 reflect regulations as described in an EPA regulatory impact analysis (EPA 2009d), which is in support of a rule controlling emissions from new marine compression-ignition engines at or above 30 L per cylinder (Category 3 vessels). The NO_x emission factor value for vessels burning RO is from the baseline Tier 1 value in the rule. Tier 1 controls per the rule come into effect for model year 2000 through 2010 engines. The NO_x emission factors for vessels burning MD are the Tier 0 NO_x factors for control areas, in which engines will burn distillate fuels. Tier 0 emission factors are the same as Tier 1 emission factors in this case. NO_x emissions factors for different engine types during phases of the rule's implementation are in Table 3-70 of EPA (2009d).

SO_x and CO_2 emissions are calculated by elemental balance, on the basis of the sulfur and carbon content in the fuel, as in Equations 3 and 4.

$$EF_{SOx} = m_s \times \frac{64\ g\ SO_2}{32\ g\ S} \times BSFC, \qquad [3]$$

where m_s is the weight fraction of sulfur in the fuel.

$$EF_{CO2} = \left(m_c \times BSFC - (EF_{VOC}R_{VOC} + EF_{CO}R_{CO} + EF_{CH4}R_{CH4})\right) \times \frac{1}{R_{CO2}}, \qquad [4]$$

where
m_c = weight fraction of carbon in fuel;
EF_{VOC} = VOC emission factor (g/kWh);
R_{VOC} = VOC carbon ratio (0.85);
EF_{CO} = CO emission factor (g/kWh);
R_{CO} = CO carbon ratio (0.43);
EF_{CH4} = CH_4 emission factor (g/kWh);
R_{CH4} = CH_4 carbon ratio (0.75); and
R_{CO2} = CO_2 carbon ratio (0.27).

Finally, emission factors for N_2O and CH_4 are from Cooper and Gustafsson (2004). The CH_4 factors are based on eight measured ratios of CH_4 to non-methane VOCs from four high-speed diesel vessels burning MD, and are relatively uncertain. The N_2O factors are based on measurements of uncontrolled emissions from seven ships with 12 different engine types that all burned RO. As with the CH_4 emissions factors, the N_2O factors have relatively high uncertainty. One value (0.03 g N_2O/kWh) is assumed to be valid for all engines and fuel types for both pollutants.

Separate emission factor and activity data were developed for hoteling (Table 10). The emission factor sources are the same as for the main engine with the exception of NO_x emissions, which are from the EnTec (2002) study (and used in ICF Consulting (2005)), rather than from EPA (2009d). Fuel property data for RO and MD are the same as in Table 9. We assume that MD is used in auxiliary engines in California ports; vessels docking outside of California use RO in their auxiliary engines.

Table 10: Fuel consumption and emission factors for hoteling (g/kWh)

Fuel	**BSFC**	**NO_x**	**VOCs**	**CO**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**CO_2**	**CH_4**	**N_2O**
RO	227	15	0.40	1.1	12	1.44	1.3	720	4.0×10^{-4}	0.031
MD	217	14	0.40	1.1	0.87	0.22	0.18	690	4.0×10^{-4}	0.031

The above discussion provides emission factors and fuel consumption for vessels burning the conventional fossil fuels RO and MD. The GREET marine module also includes alternative fuels that could be adopted in marine vessels as described in Section 2.2. In GREET, emission factors and fuel consumption for vessels burning these alternative fuels are included as relative values compared to baseline fossil fuels. At present, the literature contains very little information to inform the selection of these relative values. As a result, they are currently set to 100% as placeholders, with two notable exceptions, until we find credible sources to populate them in future updates of the marine module in GREET. The first exception to this approach is SO_2 emissions from the combustion of renewable diesel and FT diesel fuels. The sulfur content of these fuels is vanishingly low and so these emission factors are set to zero. SO_2 emissions for biodiesel are calculated on the basis of percentage of biodiesel blended with marine distillate. The sulfur content of biodiesel is virtually zero, but the SO_2 emissions from combusting the biodiesel blend will be based on Equation 3. The second exception is the treatment of CO_2 emissions from the combustion of bio-based marine fuels. In GREET, the CO_2 emitted from the combustion of these fuels is largely offset by the uptake of CO_2 during feedstock growth.

3.5 CALCULATION OF FUEL CONSUMPTION AND EMISSIONS

The activity data, engine characteristics, load factors, and emissions factors in the preceding sections for each element of a trip and for hoteling are used together to calculate fuel consumption and emissions per trip. Equations 5–12 show the details of calculating fuel consumption per trip. A similar approach can be used to calculate the emissions per trip.

$$F_{Total} = F_{Hotel1} + F_{RSZ1} + F_{C\_CA1} + F_C + F_{C\_CA2} + F_{RSZ2} + F_{Hotel2}\ , \qquad [5]$$

where

F_{Total} = fuel consumption for one trip (g/trip);
F_{Hotel1} = fuel consumption during hoteling at port of origin (g/trip);
F_{RSZ1} = fuel consumption in RSZ_1 while leaving port of origin (g/trip);
F_{C_CA1} = fuel consumption during cruising in California waters while leaving port of origin (g/trip) (not applicable if port of origin is not a California port);
F_C = fuel consumption during cruising (g/trip);
F_{C_CA2} = fuel consumption during cruising in California waters while arriving at port of destination (g/trip) (not applicable if port of destination is not a California port);
F_{RSZ2} = fuel consumption in RSZ_2 while arriving at port of destination (g/trip); and
F_{Hotel2} = fuel consumption during hoteling at port of destination (g/trip).

Equations 6–12 are used to calculate the individual contributions to F_{Total} for large container ships traveling internationally. These individual contributions are calculated separately because load factors and fuel/engine types used at ports of origin and destination and in RSZs 1 and 2 may be different, affecting the BSFC used in the calculation. Additionally, characteristic distances may be different for RSZs and, if applicable, California cruise distances on either end of a trip. Note that the parameters in Equations 6–12 (e.g., speeds, dwell times) vary by vessel type, as explained in the preceding sections. For domestic trips, parameters in Table 5 should be used in place of those in Table 4. For tanker VLCC and bulk vessels, RSZs do not apply as described in section 3.3.

$$F_{Hotel1} = BSFC_{H1} \times P_A \times LF_H \times t_{H1} \ , \qquad [6]$$

where
$BSFC_{H1}$ = BSFC during hoteling at port of origin (g/kWh) (see Table 10);
P_A = auxiliary engine power (kW) (see Table 3);
LF_H = load factor during hoteling (see section 3.3); and
t = dwell time (hr) (see section 3.2).

$$F_{RSZ1} = BSFC_{RSZ1} \times P_M \times LF_{RSZ1} \times D_{RSZ1} \times \frac{1}{\upsilon_{adj,RSZ1}} \ , \qquad [7]$$

where
$BSFC_{RSZ1}$ = BSFC during transit of RSZ_1 (g/kWh) (see Table 9);
P_M = power of main engine (kW) (see Table 3);
LF_{RSZ1} = load factor during transit of RSZ_1 (see Table 4);
D_{RSZ1} = length of RSZ_1 (Nmi); and
$\upsilon_{adj,RSZ1}$ = adjusted speed in RSZ_1 (Nmi/hr) (see Table 5).

$$F_{C\_CA1} = BSFC_{C\_CA1} \times P_M \times LF_{C\_CA1} \times D_{C\_CA1} \times \frac{1}{\upsilon_{adj,C\_CA1}} \ , \qquad [8]$$

where
$BSFC_{C\_CA1}$ = BSFC while cruising in California waters after leaving port of origin (g/kWh) (see Table 9);
LF_{C_CA1} = load factor while cruising in California waters after leaving port of origin (see Table 4);
D_{C_CA1} = distance that vessel cruises in California waters after leaving port of origin (Nmi); and
υ_{adj,C_CA1} = adjusted speed while cruising in California waters after leaving port of origin (Nmi/hr) (see Table 4).

$$F_C = BSFC_C \times P_M \times LF_C \times D_C \times \frac{1}{\upsilon_{adj,C}} \ , \qquad [9]$$

where
$BSFC_C$ = BSFC during cruising (g/kWh) (see Table 9);
LF_C = load factor during cruising (see Table 4);
D_C = distance that vessel cruises in global (non-California, non-RSZ) waters (Nmi); and
$\upsilon_{adj,C}$ = adjusted speed during cruising in global waters (Nmi/hr) (see Table 4).

$$F_{C\_CA2} = BSFC_{C\_CA2} \times P_M \times LF_{C\_CA2} \times D_{C\_CA2} \times \frac{1}{\upsilon_{adj,C\_CA2}} \ , \qquad [10]$$

where
$BSFC_{C\_CA2}$ = BSFC while cruising in California waters before arrival at port of destination (g/kWh) (see Table 9);
LF_{C_CA2} = load factor while cruising in California waters before arrival at port of destination (see Table 4);
D_{C_CA2} = distance vessel cruises in California waters before arrival at port of destination (Nmi); and
υ_{adj,C_CA2} =adjusted speed while cruising in California waters before arrival at port of destination (Nmi/hr) (see Table 4).

$$F_{RSZ2} = BSFC_{RSZ2} \times P_M \times LF_{RSZ2} \times D_{RSZ2} \times \frac{1}{\upsilon_{adj,RSZ2}} \quad , \qquad [11]$$

where
$BSFC_{RSZ2}$ = BSFC during transit of RSZ2 (g/kWh) (see Table 9);
P_M = power of main engine (kW) (see Table 3);
LF_{RSZ2} = load factor during transit of RSZ2 (see Table 4);
D_{RSZ2} = length of RSZ2 (Nmi); and
$\upsilon_{adj,RSZ2}$ = adjusted speed in RSZ2 (Nmi/hr) (see Table 4).

$$F_{Hotel2} = BSFC_{H2} \times P_A \times LF_H \times t \quad , \qquad [12]$$

where
$BSFC_{H2}$ = BSFC during hoteling at port of origin (g/kWh);
P_A = auxiliary engine power (kW) (see Table 3);
LF_H = load factor during hoteling (see section 3.3); and
t = dwell time (hr) (see section 3.2).

Note that the engine power, speed, dwell time, and characteristic distances in Equations 6–12 vary by vessel type and, in some cases by trip type, as explained in the preceding sections.

To calculate emissions of air pollutants per trip, including GHGs, BSFC values in equations 6–12 can be replaced with the emission factors in Table 9. The next section explains how these calculations for the PTH portion of the marine fuel life cycle are conducted in GREET.

4. THE GREET MARINE MODULE FOR WELL-TO-HULL CALCULATIONS

In this section, we discuss the layout and operation of the GREET marine module, which is contained on two tabs within GREET called MarineFuel_PTH and MarineFuel_WTH. PTH and WTH are abbreviations for pump-to-hull and well-to-hull, respectively. The PTH tab covers the operation of the marine vessel and allows the user to select among fuel choices. The WTH tab calculates full life-cycle energy consumption and emissions that take into account upstream impacts of fuel production and the impacts of vessel operation. Section 4.1 reviews the two tabs of the GREET marine module. In Section 4.2, we discuss planned expansions and updates for the GREET marine module.

4.1 PTH AND WTH TABS

The PTH tab is divided into sections 1 through 7. In section 1, the user chooses the type of fuel that is used for different operational modes in either California waters or non-California waters. In general, pink boxes contain drop-down lists for users to make selections and yellow cells are key inputs that the user can change. First, users choose a fuel used for cruise mode, RSZ, and hoteling at each trip endpoint. These are denoted as RSZ or Hotel 1 and 2. In the next block of cells, users select among different feedstocks for each fuel. Possibilities available to the user are shown in Table 11.

Table 11: Feedstock choices for fuels in GREET marine module

<table>
<tr><th>Fuel</th><th>Feedstock choices</th></tr>
<tr><td>MD and low-sulfur MD[a]</td><td>Crude oil, hydrotreated pyrolysis oil</td></tr>
<tr><td>FT diesel</td><td>Natural gas, gasified biomass, gasified coal, gasified coal/biomass combination</td></tr>
<tr><td>Hydrotreated renewable diesel</td><td rowspan="2">Soybeans, palm, rapeseed, jatropha, camelina, algae</td></tr>
<tr><td>Biodiesel[a]</td></tr>
</table>

[a] Just below fuel choices, users can specify the share of marine diesel that is low-sulfur and the percent of pure renewable (100% bio-derived) diesel blended with MD.

Next, the fuel properties of the different fuels incorporated into the module are listed.

Section 2 deals with marine vessel characteristics. Section 2.1 lists the power rating of both the main and auxiliary engines for the vessels included in the module. Section 2.2 allows the user to specify relative energy consumption and emissions of alternative fuels to baseline RO. Section 2.3 of the GREET marine module incorporates the BSFC and emission factors for the main (Category 3) and auxiliary (Category 2) engines, as discussed in Section 3.4 of this report.

Section 3 of the PTH tab contains the characteristic distance, speed, load factor, and port dwell-time data used in calculating emissions per trip as described in Section 3.5. Users can change yellow-highlighted cells without breaking links between cells in GREET, thus facilitating the use of user-defined or custom data to understand the impacts of a specific vessel fleet. Section 3 of the tab is broken out by vessel type and region. On a regional basis, data are provided for the applicable trip types as shown in Figure 13.

Section 4 of the PTH tab shows the regional payload for all three vessels considered in the marine module. This allows users to estimate the energy use and emissions on a payload basis to determine the efficiency of freight transport.

Sections 5 and 6 provide PTH results for vessels fueled with conventional and alternative fuels, respectively. In Section 6, results are provided per unit energy of the fuel consumed by the vessel. In this section, WTP energy and emissions for each fuel are brought in from data on other GREET tabs such as Petroleum, Pyrolysis, and BioOil. Energy consumption and emissions during fuel combustion are calculated from data on the PTH tab.

The WTH data catalogue the results for all vessel types, for each trip type in the four U.S. regions. Users can select the vessel type and region from the drop-down list at the top of the WTH tab. Clicking the "Go" button for either conventional or alternative fuels will scroll to the corresponding table of results. Users can choose functional units for energy and emissions in the drop-down boxes on the top right section of the WTH tab. Specifically, users can choose between three service functional units: per trip, per mile, and per ton mile. Section 1 of the WTH tab presents results for conventional fuels, Section 2 for alternative fuels, while results per MJ of fuel use are provided in Section 3 of the WTH tab.

4.2 PLANNED EXPANSIONS AND UPDATES FOR THE GREET MARINE MODULE

Future expansions and updates for the GREET marine module may include the introduction of probability distribution functions for trip distances to replace the current point estimates of distances in the module. Additionally, we will investigate whether there are sufficient data to provide reasonable values for the energy consumption and emissions of alternatively fueled marine vessels relative to vessels operating on conventional fuels in Section 2.2 of the PTH tab. We will add time series to reflect potential changes in vessel emissions due to fuel and vessel technology advances and regulations that will come into play in future years. For example, analyses for years 2020 and beyond will take into account the new North American ECA requirements. Moreover, vessels have several control options that can be incorporated to reduce fuel consumption and emissions beyond what regulations require. Example technologies include fuel injection improvements, selective catalytic reduction, exhaust gas recirculation, and hybrid technology. We may introduce emission control options for different vessels and the corresponding emission reductions into the module. Finally, additional vessel types may be added to the module.

5. REFERENCES

ACE (U.S. Army Corps of Engineers). 2013a. *Vessel Entrances and Clearances Calendar Year 2011*. http://www.navigationdatacenter.us/data/dataclen.htm. Accessed October 4, 2013.

ACE (U.S. Army Corps of Engineers.) 2013b. *Waterborne Commerce Data 2011*. http://www.iwr.usace.army.mil/About/TechnicalCenters/WCSCWaterborneCommerceStatisticsCenter.aspx. Accessed October 4, 2013.

ASTM. 2006. *Standard Specification for Diesel Fuel Oils, ASTM Standard D 975-98b*. ASTM Standards. West Conshohocken, PA: ASTM International.

Bengtsson, S., Andersson, K., and Fridell, E. 2011. *A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels.* Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 225(2), 97‒110.

Bradley, D. 2006. *European market study for BioOil (Pyrolysis oil)*. In IEA Bioenergy Task (Vol. 40). U.S. Environmental Protection Agency, Office of Transportation and Air Quality (OTAQ). Docket EPA-HQ-OAR-2007‒0121

Buhaug, O., J. Corbett, V. Eyring, Ø Endresen, J. Faber, S. Hanayama, D. Lee, D. Lee, H. Lindstad, A. Markowska, A. Mjelde, D. Nelissen, J. Nilsen, C. Pålsson, W. Wu, J. Winebrake, and K. Yoshida. 2009. *Second IMO GHG Study 2009*. London: International Maritime Organization.

Burnham, A., J. Han, C.E. Clark, M. Wang, J.B. Dunn, and I. Palou-Rivera. 2012. *Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum*. Environmental Science and Technology, 46(2), 619–627. DOI: 10.1021/es201942m.

Cai, H., G. Forman, V. Divita, M. Wang, A. Elgowainy, and J. Han. 2013. *Analysis of Petroleum Refining: Overall Efficiency of Refineries in the United States*. Argonne National Laboratory, Argonne, IL.

California Air Resources Board. 2012. *Advisory to Owners or Operators of Ocean-Going Vessels or Ships Visiting California Ports: Upcoming Requirements in the Regulation for Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline (California OGV Fuel Regulation)*. Marine Notice 2012‒1.

CIMAC (International Council on Combustion engines). 2013. *Guideline for Ship Owners and Operators on Managing Distillate Fuels up to 7.0% v/v FAME (Biodiesel) V1.0, 2013* http://www.cimac.com/cimac_cms/uploads/explorer/Working%20groups/CIMAC_WG7_Fuels_Guide_to_Handling_Marine_Fuels_with_FAME_V1_00_May_2013.pdf. Accessed on July 26, 2013.

Cooper, D., and T. Gustafsson. 2004. *Methodology for calculating emissions from ships: 1. Update of emission factors*. Rep. Ser. SMED and SMED & SLU 4, Swedish Methodology for Environmental Data.

Corbett, J. 2004. *Marine transportation and energy use*. pp. 745–758 in: J.C. Cutler (Ed.), Encyclopedia of Energy. New York: Elsevier.

Corbett, J., J. Winebrake, E.H. Green, P. Kasibhatla, V. Eyring, and A. Lauer. 2007. *Mortality from ship emissions: a global assessment*. Environmental Science & Technology, 41(24), 8512–8518.

Corbett, J., H. Wang, and J. Winebrake. 2009. *The effectiveness and costs of speed reductions on emissions from international shipping*. Trans. Res. D, 14, 593–598. DOI: 10.1016/j.trd.2009.08.005.

Corbett, J., J. Winebrake, and E.H. Green. 2010. *An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping*, Carbon Management. 1, 207–225. DOI: 10.4155/cmt.10.27.

DOD (U.S. Department of Defense). 2006. *Performance Specification Fuel, Naval Distillate, Military Specification*. MIL-PRF-16884L. Washington, D.C.: U.S. Department of Defense.

DOE (U.S. Department of Energy). 2013. *Alternative Fuels Data Center*. http://www.afdc.energy.gov/. Accessed on October 4, 2013.

DOT (U.S. Department of Transportation). 2008a. *U.S. Water Transportation Statistical Snapshot*. Washington, D.C.: Maritime Administration. http://www.marad.dot.gov/documents/US_Water_Transportation_Statistical_snapshot.pdf. Accessed July 30, 2013.

DOT (U.S. Department of Transportation). 2008b. *U.S. Waterborne Foreign Container Trade by U.S. Customs Ports*. Washington, D.C.: Maritime Administration. http://www.marad.dot.gov/library_landing_page/data_and_statistics/Data_and_Statistics.htm.

DOT (U.S. Department of Transportation). 2011. *Office of Freight Management and Operations, Freight Analysis Framework*, version 3.2. Washington, D.C.: Federal Highway Administration.

Dynomotive Energy Systems. 2013. *Pyrolysis oil producer* http://www.dynamotive.com/fuels/. Accessed on September 26, 2013.

Eberhardt, J. 2002. *Fuels of the future for cars and trucks*. Presented at the 2002 Diesel Engine Emissions Reduction (DEER) Workshop, August 25–29.

EIA (U.S. Energy Information Administration). 2012a. *Refinery Capacity Report* 2012. http://www.eia.gov/petroleum/refinerycapacity/archive/2012/refcap2012.cfm. Accessed on October 3, 2013.

EIA (U.S. Energy Information Administration). 2012b. *Petroleum Supply Annual* 2011. http://www.eia.gov/petroleum/supply/annual/volume1. Accessed on October 3, 2013.

Elgowainy, A., J. Han, M. Wang, N. Carter, R. Stratton, J. Hileman, A. Malwitz, and S. Balasubramanian. 2012. *Life-cycle Analysis of Alternative Aviation Fuels in GREET*. ANL/ESD/12‒8. Argonne National Laboratory, Argonne, IL.

EnTec. 2002. *Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community*. Prepared for the European Commission.

EPA (U.S. Environmental Protection Agency). 2007a. *An Environmental Management System (EMS) Primer for Ports: Advancing Port Sustainability*. Prepared by ICF International. http://www.epa.gov/cleandiesel/documents/ems_primer.pdf. Accessed August 28, 2013.

EPA (U.S. Environmental Protection Agency). 2007b. *Category 2 Vessel Census, Activity, and Spatial Allocation Assessment and Category 1 and Category 2 In-port/at-sea Splits*. Prepared by Eastern Research Group, Inc., for the Office of Transportation and Air Quality.

EPA (U.S. Environmental Protection Agency). 2008a. *Global Trade and Fuels Assessment—Future Trends and Effects of Requiring Clean Fuels in the Marine Sector*. EPA420-R-08‒021.

EPA (U.S. Environmental Protection Agency). 2008b. *EPA Finalizes More Stringent Emissions Standards for Locomotives and Marine Compression-Ignition Engines*. EPA-420-F-08‒004. Office of Transportation and Air Quality: Regulatory Announcement. http://www.epa.gov/nonroad/420f08004.pdf. Accessed August 28, 2013.

EPA (U.S. Environmental Protection Agency). 2009a. *Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories: Final Report*. Prepared by ICF International. http://www.epa.gov/sectors/sectorinfo/sectorprofiles/ports/ports-emission-inv-april09.pdf. Accessed August 28, 2013.

EPA (U.S. Environmental Protection Agency). 2009b. *EPA Finalizes More Stringent Standards for Control of Emissions from New Marine Compression-Ignition Engines At or Above 30 Liters per Cylinder*. EPA-420-F-09–068. Office of Transportation and Air Quality: Regulatory Announcement. http://www.epa.gov/otaq/regs/nonroad/marine/ci/420f09068.pdf. Accessed August 28, 2013.

EPA (U.S. Environmental Protection Agency). 2009c. Chapter 2: Emission Inventory. In: *Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides and Particulate Matter: Technical Support Document.* EPA-420-R-09–007.

EPA (U.S. Environmental Protection Agency). 2009d. *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Category 3 Marine Diesel Engines.* EPA-420-R-09–019.

EPA (U.S. Environmental Protection Agency). 2010. *Designation of North American Emission Control Area to Reduce Emissions from Ships.* EPA-420-F-10–015. Office of Transportation and Air Quality: Regulatory Announcement.

EPA (U.S. Environmental Protection Agency). 2011. *National Emissions Inventory Data and Documentation*. http://www.epa.gov/ttnchie1/net/2011inventory.html.

European Union Biotechnology Platform. 2013. *Biofuels for Boats and Shipping*. http://www.biofuelstp.eu/boats.html. Accessed on October 3, 2013.

Eyring, V., W. Kohler, J. van Aardenne, and A. Lauer. 2005. *Emissions from international shipping: 1. The last 50 years.* Journal of Geographical Research, 110, D17305. DOI: 10. 1029/2004JD0005619.

Florentinus, A., C. Hamelinck, A. van den Bos, R. Winkel, and M. Cuijpers. 2012. *Potential of Biofuels for Shipping.* Utrecht: ECOFYS Netherlands BV.

Frank, E.D., J. Han, I. Palou-Rivera, A. Elgowainy, and M.Q. Wang. 2011. *Life-cycle Analysis of Algal Lipid Fuels with the GREET Model*. ANL/ESD/11-5, Argonne National Laboratory, Argonne, IL.

Frank, E.D., J. Han, I. Palou-Rivera, A. Elgowainy, and M.Q. Wang. 2012. *Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels*. Environmental Research Letters, 7(1), 014030.

Green Car Congress. 2013. *Mærsk Group exploring use of lignin-based marine biofuels; CyclOx and B21st*. Available at: http://www.greencarcongress.com/2013/03/maersk-20130320.html. Accessed on October 3, 2013.

Han, J., A. Elgowainy, I. Palou-Rivera, J.B. Dunn, and M.Q. Wang. 2011. *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with the GREET Model*. ANL/ESD/11–8. Argonne National Laboratory, Argonne, IL.

Han, J., A. Elgowainy, H. Cai, and M.Q. Wang, M. 2013. *Life-cycle analysis of bio-based aviation fuels*. Bioresource Technology, in press. DOI 10.1016/j.biotech.2013.07.153

Hileman, J., J.B. Katz, J. Mantilla, and G. Fleming. 2008. *Payload fuel energy efficiency as a metric for aviation environmental performance.* Proceedings of the 26th International Congress of the Aeronautical Sciences, pp. 1–11.

Huo, H, M. Wang, C. Bloyd, and V. Putsche. 2008. *Life Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-derived Biodiesel and Renewable Fuels*. ANL/ESD/08–2., Argonne National Laboratory, Argonne, IL.

ICF Consulting. 2005. *Emission Reduction Incentives for Off-Road Diesel Equipment Used in the Port and Construction Sectors*: *Final Report*. May 19. Prepared for the U.S. Environmental Protection Agency.

IHS. 2013. *Register of Ships*. Available at http://www.ihs.com/products/maritime-information/ships/register.aspx. Accessed on October 4, 2013.

IMO (International Maritime Organization). 2013. *Special Areas under MARPOL*. Available at http://www.imo.org/OurWork/Environment/PollutionPrevention/SpecialAreasUnderMARPOL/Pages/Default.aspx. Accessed on August 30, 2013

ISO (International Organization for Standardization). n.d. *ISO 8217:2012. Petroleum Products—Fuels (class F)—Specifications of Marine Fuel*s, fifth edition. Stage: 90.92 | TC 28/SC 4, ICS: 75.160.20. http://www.iso.org/iso/catalogue_detail.htm?csnumber=59479.

Irvine, S. 2009. *Marine Fuel Industry Overview*. Ann Arbor, MI: U.S. Environmental.

Jameson, N. 2008. *Complete Guide to the Bunker Market 2008*. Singapore: Petromedial Pte Ltd.

Lin, C.Y. 2013. *Strategies for promoting biodiesel use in marine vessels*. Marine Policy 40, 84–90.

Mushrush, W., D. Willauer, W. Bauserman, and W. Williams. 2009. *Incompatibility of Fischer−Tropsch diesel with petroleum and soybean biodiesel blends*. Industrial & Engineering Chemistry Research, 48(15), 7364–7367.

Nayyar, M. P. 2010. *The Use of Biodiesel Fuels in the US Marine Industry*. Prepared for the U.S. Maritime Administration.

Omni Tech International. 2010. *Life Cycle Impact of Soybean Production and Soy Industrial Products.* Prepared for the United Soybean Board.

Opdal, O.A., and J. Fjell Hojem. 2007. *Biofuels in Ships: A Project Report and Feasibility Study into the Use of Biofuels in the Norwegian Domestic Fleet*. ZERO Emission Resource Organization.

Pearlson, M., C. Wollersheim, and J. Hileman. 2013. *A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production.* Biofuels, Bioproducts, Biorefining, 7, 89–96.

Petzold, A., P. Lauer, U. Fritsche, J. Hasselbach, M. Lichtenstern, H. Schlager, and F. Fleischer. 2011. *Operation of marine diesel engines on biogenic fuels: modification of emissions and resulting climate effects*. Environmental Science and Technology, 45, 10394–10400.

Pradhan, A., D.S. Shrestha, A. McAloon, W. Yee, M. Haas, and J.A. Duffield. 2011. *Energy life-cycle assessment of soybean biodiesel revisited*. Transactions of the ASABE, 54(3), 1031–1039.

Righi, M., C. Klinger, V. Eyring, J. Hendricks, A Lauer, and A. Petzold. 2011. *Climate impact of biofuels in shipping: global model studies of the aerosol indirect effect*. Environmental Science and Technology, 45, 3519–3525.

Searates. 2013. *Transit Time/Distance Calculator*. http://www.searates.com/reference/portdistance/. Accessed October 4, 2013.

Shonnard, D.R., L. Williams, and T.N. Kalnes. 2010. *Camelina-derived jet fuel and diesel: sustainable advanced biofuels*. Environmental Progress & Sustainable Energy, 29(3), 382–392.

Stamper, D.M., and G.F. Lee. 2008. *The Explicit and Implicit Qualities of Alternative Fuels: Issues to Consider for Their Use in Marine Diesel Engines*. NSWCCD-61-TR-2008/15. Naval Surface Warfare Center, Carderock Div., Bethesda, MD, Survivability Structures and Materials Directorate.

Stratton, R.W., H.M. Wong, and J.I. Hileman. 2010. *Life cycle greenhouse gas emissions from alternative jet fuels*. PARTNER Project, 28, 133.

Stratton, R.W., H.M. Wong, and J.I. Hileman. 2011. *Quantifying variability in life cycle greenhouse gas inventories of alternative middle distillate transportation fuels.* Environmental Science & Technology, 45(10), 4637–4644.

UNCTAD. 2012. *Review of Maritime Transport*. UNCTAD/RMT/2012. http://unctad.org/en/PublicationsLibrary/rmt2012_en.pdf. Accessed July 30, 2013.

Wallace, J., M. Wang, T. Weber, and A. Finizza. 2001. *GM Study: Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis – Volume 3: Transportation Fuels. Prepared by* General Motors Corporation, Argonne National Laboratory, BP, ExxonMobil, and Shell. http://greet.es.anl.gov/publication-wft2tv3v. Accessed September 30, 2013.

Wang, M., H. Lee, and J. Molburg. 2004 *Allocation of energy use in petroleum refineries to petroleum products: implications for life-cycle energy use and emission inventory of petroleum transportation fuels*. International Journal of Life Cycle Analysis, 9(1), 34–44.

Wang, Z., J.B. Dunn, J. Han, and M. Wang. 2013. *Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels.* ANL/ESD-13/9. Argonne National Laboratory, Argonne, IL.

Waterways Journal, Inc. 2013. *Inland River Record.* http://www.wjinc.net/irr_2013.html. Accessed October 23, 2013.

Wiesmann, A. (2010). *Slow steaming–a viable long-term option*? Wartsila Technical Journal, 2, 49–55.

Winebrake, J.J., J.J. Corbett, E.H. Green, A. Lauer, and V. Eyring. 2009. *Mitigating the health impacts of pollution from oceangoing shipping: An assessment of low-sulfur fuel mandates*. Environ. Sci. Technol. 43, 4776–4782.

World Shipping Council. 2010. *Facts about Serving U.S. Export Commerce*. February.

Xie, X., M. Wang, and J. Han. 2011. *Assessment of Fuel-cycle Energy Use and Greenhouse Gas Emissions for Fischer-Tropsch Diesel from Coal and Cellulosic Biomass*. Environmental Science and Technology 45(7), 3047–3053.

APPENDIX A

TABLE A1. SPECIFICATIONS FOR MARINE DISTILLATE FUELS

Characteristic	Unit	Limit	Category ISO-F				Test Method Reference
			DMX	DMA	DMB	DMC	
Density at 15°C	kg/m^3	max.	--	890.0	900.0	920.0	ISO 3675 or ISO 12185 (see also 7.1)
Viscosity at 40°C	mm^2/s[a]	min. max.	1.40 5.50	1.50 6.00	-- 11.0	-- 14.0	ISO 3104 ISO 3104
Flash point	°C	min. max.	-- 43	60 --	60 --	60 --	ISO 2719 (see also 7.2)
Pour point (upper) - Winter quality - Summer quality	°C	max. max.	-- --	-6 0	0 6	0 6	ISO 3016 ISO 3016
Cloud point	°C	max.	-16[b]	--	--	--	ISO 3015
Sulfur	% (*m/m*)	max.	1.00	1.50	2.00[c]	2.00[c]	ISO 8754 or ISO 14596 (see also 7.3)
Cetane index	--	min.	45	40	35	--	ISO 4264
Carbon residue on 10% (V/V) distillation bottoms	% (*m/m*)	max.	0.30	0.30	--	--	ISO 10370
Carbon residue	% (*m/m*)	max.	--	--	0.30	2.50	ISO 10370
Ash	% (*m/m*)	max.	0.01	0.01	0.01	0.05	ISO 6245
Appearance	--	--	Clear and bright		d	--	See 7.4 and 7.5
Total sediment, existent	% (*m/m*)	max.	--	--	0.10[d]	0.10	ISO 10307-1 (see 7.5)
Water	% (*V/V*)	max.	--	--	0.3[d]	0.3	ISO 3733
Vanadium	mg/kg	max.	--	--	--	100	ISO 14597 or IP 501 or IP 470 (see 7.8)
Aluminum plus silicon	mg/kg	max.	--	--	--	25	ISO 10478 or IP 501 or IP 470 (see 7.9)
Used lubricating oil (ULO) - Zinc - Phosphorus - Calcium	mg/kg mg/kg mg/kg	max. max. max.	-- -- --	-- -- --	-- -- --	The fuel shall be free of ULO[e] 15 15 30	IP 501 or IP 470 IP 501 or IP 500 IP 501 or IP 470 (see 7.7)

[a] 1 mm^2/s = 1cSt

[b] This fuel is suitable for use without heating at ambient temperatures down to -16°C.

[c] A sulfur limit of 1.5% (*m/m*) will apply in SO_x emission control areas designated by the International Maritime Organization, when its relevant protocol enters into force. There may be local variations; for example, the EU requires that sulfur content of certain distillate grades be limited to 0.2% (*m/m*) in certain applications.

[d] If the sample is clear and with no visible sediment or water, the total sediment existent and water tests shall not be required. See 7.4 and 7.5.

[e] A fuel shall be considered to be free of used lubricating oils (ULOs) if one or more of the elements zinc, phosphorus and calcium are below or at the specified limits. All three elements shall exceed the same limits before a fuel shall be deemed to contain ULOs.

TABLE A2. SPECIFICATIONS FOR MARINE RESIDUAL FUELS

Characteristic	Unit	Limit	Category ISO-F RMA 30	RMB 30	RMD 80	RME 180	RMF 180	RMG 380	RMH 380	RMK 380	RMH 700	RMK 700	Test Method Reference
Density at 15°C	kg/m^3	max.	960.0	975.0	980.0	991.0		991.0		1010.0	991.0	1010.0	ISO 3675 or ISO 12185 (see also 7.1)
Kinematic viscosity at 50°C	mm^2/s[a]	max.	30.0		80.0	180.0		380.0			700.0		ISO 3104
Flash point	°C	max.	60		60	60		60			60		ISO 2719 (see also 7.2)
Pour point (upper)[b]													
- Winter quality	°C	max.	0	24	30	30		30			30		ISO 3016
- Summer quality	°C	max.	6	24	30	30		30			30		ISO 3016
Carbon residue	% (*m/m*)	max.	10		14	15	20	18	22		22		ISO 10370
Ash	% (*m/m*)	max.	0.10		0.10	0.10	0.15	0.15			0.15		ISO 6245
Water	% (*V/V*)	max.	0,5		0,5	0,5		0,5			0,5		ISO 3733
Sulfur[c]	% (*m/m*)	max.	3.50		4.00	4.50		4.50			4.50		ISO 8754 or ISO 14596 (see also 7.3)
Vanadium	mg/kg	max.	150		350	200	500	300	600		600		ISO 14597 or IP 501 or IP 470 (see 7.8)
Total sediment potential	% (*m/m*)	max.	0.10		0.10	0.10		0.10			0.10		ISO 10307-2 (see 7.6)
Aluminum plus silicon	mg/kg	max.	80		80	80		80			80		ISO 10478 or IP 501 or IP 470 (see 7.9)
Used lubricating oil (ULO)			The fuel shall be free of ULO[d]										
- Zinc	mg/kg	max.	15										IP 501 or IP 470 (see 7.7)
- Phosphorus	mg/kg	max.	15										IP 501 or IP 500 (see 7.7)
- Calcium	mg/kg	max.	30										IP 501 or IP 470 (see 7.7)

[a] Annex C gives a brief viscosity/temperature table, for information purposes only, 1 mm^2/s = 1 cSt

[b] Purchasers should ensure that this pour point is suitable for the equipment on board, especially if the vessel operates in both the northern and southern hemispheres.

[c] A sulfur limit of 1,5% (m/m) will apply in SO_x emission control areas designated by the International Maritime Organization, when its relevant protocol comes into force. There may be local variations.

[d] A fuel shall be considered to be free of ULO if one or more of the elements zinc, phosphorus and calcium are below or at the specified limits. All three elements shall exceed the same limits before a fuel shall be deemed to contain ULO.

APPENDIX B

TABLE B1: EMISSION FACTORS FOR CATEGORY 2 AND CATEGORY 3 ENGINES WITH DIFFERENT FUELS IN 2011

Engine Category	Tier	Fuel	ppm S	BSFC	NO_x	VOCs	CO	SO_2	PM_{10}	$PM_{2.5}$	CO_2	CH_4	N_2O	Black Carbon
Steam		RO	27,000	305	2.1	0.1	0.2	16	1.5	1.4	970	2.0×10^{-3}	0.08	0.03
2	0			213	14	0.5	1.1	12	1.4	1.3	670	4.0×10^{-3}	0.03	0.03
2	1			213	13	0.5	1.1	12	1.4	1.3	670	4.0×10^{-3}	0.03	0.03
3	0			195	18	0.6	1.4	11	1.4	1.3	620	0.01	0.03	0.03
3	1			195	16	0.6	1.4	11	1.4	1.3	620	0.01	0.03	0.03
Steam		MD	2,000	290	2	0.1	0.2	1.2	0.58	0.53	920	2.0×10^{-3}	0.08	0.01
2	0			203	13	0.5	1.1	0.81	0.21	0.17	640	4.0×10^{-3}	0.03	4.3×10^{-3}
2	1			203	12	0.5	1.1	0.81	0.21	0.17	640	4.0×10^{-3}	0.03	4.3×10^{-3}
3	0			185	17	0.6	1.4	0.74	0.22	0.19	580	0.01	0.03	4.3×10^{-3}
3	1			185	15	0.6	1.4	0.74	0.22	0.19	580	0.01	0.03	4.3×10^{-3}
			Source	ICF 2005	EPA 2009a	ICF 2005	ICF 2005	S balance	EPA 2009c	EPA 2009c	C balance	SMED 2004	SMED 2004	ICF 2005

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