Natural Gas for Waterborne Freight Transport:
A Life Cycle Emissions Assessment with Case Studies

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Terminology and Acronyms

ANL	Argonne National Laboratory
Btu	British Thermal Unit
Case	A collection of "fuel pathway scenarios for a particular vessel on a given route (port to port)" (see Scenario below)
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DWT	Deadweight Ton
ECA	Emissions Control Area
GIFT	Geospatial Intermodal Freight Transportation Model
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
GHG	Greenhouse Gas
IMO	International Maritime Organization
Import Terminal	Facility that is licensed to accept natural gas from overseas
kW	Kilowatt
LA/LB	Los Angeles/Long Beach
LCA	Life Cycle Analysis
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
LUC	Land Use Change
MARAD	U.S. Department of Transportation, Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
mmBtu	Million British Thermal Units
N_2O	Nitrous Oxide
NG	Natural Gas
NA NG	North American Natural Gas – Natural Gas that is drilled in North America
NNA NG	Non-North American Natural Gas – Natural Gas that is drilled overseas and brought to North America via an LNG tanker to a specialized import terminal
NO_x	Nitrogen Oxides
OGV	Ocean Going Vessel
PANYNJ	Port Authority of New York and New Jersey
PM_{10}	Particulate Matter (with aerodynamic diameter less than 10 microns)
Pathway	The set of processes used to transform and transport feedstock from the wellhead to usable fuel at the port.
Scenario	A fuel pathway (feedstock, production, and consumption) for a particular vessel operating on a given route. A collection of "scenarios" makes up a "case" (see Case above).
S	Sulfur
SO_x	Sulfur Oxides
TEAMS	Total Energy and Environmental Analysis for Marine Systems
TFCA	Total Fuel Cycle Analysis, which is a life cycle analysis of fuel production and use
TFC	Total Fuel Cycle
USDOT	U.S. Department of Transportation
VOC	Non-methane Volatile Organic Compounds

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Abstract

This study evaluates the total fuel cycle emissions associated with natural gas as a marine fuel. The study uses updated data on leakage rates in the natural gas fuel cycle to compare emissions from liquefied natural gas (LNG) or compressed natural gas (CNG) to petroleum marine fuels. We find that total fuel cycle analyses for maritime case studies show that natural gas fuels reduce air quality pollutants substantially, and reduce major greenhouse gas (GHG) emissions slightly when compared to conventional marine fuels (low-sulfur and high-sulfur petroleum). We also find that the upstream configuration for natural gas supply matters in terms of minimizing GHG emissions on a total fuel cycle basis, and current infrastructure for marine fuels may produce fewer GHGs. Continued improvements to minimize downstream emissions of methane during vessel-engine operations will also contribute to lower GHG emissions from marine applications of natural gas fuels. This is important because growing supplies of natural gas can provide a feasible and economic alternative fuel to improve air quality in and near populated regions of the world.

1 Introduction

1.1 Purpose

The purpose of this research is to investigate energy use and emissions associated with the use of natural gas fuels (both compressed natural gas [CNG] and liquefied natural gas [LNG]) for waterborne freight transportation in an American Marine Highway context. Using best available data reflecting recent research on natural gas leakage of methane, we apply a total fuel cycle analysis (TFCA) methodology to evaluate “well-to-hull” emissions for vessel operations. The analysis – a type of life cycle analysis (LCA) for fuel production and use – evaluates emissions along the entire fuel pathway, including extraction, processing, distribution, and use of particular fuels in vessels. We conduct our analyses for a variety of natural gas fuel pathways and vessel types assembled into cases specific to several U.S. routes, and compare results to standard distillate fuels in these cases.

1.2 Scope Summary

For this study we quantified total fuel cycle (TFC) energy consumption (total, fossil fuel-based, and petroleum-based) and emissions (carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], volatile organic compounds [VOC], carbon monoxide [CO], nitrogen oxides [NO_x], particulate matter [PM_{10}], and sulfur oxides [SO_x]) on a set of three vessel types (large ocean-going vessel [OGV], inland tug/tow, and coastwise OGV). We model these vessels as traveling typical fixed routes using natural gas and emissions control area (ECA)-compliant distillate fuels meeting 2012 and 2015 standards (that is, 10,000 ppm sulfur [S] and 1,000 ppm S, respectively).

Specifically, a large OGV is evaluated transiting on two West Coast routes, one from Los Angeles/Long Beach (LA/LB) to Shanghai, China, and the other from LA/LB to Honolulu, HI; an inland tug/tow vessel is evaluated transiting the Mississippi River between Peoria, IL and New Orleans, LA; and a coastwise OGV is evaluated transiting the East Coast of the United States (US) between the Port Authority of New York and New Jersey (PANYNJ) and Jacksonville, FL. In all cases, we evaluate the use of LNG as an alternative to distillate fuels. For the inland tug/tow, we also evaluate the use of CNG.

These three cases were chosen because they represent typical transits by marine vessels in the US and encompass many service conditions encountered by US vessels. However, the results do not provide a complete uncertainty analysis of all possible upstream scenarios. Further uncertainty analysis would provide a more comprehensive analysis on the nature of key factors that may affect results.

1.3 Report Organization

Section 2 presents an introduction and background of TFCA, the American Marine Highway network, and motivation for considering natural gas fuels as an alternative to current petroleum marine fuels. Section 3 describes the methodology used. The next three sections (Section 4 for the West Coast Case, Section 5 for the Inland River Case, and Section 6 for the East Coast Case) describe case study results, and can be used as stand-alone reports for those interested in one regional analysis specifically. As these are designed to be stand-alone sections, there is some repetition among them. Finally, Section 7 presents overall conclusions and describes areas of further research.

2 Background

2.1 Overview of TFCA

We use TFCA as a way to calculate the total emissions profile associated with the use of a given fuel in a vessel. Total fuel cycle analysis accounts for emissions along the entire “fuel cycle,” which includes the following stages:

- *Feedstock stage* – encompassing the extraction of the raw material through delivery to the refinery;
- *Fuel processing stage* – encompassing the delivery of a fuel from the refinery to the vessel; and,
- *Operation stage* – encompassing the use of the fuel in the vessel itself.

Many pathways exist to get fuel from the ground to the ship (Lowell, Wang, & Lutsey, 2013), and a number of these pathways will be evaluated in this study. Looking at the emissions from multiple pathways can help analysts evaluate those fuel production pathways that may incur the least energy use or emissions penalties compared to others.

Fuel cycle analyses were first published in the life-cycle analysis (LCA) literature as a subset of product life-cycle quantification, and mainly aimed at economic or carbon metrics (DeLuchi, 1991; Manne, Richels, & Weyant, 1979). TFCA became a specialized and unique type of LCA as alternative fuels were considered for both air quality and carbon emissions (Schlamadinger & Marland, 1996; TIAX LLC, 2007a; TIAX LLC, 2007b), and as dedicated models focused on current and alternative pathways for transportation fuel (Wang, 2002; Winebrake, Wang, & He, 2001). TFCA became even more critical with the emergence of Low-Carbon Fuel Standards regulation and recognition of the importance of land use change (LUC) and emerging extraction methods (e.g., fracking).

In these models and studies, ship activity was only considered as a transportation and distribution function; this necessary but minor element of the fuel pathway did not contribute significantly to TFCA totals, so placeholder inputs were used in a generic context. As shipping energy inputs have become better studied by the U.S. Maritime Administration, other federal agencies, and international bodies like the International Maritime Organization (IMO), the value of specific TFCA for commercial vessels became apparent.

With regard to marine vessels and marine fuels, the TFCA emissions require specialized understanding of "downstream" or operational characteristics of these vessels and fuels. Work in this vein was first developed through funded research supported by the U.S. Maritime Administration (MARAD), and published in several papers (Corbett & Winebrake, 2008b; Winebrake, Corbett, & Meyer, 2007). In addition, the State of California commissioned a study that evaluated uncertainty in fundamental inputs for TFCA from commercial marine vessels (Corbett & Winebrake, 2008a).

2.2 American Marine Highways Network

Marine cargo in the US transits one of five main routes: i) calling on ports along the East Coast (in regional and trans-Atlantic service); ii) moving barges up and down the Mississippi River and other inland rivers; iii) transiting the Great Lakes; iv) calling on ports along the Gulf Coast; or v) calling on ports on the West Coast (in regional and trans-Pacific service to Asia/Australia). The U.S. Department of Transportation (USDOT) has begun to designate certain routes as part of the American Marine Highway system, encouraging shippers to use marine routes in domestic service to ease congestion on land routes. Two domestic routes examined in this report are a part of this system, while the other two transit the ocean, and there is no equivalent land-based route in the US.

Cases describing several potential routes were included in the scope of this report, with the understanding that these provide sufficient insight to consider the maritime sector as part of the US natural gas picture. The first two routes analyzed leave from the Port of LA/LB. Ships from there transit to Shanghai, China, or Honolulu, HI. The inland route transits the Mississippi River between Peoria, IL and New Orleans, LA. On the East Coast route ships transit between PANYNJ and Jacksonville, FL. The last two routes are formally identified within the US DOT-designated American Marine Highways Network.

2.3 Overview of Motivating Situation in North America

The International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted by the IMO in 1973 to address the issue of pollution emitted from ships entering the marine environment. MARPOL has been amended several times as new information about the causes, effects, and extent of marine pollution has been discovered. Annex VI was first adopted in 1997 to address air pollution, specifically SO_x and NO_x. Subsequent changes have decreased the allowed emissions globally and assigned areas designated as ECAs with even stricter emissions requirements (IMO, 2013). As marine fuels tend to have high sulfur content, these stricter requirements have led to exploration of different fuels – such as natural gas – for marine transportation. The literature is clear that natural gas fuels can significantly reduce local pollutants from vessel operations; however, the advantages from a GHG emissions perspective remain uncertain. Natural gas fuel production pathways can be relatively energy intensive compared to petroleum pathways, and the leakage of CH_4 that accompanies natural gas extraction and distribution may have important GHG impacts. Since the US is concerned with both local pollution and GHG emissions, decision makers find it important to look at the life-cycle emissions generated by natural gas fuels compared to traditional marine bunkers.

2.4 Consideration of Natural Gas Fuels for Marine Vessels

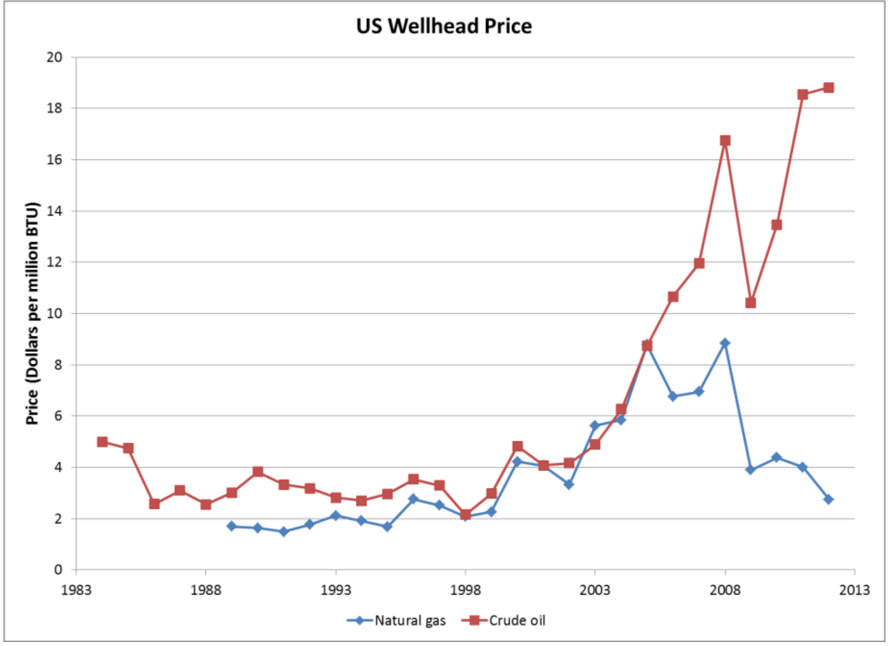
The emissions signature of natural gas meets all current, pending, and proposed standards for marine vessel operations, and the current price differential favoring natural gas suggests an economic advantage may exist. Recently, the shipping industry has joined other sectors in considering the merits of gaseous fuels as a feasible, economical, and low-emitting alternative to traditional petroleum fuels. For these reasons, natural gas is emerging as an attractive fuel, with many newly constructed vessels powered either by natural gas exclusively or by a combination of conventional diesel and natural gas (MarineLink, 2013; Posplech, 2013; Walls & Abrahamsen, 2012). The emergence of market-ready reciprocating internal combustion engines capable of natural gas and/or dual fuel operation in maritime service makes studies such as this one more important for industry leaders and policy decision makers. Multiple firms are building or are planning to build vessels using these engines, making this work extremely relevant to current investment decisions (Germanischer Lloyd, 2011; Rolls Royce, 2013).

Of course, existence of the technology is not the only thing considered when deciding whether or not to switch to alternative fuels. Operators are also looking at cost and technical feasibility issues, including:

- the ability to operate within and beyond emission control areas, without the need for aftertreatment of exhaust gases for traditional pollutants;
- the price differentials for LNG/CNG versus other marine fuels, including residual heavy fuel oil; the existence of infrastructure networks for obtaining LNG/CNG fuel; and,
- attractive financing of LNG/CNG vessels in fleet modernization/replacement strategies.

Regarding the second point above, recent trends in the prices of crude oil and natural gas are making natural gas a more attractive marine fuel, as shown in Figure 1. In addition, natural gas infrastructure is growing (Fullenbaum, Fallon, & Flanagan, 2013), making it more plausible to fuel ships with natural gas in the future.

Figure 1 Historical wellhead price of crude oil and natural gas showing the increasing price differential between these two fuels that has emerged since 2005.



Data obtained from (BP, 2013)

3 Approach and Data

3.1 Models

In order to conduct our TFCA, three models were used: GREET, TEAMS, and GIFT. These models calculate total energy and emissions for a variety of fuels over the total fuel cycle and have been extensively discussed in peer-reviewed published literature (Corbett & Winebrake, 2008b; Elgowainy, Burnham, Wang, Molburg, & Rousseau, 2009; Huo, Wu, & Wang, 2009; Milliken, Joseck, Wang, & Yuzugullu, 2007; Wang, Wu, Huo, & Liu, 2008; Winebrake et al., 2001; Winebrake et al., 2007; Y. Wu, Wang, Sharer, & Rousseau, 2006).

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was developed by Argonne National Laboratory (ANL). GREET allows researchers to examine the well-to-wheels emissions for a wide variety of fuels obtained using over 100 different pathways. GREET has been widely used in TFCA (Elgowainy, Gaines, & Wang, 2009; Huo, Wang, Bloyd, & Putsche, 2008; Meyer, Green, Corbett, Mas, & Winebrake, 2011; Wang, 2002; Winebrake et al., 2001; M. Wu, Wu, & Wang, 2006). Older versions of GREET focused solely on light-duty vehicles (LDVs). However, during the course of this research GREET 2013 was released. GREET 2013 included additional options for natural gas fuel pathways, as well as some preliminary analysis of fuels for marine vessels. We found GREET 2013 to have many limitations with respect to marine fuel analysis. In particular, although GREET 2013 does an excellent job of accounting for the upstream stages of fuel production (namely the Feedstock Stage and the Fuel Processing Stage), the model does not allow for modification of vessel characteristics at the end-use stage. This weakness severely limited its use for our purposes. Therefore, we turned to TEAMS to capture the operations stages of the fuel life-cycle.

The Total Energy and Environmental Analysis for Marine Systems (TEAMS) model was developed with support from MARAD to assist TFCA modeling for marine vessels. TEAMS was used in previous evaluations by these authors for MARAD (Corbett & Winebrake, 2008b; Winebrake et al., 2007). The advantage of TEAMS is that it offers greater flexibility for modeling the downstream (i.e., end-use) stages of the fuel cycle (i.e., vessel fuel use).

Given the specific geographic context for our case studies, the desktop version of the Geospatial Intermodal Freight Transport (GIFT) model was also used to visualize the pathway distances represented in GREET and TEAMS. The GIFT model (Winebrake, Corbett et al. 2008, Comer, Corbett et al. 2010) combines networks for roadways, railroads and the waterways of the U.S. and Canada, along with the intermodal facilities in the North American continent on the ArcGIS™ Network Analyst platform. We used publicly available information to approximate natural gas pipelines and facilities for this analysis.

Thus, taken in combination, we used a modeling approach that incorporated GREET 2013 for our upstream analysis with TEAMS for our downstream analysis, with GIFT measurement of input distances and case visualization. By using these three models, we were able to construct an analysis that integrated the best of these modeling environments.

3.1.1 Methane Emissions Factors

While inputs to the models will be discussed in further detail in later sections, a portion of this research is on methane emissions from the various fuels. Since this has been an issue receiving much attention in the literature, we present additional background on the topic here.

As mentioned above, during the course of this research GREET 2013 was released, following GREET 2012. This new release contained changes in the emissions factors for various methane processes, as shown in Table 1 and discussed in Burnham et al (2013). Others also recommended changing the emissions factors, including Brandt (2014), who found that EPA estimates were likely to undercount methane emissions, suggesting that "methane emissions from … natural gas systems appear larger than official estimates." That study also used source attribution, inventory comparisons, and records of atmospheric observations to suggest that "CH_4 emissions with fossil signatures are larger than expected." Alvarez, Pacala, Winebrake, Chameides, and Hamburg (2012) also recommended further study on methane leakage rates, citing the study by Howarth, Santoro and Ingraffea (2011).

Previous research has demonstrated that the inputs used for upstream processes can affect final TFCA results. For instance, Choi and Song (2014) found that in Korea the emissions were higher than in the US, because Korea imports almost all of its natural gas, which takes more energy than simply running it through a pipeline as in the US.

The main implications of the updated CH_4 emissions factors in GREET 2013, then, are these: a) production stage upstream emissions decrease; and b) processing, transmission, and distribution stages emissions increase (Table 1). This is critical to the analysis of overall GHG emissions because transmission and distribution stages may result in natural gas "leakage" across longer distances. These new rates of leakage, therefore, might produce TFCA results that differ from previous studies using lower methane leakage rates. Our case studies also evaluate how much this may matter using different distances.

Table 1 Summary of Differences in Results between GREET 2012 and GREET 2013 (Units: g CH_4/million Btu NG)

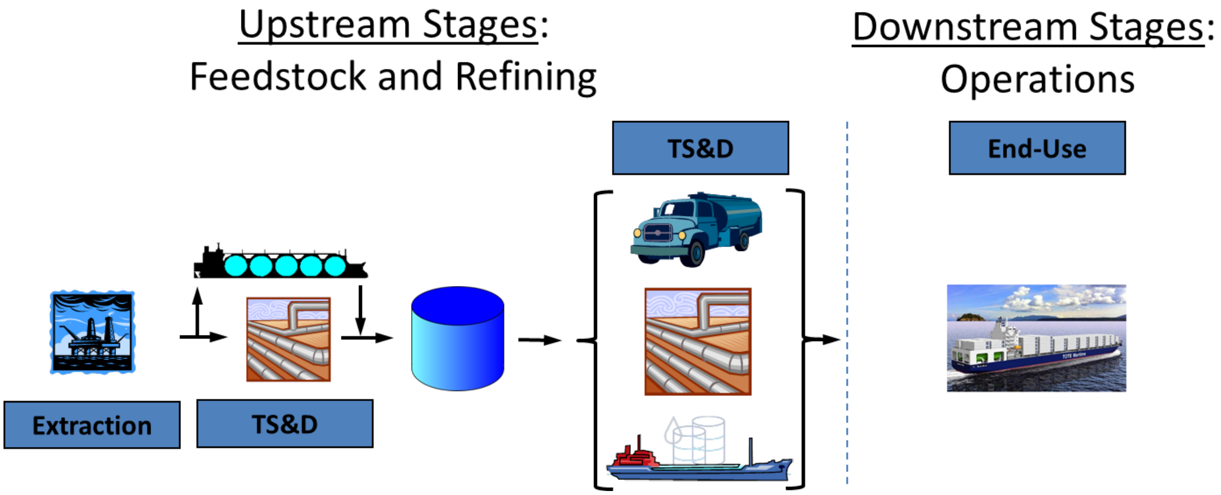
Sector	Process	Shale GREET 2012	Conventional GREET 2012	Shale GREET 2013	Conventional GREET 2013	% Change in Upstream Emissions for Shale Gas (2012 to 2013)	% Change in Upstream Emissions for Conventional Gas (2012 to 2013)
Production	Completion	31.5	0.6	42.8	0.5	36%	-9%
	Workover	63	0.1	8.6	0	-86%	-91%
	Liquid Unloading	0	247.1	10.2	10.2	N/A	-96%
	Well Equipment	151	151	59.1	59.1	-61%	-61%
Processing	Processing	32.9	32.9	37	37	12%	12%
Transmission	Transmission and Storage (assuming 680 miles)	79.9	79.9	87.4	87.4	9%	9%
Distribution	Distribution	57.4	57.4	94.2	94.2	64%	64%

Quoted from Table 3 of Burnham (2013); NOTE: GREET distribution leakage in this work discount the 94.2 distribution value for residential conditions by ~25% to represent industrial conditions.

3.2 Fuel Pathways

A "fuel pathway" represents the series of processes that are necessary for fuel production and use. There are various steps in the process in which decisions can be made, shown generically in Figure 2. Consequently, there are multiple fuel pathways for a given fuel, and in this section we describe each of the major pathways that we evaluate in this study. In this study, we explored 28 possible fuel pathways for natural gas fuels. We summarize these pathways in Table 2 which identifies for each pathway the fuel type and source, type of liquefaction (if applicable), transportation mode for the processed fuel, and whether storage exists. Not every fuel pathway applies to all locations (i.e., ports); therefore, each "scenario" description specifies which fuel pathways are applicable for a given vessel, route, and fuel analysis. Table 2 also shows for which ports (from our case studies) these pathways apply. Additional information on certain aspects of these fuel pathways is discussed below.

Figure 2 Generic Pathways for Getting Fuel from Wellhead to Ship

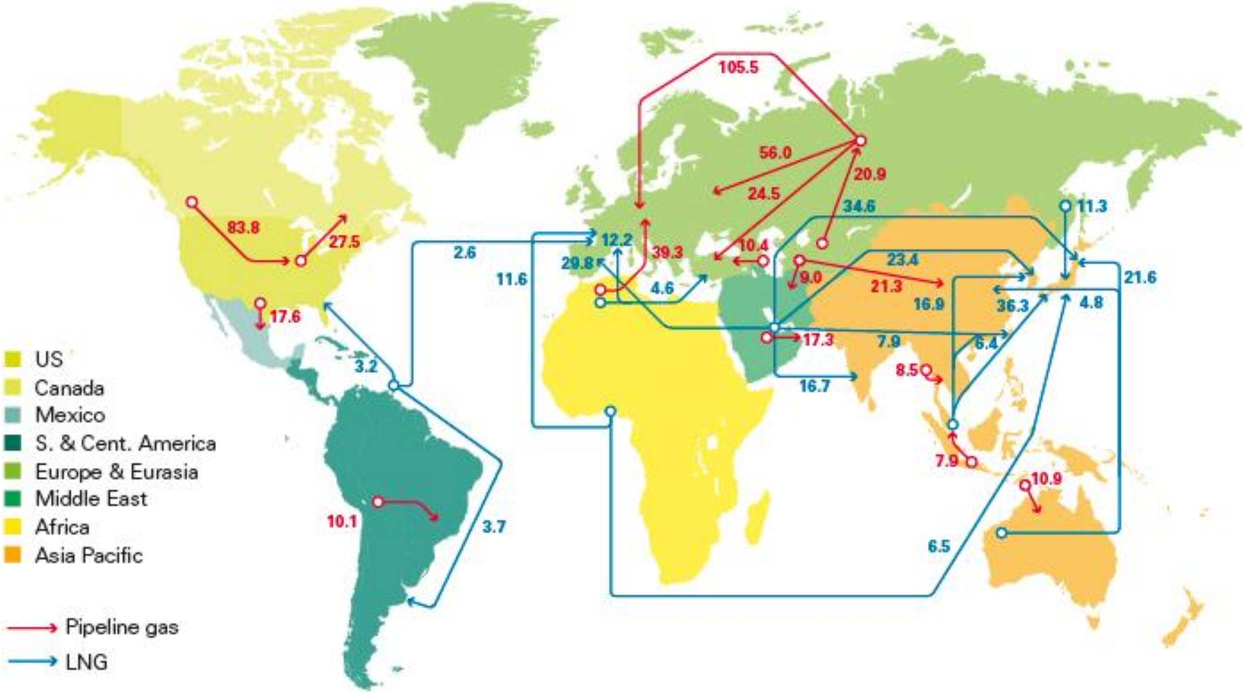


Two distillate fuels are also examined in this report, namely ECA-compliant distillate fuels meeting 2012 and 2015 sulfur standards (that is, 10,000 ppm S and 1,000 ppm S, respectively). Unlike the natural gas market, where different upstream pathways are being examined for economic and environmental criteria, the distillate fuel market is mature, with established upstream pathways. Therefore different pathways were not analyzed. Instead, we used default GREET 2013 pathways for all upstream distillate processes.

3.2.1 Location of Natural Gas Drilling

Natural gas can either be drilled and created in North America (NA NG), or imported via tanker from overseas to an import terminal (Non-North American Natural Gas, or NNA NG). While the US is currently in transition from a NG importer to a NG exporter, NNA NG was still explored as part of the scope for completeness. Also, as this transition is still ongoing some NG is still imported from NNA sources, as shown in Figure 3, and it is plausible that economics could again shift and NG imports increase again.

Figure 3 Natural Gas Trade Movements 2012 (trade flows in billion cubic meters)



Taken from (BP, 2013)

NNA NG

Once brought to an import terminal, the LNG can be regasified and injected into the US pipeline system and then reliquefied at a currently existing facility or transported directly from the import terminal. Once at the terminal or the liquefaction facility, it becomes similar to NA NG at the liquefaction facility and the same transport options apply, as discussed below.

NA NG

North American natural gas can come from conventional sources, where the natural gas is in a pocket that can be tapped, or from shale sources, where the gas is trapped inside shale rock and the rock must be broken in order to retrieve the gas inside. While conventional gas has been drilled for years, it is only recently that obtaining the gas from shale has become economically feasible. While some fields can have only one kind of gas, the fields examined in this study produce both.

3.2.2 Liquefaction and Compression

In an LNG system, once the natural gas has been pulled from the ground, it is transported via pipeline to a liquefaction facility. While some of the ports examined in this study have a liquefaction facility nearby, others do not. For port facilities without on-site liquefaction, we also considered the possibility that a new facility would be built closer to the port in question. This report doesn’t examine the economics of the construction, but does assume that if LNG becomes a significant fuel at the port it will be efficient to build a facility closer to the port. As a result of conversations with industry experts, the location of the facility was assumed to be at the end of the closest natural gas pipeline. In some cases the pipeline terminus was at the port, so no further transportation was needed. In other cases the end of pipeline facility was simply closer to the port, and so transportation was necessary. In a CNG system, gas is delivered via pipeline to the end use location and then compressed to sufficient pressure to fuel the vessel.

3.2.3 Transportation

Once the LNG is created at the liquefaction facility or taken off the LNG tanker at the import terminal, it must then be transported to the port if not already there. This can be done via either truck or barge. As stated previously, CNG is compressed on-site and so no transportation as LNG is necessary.

3.2.4 Storage

The natural gas supply chain will not always be an on demand system, so sometimes storage of the LNG is needed. Some storage is already assumed as part of the process of production, and is accounted for in the GREET model. However, it is likely that additional storage time may be needed, and so this report looks at both a case where there is no storage and a case where there is storage. Storage was assumed to be 30 days because that is the approximate length of time LNG can be stored before the pressure increases above a safety threshold and must be relieved, causing some of the product to be lost and affecting the amount of energy it can produce. CNG is compressed at the port on an as-needed basis, so no storage of CNG was considered beyond that already accounted for in the GREET model defaults.

3.3 Vessels

We assign different vessels to each of the routes described above corresponding to its typical commercial service based on port databases of vessel calls. For each route a characteristic vessel was determined and used in the TEAMS model. In the West Coast case, a large container vessel was analyzed. In the Inland case, a tug/tow vessel was considered most characteristic of the route, and in the East Coast case a smaller container vessel was used. Further details about the specific vessels will be discussed in each case report.

Table 2 Pathway Variables and Applicability to Ports for Natural Gas Based Fuels (LNG)

	Extraction Method		Liquefaction			Transportation from Liquefaction Facility				Ports				
Pathways	Conventional	Shale	NNA	Existing Facility	End of Pipeline Facility	Truck	Barge	Regasification and Pipeline	Storage	(A) LA/Long Beach	(B) Peoria	(C) New Orleans	(D) PANYNJ	(E) Jacksonville
1	X		X			X				X	X	X	X	X
2	X		X				X			X	X	X	X	X
3	X		X					X		X	X	X	X	X
4	X		X											
5	X			X		X			X	X	X	X		X
6	X			X		X				X	X	X		X
7	X			X			X		X			X		
8	X			X			X					X		
9	X			X					X				X	
10	X			X									X	
11	X				X	X			X		X	X		X
12	X				X	X					X	X		X
13	X				X		X		X			X		
14	X				X		X					X		
15	X				X				X	X				
16	X				X					X				
17		X		X		X			X	X	X	X		X
18		X		X		X				X	X	X		X
19		X		X			X		X			X		
20		X		X			X					X		
21		X		X					X				X	
22		X		X									X	
23		X			X	X			X		X	X		X
24		X			X	X					X	X		X
25		X			X		X		X			X		
26		X			X		X					X		
27		X			X				X	X				
28		X			X					X				

3.4 Cases and Scenarios

The next three sections of this report are designed as standalone sections where we evaluate three different case studies, which are comprised of a collection of scenarios. A “scenario” represents a combination of a particular vessel operating out of a given port, along a fixed route, and refueling using a defined fuel pathway. Thus, a “scenario” is a “vessel-port-route-fuel” combination, and a “case” represents a collection of scenarios.

To facilitate the reporting of our results, we use a numbering system for each fuel pathway, as shown in Table 2. These numbered pathways remain the same across all cases. We also use a lettering system for each port (also shown in Table 2, where A refers to the Port of LA/LB; B refers to the Port of Peoria; C refers to the Port of New Orleans; D refers to the Port of NY/NJ; and E refers to the Port of Jacksonville). Therefore, a scenario label for a vessel refueling at the Port of LA/LB using fuel pathway #1 would be designated at “A1”. Each section provides tables with relevant inputs for our analysis, as well as outputs by scenario. Each section is designed to be standalone; some discussion will overlap across cases, but will not reference other cases. Overall conclusions from the three cases are presented in Section 0 of this report.

For all cases, we consider state-of-the-art engines that represent engines likely to be used in a large-scale marine deployment of NG when considering engine efficiency and control of methane emissions, sometimes called “methane slip.” Engine manufacturers are providing gas and dual-fueled engines that have the potential to increase efficiency from ~40% to ~50% for bigger engines (Wärtsilä gas-fired engines; Bergen_C-gas engine). This higher engine efficiency value represents a state-of-achievement efficiency for new engines likely to be used in modernization and repowering associated with a large-scale increase in marine applications of LNG. For this work, we select the middle of the range of reported efficiencies (45%) for new and emerging LNG marine engines as well as current diesel engines.

We apply common engine emissions rates representing downstream exhaust pollutant profiles for both natural gas and diesel fuels in marine engines. These are shown in Table 3. For oceangoing vessels using low-speed diesel engines operating on natural gas, the TEAMS model uses emissions rates for diesel-ignited natural gas engines, or petroleum fueled diesel engines. However, recent research suggests that the emissions factors for spark-ignited 4-stroke combustion engines are different for some pollutants than the factors used in TEAMS (Kunz & Gorse, 2013). These engines operate at medium speeds, which is more typical of smaller inland river vessels. Therefore, these new values are used for the inland river case, where this type of engine is most likely to be used. We use the 2013 default values in GREET for upstream CH_4 and CO_2 emissions from leakage, venting, and flaring during various stages, as shown in Table 4. Lastly, we use the 100-year Global Warming Potential multipliers in GREET and TEAMS, shown in Table 5 to calculate the total GHGs, combining CO_2, CH_4, and N_2O emissions.

Table 3 Downstream (TEAMS) Emissions Factors (grams/mmBTU)

Pollutant	Diesel – Ignited Natural Gas Engine	Spark – Ignited Natural Gas Engine	Petroleum fueled engine (low-sulfur diesel)	Petroleum fueled engine (high-sulfur diesel)
VOC	94	25	93	93
CO	215	215	430	430
NO_x	2,481	237	2,480	2,480
PM_{10}	0.7	5	73	73
SO_x	0.3	0.3	10	259
CH_4	92	659	5	5
N20	2	2	2	2
CO_2	59,000	58,532	77,219	84,101

Source: TEAMS default values and Kunz & Gorse, 2013

Table 4 Emissions Rates for CH_4 and CO_2 during various upstream processes

	Unit	Conventional NG	Shale gas
CH_4			
Recovery - Completion CH_4 Venting	g CH_4/mmBtu NG	0.55	42.827
Recovery - Workover CH_4 Venting	g CH_4/mmBtu NG	0.008	8.56
Recovery - Liquid Unloading CH_4 Venting	g CH_4/mmBtu NG	10.19	10.19
Well Equipment - CH_4 Venting and Leakage	g CH_4/mmBtu NG	59.10	59.10
Processing - CH_4 Venting and Leakage	g CH_4/mmBtu NG	36.98	36.98
Transmission and Storage - CH_4 Venting and Leakage	g CH_4/mmBtu NG/ 680 miles	87.40	87.40
Distribution - CH_4 Venting and Leakage	g CH_4/mmBtu NG	70.67	70.67
CO_2			
Recovery - Flaring	Btu NG/mmBtu NG	6870.0	6870.0
Recovery - Venting	g CO2/mmBtu NG	20.59	20.59
Processing - Acid Gas Removal Equipment Venting	g CO2/mmBtu NG	849.30	849.30

Source: GREET 2013 model.

Table 5 100-Year Global Warming Potentials of Greenhouse Gases

CO_2	CH_4	N_2O
1	25	298

Source: Burnham et al., 2013.

4 West Coast Case

4.1 Overview of the West Coast Case

The West Coast Case includes a collection of scenarios that examine the energy use and emissions from using a liquefied natural gas (LNG) powered vessel to transport goods from the Port of Los Angeles/Long Beach (LA/LB) to either: (1) Shanghai, China, or (2) Honolulu, Hawaii. The case includes evaluation of all relevant fuel pathways, based on our research of the fueling situation in and around LA/LB. The LNG is obtained by either importing it from a Non-North American natural gas (NNA NG) source as LNG via tanker or it may be processed from North American natural gas (NA NG). We assume that NA NG is extracted from an existing well and delivered via pipeline to a liquefaction facility. We also assume that liquefaction occurs at an existing facility, though the possibility of future construction of a facility closer to the port at the nearest terminus of existing large volume pipelines is also examined. The LNG is delivered by truck or barge from the liquefaction facility to the port. For each North American possibility discussed, there is one pathway that assumes the LNG is not stored along the way and a second pathway that assumes storage of 30 days before the LNG is used in a ship. Traditional marine fuels usable in marine diesel engines are used as the comparators for these LNG pathways. These traditional fuels include high-sulfur residual marine fuel (high-sulfur diesel) and low-sulfur distillate marine fuel (low-sulfur diesel).

4.2 Fuel Pathways to the Port of Los Angeles/Long Beach

The Port of LA/LB is located in southern California. For NNA NG, we assume imported LNG will come from Qatar to the nearest import terminal in Ensenada, Baja California, Mexico, and then be transported by truck, barge, or pipeline (after re-gasification) to the port. For NA NG, we assume the natural gas is extracted from the closest natural gas field to this port (Elk Hills, CA), and is pipelined to the closest existing liquefaction facility (north of the port in Boron, CA). There is a pipeline terminus located closer to the port in Long Beach, California. Figure 4 shows the facilities on the map, and Table 6 shows the distances for each of the transportation segments of this fuel pathway.

Figure 4 Depiction of various fuel pathways for the West Coast Case showing transportation modes along the pathway network

Table 6 Los Angeles/Long Beach Facilities Locations and GREET Inputs

Trip Origin	Trip Destination	Mode	Distance (miles)
Qatar (Exporting Nation)	Ensenada, Baja California, Mexico (Import Terminal)	Ship	12,500
Elk Hills, CA (NG Field)	Boron, CA (Liquefaction Facility)	Pipeline	137
Elk Hills, CA (NG Field)	Long Beach, CA (End of Pipeline)	Pipeline	125
Boron, CA (Liquefaction Facility)	LA/LB, CA (Port)	Truck	45
Ensenada, Baja California, Mexico (Import Terminal)	LA/LB, CA (Port)	Truck	250
Ensenada, Baja California, Mexico (Import Terminal)	LA/LB, CA (Port)	Barge	440
Ensenada, Baja California, Mexico (Import Terminal)	Boron CA (Liquefaction Facility)	Pipeline	275

4.3 West Coast Vessel Characteristics

Table 7 describes the typical port calls for international vessels at the Port of LA/LB in 2004. The year 2004 was chosen because data from the Lloyd's database, a comprehensive directory of all vessels registered by any nations, was available for that year, and it is assumed that the 2013 port calls were of a similar distribution. On this route, the scope of the work was to look at container vessels, and as over 50% of the port calls were made by container vessels, container vessels were examined as the typical vessel making the transit from LA/LB to Shanghai and Honolulu. The table also indicates the average size for container vessels coming in to the port.

Table 8 shows the characteristics used for a typical container vessel on the Shanghai route, based on values obtained from the Lloyd's database for container vessels of approximately 50,000 deadweight tonnage (DWT). For most other variables (e.g. emission factors) the default TEAMS values were used, however, because "slow steaming" is becoming the transiting method of choice in order to save fuel (Jorgensen, 2012; Savvides, 2008), the default TEAMS inputs for operating mode were changed so that the majority of the time was spent in slow steaming mode. For the Hawaii route, some container vessels are currently converting to natural gas fuel, and we used characteristics for these vessels in our analysis, as shown in Table 9.

Table 7 Vessel calls at the Port of LA/LB showing number of calls and container capacity by vessel type

Vessel Type	Calls	Average Capacity (DWT)	% Calls
Tanker	946	83	18%
Product Tanker	576	42	11%
Crude Tanker	370	148	7%
Container	3,082	50	58%
Dry Bulk	638	45	12%
Ro-Ro	325	18	6%
Vehicle	240	16	5%
Gas Carrier	7	550	0%
Combination	12	72	0%
General Cargo	280	28	5%
All Types	*5,290*	*53*	*100%*

Table 8 TEAMS inputs for the Shanghai route for the West Coast Case

Vessel Characteristic	Value
Vessel Type	Container
Average DWT	50,000
Rated Power (kW)	36,500
Distance (miles)	6,130
Rated Speed (knots)	24
Time for one-way trip (HH:MM)	327:47
Engine Efficiency (%)	45%
Time Spent in Each Operating Stage as a Percentage of Total Trip Time (%)	
Idle	1.25%
Maneuvering	1.75%
Precautionary	5.00%
Slow Cruise	85.00%
Full Cruise	7.00%

Table 9 TEAMS inputs for the Hawaii route for the West Coast Case

Vessel Characteristic	Value
Vessel Type	Container
Average DWT	32,000
Rated Power (kW)	23,860
Distance (miles)	2,230
Rated Speed (knots)	22
Time for one-way trip (HH:MM)	130:15
Engine Efficiency (%)	45%
Time Spent in Each Operating Stage as a Percentage of Total Trip Time (%)	
Idle	1.25%
Maneuvering	1.75%
Precautionary	5.00%
Slow Cruise	85.00%
Full Cruise	7.00%

4.4 West Coast Case Results

Our results are presented in a collection of tables and graphs. Energy use and emissions were calculated for the four stages of the fuel pathway for each scenario. These results represent total energy use and emissions for a given “trip.” For example, “Total Energy” represents the energy (in BTUs) needed to obtain, process, transport, and consume the fuel needed to transport the ship across the specified distance for the West Coast Case. The feedstock stage and fuel processing stage describe energy use and emissions occurring *upstream* (well-to-pump); the main and auxiliary engine operations describe emissions occurring *downstream* (pump-to-hull). Table 10a and Table 10b show results for each scenario. Full graphical results are presented in Appendix A, with summary graphs of selected variables presented here. Each graph shows the average of the natural gas pathways in the first column, with the bars depicting the range of the scenarios. The second and third columns are the low and high sulfur petroleum fuel scenarios, respectively.

Table 10a West Coast Case results for total fuel cycle energy use for trip from Port of LA/LB to Shanghai (S) or Honolulu (H)

Scenario Code	Fuel Type	Port of Destination	Total Energy (mmBTU)	Fossil Fuel Energy (mmBTU)	Petroleum Energy (mmBTU)
A1_S	LNG	Shanghai, China	58,526	58,467	5,883
A2_S	LNG	Shanghai, China	57,934	57,877	5,286
A3_S	LNG	Shanghai, China	58,729	58,668	5,402
A5_S	LNG	Shanghai, China	56,713	56,657	4,736
A6_S	LNG	Shanghai, China	56,251	56,197	4,726
A15_S	LNG	Shanghai, China	56,471	56,417	4,560
A16_S	LNG	Shanghai, China	56,016	55,963	4,555
A17_S	LNG	Shanghai, China	56,773	56,718	4,726
A18_S	LNG	Shanghai, China	56,310	56,256	4,717
A27_S	LNG	Shanghai, China	56,531	56,477	4,550
A28_S	LNG	Shanghai, China	56,074	56,022	4,545
WC_LS_S	Low-Sulfur Petroleum	Shanghai, China	57,974	57,718	51,016
WC_HS_S	High-Sulfur Petroleum	Shanghai, China	57,974	57,718	51,016
A1_H	LNG	Honolulu, HI	15,489	15,474	1,814
A2_H	LNG	Honolulu, HI	15,335	15,320	1,659
A3_H	LNG	Honolulu, HI	15,542	15,526	1,689
A5_H	LNG	Honolulu, HI	15,018	15,003	1,516
A6_H	LNG	Honolulu, HI	14,898	14,884	1,513
A15_H	LNG	Honolulu, HI	14,955	14,941	1,470
A16_H	LNG	Honolulu, HI	14,837	14,823	1,469
A17_H	LNG	Honolulu, HI	15,033	15,019	1,513
A18_H	LNG	Honolulu, HI	14,913	14,899	1,511
A27_H	LNG	Honolulu, HI	14,971	14,957	1,468
A28_H	LNG	Honolulu, HI	14,852	14,838	1,466
WC_LS_H	Low-Sulfur Diesel	Honolulu, HI	15,346	15,279	13,538
WC_HS_H	High-Sulfur Diesel	Honolulu, HI	15,346	15,279	13,538

Note: Scenario Code refers to the port of origin (“A” being the Port of LA/LB) and the fuel pathway for refueling (indicated by the number as referenced in Table 2).

Table 10b West Coast Case results for total fuel cycle emissions (in kg/trip) of pollutants included in this study for travel from the Port of LA/LB to either Shanghai, China (S) or Honolulu, HI (H)

Scenario Code	Kilograms emitted per trip								
	CO_2	CH_4	N_2O	GHGs	VOC	CO	NO_x	PM_{10}	SO_x
A1_S	3,517,637	18,616	110	4,015,845	4,854	11,389	122,368	379	1,202
A2_S	3,468,568	18,832	109	3,971,977	4,833	11,326	122,206	366	1,194
A3_S	3,513,750	20,787	134	4,073,235	4,930	11,626	122,628	369	1,202
A5_S	3,379,160	19,092	118	3,891,763	4,764	11,278	119,383	236	754
A6_S	3,372,513	13,796	118	3,752,531	4,755	11,262	119,335	235	738
A15_S	3,361,220	18,954	117	3,869,904	4,752	11,240	119,277	231	748
A16_S	3,355,018	13,661	116	3,731,214	4,744	11,225	119,232	230	733
A17_S	3,374,505	21,846	118	3,955,936	4,762	11,265	119,343	235	753
A18_S	3,367,964	16,481	118	3,815,086	4,753	11,249	119,296	234	737
A27_S	3,356,569	21,705	117	3,934,009	4,750	11,227	119,237	231	747
A28_S	3,350,474	16,343	116	3,793,703	4,742	11,212	119,193	229	731
WC_LS_S	4,515,096	5,484	109	4,684,721	4,813	20,971	119,821	3,742	3,412
WC_HS_S	4,826,726	5,484	109	4,996,351	4,813	20,971	119,821	3,742	12,920
A1_H	935,829	4,837	29	1,063,238	1,288	3,081	32,496	120	326
A2_H	923,083	4,893	29	1,051,843	1,282	3,065	32,454	116	324
A3_H	934,829	5,401	35	1,078,159	1,307	3,143	32,563	117	326
A5_H	899,857	4,961	31	1,031,006	1,264	3,053	31,721	82	210
A6_H	898,131	3,585	31	994,837	1,262	3,048	31,708	82	206
A15_H	895,197	4,925	31	1,025,327	1,261	3,043	31,693	81	209
A16_H	893,586	3,550	31	989,300	1,259	3,039	31,681	81	204
A17_H	898,648	5,676	31	1,047,676	1,264	3,049	31,710	82	210
A18_H	896,949	4,283	31	1,011,087	1,261	3,045	31,698	82	205
A27_H	893,989	5,640	31	1,041,980	1,261	3,039	31,683	81	208
A28_H	892,406	4,247	31	1,005,533	1,259	3,035	31,671	81	204
WC_LS_H	1,194,939	1,426	29	1,239,040	1,277	5,570	31,834	993	900
WC_HS_H	1,275,891	1,426	29	1,319,991	1,277	5,570	31,834	993	3,370

Note GHGs represent the GWP_{100} weighted combination of CH_4, CO_2, and N_2O

Note: Scenario Code refers to the port of origin ("A" being the Port of LA/LB) and the fuel pathway for refueling (indicated by the number as referenced in Table 2).

Figure 5 and Figure 6 show the energy needed for the whole fuel cycle for the Shanghai route and the Hawaii route, respectively. For each route, the natural gas scenarios needed more energy than the diesel scenarios, likely due to the energy needed for liquefaction of the natural gas.

Figure 5 West Coast Case results for total energy use for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

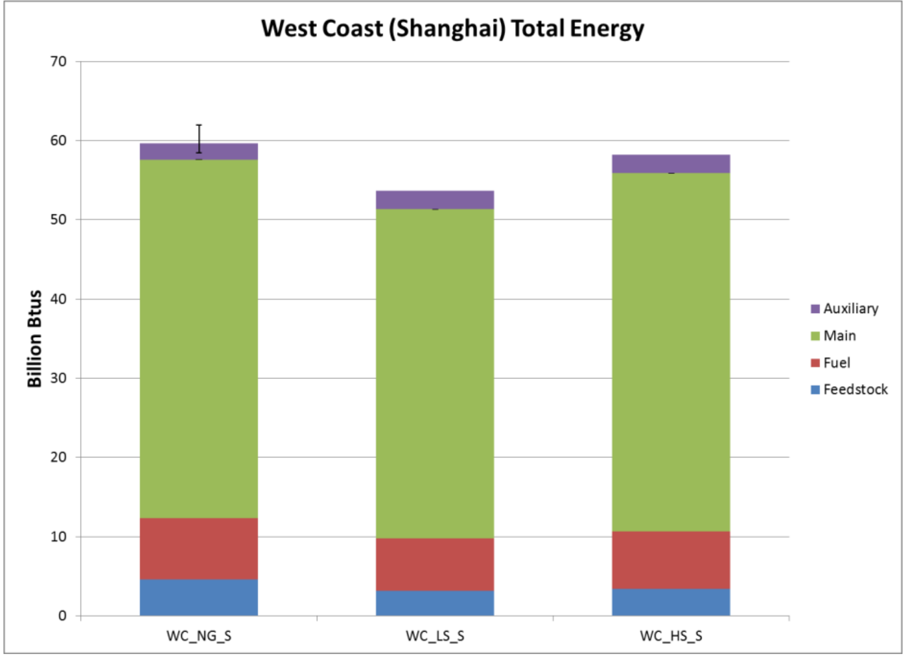
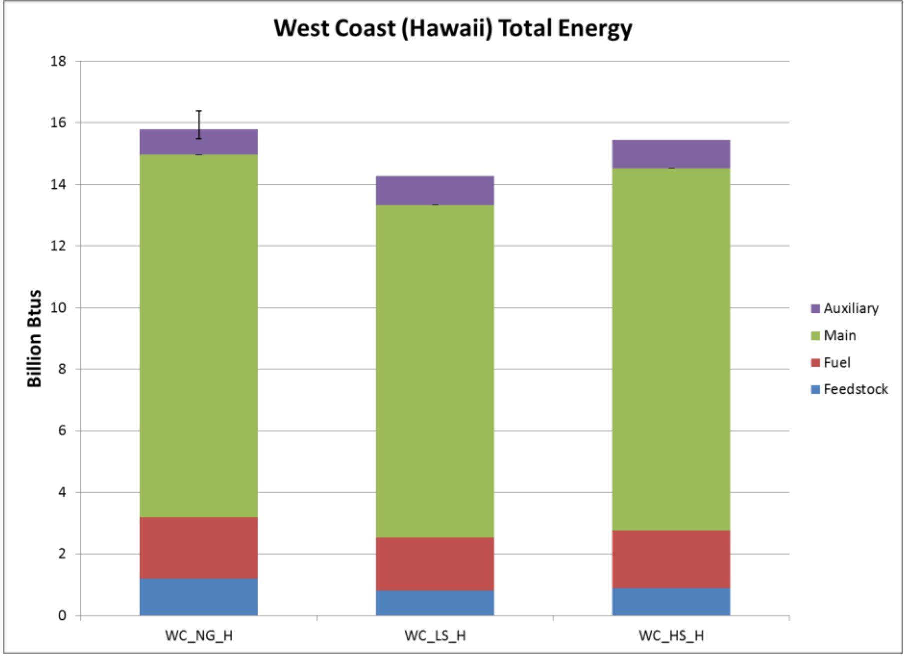


Figure 6 West Coast Case results for total energy use for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively



The next set of graphs show the GHG results for these routes. The emissions of CO_2 for the LNG scenarios are lower than those of the diesel scenarios, as shown in Figure 7 and Figure 8. Although the emissions of CH_4 (Figure 9 and Figure 10) and N_2O (Figure 11 and Figure 12) are higher than the diesel cases, the overall volume of CO_2 makes the GHG emissions of the LNG scenarios less than those of both the high sulfur petroleum and the low sulfur petroleum. For both CO_2 and N_2O most of the emissions come from the downstream stages, so changes to the upstream pathway will not greatly affect the overall emissions. However, for CH_4 the upstream processes do have an effect, so those are looked at in more detail in Figure 15. There it can be seen that natural gas obtained from shale has higher methane emissions than that from conventional gas. In addition, shorter storage times decrease the emissions. Components that affect the amount of methane released are the amount of methane slip in the engine and the amount of leakage that occurs during processing, including during pipeline transport and the switching of modes. As discussed in the introduction, the values used here are the best available, consistent with recent evidence supporting higher leakage rates (Brandt et al., 2014). These are factors that can be considered when deciding on the upstream pathway that ultimately will be utilized.

Figure 7 West Coast Case results for CO_2 emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

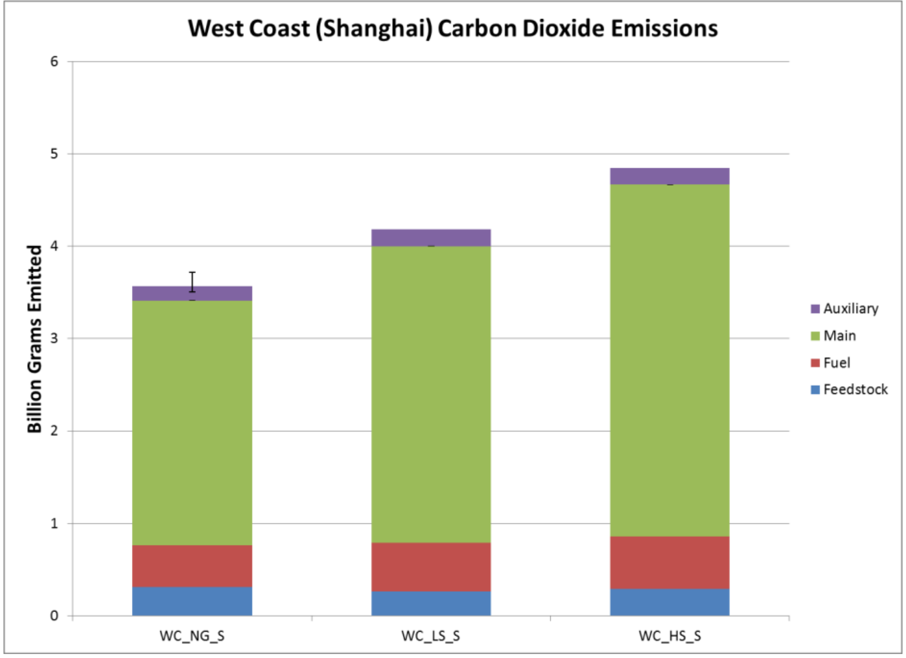


Figure 8 West Coast Case results for CO_2 emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

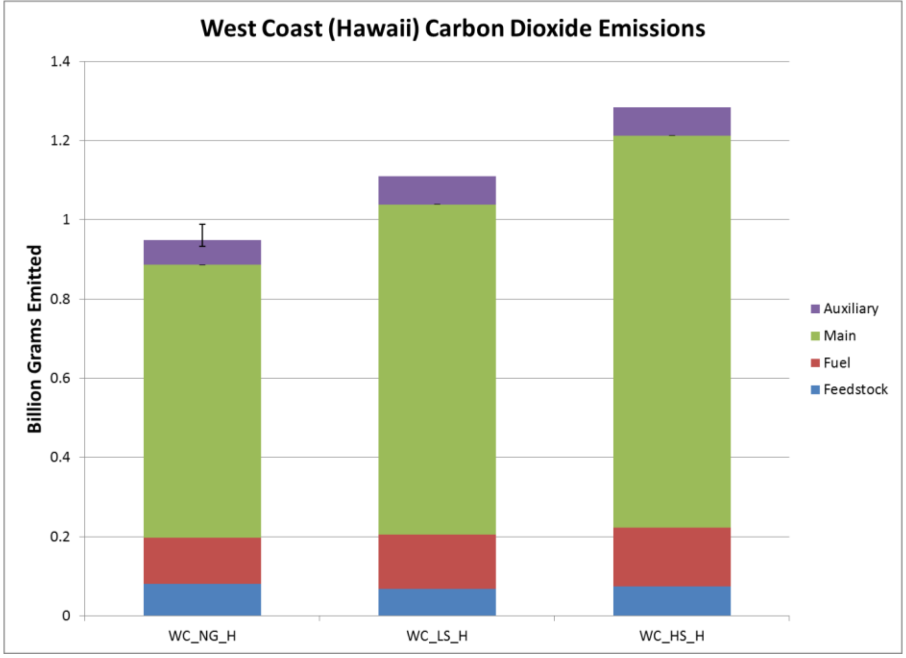


Figure 9 West Coast Case results for CH_4 emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

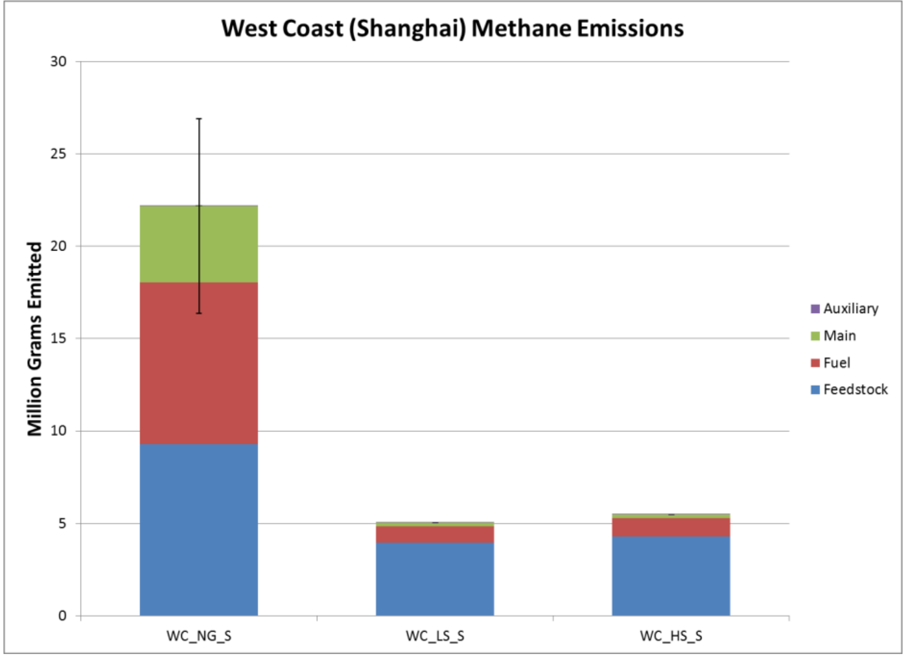


Figure 10 West Coast Case results for CH_4 emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the range; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

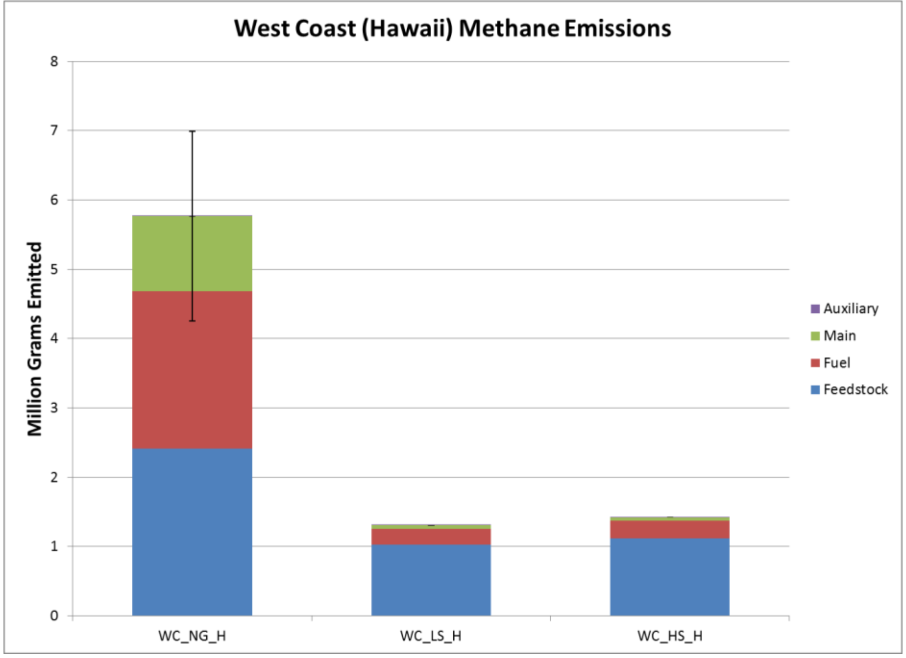


Figure 11 West Coast Case results for N_2O emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

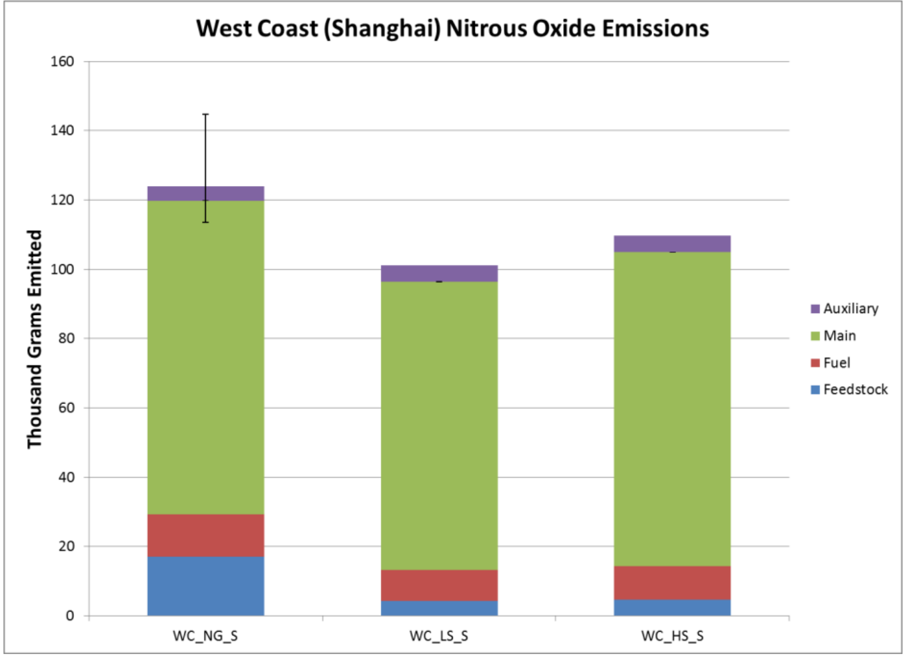


Figure 12 West Coast Case results for N_2O emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

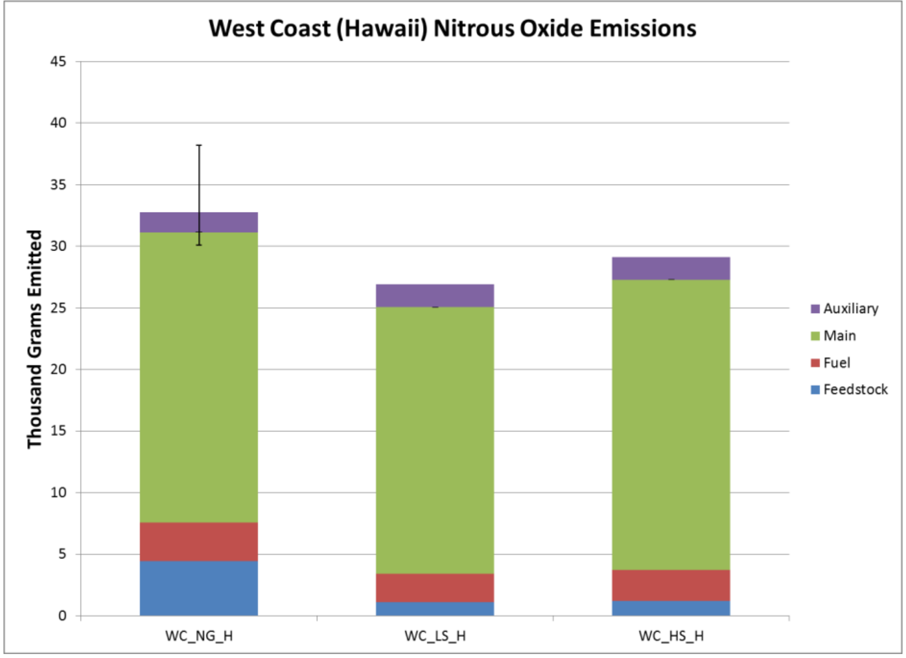


Figure 13 West Coast Case results for GHG emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

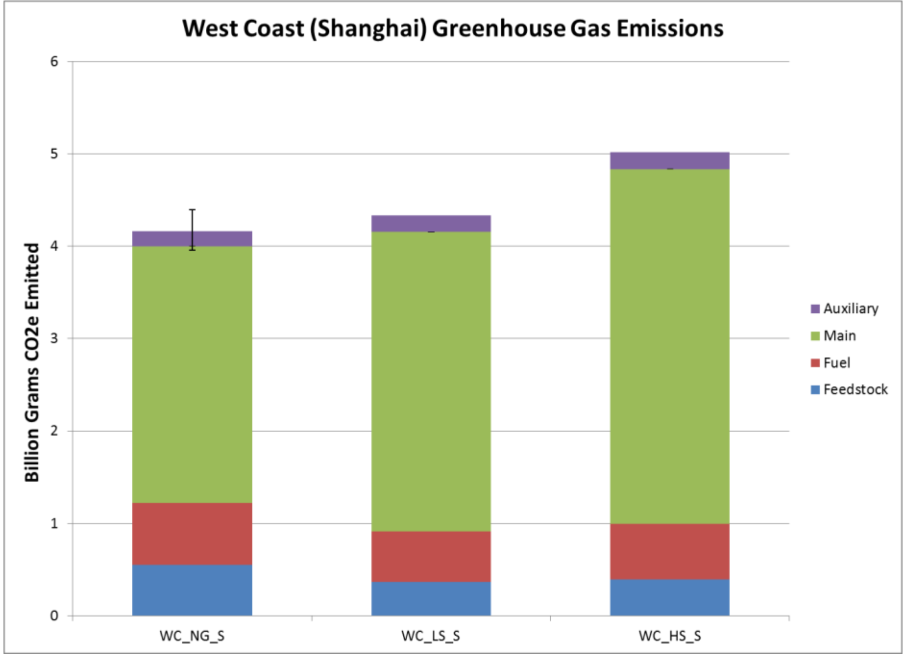


Figure 14 West Coast Case results for GHG emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

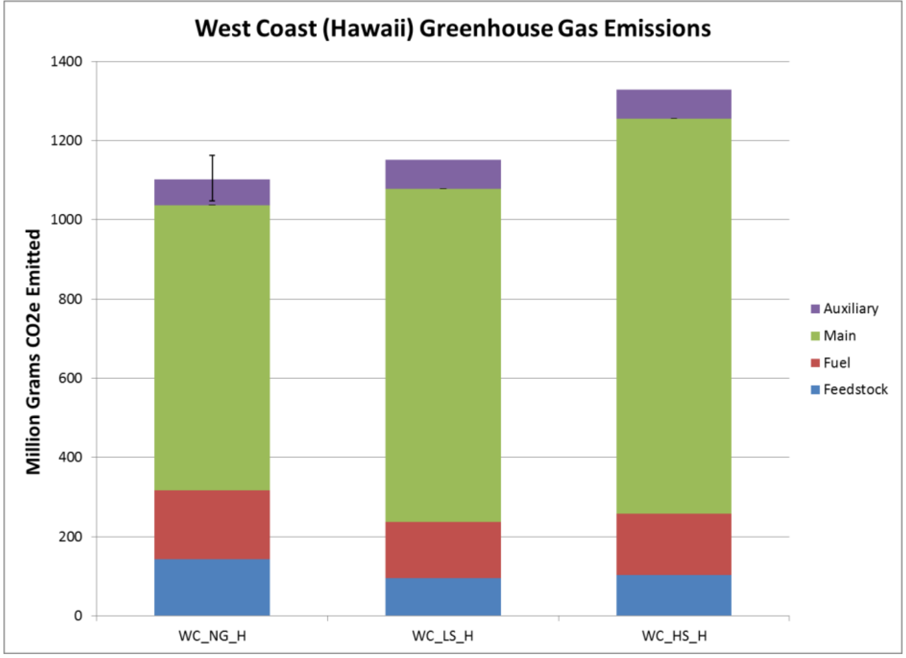
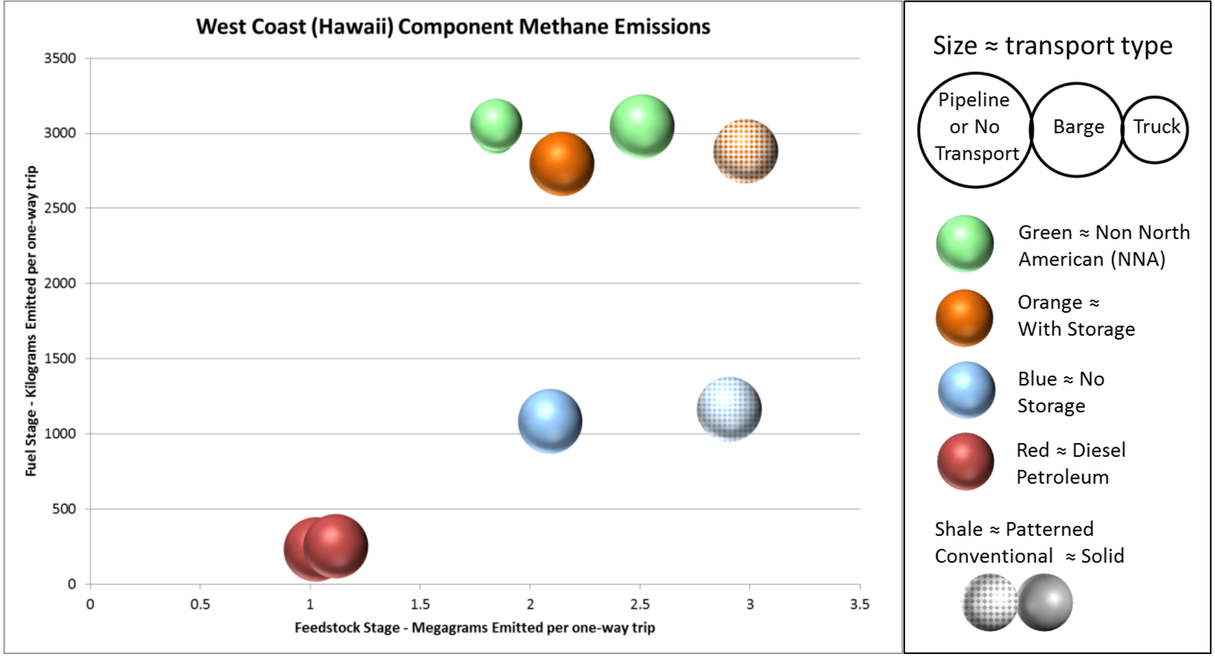


Figure 15 Breakdown of West Coast Case results for CH_4 emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions



Finally, three criteria pollutants are examined. Most of the NO_x emissions come from the operations phases of the vessel, and the LNG scenarios produce emissions approximately equivalent to the high sulfur scenario and slightly higher than the low sulfur scenario, as shown in Figure 16 and Figure 17. However, the LNG scenarios produce significantly less PM_{10} (shown in Figure 18 and Figure 19) and SO_x (shown in Figure 20 and Figure 21) than the diesel scenarios.

Figure 16 West Coast Case results for NO_x emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

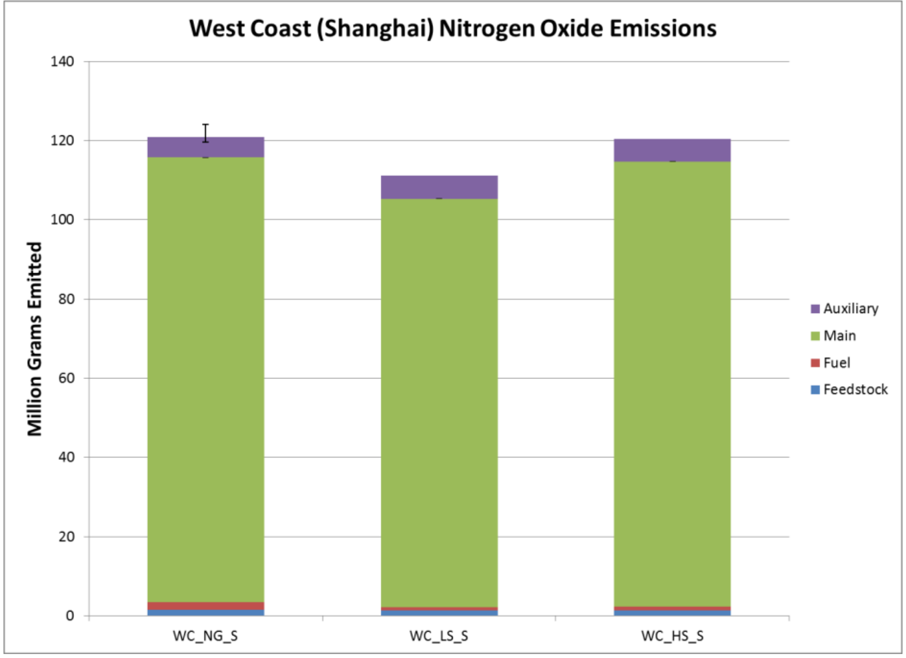


Figure 17 West Coast Case results for NO_x emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

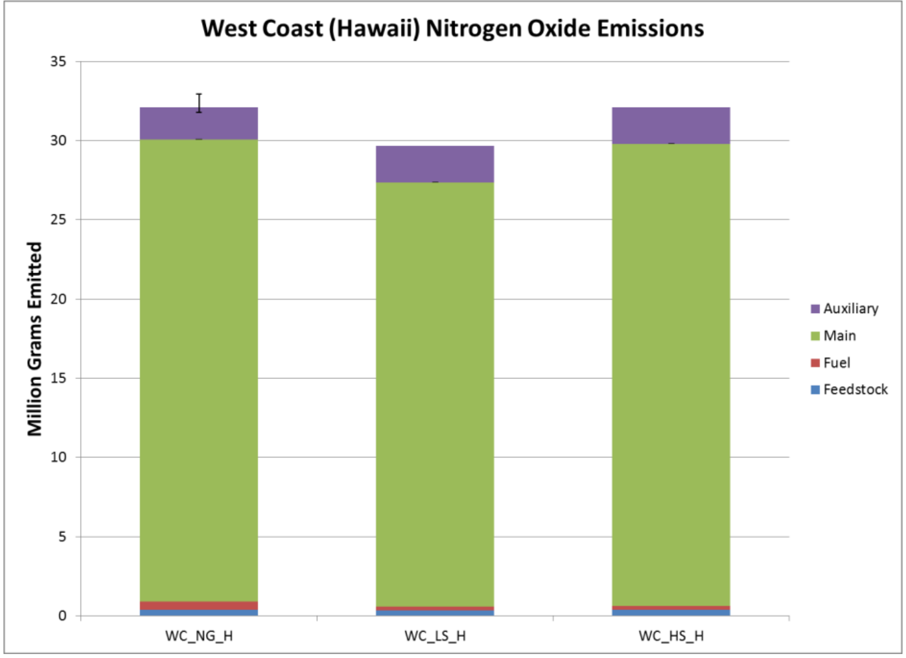


Figure 18 West Coast Case results for PM_{10} emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

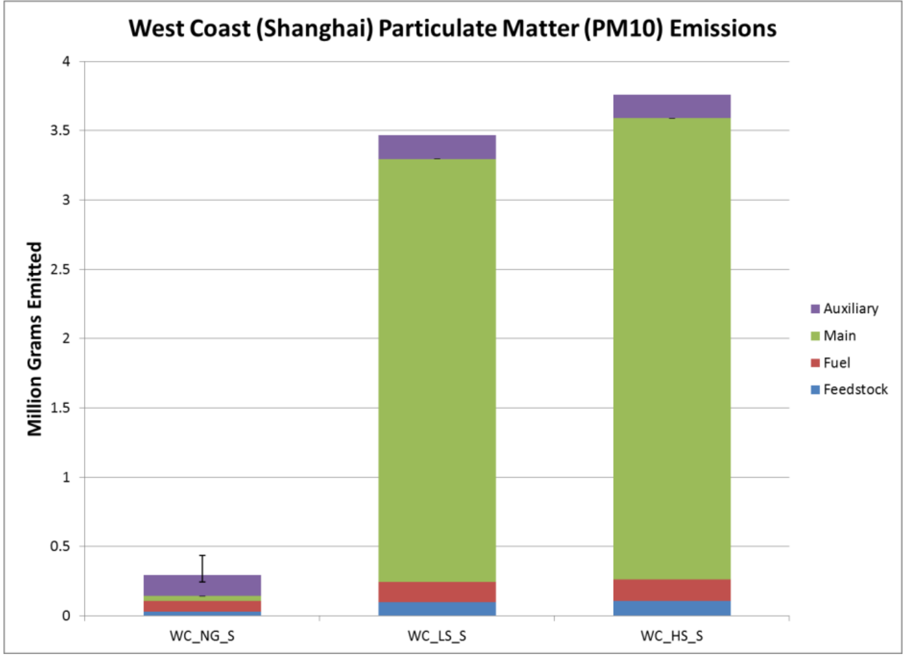


Figure 19 West Coast Case results for PM_{10} emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

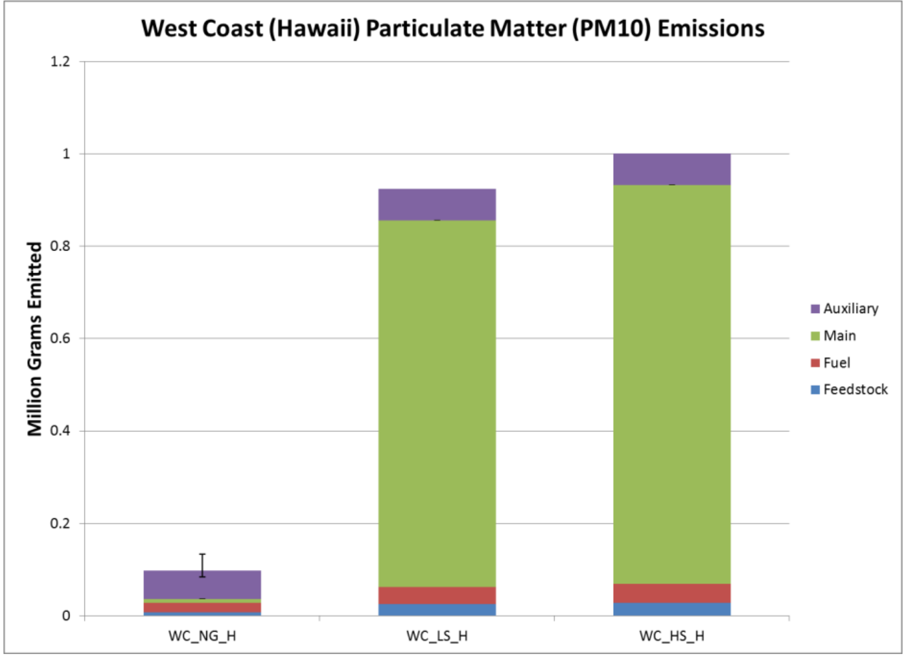


Figure 20 West Coast Case results for SO_x emissions for trip from Port of LA/LB to Shanghai (S); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

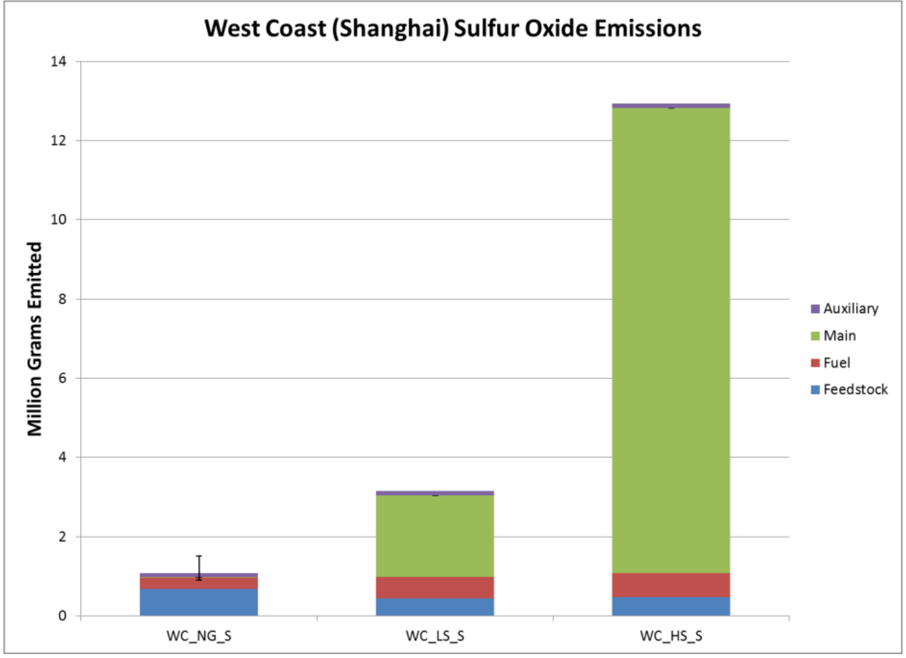
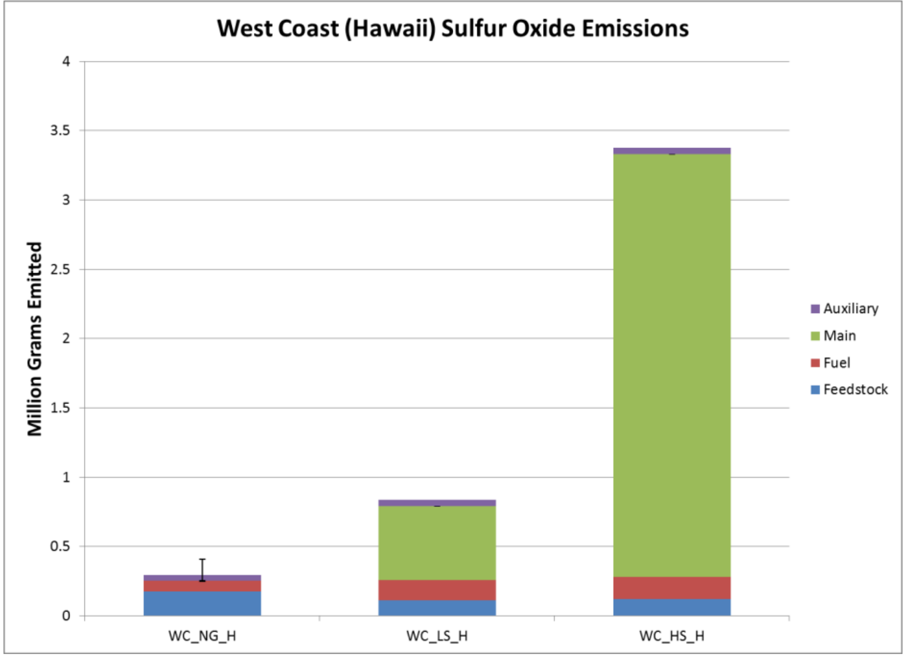


Figure 21 West Coast Case results for SO_x emissions for trip from Port of LA/LB to Hawaii (H); first column is average of all natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively



4.5 West Coast Case Discussion

Results show that the upstream processes did not significantly affect the overall results for energy needed or for any emissions other than GHGs. Either most of the energy or emissions came in the downstream processes (Total Energy and NO_x) or the variation did not affect the results relative to the diesel scenarios (SO_x and PM_{10}) or both (N_2O). It was only for CO_2 and CH_4 (and thus GHG overall) that the upstream processes contributed significantly to the range of emissions. For these pollutants, scenarios that used shale gas and those that had storage all had higher emissions than those that didn't. For shale gas, this is because emissions factors are higher due to venting during the recovery process, as shown in Table 4. Pathways with more days storage have higher emissions due to a boil-off rate of 0.1% per day, which is the GREET 2013 default.

When comparing energy needed and emissions produced using natural gas or traditional diesel fuel, results were again mixed. The total energy needed to make the trip is higher in the natural gas scenarios, as is the amount of CH_4, N_2O, and NO_x produced. In the diesel scenario more CO_2, PM10, and SOx are produced. Additionally, when taking into account the global warming potential of CH_4, N_2O, and CO_2, diesel is found to produce more overall GHG emissions (as measured in CO_2 equivalent units), under either low-sulfur distillate (depending on pathway) or high-sulfur residual fuels (across all natural gas pathways). Switching to natural gas will likely achieve MARPOL standards.

5 Inland River Case

5.1 Overview of Inland River Case

The Inland River Case includes a collection of scenarios that examine the energy use and emissions from using a natural gas (both liquefied natural gas [LNG] and compressed natural gas [CNG]) powered vessel to transport goods from the Port of Peoria, IL to New Orleans, LA. The case includes evaluation of all relevant fuel pathways, based on our research of the fueling situations in and around Peoria and New Orleans. The NG is obtained by either importing it from a Non-North American source as LNG via tanker or it may be processed from North American natural gas. We assume that NA NG is extracted from an existing well and delivered via pipeline to a liquefaction facility. We also assume that liquefaction occurs at an existing facility, though the possibility of future construction of a facility closer to the port at the nearest terminus of existing large volume pipelines is also examined. The LNG is delivered by truck or barge from the liquefaction facility to the port. For each North American possibility discussed, there is one pathway that assumes the LNG is not stored along the way and a second pathway that assumes storage of 30 days before the LNG is used in a ship. For this case the use of CNG is also examined. The pathways examined are similar to those of LNG, though fewer apply. The CNG pathways are described in Table 11. Traditional marine fuels usable in marine diesel engines are used as the comparators for these LNG/CNG pathways; they include high-sulfur distillate marine fuel (high-sulfur diesel) and low-sulfur distillate marine fuel (low-sulfur diesel).

Table 11 Pathway Variables for CNG

	Fuel Type		**Liquefaction**			**Transportation from Liquefaction Facility**					
Pathways-->	**Conventional**	**Shale**	**NNA**	**Existing Facility**	**End of Pipeline Facility**	**Truck**	**Barge**	**Pipeline**		**(B) Peoria**	**(C) New Orleans**
29	X		X					X		X	X
30	X				X			X		X	X
31		X			X			X		X	X

5.2 Fuel Pathways to the Port of Peoria

The port in Peoria is located along the Illinois River in central Illinois. Imported natural gas will either be brought in from Norway to Cove Point, MD and transported to the port by truck or it will be brought in at Cameron LA and transported by barge or regasified and transported by pipeline to the port. Natural gas used in this port will be drilled from the closest natural gas field in Antrim, MI. The nearest liquefaction facility is located in western Illinois but there is a pipeline terminus located nearer the port in Farmington, IL. Therefore the emissions produced if a facility were to be constructed there will also be examined. Figure 22 shows the geographic location of the various components of the pathways. Table 12 indicates the inputs used in the GREET runs.

Figure 22 Depiction of various fuel pathways for the Peoria end of the Inland Case showing transportation modes along the pathway network

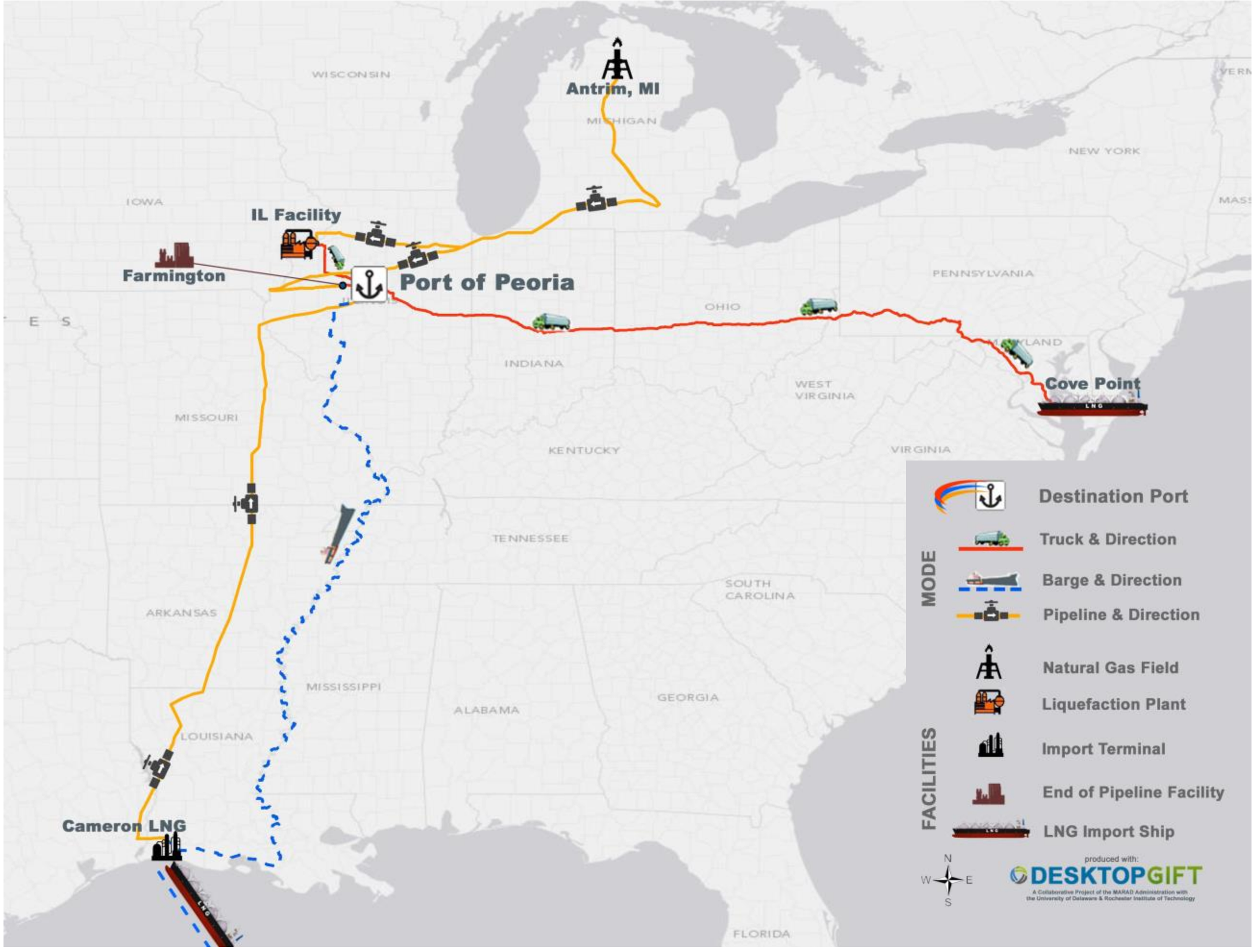


Table 12 Peoria Facilities Locations and GREET Inputs

	Trip Origin	Trip Destination	Mode	Distance (miles)
LNG	Norway (Exporting Nation)	Cove Point, MD (Import Terminal)	Ship	4,200
	Norway (Exporting Nation)	Cameron, LA (Import Terminal)	Ship	5,840
	Antrim, MI (NG Field)	Western IL (Liquefaction Facility)	Pipeline	445
	Antrim, MI (NG Field)	Farmington, IL (End of Pipeline)	Pipeline	665
	Western IL (Liquefaction Facility)	Peoria, IL (Port)	Truck	80
	Farmington, IL (End of Pipeline)	Peoria, IL (Port)	Truck	25
	Cove Point, MD (Import Terminal)	Peoria, IL (Port)	Truck	850
	Cameron, LA (Import Terminal)	Peoria, IL (Port)	Barge	995
	Cove Point, MD (Import Terminal)	Western IL (Liquefaction Facility)	Pipeline	1,065
	Cameron, LA (Import Terminal)	Western IL (Liquefaction Facility)	Pipeline	955
CNG	Cameron, LA (Import Terminal)	Peoria, IL (Port)	Pipeline	915
	Antrim, MI (NG Field)	Peoria, IL (Port)	Pipeline	690

5.3 Fuel Pathways to the port of New Orleans

The port in New Orleans is located in eastern Louisiana at the mouth of the Mississippi River. Imported natural gas will be brought in from Norway to Cameron, LA, and transported to the port by truck, barge, or be regasified and transported by pipeline to the port. Natural gas used in this port will be drilled from the closest natural gas field at the Hayesville Shale Unit in LA. The nearest liquefaction facility is located in east Texas. There is a pipeline terminus at the port in Avondale, LA, so the emissions produced if a facility were to be constructed there will also be examined. Table 13 indicates the inputs used in the GREET runs. Figure 23 shows the geographic locations for the various facilities involved in the pathways.

Figure 23 Depiction of various fuel pathways for the New Orleans end of the Inland Case showing transportation modes along the pathway network

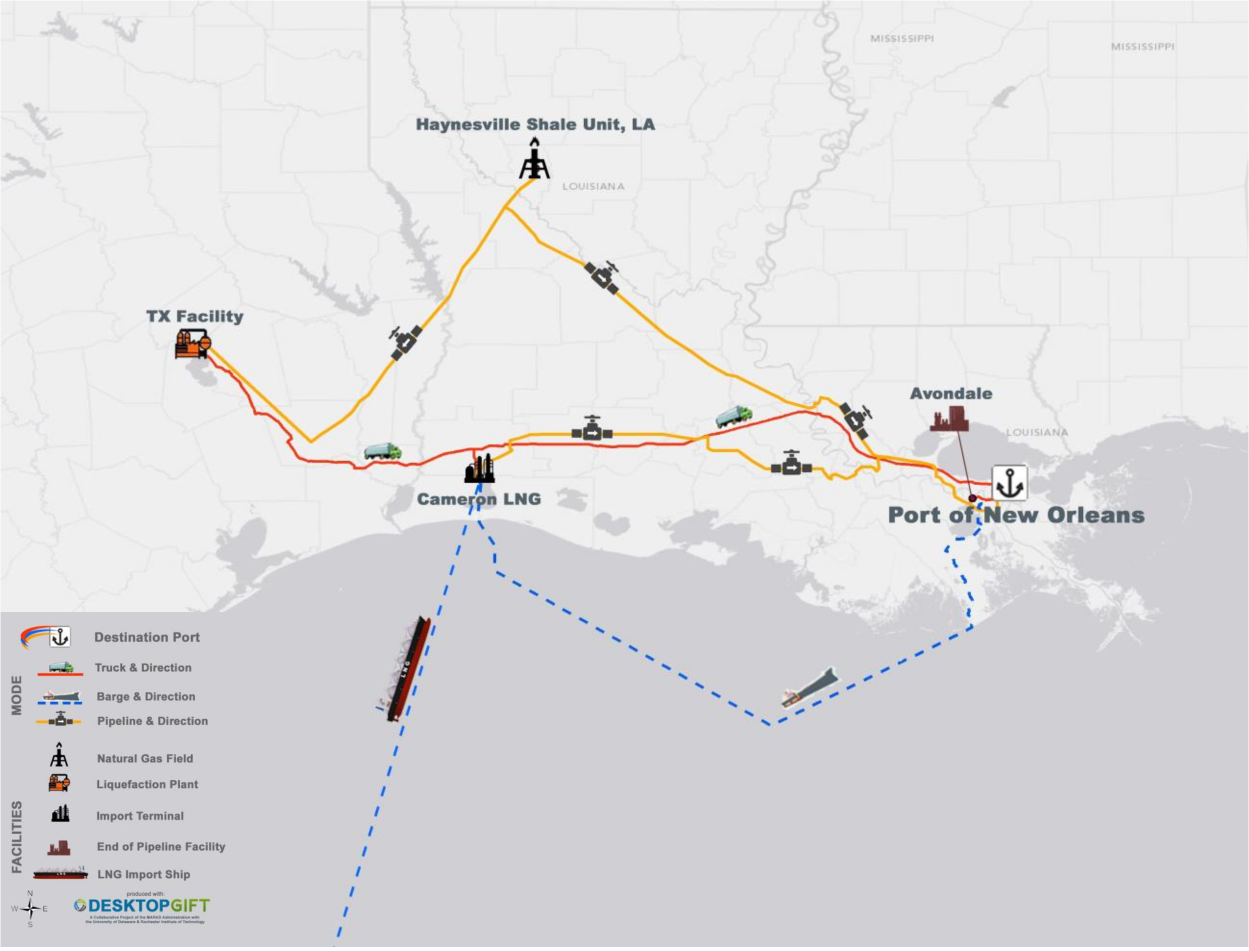


Table 13 New Orleans Facilities Locations and GREET Inputs

	Trip Origin	Trip Destination	Mode	Distance (miles)
LNG	Norway (Exporting Nation)	Cameron, LA (Import Terminal)	Ship	5,840
	Haynesville Shale Unit, LA (NG Field)	Eastern Texas (Liquefaction Facility)	Pipeline	197
	Haynesville Shale Unit, LA (NG Field)	Avondale, LA (End of Pipeline)	Pipeline	375
	Eastern Texas (Liquefaction Facility)	New Orleans, LA (Port)	Truck	357
	Eastern Texas (Liquefaction Facility)	New Orleans, LA (Port)	Barge	420
	Cameron, LA (Import Terminal)	New Orleans, LA (Port)	Truck	250
	Cameron, LA (Import Terminal)	New Orleans, LA (Port)	Barge	440
	Cameron, LA (Import Terminal)	Eastern Texas (Liquefaction Facility)	Pipeline	135
CNG	Cameron, LA (Import Terminal)	New Orleans, LA (Port)	Pipeline	225
	Haynesville Shale Unit, LA (NG Field)	New Orleans, LA (Port)	Pipeline	375

5.4 Inland River Vessel Characteristics

Data for typical vessels traversing the Mississippi River was obtained from the Army Corps of Engineer’s Waterway Link Network. The weighted average for the vessels transiting the segments of the Illinois and the Mississippi between Peoria and New Orleans was used as the typical vessel. Table 14 shows the inputs used for a typical towboat vessel, based on the values reported in the database. It was assumed that the vessel spent equal amounts of time in full and slow steaming, due to the repeated need to slow down for navigation and to get through the locks.

Table 14 TEAMS Vessel Inputs

Vessel Characteristic	Value
Vessel Type	Towboat
Rated Power (kW)	2,850
Distance (miles)	1,331
Rated Speed (knots)	7.3
Time for one-way trip (HH:MM)	213:45
Engine Efficiency (%)	45
Time Spent in Each Operating Stage as a Percentage of Total Trip Time (%)	
Idle	1.25%
Maneuvering	1.75%
Precautionary	5.00%
Slow Cruise	46.00%
Full Cruise	46.00%

5.5 Inland River Results

Our results are presented in a collection of tables and graphs. Energy use and emissions were calculated for the four stages of the fuel pathway for each scenario. These results represent total energy use and emissions for a given “trip.” For example, “Total Energy” represents the energy (in BTUs) needed to obtain, process, transport, and consume the fuel needed to transport the ship between Peoria and New Orleans. The feedstock stage and fuel processing stage describe energy use and emissions occurring upstream (well-to-pump); the main and auxiliary engine operations describe emissions occurring downstream (pump-to-hull). Table 15a and Table 15b show results for each scenario. Full graphical results are presented in Appendix B with summary graphs of selected variables presented here. Each graph shows the average of the natural gas pathways in the first two columns, with the bars depicting the range of the scenarios. The third and fourth columns are the low and high sulfur petroleum scenarios, respectively.

Table 15a Inland River Case results for total fuel cycle energy needed for travel between the Port of Peoria, IL and the Port of New Orleans, LA

Scenario Code	Fuel Type	Total Energy (mmBtu)	Fossil Fuels (mmBtu)	Petroleum (mmBtu)
B1	LNG	4,331	4,328	1,892
B2	LNG	4,210	4,207	1,751
B3	LNG	4,304	4,300	1,745
B5	LNG	4,208	4,205	1,730
B6	LNG	4,183	4,180	1,729
B11	LNG	4,225	4,222	1,719
B12	LNG	4,200	4,197	1,718
B17	LNG	4,211	4,208	1,729
B18	LNG	4,186	4,183	1,729
B23	LNG	4,229	4,225	1,718
B24	LNG	4,203	4,200	1,718
C1	LNG	4,210	4,207	1,778
C2	LNG	4,179	4,176	1,739
C3	LNG	4,253	4,250	1,800
C5	LNG	4,236	4,233	1,785
C6	LNG	4,211	4,208	1,783
C7	LNG	4,179	4,176	1,723
C8	LNG	4,155	4,152	1,722
C15	LNG	4,180	4,177	1,714
C16	LNG	4,155	4,152	1,713
C17	LNG	4,240	4,236	1,785
C18	LNG	4,214	4,211	1,783
C19	LNG	4,182	4,179	1,722
C20	LNG	4,158	4,155	1,722
C27	LNG	4,183	4,180	1,713
C28	LNG	4,158	4,156	1,713
I_LS	Low-Sulfur Diesel	4,222	4,209	3,865
I_HS	High-Sulfur Diesel	4,222	4,209	3,865
B29	CNG	4,396	4,376	1,733
B30	CNG	4,053	4,035	1,715
B31	CNG	4,056	4,038	1,715
C29	CNG	4,311	4,291	1,732
C30	CNG	4,018	4,000	1,715
C31	CNG	4,021	4,002	1,714

Note: Scenario Code refers to the port of origin (“B” being the Port of Peoria, IL) and the fuel pathway for refueling (indicated by the number as referenced in Table 2).

Table 15b Inland River Case results for total fuel cycle emissions (in kg/trip) of pollutants included in this study for travel between the Port of Peoria, IL and the Port of New Orleans, LA

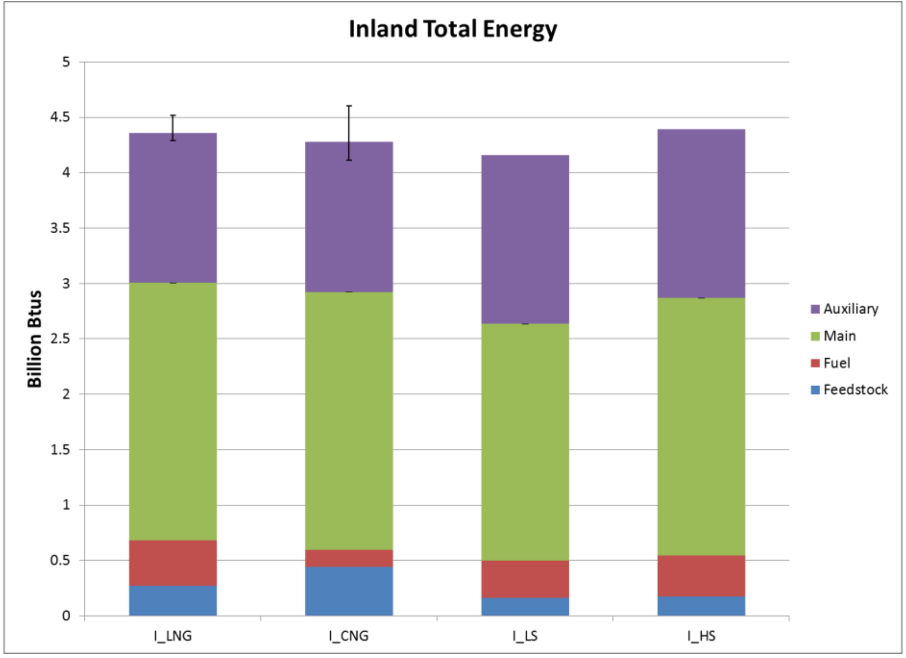
Scenario Code	Kilograms emitted per trip								
	CO_2	CH_4	N_2O	GHGs	VOC	CO	NO_x	PM_{10}	SO_x
B1	284,827	2,093	8	339,597	207	1,130	4,117	120	111
B2	274,173	2,213	8	331,891	203	1,118	4,109	118	113
B3	278,787	2,503	12	345,006	219	1,165	4,152	118	112
B5	272,719	2,430	10	336,430	208	1,133	4,037	115	101
B6	272,306	2,155	10	329,125	207	1,131	4,034	114	100
B11	273,325	2,519	11	339,534	211	1,143	4,052	114	101
B12	272,905	2,241	11	332,160	210	1,142	4,048	114	101
B17	272,471	2,573	10	339,766	207	1,132	4,035	114	101
B18	272,069	2,295	10	332,382	207	1,131	4,032	114	100
B23	273,080	2,663	11	342,908	211	1,143	4,050	114	101
B24	272,666	2,383	11	335,449	210	1,141	4,046	114	100
C1	275,038	2,119	8	330,420	204	1,117	4,084	118	111
C2	272,177	2,157	8	328,495	203	1,114	4,082	118	111
C3	277,925	2,176	9	334,924	207	1,127	4,105	119	112
C5	275,893	2,335	9	336,926	205	1,126	4,041	116	102
C6	275,402	2,063	9	329,609	205	1,125	4,038	116	101
C7	270,830	2,369	9	332,700	203	1,120	4,029	114	101
C8	270,460	2,095	9	325,459	203	1,119	4,026	114	101
C15	270,765	2,400	10	333,619	206	1,127	4,024	114	101
C16	270,405	2,126	10	326,388	205	1,126	4,021	114	100
C17	275,653	2,477	9	340,235	205	1,125	4,039	116	102
C18	275,167	2,201	9	332,835	205	1,124	4,036	116	101
C19	270,589	2,512	9	336,026	203	1,120	4,027	114	101
C20	270,225	2,234	9	328,700	203	1,119	4,024	114	101
C27	270,523	2,543	10	336,948	206	1,126	4,022	114	100
C28	270,169	2,265	10	329,633	205	1,125	4,019	114	100
I_LS	327,997	287	8	337,588	364	1,612	9,242	284	237
I_HS	343,989	287	8	353,580	364	1,612	9,242	284	724
B29	285,947	2,592	12	354,249	217	1,157	4,145	120	137
B30	265,570	2,231	10	324,417	208	1,133	4,020	116	120
B31	265,351	2,361	10	327,428	208	1,132	4,019	116	120
C29	281,439	2,343	9	342,717	206	1,124	4,091	120	135
C30	263,709	2,127	9	319,617	204	1,119	3,998	116	120
C31	263,493	2,255	9	322,588	204	1,118	3,996	116	120

Note GHGs represent the GWP_{100} weighted combination of CH_4, CO_2, and N_2O

Note: Scenario Code refers to the port of origin ("B" being the Port of Peoria, IL) and the fuel pathway for refueling (indicated by the number as referenced in Table 2).

Figure 24 shows the energy needed for the whole fuel. Both the natural gas scenarios needed more energy than the low sulfur petroleum scenario, but was approximately equivalent to the high sulfur petroleum scenario. In addition, energy use for LNG production is slightly higher than CNG production, thereby leading to a slightly higher total fuel cycle energy use for LNG compared to CNG.

Figure 24 Inland River Case results for total energy needed for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively



The next set of graphs show the GHG results for these routes. The LNG emissions of CO_2 are lower to those of the diesel scenarios, as shown in Figure 25. Although the emissions of CH_4 (Figure 26) and N_2O (Figure 27) are higher than the diesel cases, the overall volume of CO_2 makes the GHG emissions of LNG less than those of both the high sulfur and the low sulfur petroleum marine fuels. For both CO_2 and N_2O most of the emissions come from the downstream stages, so changes to the upstream pathway will not greatly affect the overall emissions. However, for CH_4 the upstream processes do have an effect, so those are looked at in more detail in Figure 29. There it can be seen that natural gas obtained from shale has higher methane emissions than that from conventional gas. In addition, shorter storage times decrease the emissions. CNG had the lowest emissions in the feedstock stage, though NNA NG had higher emissions in the fuel stage. Components that affect the amount of methane released are the amount of methane slip in the engine and the amount of leakage that occurs during processing, including during pipeline transport and the switching of modes. As discussed in the introduction, the values used here are the best available, consistent with recent evidence supporting higher leakage rates (Brandt et al., 2014). These are factors that can be considered when deciding on the upstream pathway that ultimately will be utilized.

Figure 25 Inland River Case results for CO_2 emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

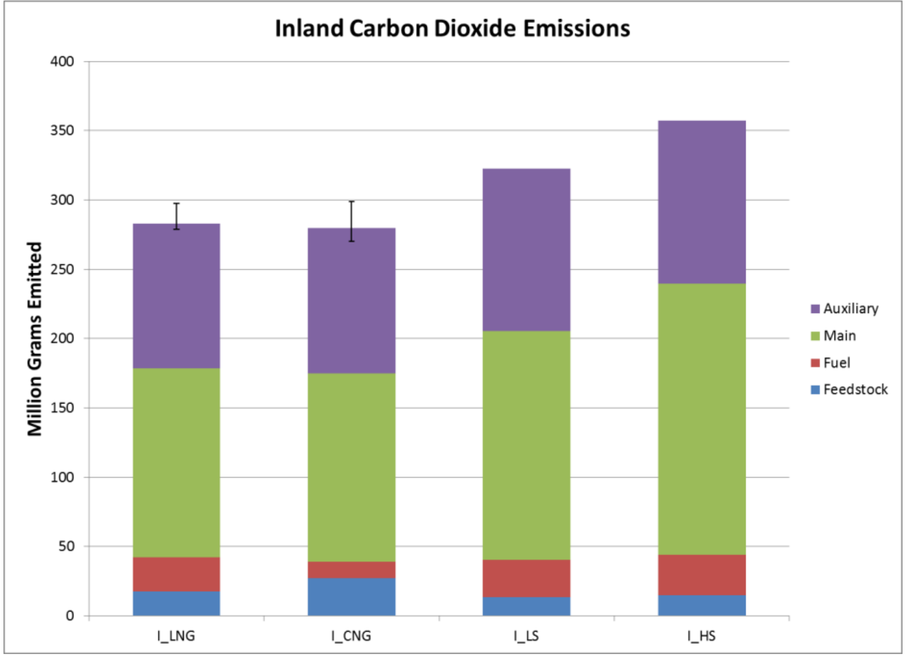


Figure 26 Inland River Case results for CH_4 emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

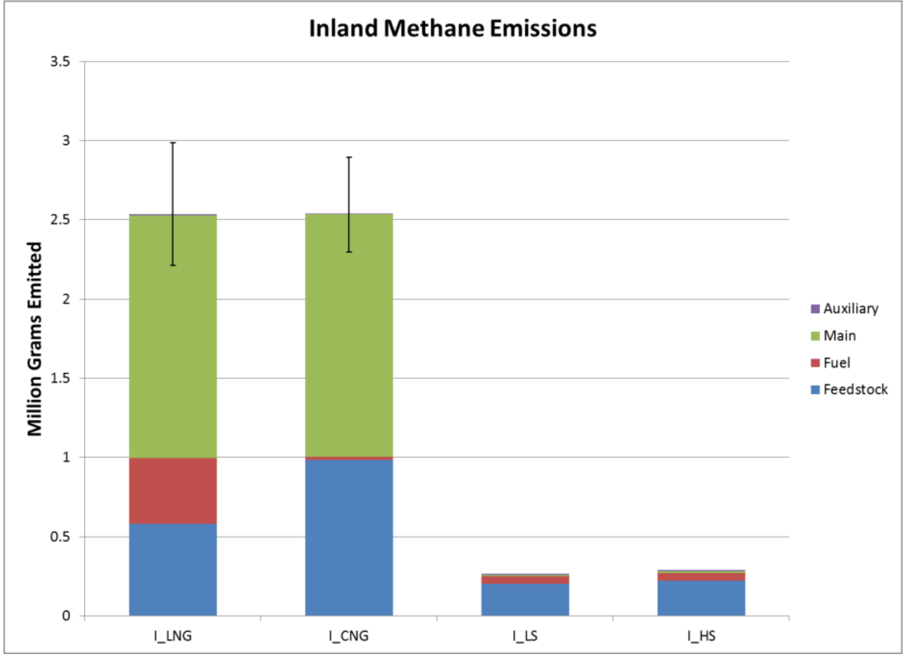


Figure 27 Inland River Case results for N_2O emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

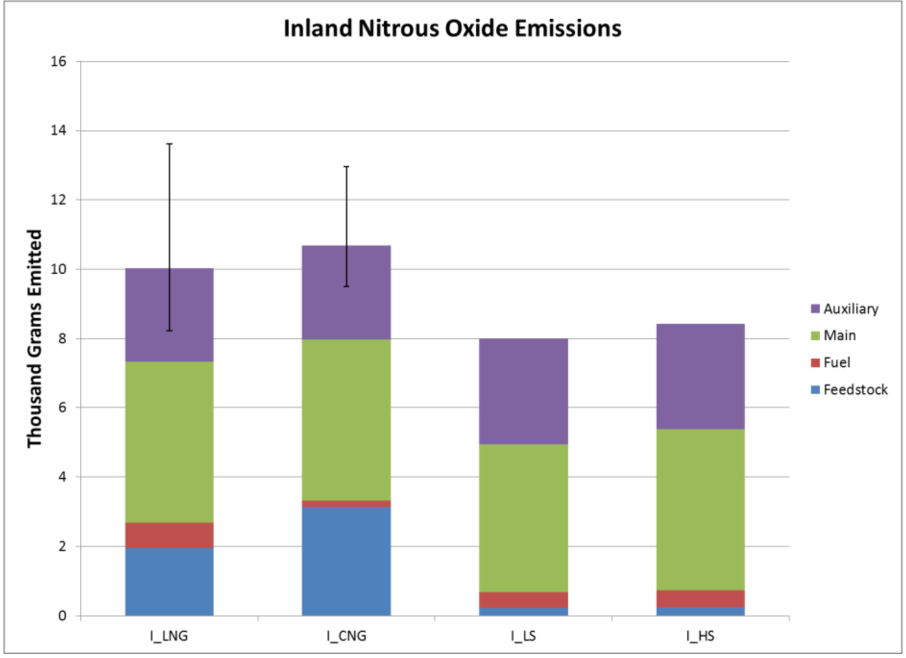


Figure 28 Inland River Case results for GHG emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

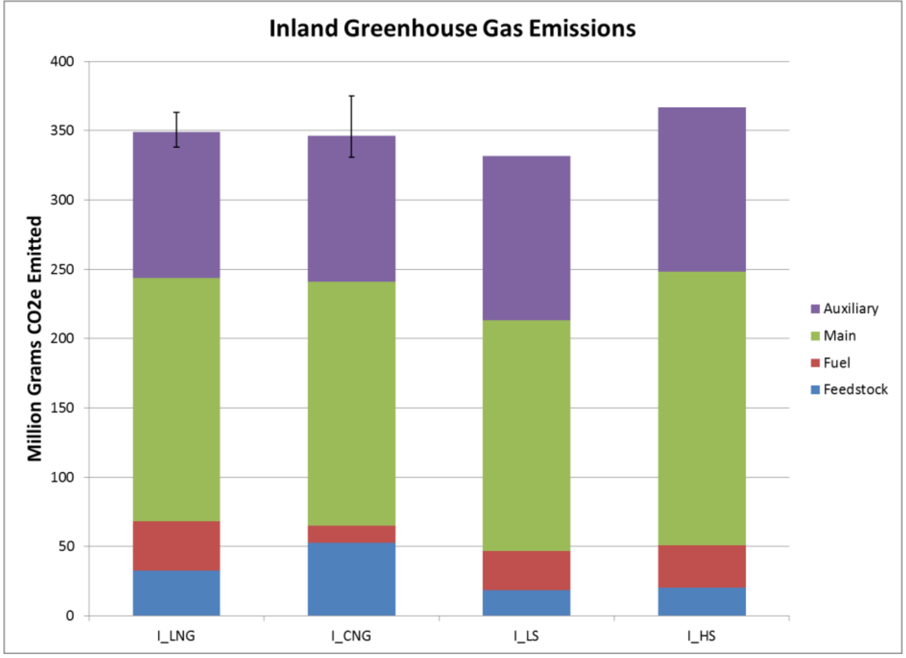
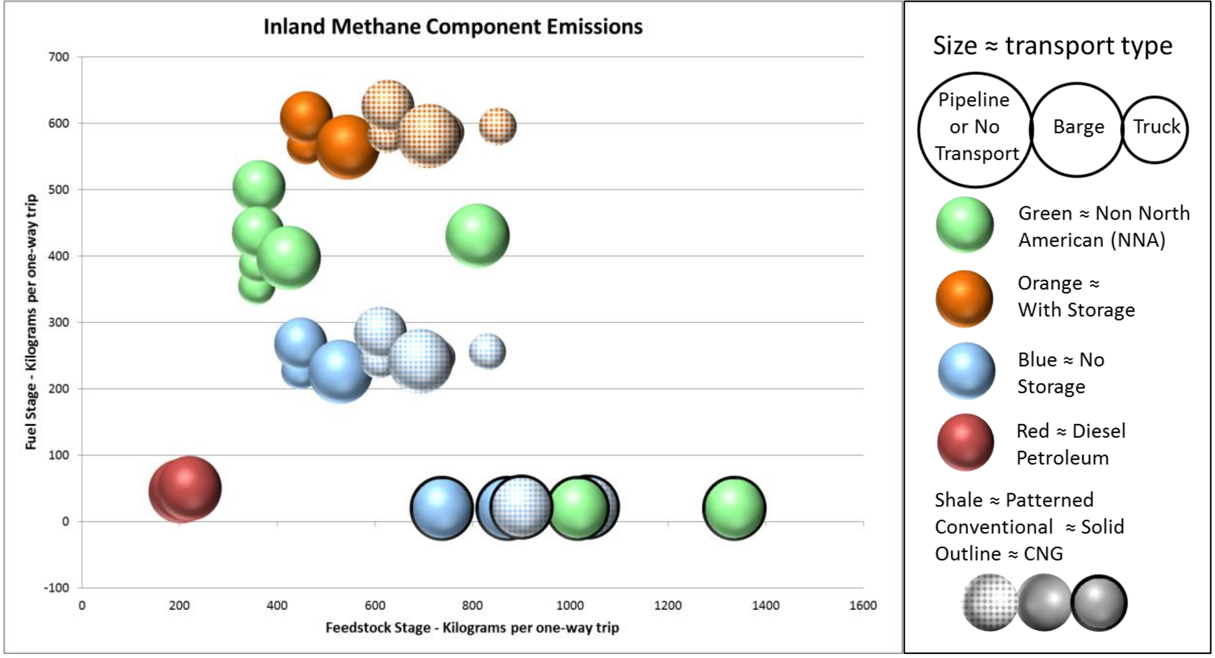


Figure 29 Breakdown of Inland River Case results for CH_4 emissions for trip from Port of Peoria, IL to Port of New Orleans showing how various pathway decisions affect upstream emissions



Finally, three criteria pollutants are examined. Most of the NO_x emissions come from the operations phases of the vessel, particularly the auxiliary engines, and the NG scenarios produce approximately half the emissions of the diesel scenarios, as shown in Figure 30. Additionally, the NG scenarios produce significantly less PM_{10} (shown in Figure 31) and SO_x (shown in Figure 32) than the diesel scenarios.

Figure 30 Inland River Case results for NO_x emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

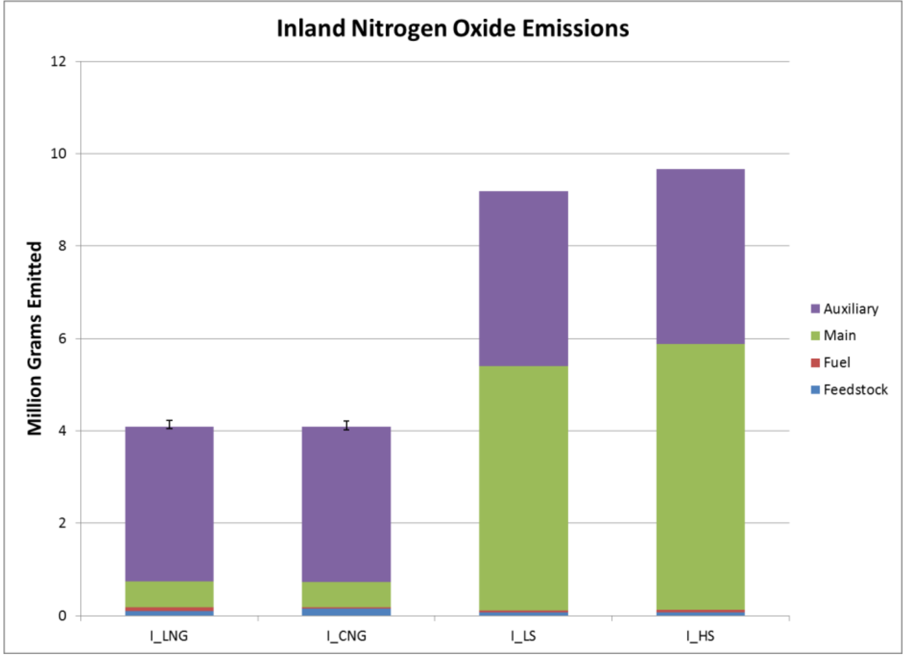


Figure 31 Inland River Case results for PM_{10} emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively

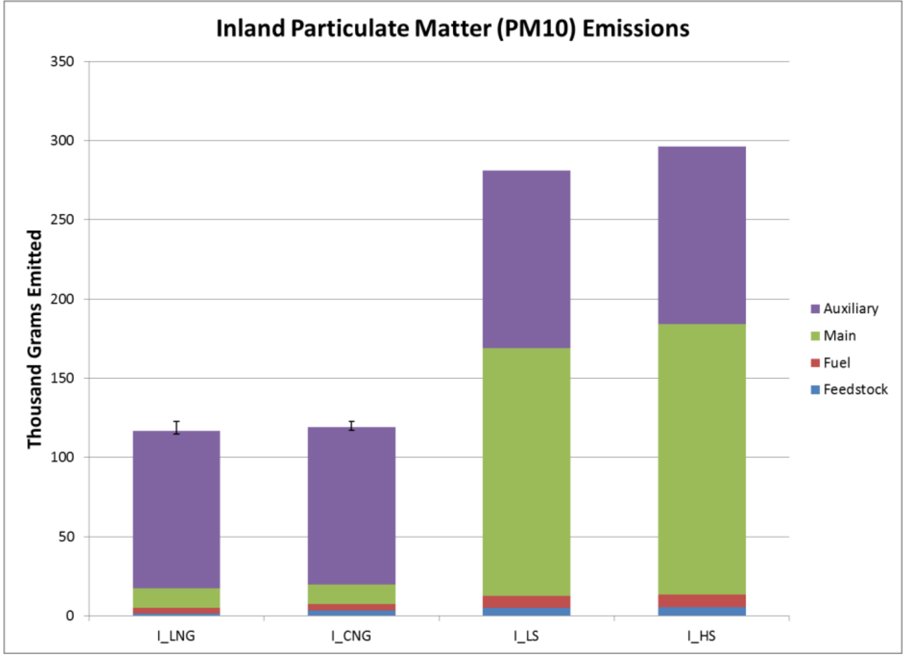
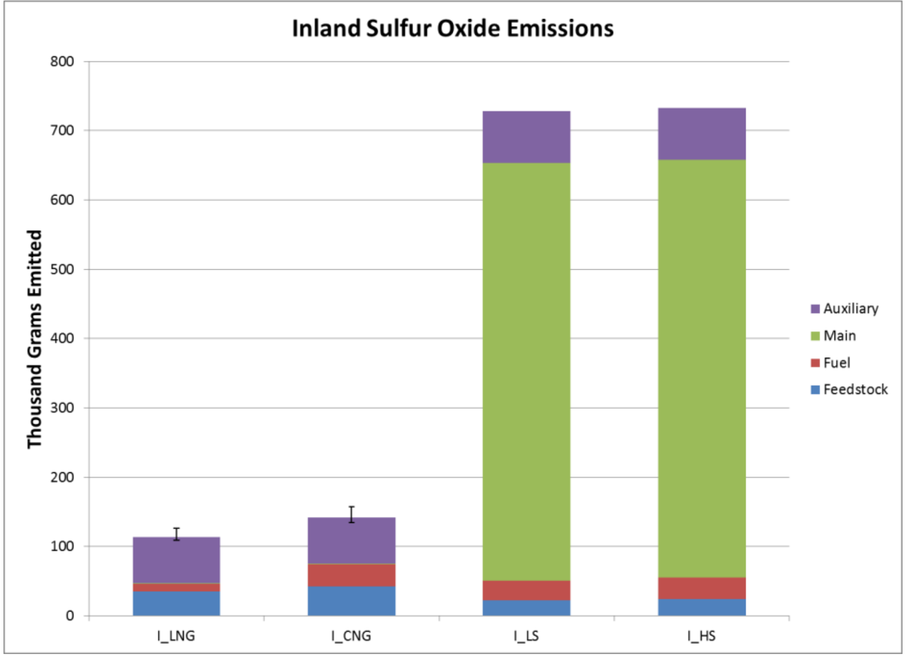


Figure 32 Inland River Case results for SO_x emissions for trip from the Port of Peoria, IL to the Port of New Orleans, LA; first two columns are the average of all liquid and compressed natural gas scenarios with bars showing the min/max of these scenarios; third and fourth columns are low-sulfur and high-sulfur diesel scenarios, respectively



5.6 Inland River Case Discussion

Results show that the upstream processes did not significantly affect the overall results for energy needed or for any emissions other than GHGs. Either most of the energy or emissions came in the downstream processes (Total Energy and NO_x) or the variation did not affect the results relative to the diesel scenarios (SO_x and PM_{10}) or both (N_2O). It was only for CO_2 and CH_4 (and thus GHG overall) that the upstream processes contributed significantly to the range of emissions. For these pollutants, scenarios that used shale gas and those that had storage all had higher emissions than those that didn't. For shale gas, this is because emissions factors are higher due to venting during the recovery process, as shown in Table 4. Pathways with more days storage have higher emissions due to a boil-off rate of 0.1% per day, which is the GREET 2013 default.

There is also a difference between using CNG and LNG, for some pollutants. The energy needed for LNG is higher because of the energy needed to cool and liquefy the natural gas. For most other pollutants LNG and CNG were similar in their emissions, with the only exceptions being nitrogen oxide and sulfur oxides.

When comparing energy needed and emissions produced using natural gas or traditional diesel fuel, results were again mixed. The total energy needed to make the trip is higher in the natural gas scenarios, as is the amount of CH_4, N_2O, and NO_x produced. In the diesel scenario more CO_2, PM10, and SOx are produced. Additionally, when taking into account the global warming potential of CH_4, N_2O, and CO_2, diesel is found to produce less overall GHG emissions (as measured in CO_2 equivalent units) using low-sulfur distillate, but more overall GHG using high-sulfur residual fuel (depending on pathway). This result can be explained by the differences in liquefaction energy for inland cases as compared with coastal/oceangoing cases.

6 East Coast Case

6.1 Overview of East Coast Case

The East Coast Case includes a collection of scenarios that examine the energy use and emissions from using a liquefied natural gas (LNG) powered vessel to transport goods from the Port Authority of New York / New Jersey (PANYNJ) to Jacksonville, FL. The case includes evaluation of all relevant fuel pathways, based on our research of the fueling situations in and around PANYNJ and Jacksonville. The LNG is obtained by either importing it from a Non-North American source as LNG via tanker or it may be processed from North American natural gas (NA NG). We assume that NA NG is extracted from an existing well and delivered via pipeline to a liquefaction facility. We also assume that liquefaction occurs at an existing facility, though the possibility of future construction of a facility closer to the port at the nearest terminus of existing large volume pipelines is also examined. The LNG is be delivered by truck or barge to the port. For each North American possibility discussed, there is one pathway that assumes the LNG is not stored along the way and a second pathway that assumes storage of 30 days before the LNG is used in a ship. Traditional marine fuels usable in marine diesel engines are used as the comparators for these LNG/CNG pathways; they include high-sulfur residual marine fuel (high-sulfur diesel) and low-sulfur distillate marine fuel (low-sulfur diesel).

6.2 Fuel Pathways to the Port Authority of New York and New Jersey

The port in New York New Jersey is located in the harbor between the two states. Imported natural gas will be brought in from Norway to Cove Point, MD, and transported to the port by truck or regasified and transported by pipeline to the port. Natural gas used in this port will be drilled from the closest natural gas field in Dimock, PA. The nearest liquefaction facility is located in the port, in Bayonne NJ, so no additional facilities need to be examined. Figure 33 shows the geographic location of the various components of the pathways. Table 16 indicates the inputs used in the GREET runs.

Figure 33 Depiction of various fuel pathways for the PANYNJ end of the East Coast Case showing transportation modes along the pathway network

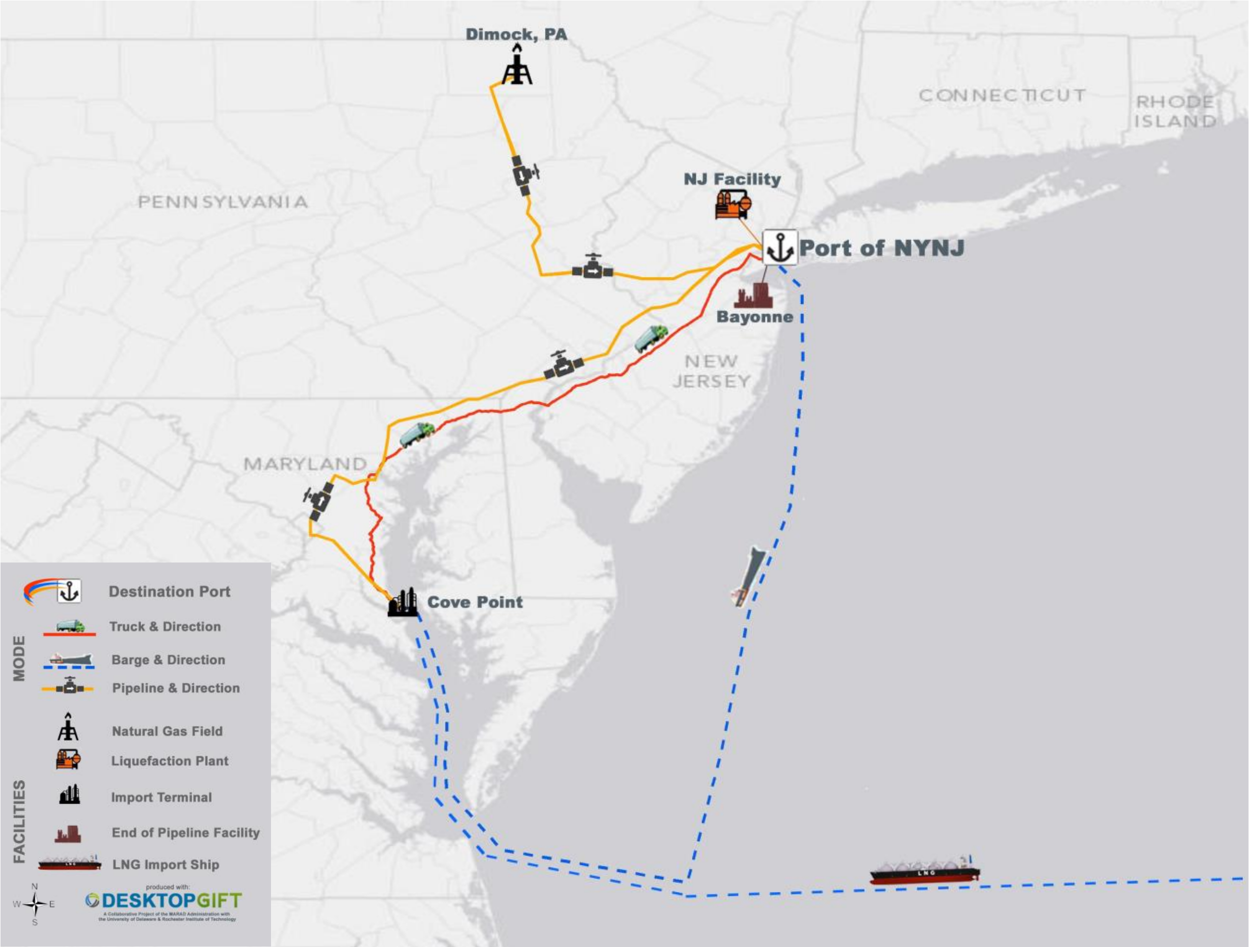


Table 16 PANYNJ Facilities Locations and GREET Inputs

Trip Origin	Trip Destination	Mode	Distance (miles)
Norway (Exporting Nation)	Cove Point, MD (Import Terminal)	Ship	4,200
Dimock, PA (NG Field)	Bayonne, NJ (Liquefaction Facility)	Pipeline	205
Cove Point, MD (Import Terminal)	PANYNJ (Port)	Truck	265
Cove Point, MD (Import Terminal)	PANYNJ (Port)	Barge	380
Cove Point, MD (Import Terminal)	Bayonne, NJ (Liquefaction Facility)	Pipeline	310

6.3 Fuel Pathways to the Port of Jacksonville

The port in Jacksonville is located in northern Florida. Imported natural gas will be brought in from Norway to Cove Point, MD, and transported to the port by truck or regasified and transported by pipeline to the port. Natural gas used in this port will be drilled from the closest natural gas field in Oakwood, VA. The nearest liquefaction facility is operated by AGL Resources and is located in Macon, GA. There is a pipeline terminus closer to the port in Alma, GA, so the emissions produced if a facility were to be constructed there will also be examined. Table 17 indicates the inputs used in the GREET runs. Figure 34 shows the geographic locations for the various facilities involved in the pathways.

Figure 34 Depiction of various fuel pathways for the Jacksonville end of the East Coast Case showing transportation modes along the pathway network

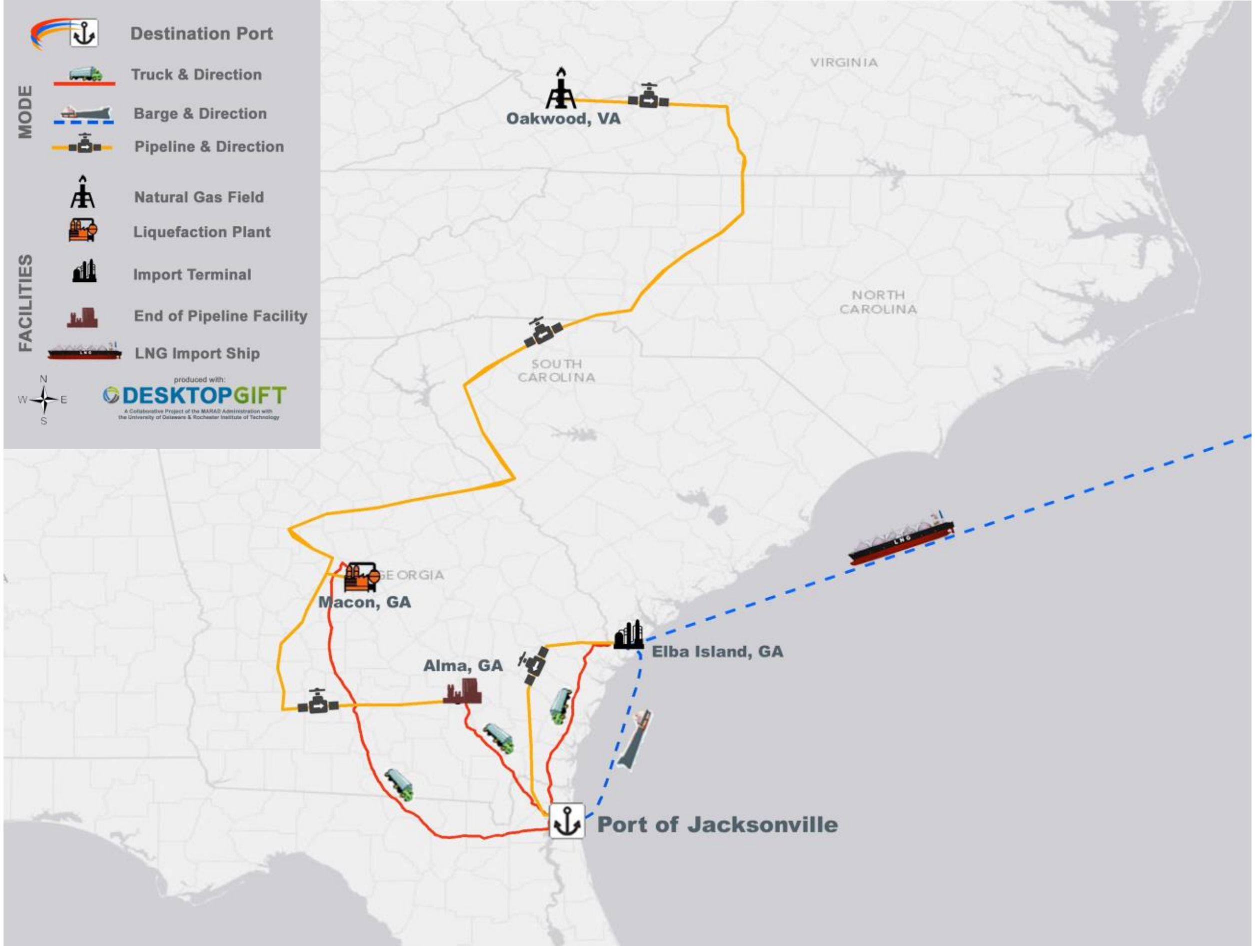


Table 17 Jacksonville Facilities Locations and GREET Inputs

Trip Origin	Trip Destination	Mode	Distance (miles)
Norway (Exporting Nation)	Elba Island, GA (Import Terminal)	Ship	4,590
Oakwood, VA (NG Field)	AGL Resources, Macon, GA (Liquefaction Facility)	Pipeline	565
Oakwood, VA (NG Field)	Alma, GA (End of Pipeline)	Pipeline	810
AGL Resources, Macon, GA (Liquefaction Facility)	Jacksonville, FL (Port)	Truck	285
Alma, GA (End of Pipeline)	Jacksonville, FL (Port)	Truck	120
Elba Island, GA (Import Terminal)	Jacksonville, FL (Port)	Truck	150
Elba Island, GA (Import Terminal)	Jacksonville, FL (Port)	Barge	125
Elba Island, GA (Import Terminal)	AGL Resources, Macon, GA (Liquefaction Facility)	Pipeline	175

6.4 East Coast Vessel Characteristics

Table 18 describes the typical port calls for vessels at the PANYNJ in 2004, while Table 19 describes the port calls in Jacksonville for the same year. The year 2004 was chosen because data from the Lloyd's database, a comprehensive directory of all vessels registered by any nations, was available for that year. It can be seen that container vessels made a majority of the calls to both ports, so container vessels were chosen as the typical vessel making the transit from PANYNJ to Jacksonville. The table also indicates the average size for container vessels coming in to the port. Table 20 shows characteristics used for a typical container vessel on the East Coast route, based on values obtained from the Lloyd's database for container vessels of approximately 37,300 DWT.

Table 18 Vessel Calls at PANYNJ showing number of calls and container capacity by vessel type

Vessel Type	Calls	Average Capacity (DWT)	% Calls
Tanker	1,337	54,587	27%
Product Tanker	1,026	41,093	21%
Crude Tanker	311	99,103	6%
Container	2,331	44,940	48%
Dry Bulk	340	36,863	7%
Ro-Ro	614	24,785	13%
Vehicle	419	17,338	9%
Gas Carrier	14	647,037	0%
Combination	53	74,807	1%
General Cargo	173	160,166	4%
All Types	*4,862*	*43,896*	*100%*

Table 19 Vessel Calls at Jacksonville showing number of calls and container capacity by vessel type

Vessel Type	Calls	Average Capacity (DWT)	% Calls
Tanker	293	43,240	20%
Product Tanker	292	43,020	20%
Crude Tanker	1	107,261	0%
Container	293	29,704	20%
Dry Bulk	226	41,511	16%
Ro-Ro	551	16,856	38%
Vehicle	380	16,058	26%
Gas Carrier	0		0%
Combination	5	58,676	0%
General Cargo	73	16,058	5%
All Types	*1,441*	*29,002*	*100%*

Table 20 TEAMS Vessel Inputs

Vessel Characteristic	Value
Vessel Type	Container
Average DWT	37,300
Rated Power (kW)	22,000
Distance (miles)	828
Rated Speed (knots)	22
Time for one-way trip (HH:MM)	40:36
Engine Efficiency (%)	45
Time Spent in Each Operating Stage as a Percentage of Total Trip Time (%)	
Idle	1.25%
Maneuvering	1.75%
Precautionary	5.00%
Slow Cruise	7.00%
Full Cruise	85.00%

6.5 East Coast Results

Our results are presented in a collection of tables and graphs. Energy use and emissions were calculated for the four stages of the fuel pathway for each scenario. These results represent total energy use and emissions for a given “trip.” For example, “Total Energy” represents the energy (in BTUs) needed to obtain, process, transport, and consume the fuel needed to transport the ship between PANYNJ and Jacksonville. The feedstock stage and fuel processing stage describe energy use and emissions occurring upstream (well-to-pump); the main and auxiliary engine operations describe emissions occurring downstream (pump-to-hull). Table 21 and Table 22 show results for each scenario. Full graphical results are presented in Appendix C, with summary graphs of selected variables presented here. Each graph shows the average of the natural gas pathways in the first column, with the bars depicting the range of the scenarios. The second and third columns are the low and high sulfur petroleum marine fuel scenarios, respectively.

Table 21 East Coast Case results for total fuel cycle energy needed for travel between the Port Authority of New York / New Jersey (PANYNJ) and the Port of Jacksonville, FL

Scenario Code	Fuel Type	Total Energy (mmBtu)	Fossil Fuels (mmBtu)	Petroleum (mmBtu)
D1	LNG	7,311	7,304	1,018
D2	LNG	7,216	7,209	909
D3	LNG	7,269	7,262	889
D9	LNG	7,203	7,196	861
D10	LNG	7,145	7,138	861
D21	LNG	7,211	7,204	860
D22	LNG	7,152	7,145	859
E1	LNG	7,256	7,249	964
E2	LNG	7,189	7,182	898
E3	LNG	7,391	7,383	1,031
E5	LNG	7,489	7,480	1,004
E6	LNG	7,423	7,415	999
E11	LNG	7,479	7,471	922
E12	LNG	7,414	7,405	920
E17	LNG	7,497	7,488	1,002
E18	LNG	7,431	7,422	998
E23	LNG	7,487	7,479	921
E24	LNG	7,421	7,413	918
EC_LS	Low-Sulfur Diesel	7,367	7,334	6,482
EC_HS	High-Sulfur Diesel	7,367	7,334	6,482

Note: Scenario Code refers to the port of origin ("D" being the PANYNJ; "E" for Jacksonville) and the fuel pathway for refueling (indicated by the number as referenced in Table 2)

Our results are presented in a collection of tables and graphs. Energy use and emissions were calculated for the four stages of the fuel pathway for each scenario. These results represent total energy use and emissions for a given "trip." For example, "Total Energy" represents the energy (in BTUs) needed to obtain, process, transport, and consume the fuel needed to transport the ship between PANYNJ and Jacksonville. The feedstock stage and fuel processing stage describe energy use and emissions occurring upstream (well-to-pump); the main and auxiliary engine operations describe emissions occurring downstream (pump-to-hull). Table 21 and Table 22 show results for each scenario. Full graphical results are presented in Appendix C, with summary graphs of selected variables presented here. Each graph shows the average of the natural gas pathways in the first column, with the bars depicting the range of the scenarios. The second and third columns are the low and high sulfur petroleum marine fuel scenarios, respectively.

Table 22 East Coast Case results for total fuel cycle pollutants emitted (in kg/trip) needed for travel between the Port Authority of New York / New Jersey (PANYNJ) and the Port of Jacksonville, FL

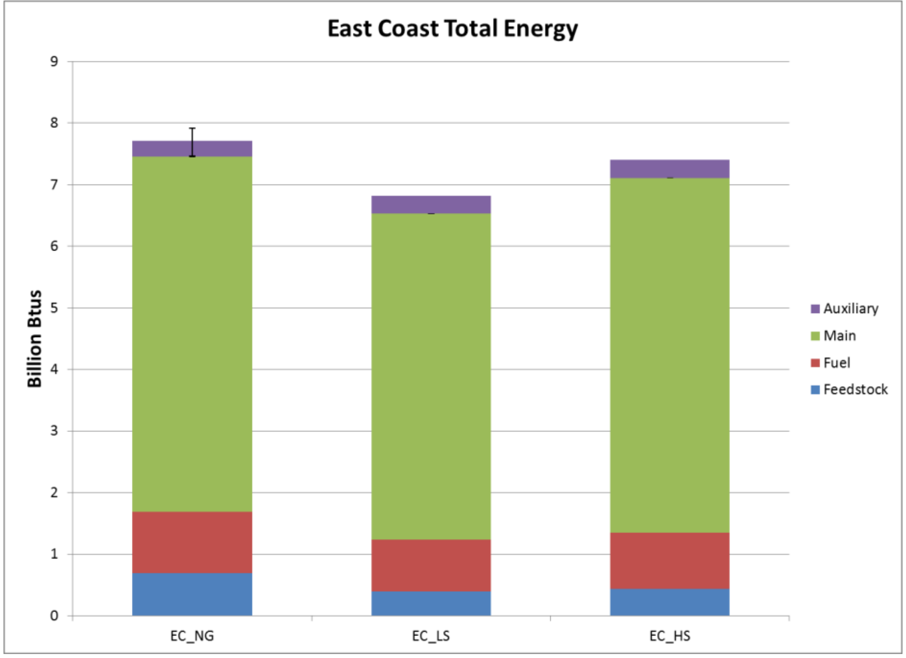
Scenario Code	Kilograms emitted per trip								
	CO_2	CH_4	N_2O	GHGs	VOC	CO	NO_x	PM_{10}	SO_x
D1	440,707	1,872	14	491,602	608	1,434	15,309	38	115
D2	432,434	1,949	14	485,227	604	1,424	15,295	35	115
D3	434,639	2,168	17	493,882	616	1,459	15,317	35	113
D9	428,428	2,492	16	495,406	607	1,438	15,171	29	95
D10	427,606	1,816	16	477,676	606	1,435	15,165	29	93
D21	427,834	2,843	16	503,590	607	1,436	15,166	29	95
D22	427,026	2,159	16	485,654	606	1,434	15,160	29	93
E1	436,148	1,888	14	487,443	606	1,427	15,296	37	115
E2	430,668	1,911	14	482,491	604	1,420	15,277	35	114
E3	445,206	2,071	16	501,660	616	1,459	15,364	38	118
E5	447,655	2,871	20	525,353	628	1,504	15,315	33	101
E6	446,365	2,186	20	506,886	626	1,500	15,305	33	99
E11	444,694	3,110	22	529,126	635	1,527	15,331	31	101
E12	443,487	2,419	22	510,574	634	1,523	15,321	31	99
E17	447,050	3,229	20	533,694	628	1,503	15,309	33	101
E18	445,774	2,535	20	515,017	626	1,499	15,300	32	99
E23	444,082	3,471	22	537,551	635	1,525	15,325	31	101
E24	442,890	2,771	22	518,787	633	1,521	15,315	31	98
EC_LS	573,748	698	14	595,317	611	2,664	15,223	475	434
EC_HS	613,384	698	14	634,953	611	2,664	15,223	475	1,643

Note: GHGs represent the GWP_{100} weighted combination of CH_4, CO_2, and N_2O

Note: Scenario Code refers to the port of origin (“D” being the PANYNJ; “E” for Jacksonville) and the fuel pathway for refueling (indicated by the number as referenced in Table 2)

Figure 35 shows the energy needed for the whole fuel. The natural gas scenarios needed more energy than the diesel scenarios, likely due to the energy needed for liquefaction and transport of the natural gas.

Figure 35 East Coast Case results for total energy needed for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively



The next set of graphs show the GHG results for these routes. The LNG emissions of CO_2 are comparable to those of the diesel scenarios, as shown in Figure 36. Although the emissions of CH_4 (Figure 37) and N_2O (Figure 38) are higher than the diesel cases, the overall volume of CO_2 makes the GHG emissions of LNG less than those of both the high sulfur and the low sulfur petroleum fuels. For both CO_2 and N_2O most of the emissions come from the downstream stages, so changes to the upstream pathway will not greatly affect the overall emissions. However, for CH_4 the upstream processes do have an effect, so those are looked at in more detail in Figure 40. There it can be seen that natural gas obtained from shale has higher methane emissions than that from conventional gas. In addition, shorter storage times decrease the emissions. Components that affect the amount of methane released are the amount of methane slip in the engine and the amount of leakage that occurs during processing, including during pipeline transport and the switching of modes. As discussed in the introduction, the values used here are the best available, consistent with recent evidence supporting higher leakage rates (Brandt et al., 2014). These are factors that can be considered when deciding on the upstream pathway that ultimately will be utilized.

Figure 36 East Coast Case results for CO_2 emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

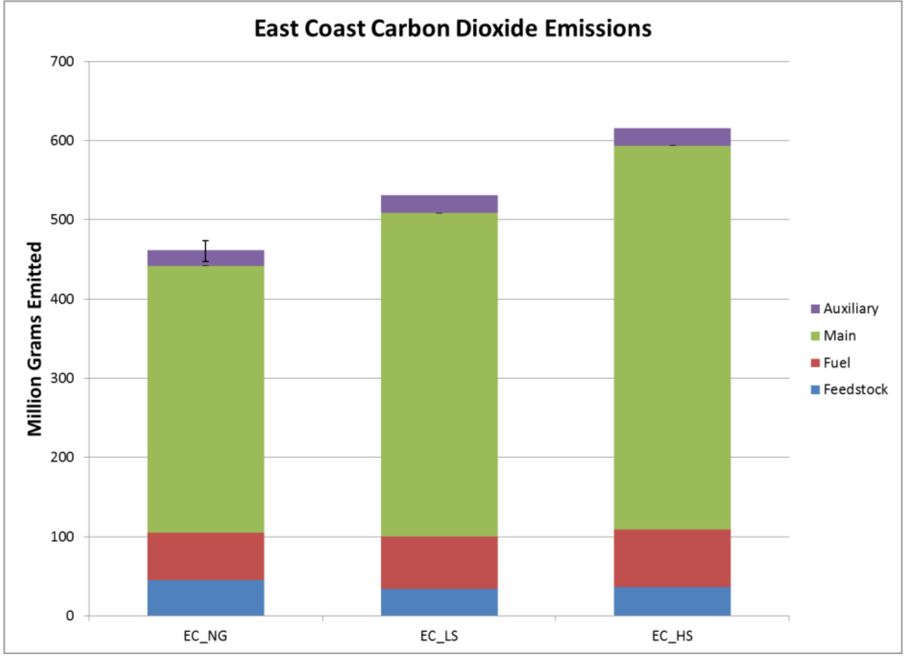


Figure 37 East Coast Case results for CH_4 emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

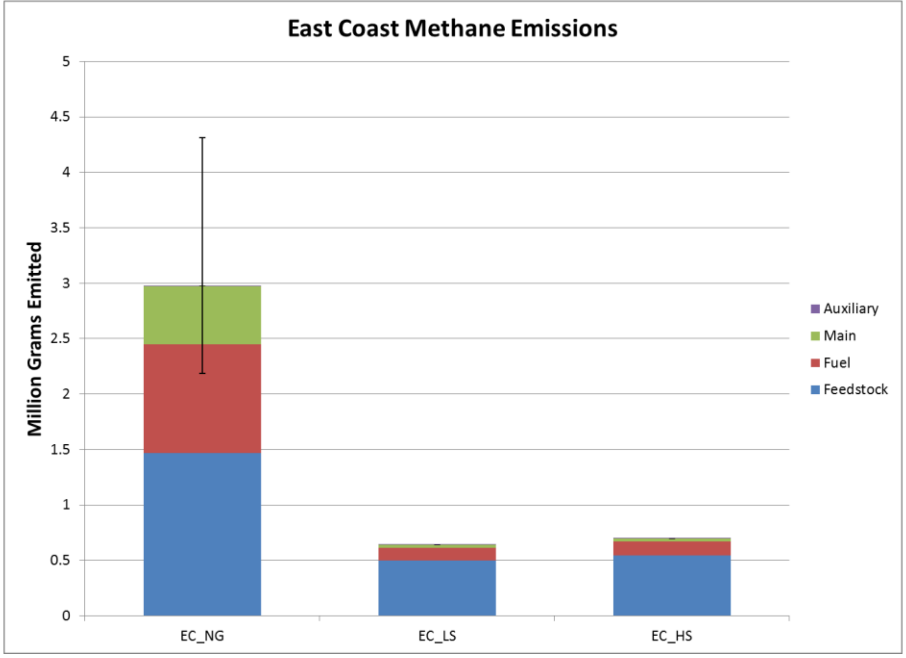


Figure 38 East Coast Case results for N_2O emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

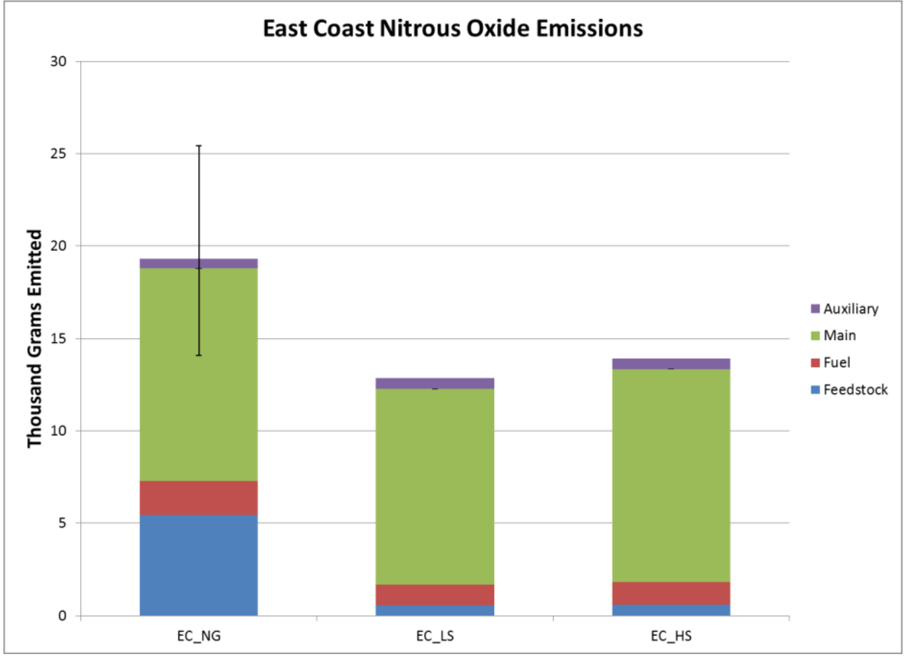


Figure 39 East Coast Case results for GHG emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

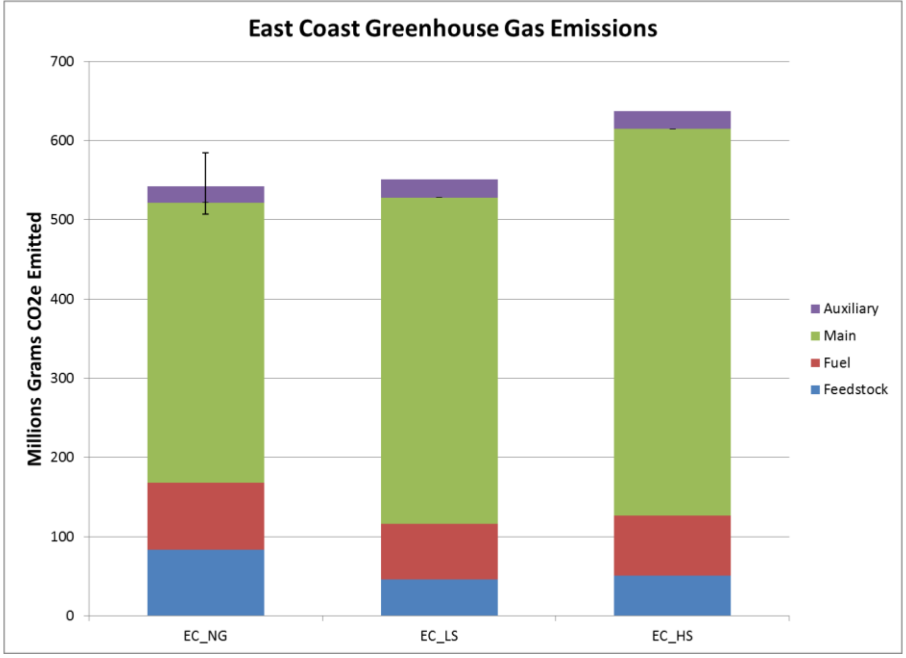
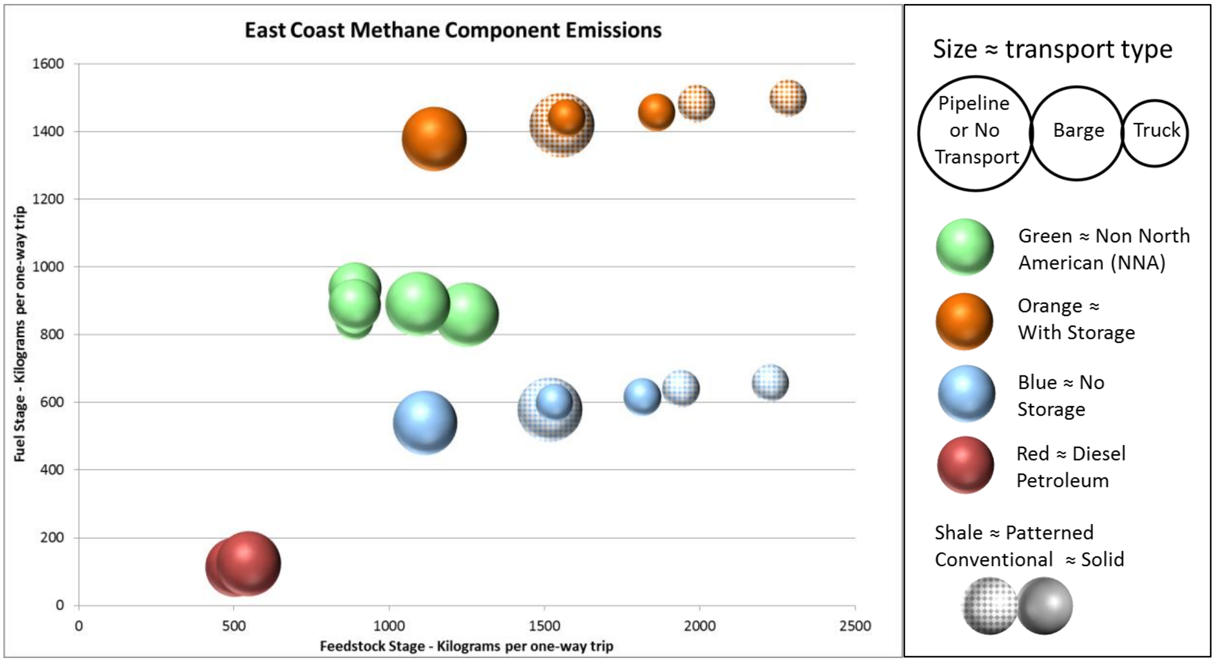


Figure 40 Breakdown of East Coast Case results for CH_4 emissions for trip from the Port of New York / New Jersey (PANYNJ) to the Port of Jacksonville showing how various pathway decisions affect upstream emissions



Finally, three criteria pollutants are examined. Most of the NO_x emissions come from the operations phases of the vessel, and the NG scenarios produce emissions approximately equivalent to the high sulfur scenario and slightly higher than the low sulfur scenario, as shown in Figure 30. However, the NG scenarios produce significantly less PM_{10} (shown in Figure 31) and SO_x (shown in Figure 32) than the diesel scenarios.

Figure 41 East Coast Case results for NO_x emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

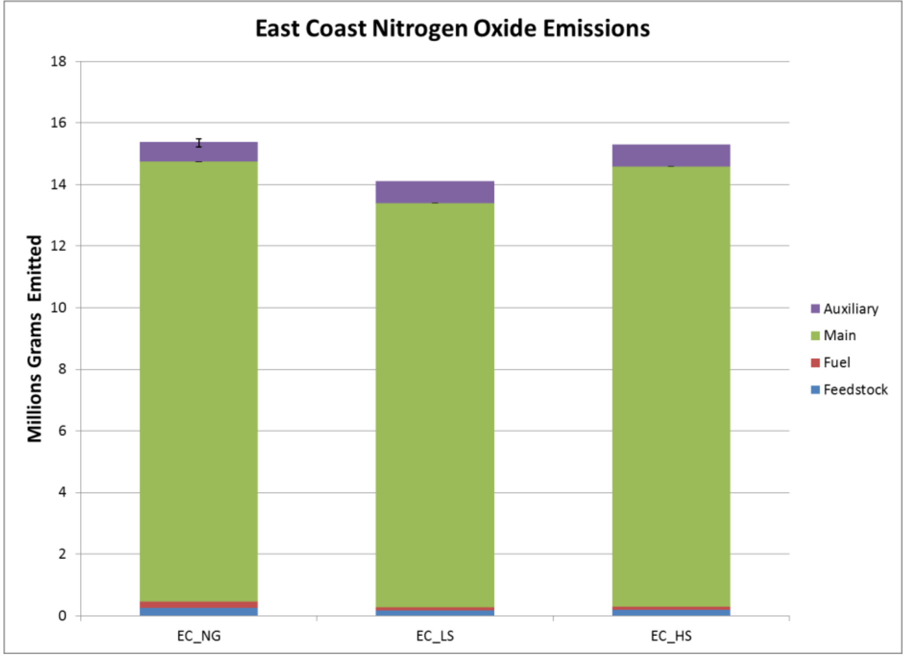


Figure 42 East Coast Case results for PM_{10} emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively

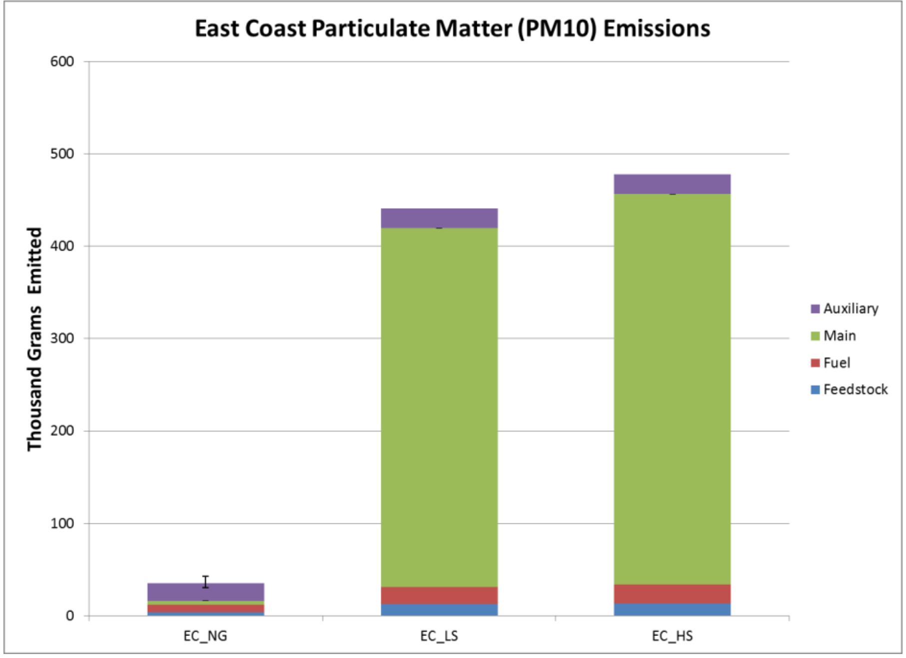
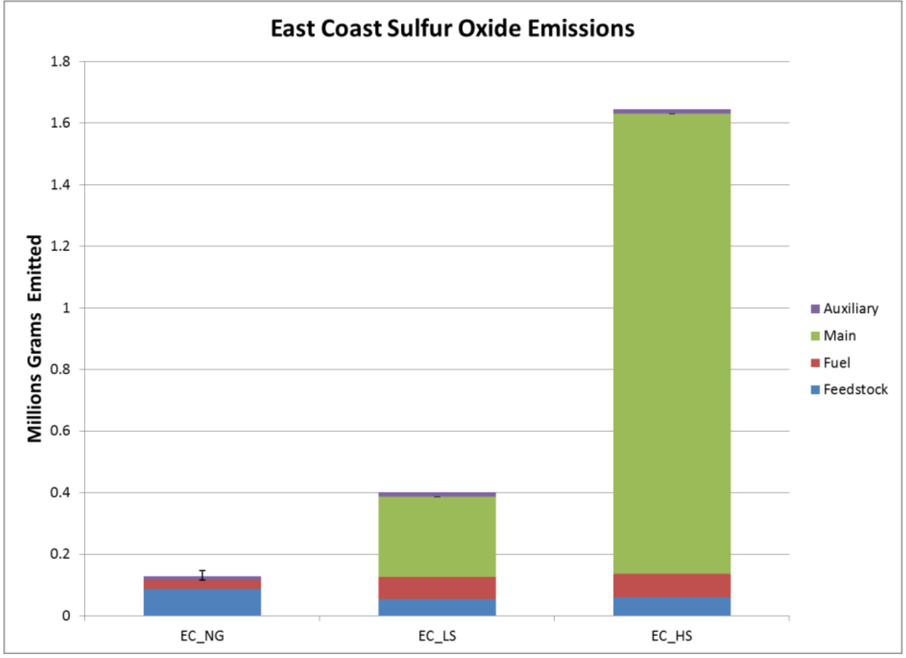


Figure 43 East Coast Case results for SO_x emissions for trip from the Port Authority of New York / New Jersey (PANYNJ) to the Port of Jacksonville, FL; first column is the average of all liquid natural gas scenarios with bars showing the min/max of these scenarios; second and third columns are low-sulfur and high-sulfur diesel scenarios, respectively



6.6 East Coast Case Discussion

Results show that the upstream processes did not significantly affect the overall results for energy needed or for any emissions other than GHGs. Either most of the energy or emissions came in the downstream processes (Total Energy and NO_x) or the variation did not affect the results relative to the diesel scenarios (SO_x and PM_{10}) or both (N_2O). It was only for CO_2 and CH_4 (and thus GHG overall) that the upstream processes contributed significantly to the range of emissions. For these pollutants, scenarios that used shale gas and those that had storage all had higher emissions than those that didn't. Shale gas emissions factors are higher due to venting during the recovery process, as shown in Table 4. Pathways with more days storage have higher emissions due to a boil-off rate of 0.1% per day, which is the GREET 2013 default.

When comparing energy needed and emissions produced using natural gas or traditional diesel fuel, results were again mixed. The total energy needed to make the trip is higher in the natural gas scenarios, as is the amount of CH_4, N_2O, and NO_x produced. In the diesel scenario more CO_2, PM10, and SOx are produced. Additionally, when taking into account the global warming potential of CH_4, N_2O, and CO_2, diesel is found to produce more overall GHG emissions (as measured in CO_2 equivalent units) using either low-sulfur distillate (depending upon pathway) or high-sulfur residual fuel (across all natural gas pathways). Switching to natural gas will likely achieve MARPOL standards.

7 Overall Results and Discussion

7.1 Summary Comparison of Scenarios

Two observations relate to the vessel and route (operational phase). The first observation should be stated for completeness – the farther a shipping vessel goes, the more fuel is needs to get it there and the longer the engines need to run, so resulting energy demand and emissions will be higher. Second, vessel operations are important – more efficient engines and engines that technologically control for pollutant formation produced fewer emissions.

With regard to the fuel pathways, the pathway's effect on total emissions depended on the pollutant in question. Methane emissions for natural gas fuel are highly affected by the way the natural gas is obtained, the amount of time (e.g., distance) in the natural gas pipeline, and the amount of time in storage. Using conventional wells and minimizing pipeline distance and storage time would both reduce methane emissions. For the other pollutants analyzed, the upstream processes did not affect the overall results. Either most of the energy or emissions came in the downstream processes (Total Energy and NO_x) or the variation did not affect the results relative to the diesel scenarios (SO_x and PM_{10}) or both (N_2O).

When comparing emissions produced using natural gas or traditional diesel fuel, results were mixed as to which would produce the fewest emissions. The total energy needed to make the trip is higher in the natural gas scenarios, as is the amount of CH_4, N_2O, and NO_x produced. In the all-diesel scenarios (both diesel main and auxiliary engines) more CO_2, PM10, and SOx are produced. Additionally, when taking into account the global warming potential of CH_4, N_2O, and CO_2, LNG fuel is found in coastal scenarios (both West Coast and East Coast) to produce less overall GHG emissions (as measured in CO_2 equivalent units) than diesel fuel scenarios using either low-sulfur distillate (depending upon pathway) or high-sulfur residual fuel. Diesel in inland river scenarios results in less overall GHG emissions (as measured in CO_2 equivalent units). Diesel in the West Coast scenario results in more overall GHG emissions (as measured in CO_2 equivalent units) under either low-sulfur distillate (depending on pathway) or high-sulfur residual fuels (across all natural gas pathways). Diesel in the East Coast scenario also results in more overall GHG emissions (as measured in CO_2 equivalent units) under either low-sulfur distillate (depending on pathway) or high-sulfur residual fuels (across all natural gas pathways). While this analysis does not include an assessment of impacts resulting from each of those pollutants, one can consider the fact that the IMO deemed NO_x and SO_x both important enough pollutants to regulate.

This is an important consideration. Natural gas is considered by many to be a win-win-win marine fuel: i) economically attractive; ii) low-emitting for key air quality pollutants; and iii) lower GHGs (primarily lower CO_2). However, natural gas may achieve some goals better than others. Other studies have found that switching to natural gas does not improve GHG emissions, especially considering methane leakage impacts on global warming potential (Brynolf, Magnusson, Fridell, & Andersson, 2013; Lowell et al., 2013; Meyer et al., 2011). This study did find a small but positive GHG benefit along with economic and local/regional air quality benefits,

These results support conclusions made by some previous studies. Bengtsson, Andersson, and Fridell (2011) concluded that natural gas did reduce the amount of GHGs emitted. Their results are consistent with lower emissions factors and leakage rates that have since been updated (Burnham et al., 2013). A later work (S. K. Bengtsson, Fridell, & Andersson, 2014), also found that LNG has a slightly better GHG potential than diesel fuel.

This study's GHG results appear consistent with emerging research studying natural gas impacts for other types of transportation. In an analysis of cars in Switzerland, researchers found that natural gas pathways fell within the range of other fuel sources, including diesel, gasoline, and biogas (Yazdanie, Noembrini, Dossetto, & Boulouchos, 2014). Future study could continue to update the state of understanding on fuel cycle methane leakage, and perform a full uncertainty analysis to determine the impact of leakage assumptions.

7.2 Recommendations for Future Study

This work provides new knowledge about the life-cycle emissions of natural gas compared to traditional petroleum-based marine fuels. Study findings also help to identify important related or follow-on research that can be recommended.

This study motivates further detailed analysis of the relative cost-effectiveness of natural gas to achieve emissions reductions, air quality compliance, or energy savings to operators. A future study could evaluate these and update comparisons of natural gas alternatives with exhaust gas abatement costs in a fleet modernization and/or repowering context.

Given the importance of upstream leakage and emissions, future study could evaluate ways to reduce or control methane releases. Such a study could adopt and infrastructure planning context to evaluate the cost-effectiveness and GHG-reductions of additional liquefaction plants, and improved mitigation of pipeline fugitive emissions.

As discussed in Section 7.1, a quantitative uncertainty analysis could be performed that allows for the emerging understanding of higher methane leakage rates throughout the fuel cycle to be rigorously evaluated. Such as study could help identify the relative merits of downstream innovation of engine designs that minimize methane slip and upstream practices and technologies that reduce methane losses.

Lastly, this work suggests that insight for ship operators and technology providers could be derived from expanding case studies to include international shipping centers, and additional centers of natural gas supply and demand (e.g., Europe). Such a study could inform natural gas exports to ensure that potential increases to GHG emissions from non-North American infrastructure and operations are adequately understood and mitigated.

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9 Appendix A West Coast Results

For each of the variables analyzed this report will be organized in the following manner. First there is a stacked bar chart showing how each of the four components (feedstock, fuel, main, and auxiliary) contribute to the overall emissions. Following that is a bubble chart showing how the variables that go into the feedstock and natural gas phases for natural gas affect the emissions. For the sake of space, only the emissions from the Hawaii route are shown, but examining the tables will show that the Shanghai route emissions follow the same patterns.

Figure 44 West Coast Case results for total energy use for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

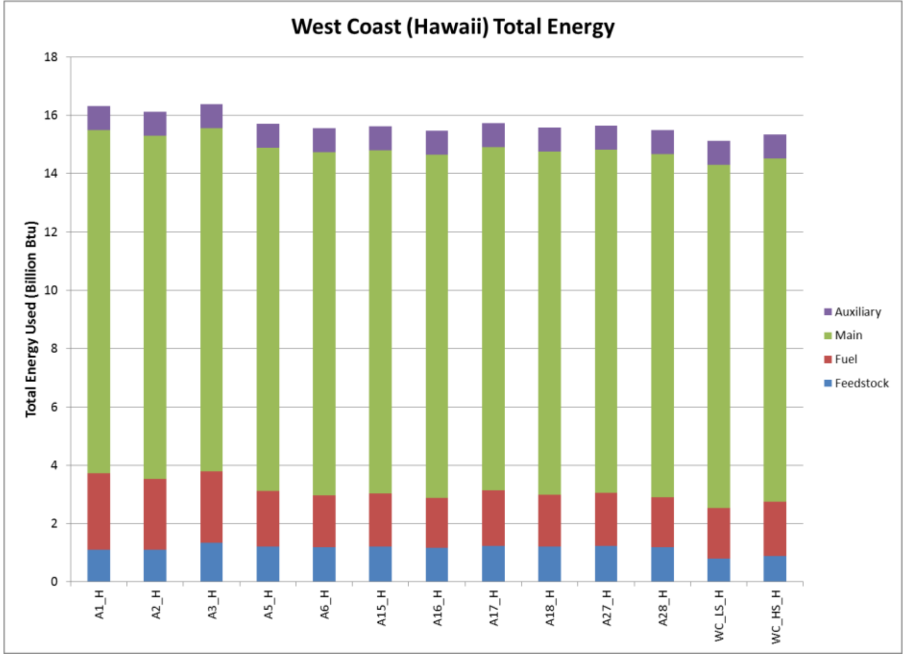


Figure 45 Breakdown of West Coast Case results for total energy for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

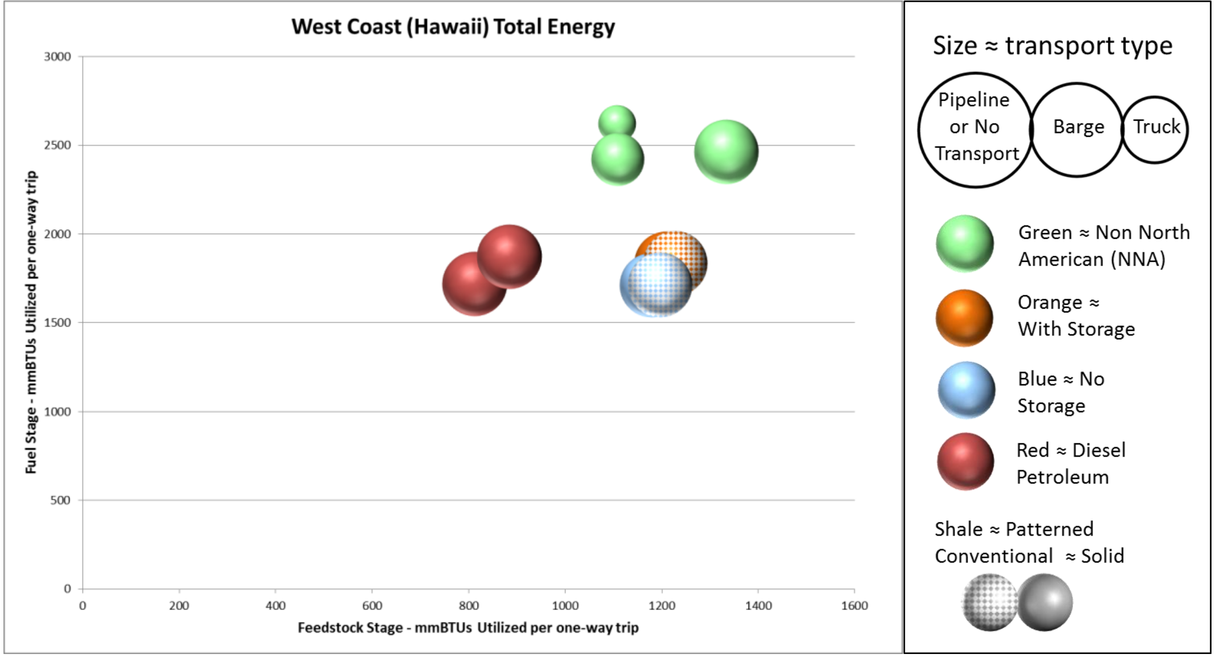


Figure 46 West Coast Case results for fossil fuel energy use for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

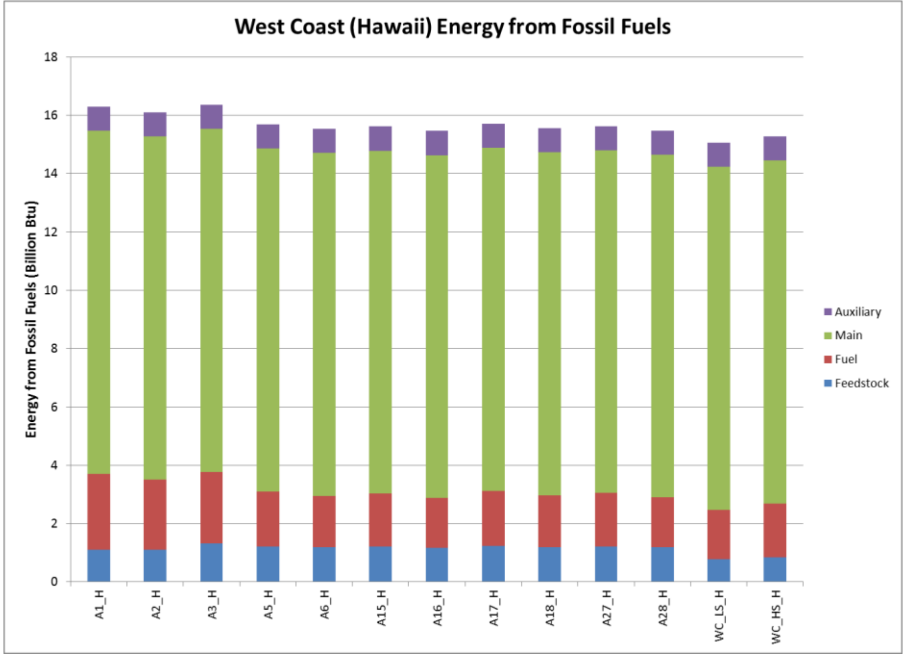


Figure 47 Breakdown of West Coast Case results for fossil fuel energy for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

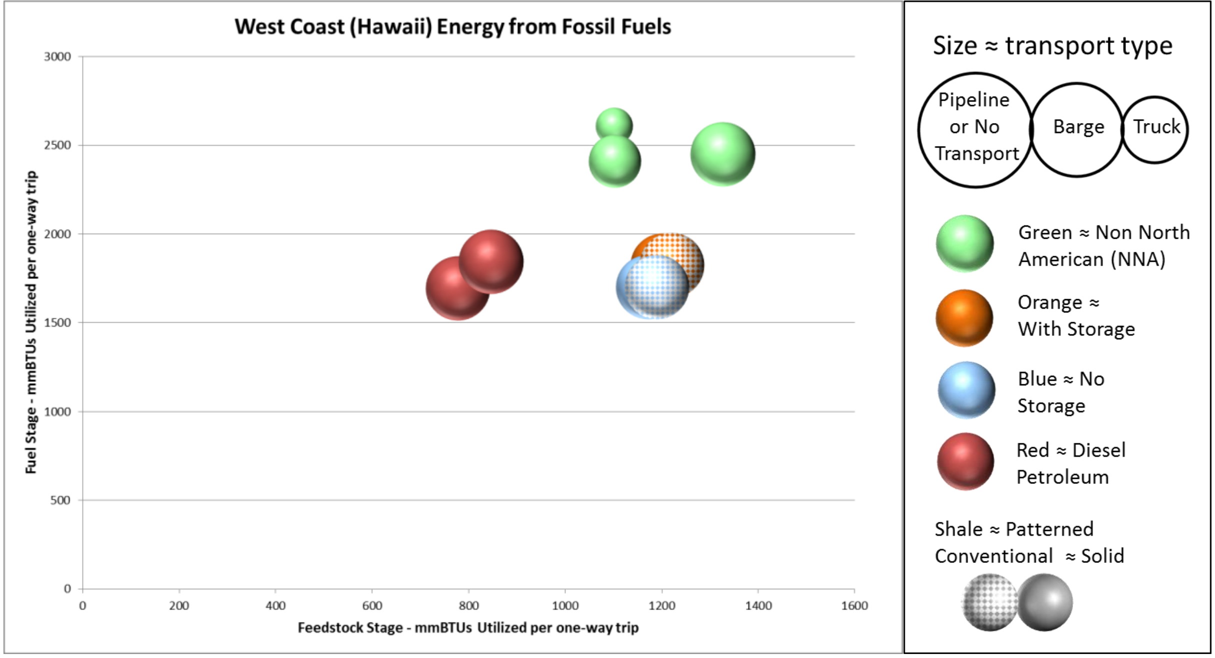


Figure 48 West Coast Case results for petroleum energy use for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

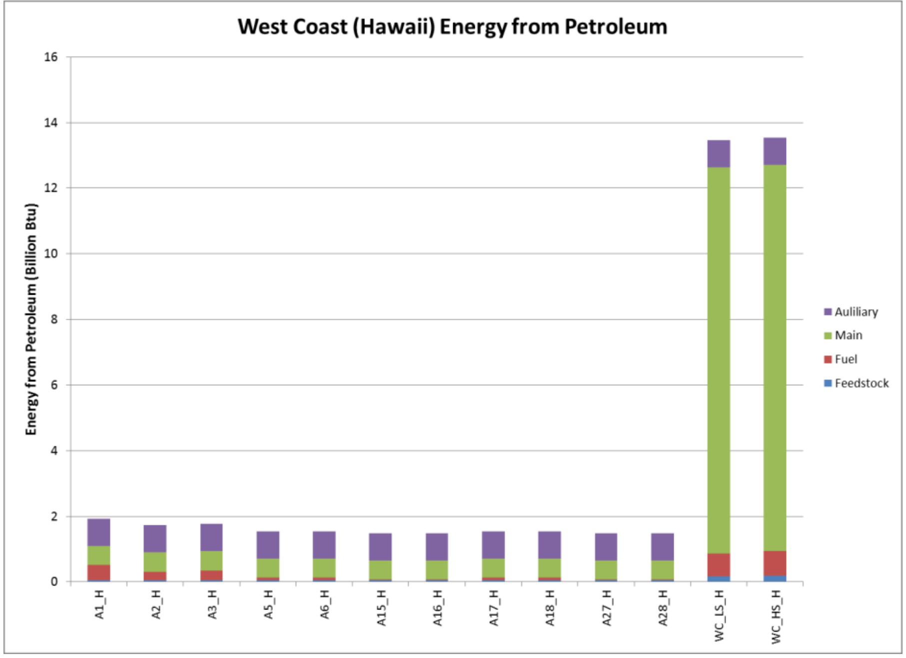


Figure 49 Breakdown of West Coast Case results for petroleum energy for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

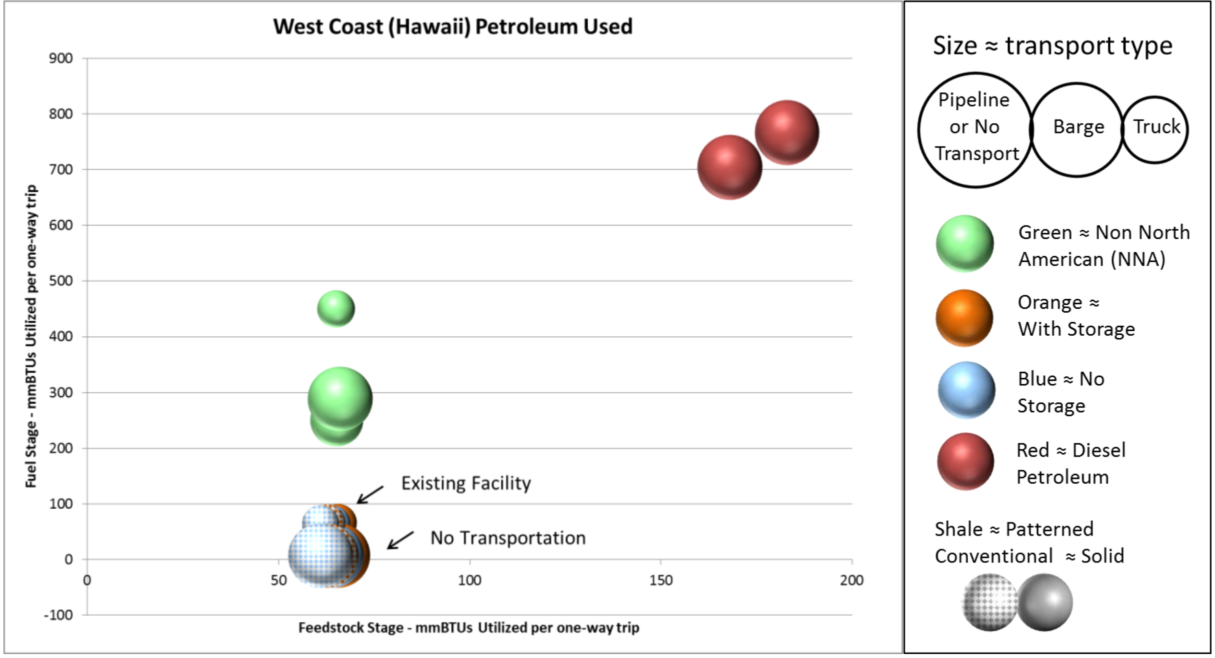


Figure 50 West Coast Case results for CO_2 emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

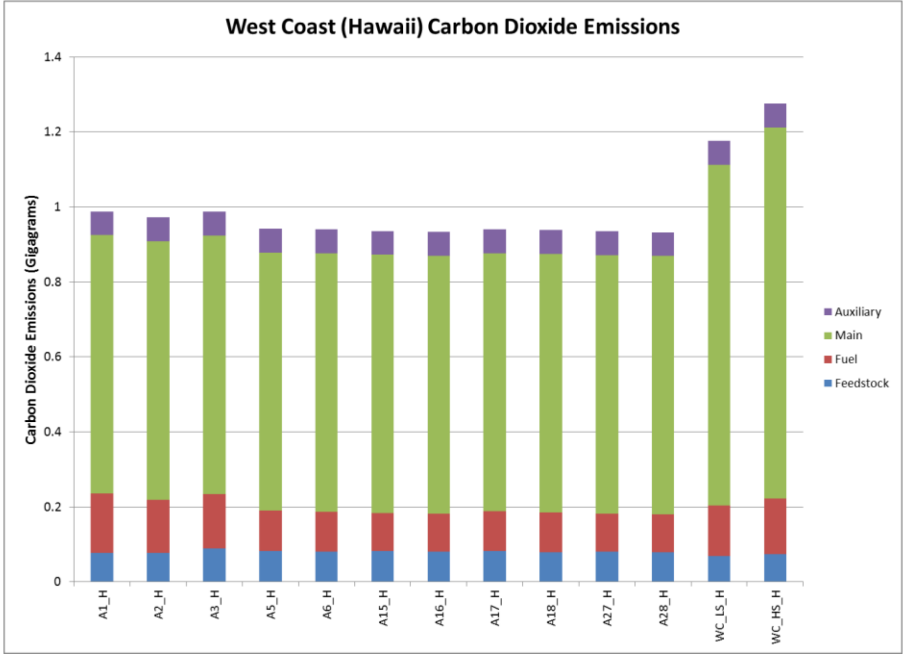


Figure 51 Breakdown of West Coast Case results for CO_2 emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

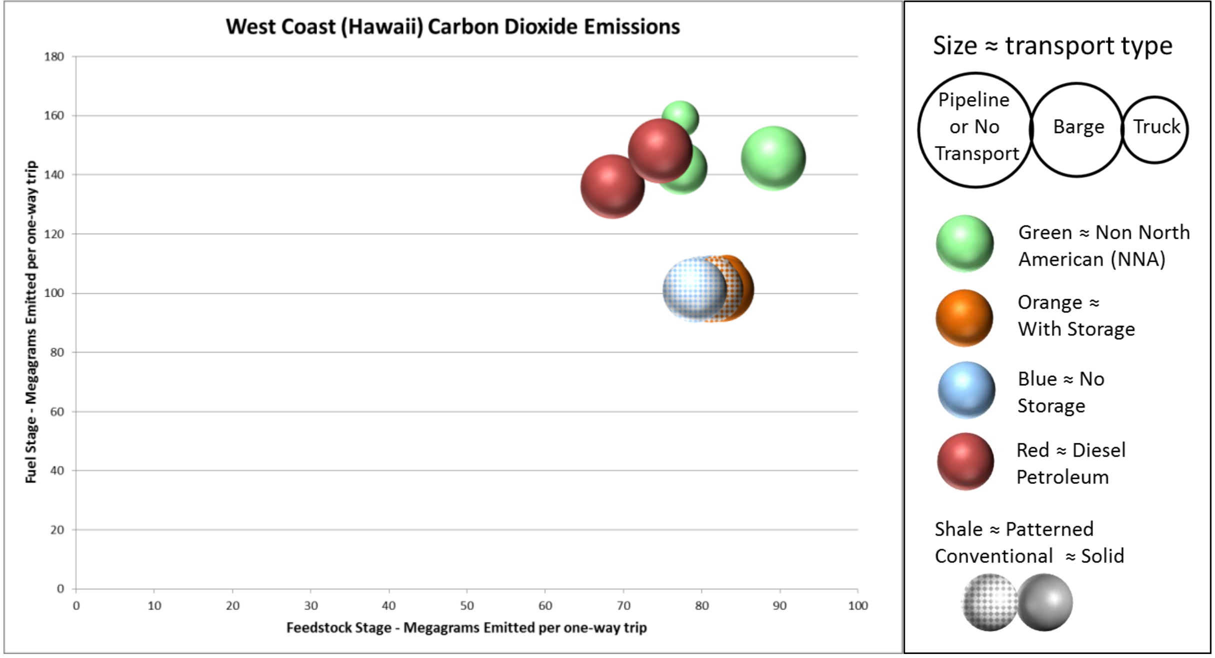


Figure 52 West Coast Case results for CH_4 emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

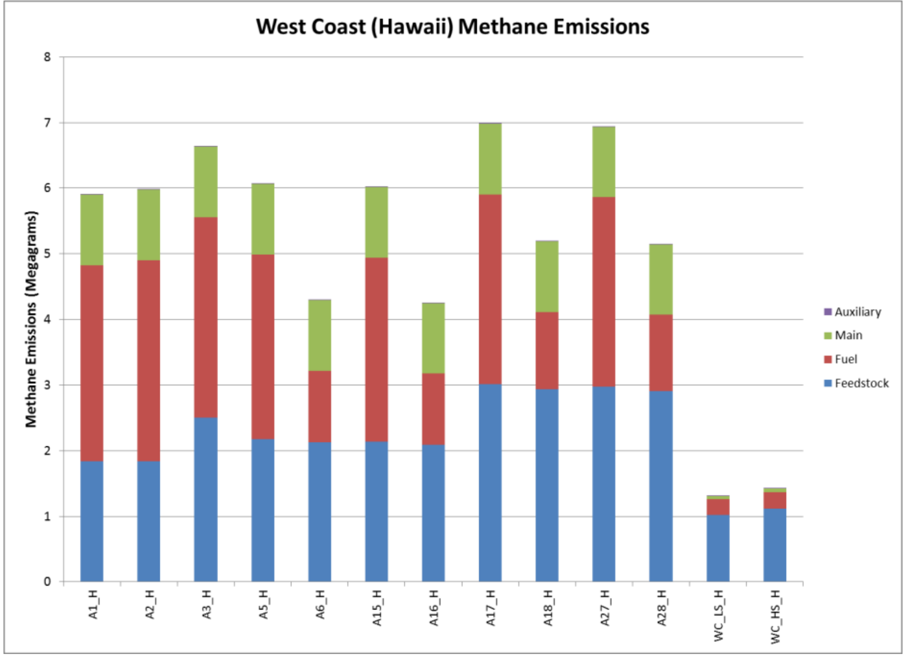


Figure 53 Breakdown of West Coast Case results for CH_4 emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

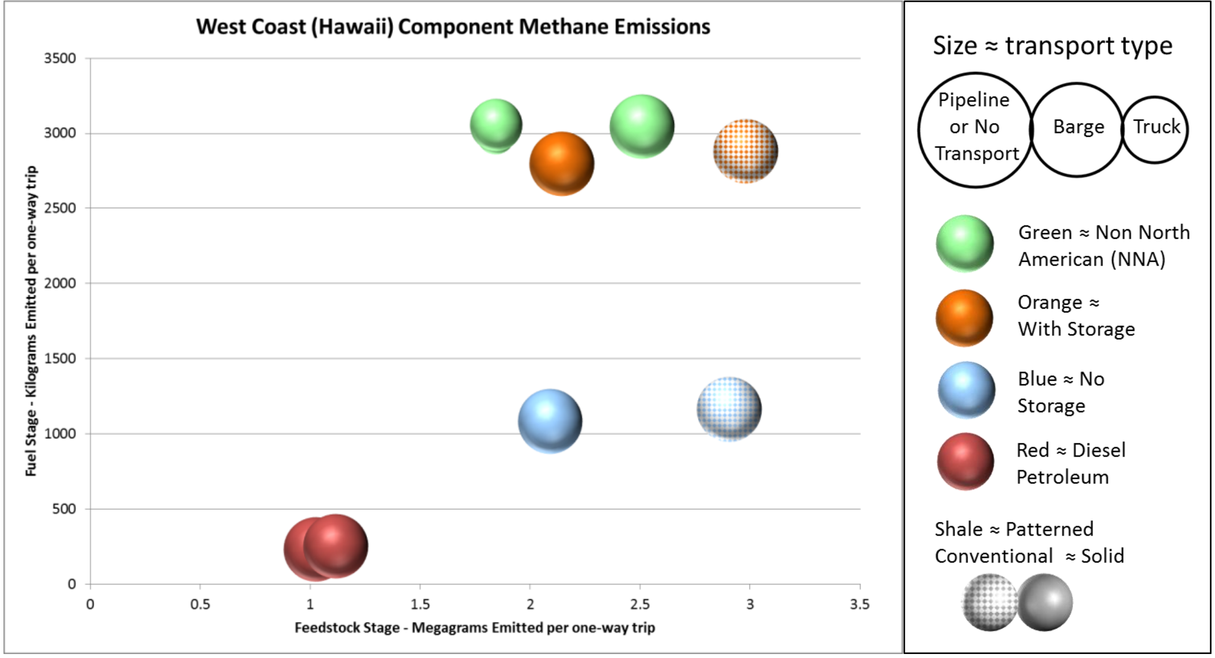


Figure 54 West Coast Case results for N_2O emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

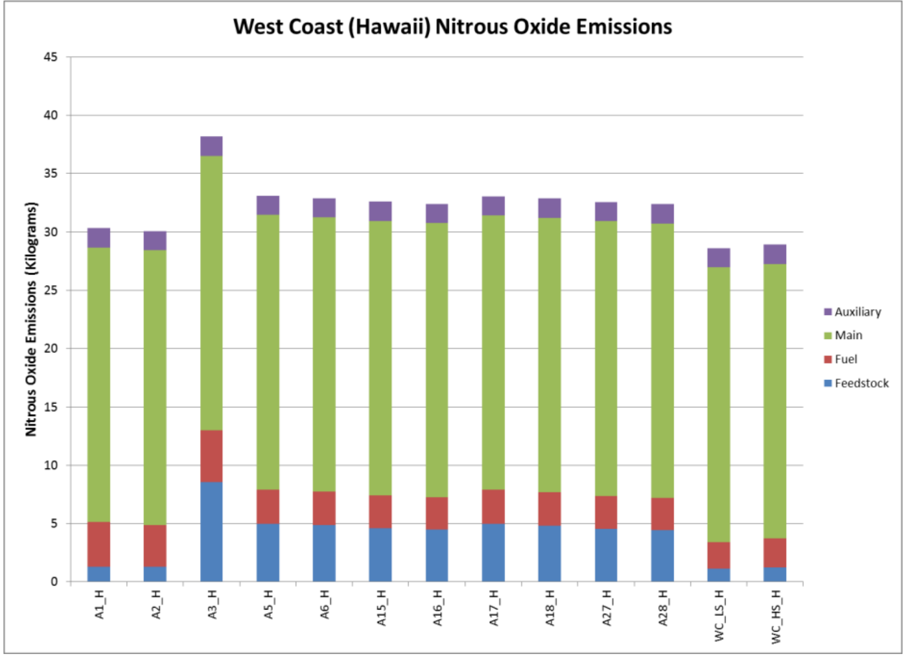


Figure 55 Breakdown of West Coast Case results for N_2O emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

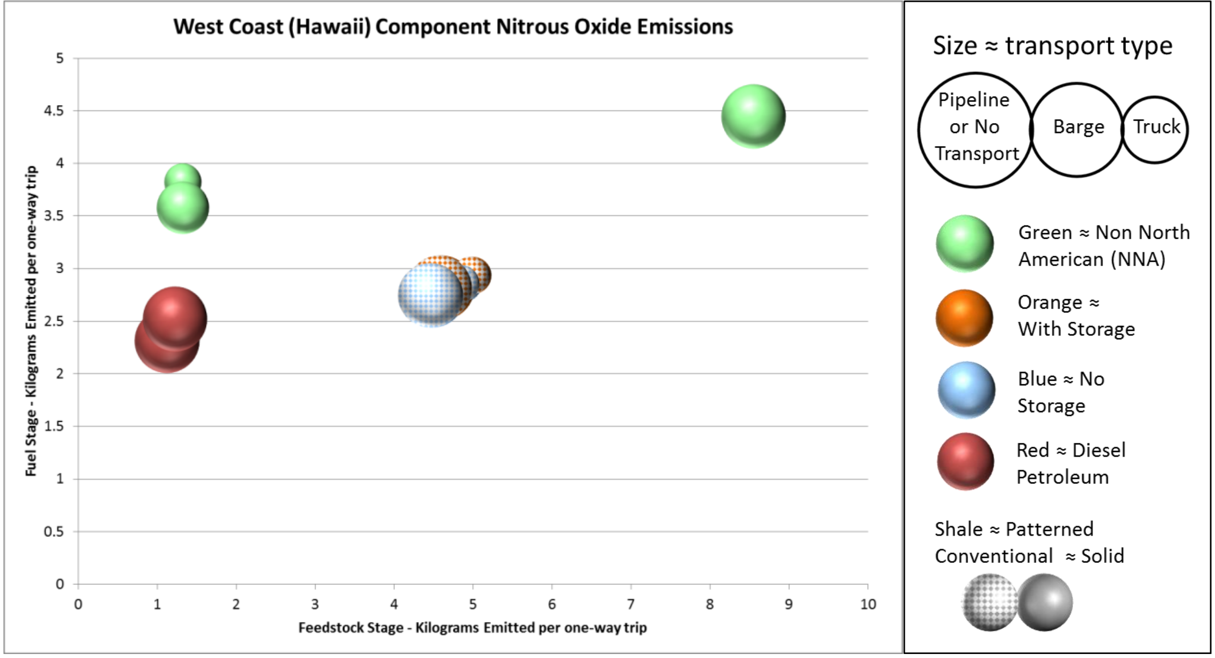


Figure 56 West Coast Case results for GHG emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

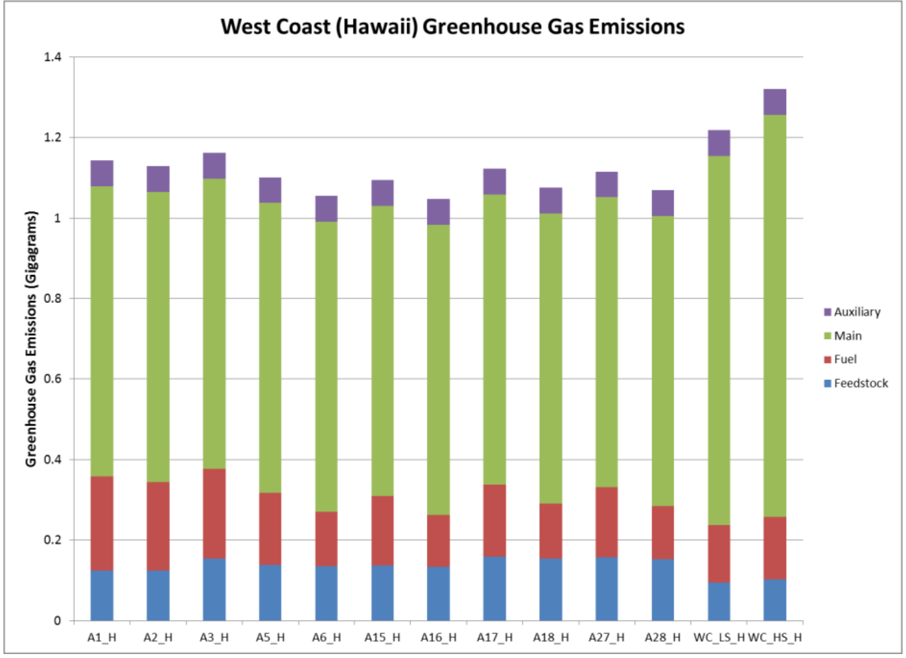


Figure 57 Breakdown of West Coast Case results for GHG emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

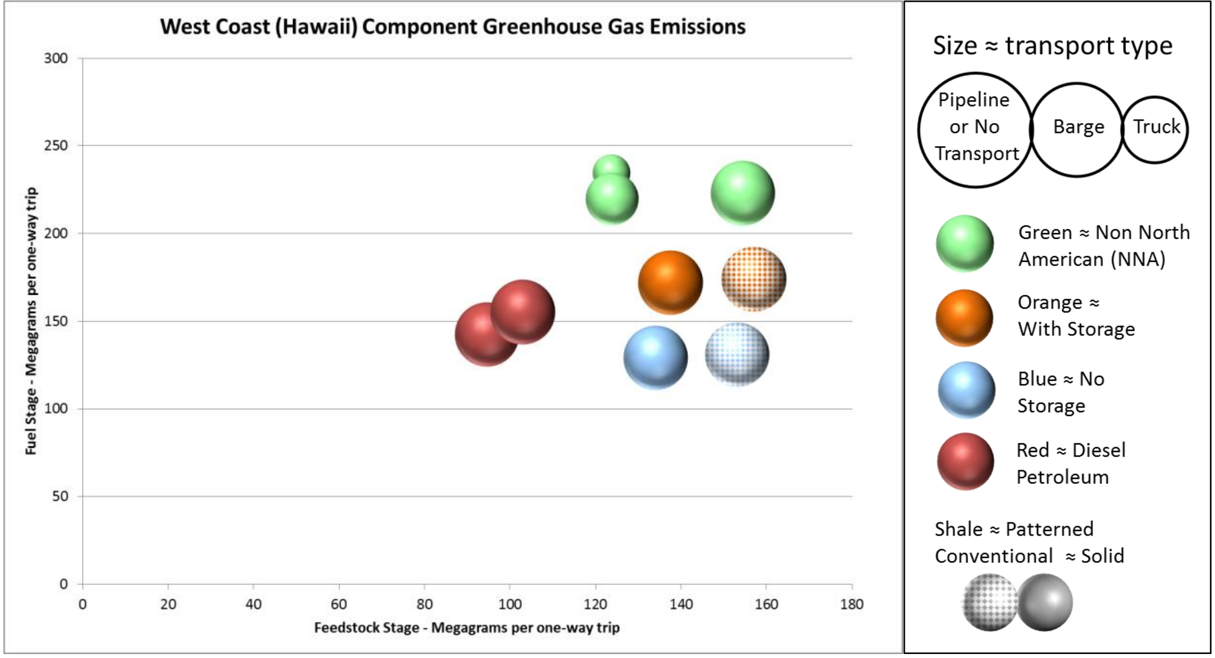


Figure 58 West Coast Case results for VOC emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

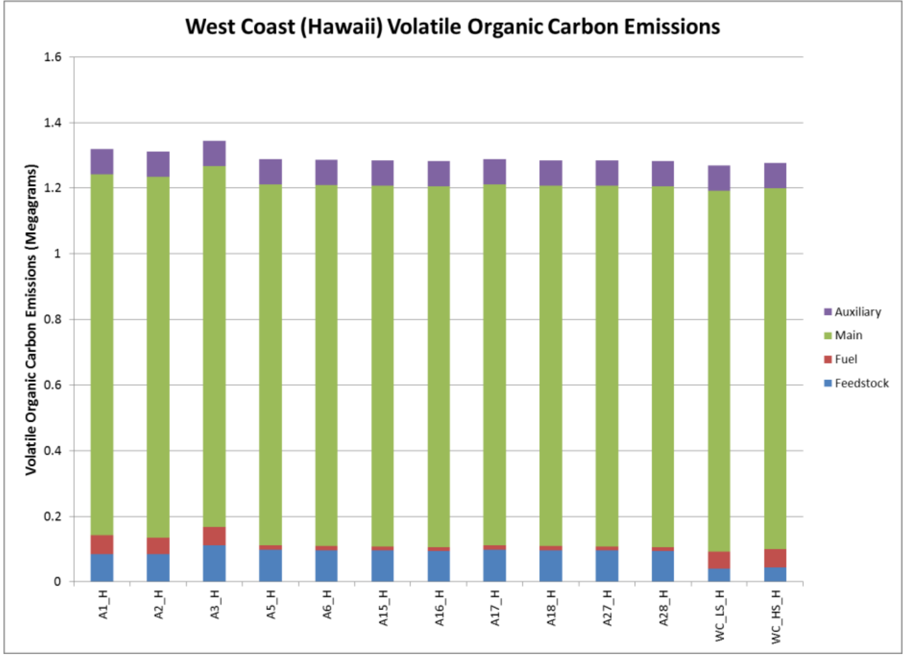


Figure 59 Breakdown of West Coast Case results for VOC emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

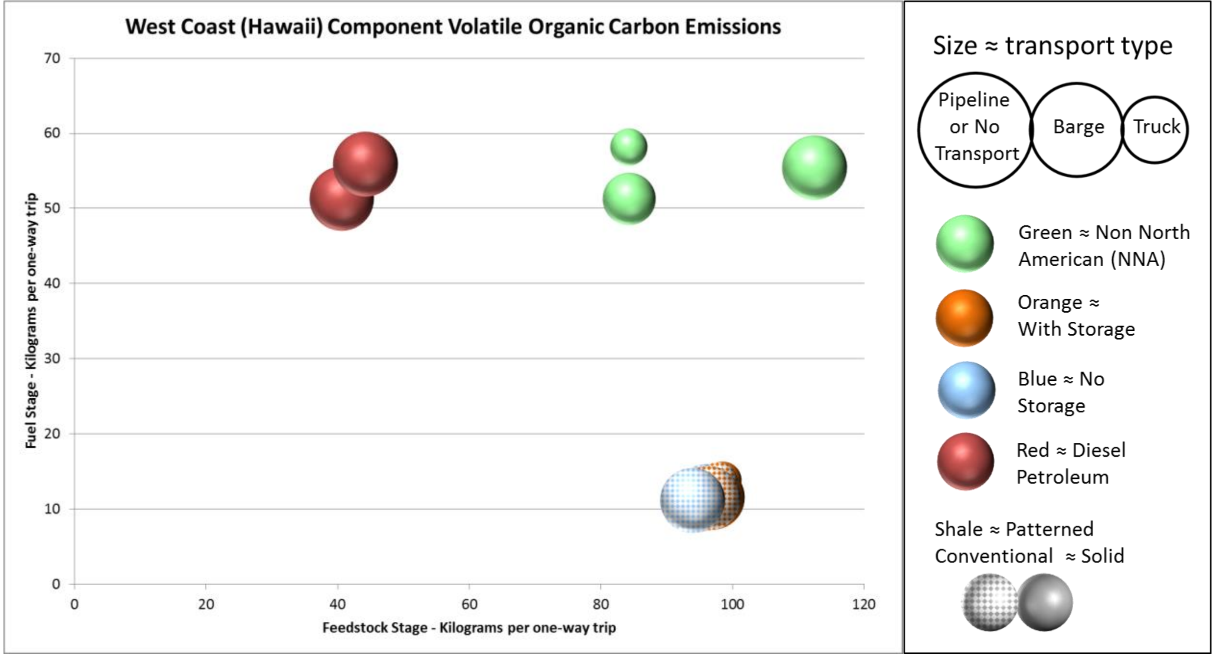


Figure 60 West Coast Case results for CO emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

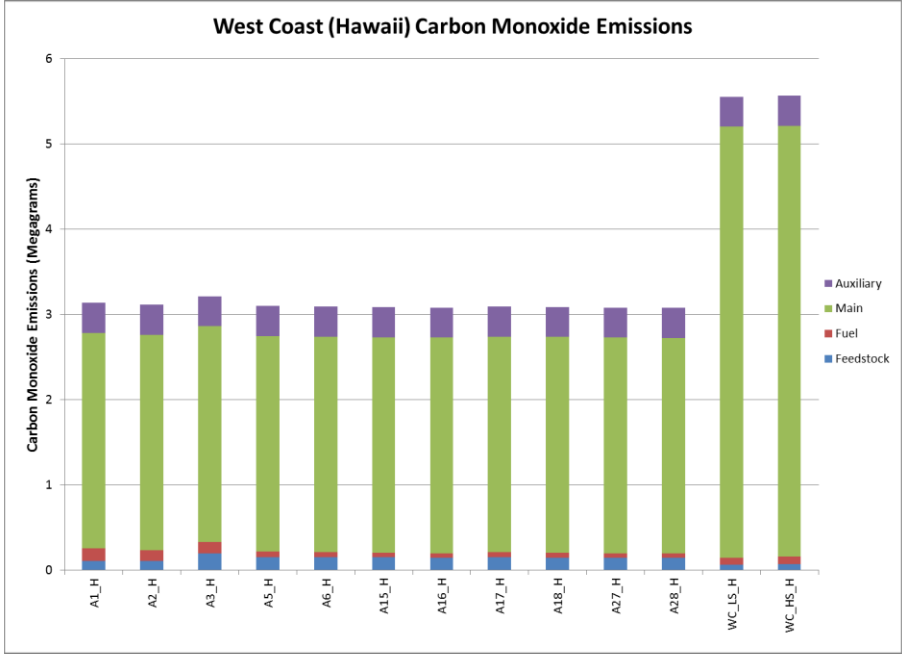


Figure 61 Breakdown of West Coast Case results for CO emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

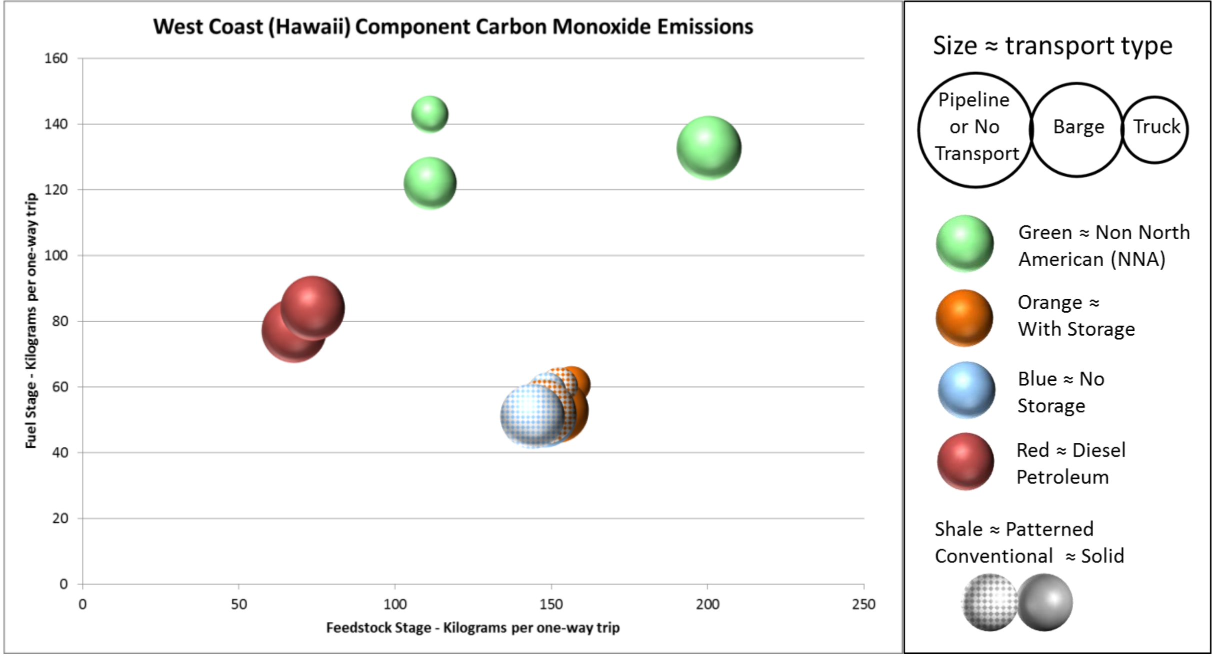


Figure 62 West Coast Case results for NO$_x$ emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

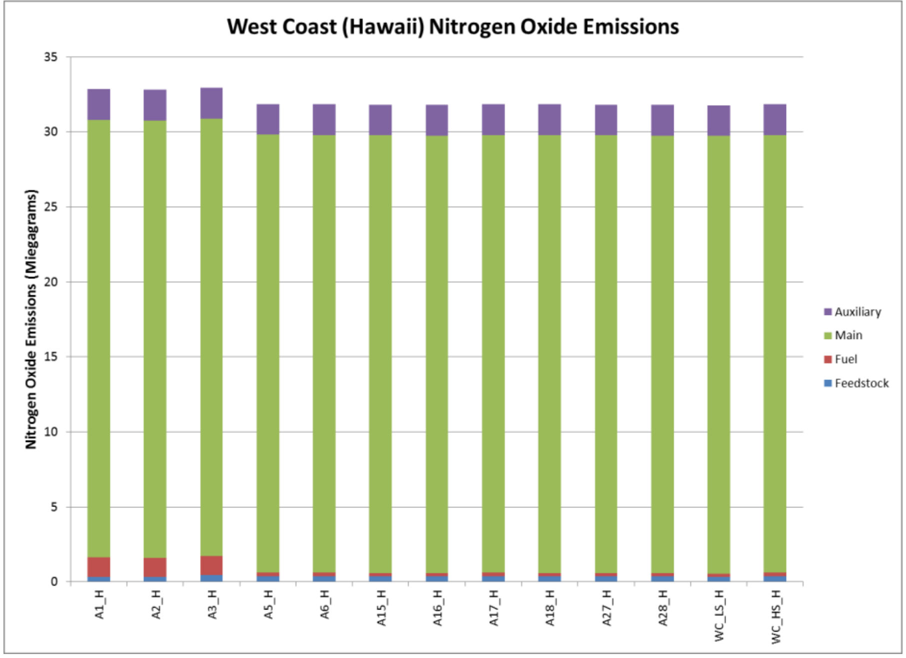


Figure 63 Breakdown of West Coast Case results for NO_x emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

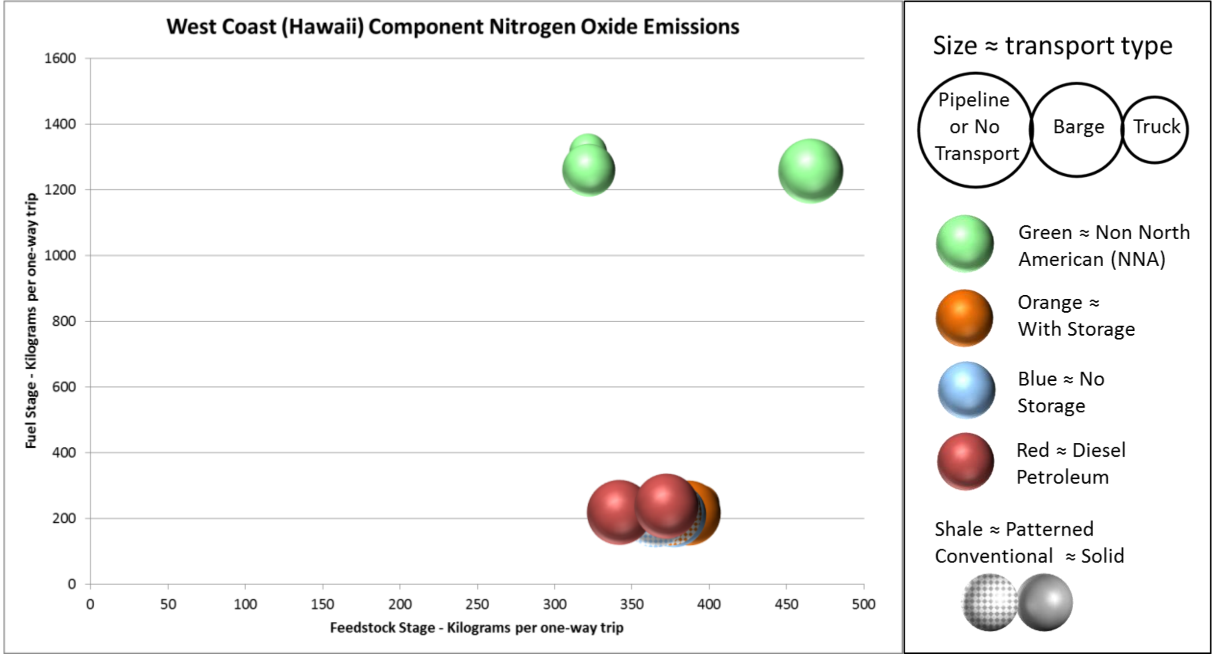


Figure 64 West Coast Case results for PM_{10} emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

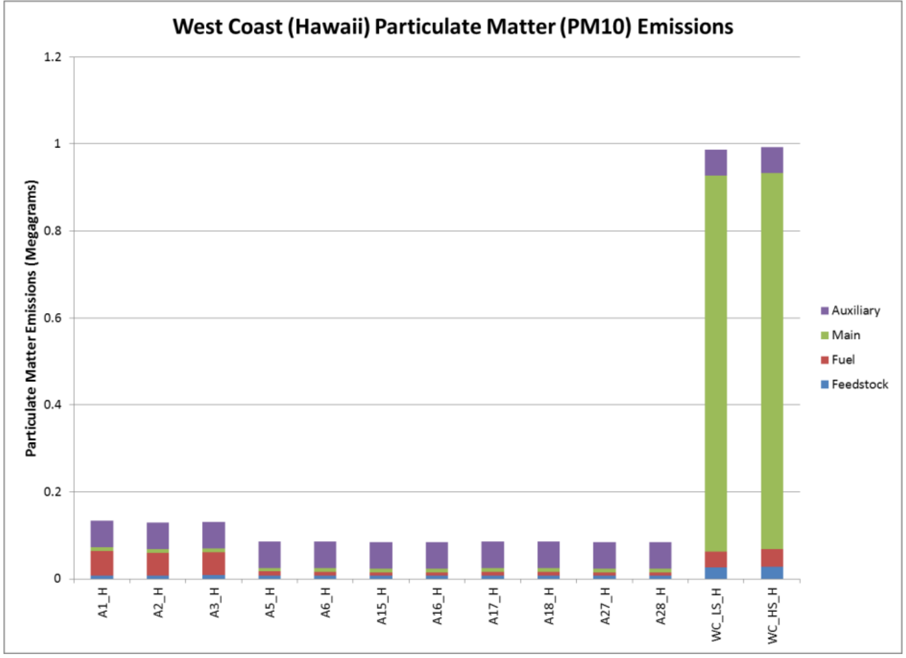


Figure 65 Breakdown of West Coast Case results for PM_{10} emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions

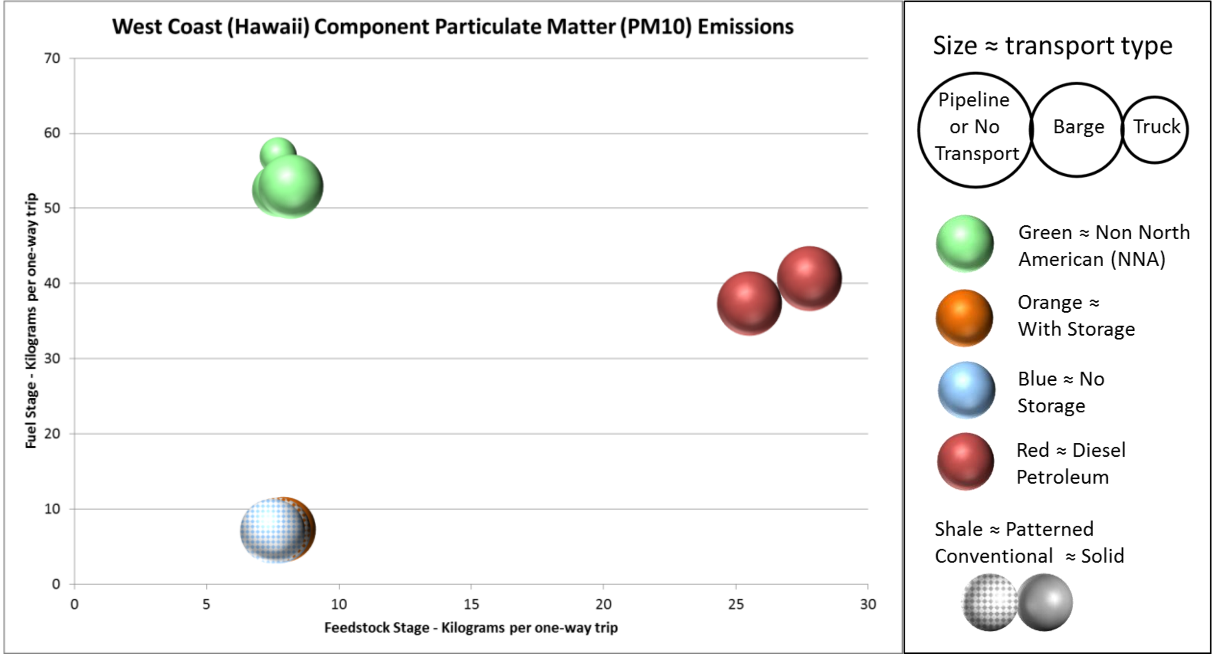


Figure 66 West Coast Case results for SO_x emissions for trip from Port of LA/LB to Hawaii (H); each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

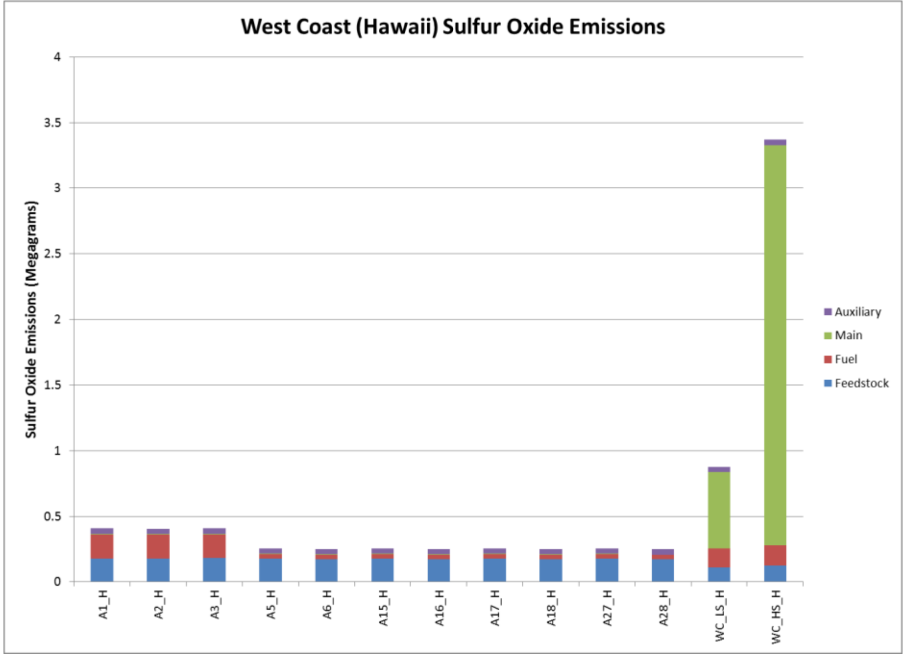
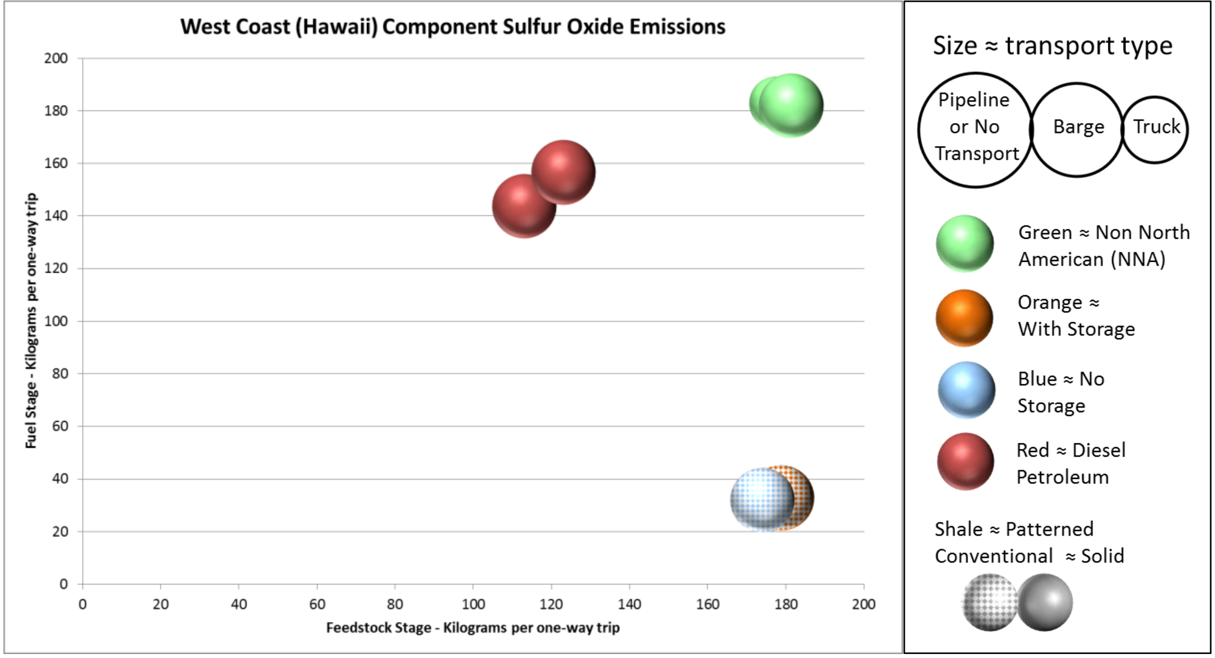


Figure 67 Breakdown of West Coast Case results for SO$_x$ emissions for trip from Port of LA/LB to Hawaii showing how various pathway decisions affect upstream emissions



10 Appendix B Inland Results

For each of the variables analyzed this report will be organized in the following manner. First there is a stacked bar chart showing how each of the four components (feedstock, fuel, main, and auxiliary) contribute to the overall emissions. Following that is a bubble chart showing how the variables that go into the feedstock and natural gas phases for natural gas affect the emissions.

Figure 68 Inland River Case results for total energy needed for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

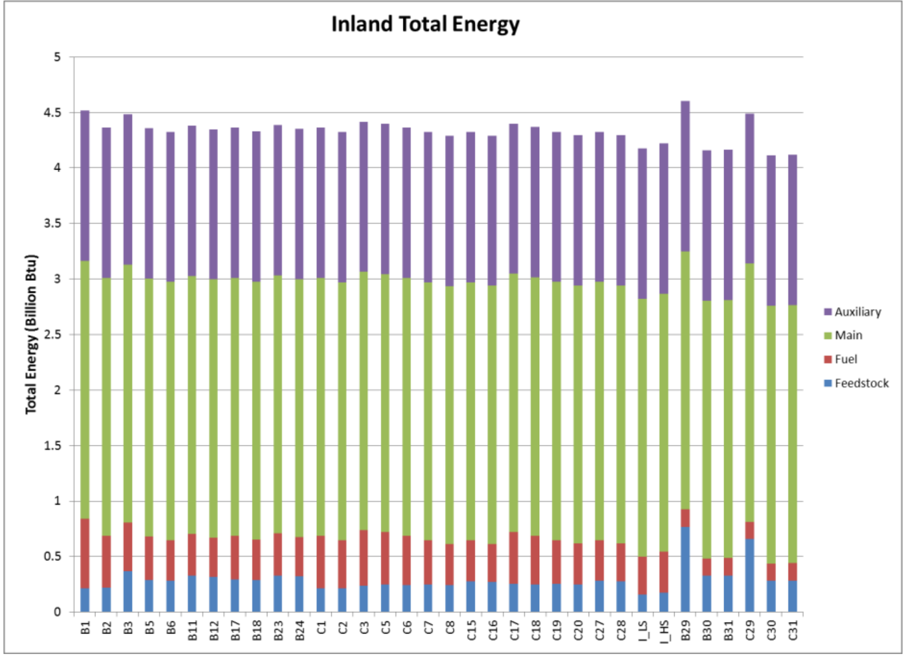


Figure 69 Breakdown of Inland River Case results for total energy for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

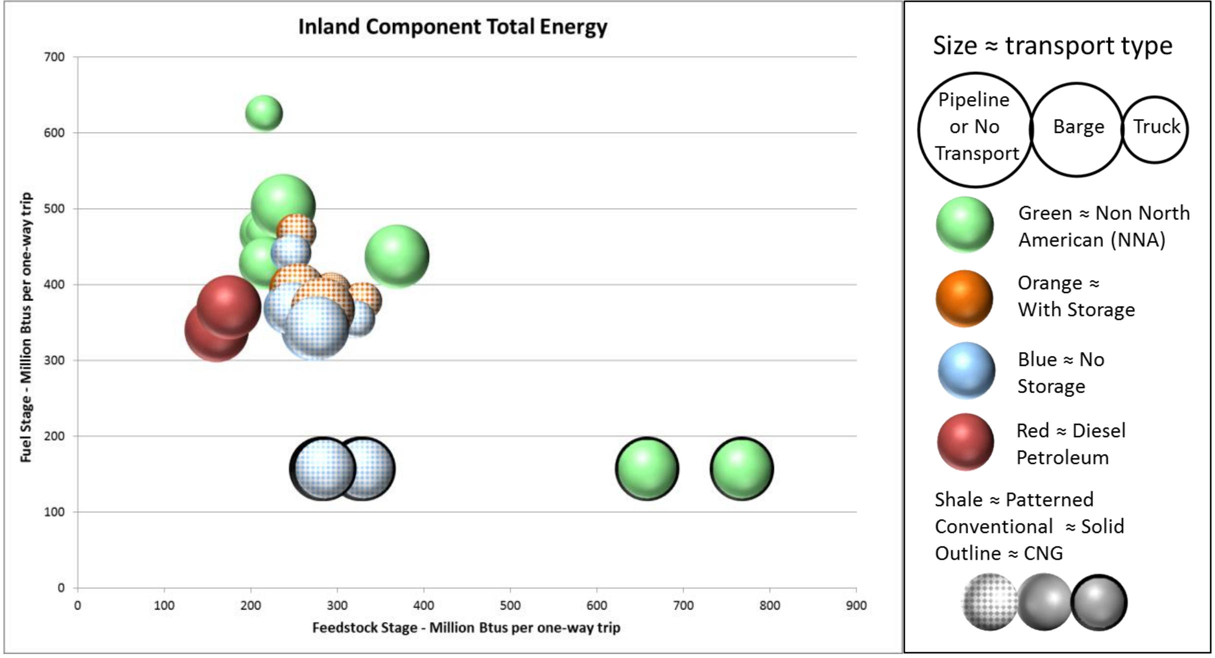


Figure 70 Inland River Case results for fossil fuel energy needed for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

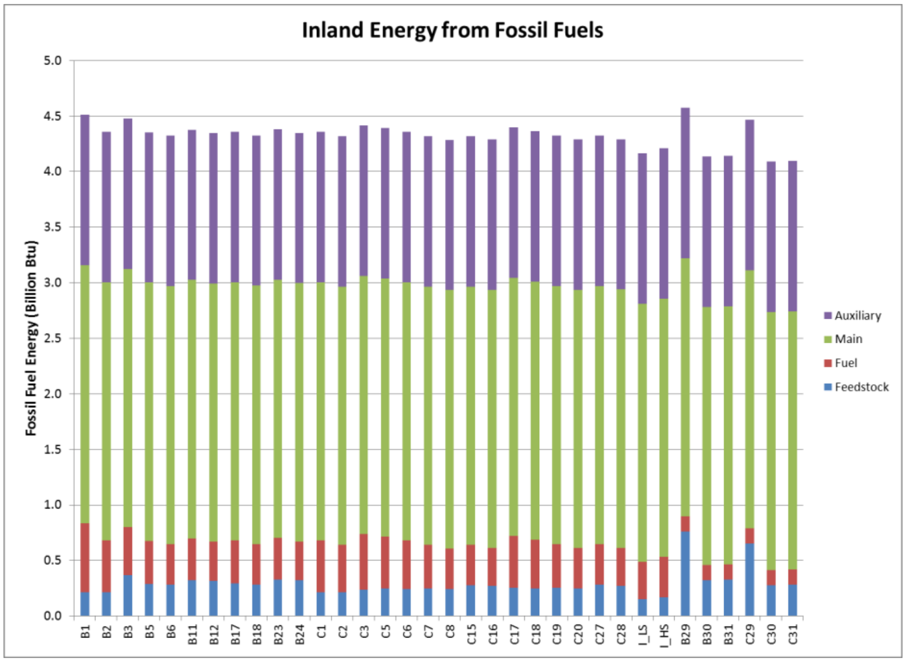


Figure 71 Breakdown of Inland River Case results for fossil fuel energy for trip from between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

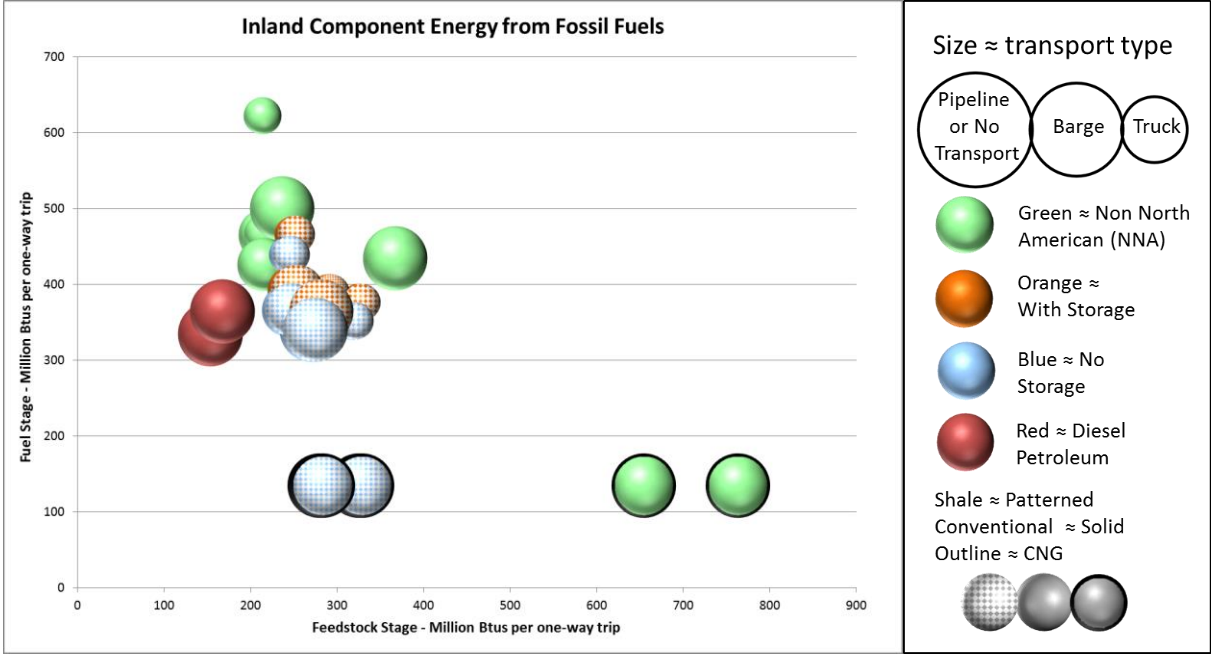


Figure 72 Inland River Case results for petroleum energy needed for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

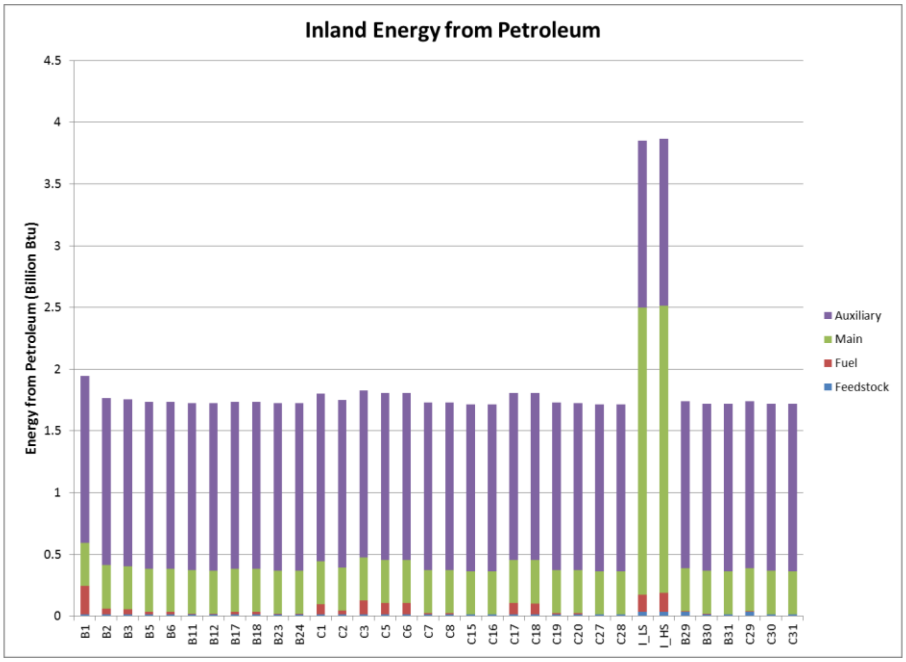


Figure 73 Breakdown of Inland River Case results for petroluem energy for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

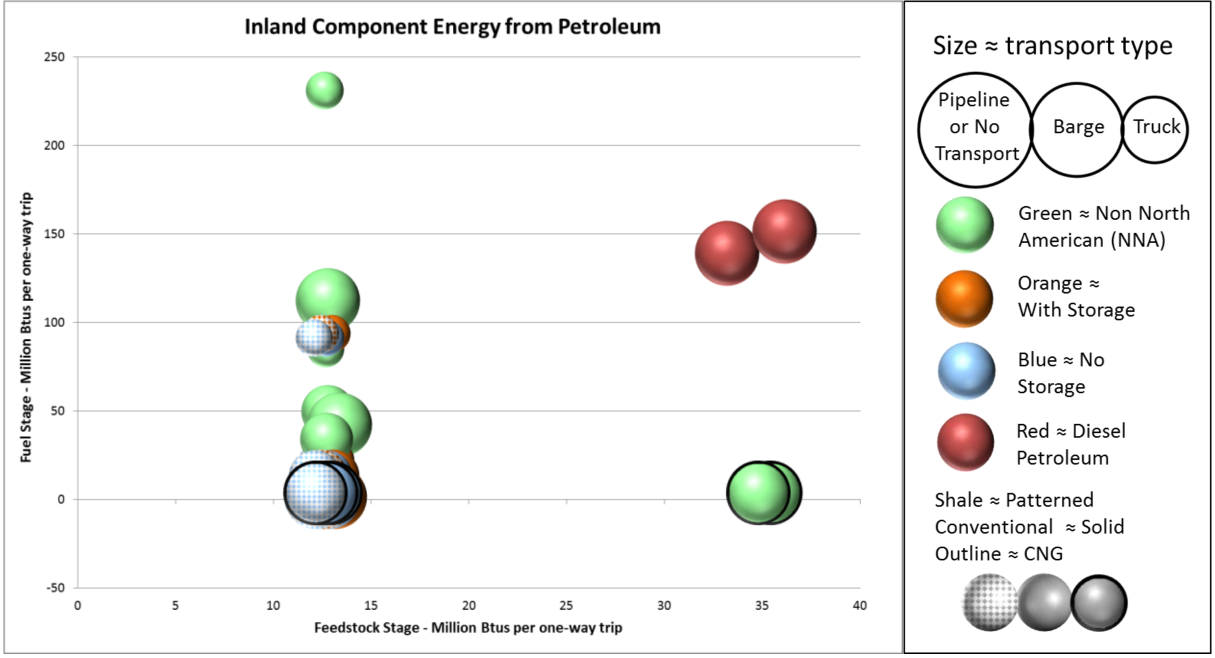


Figure 74 Inland River Case results for CO_2 emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

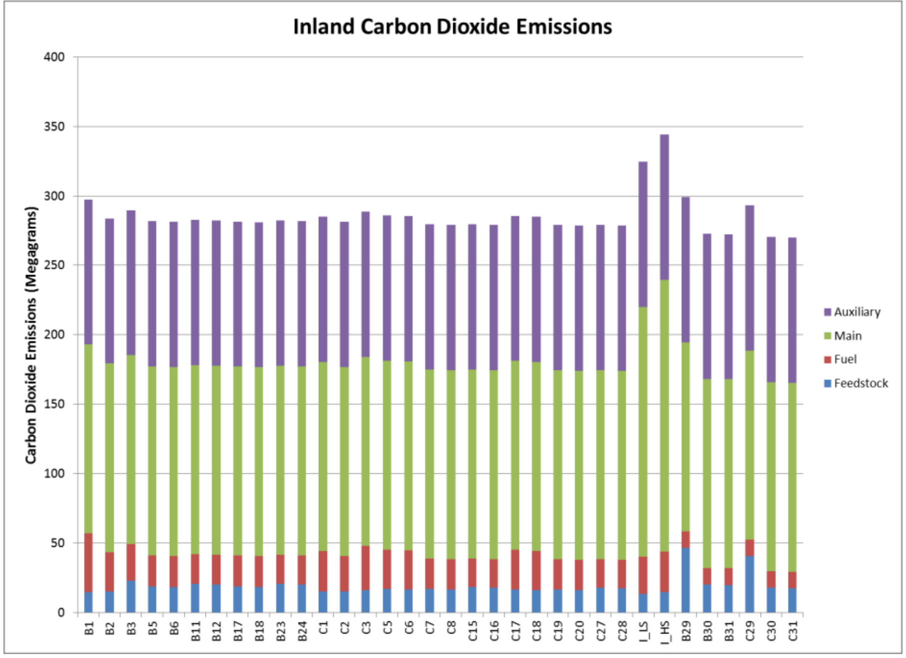


Figure 75 Breakdown of Inland River Case results for CO_2 emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

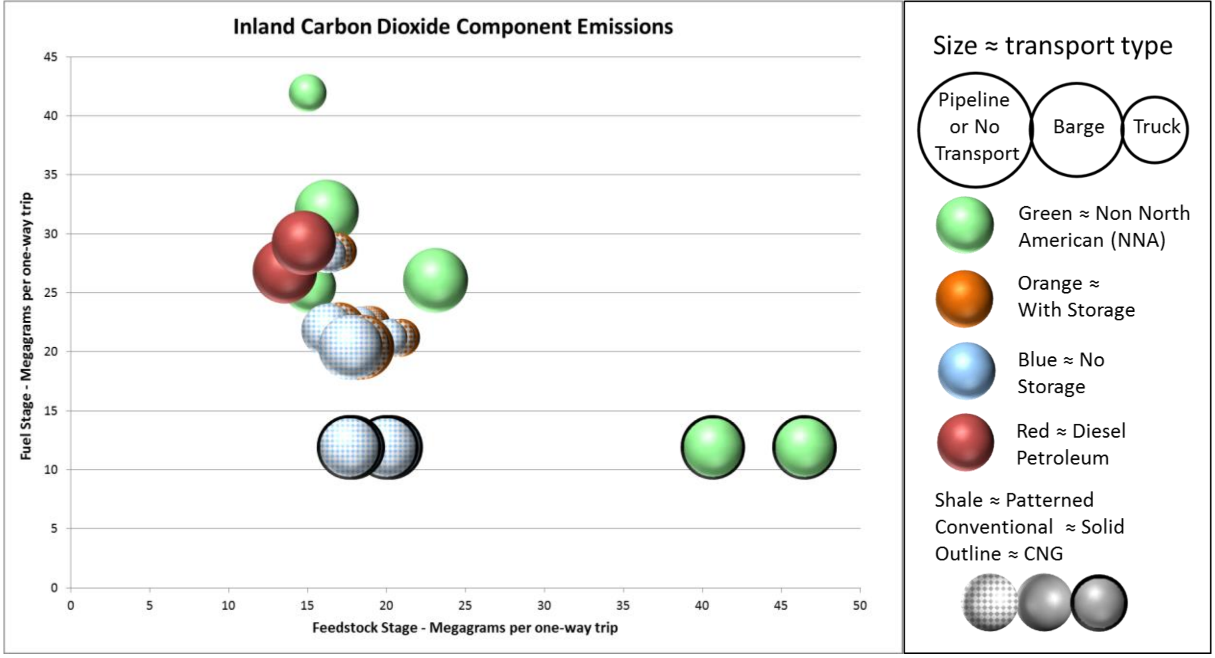


Figure 76 Inland River Case results for CH_4 emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

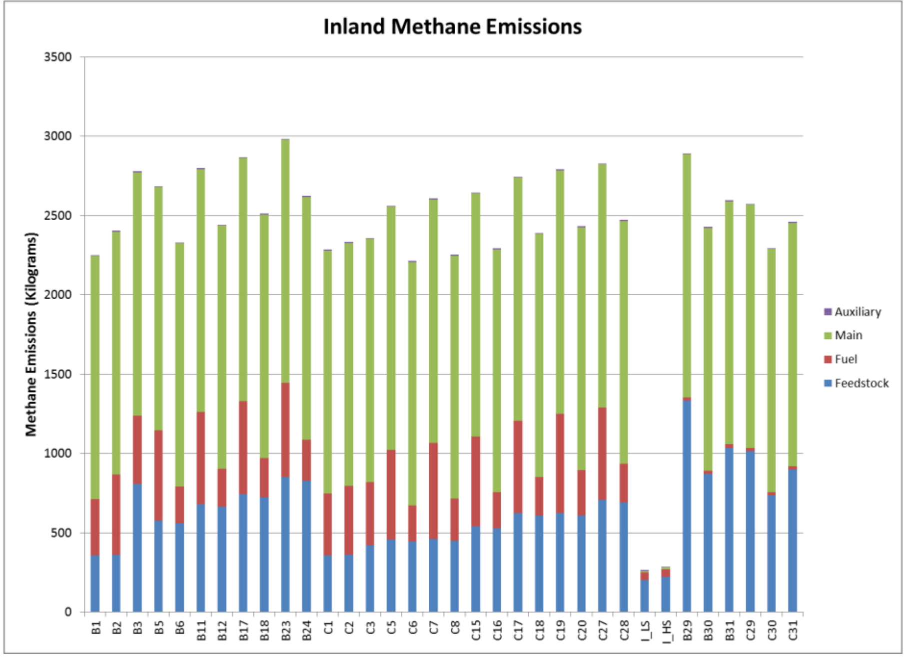


Figure 77 Breakdown of Inland River Case results for CH_4 emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

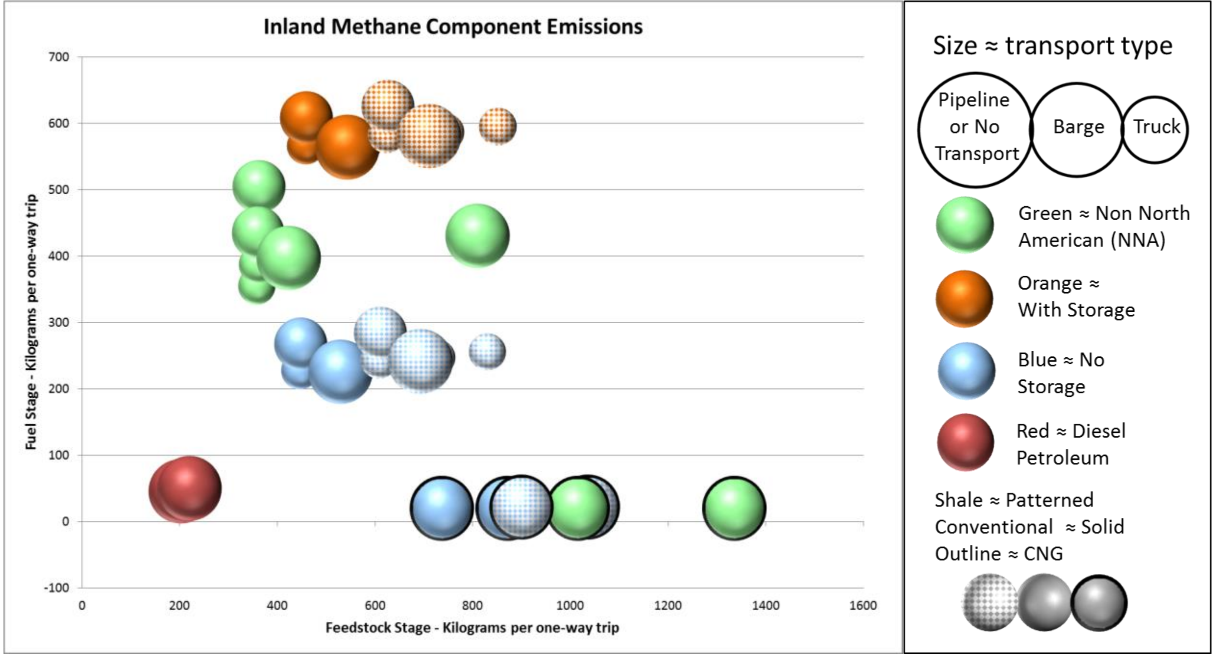


Figure 78. Inland River Case results for N_2O emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

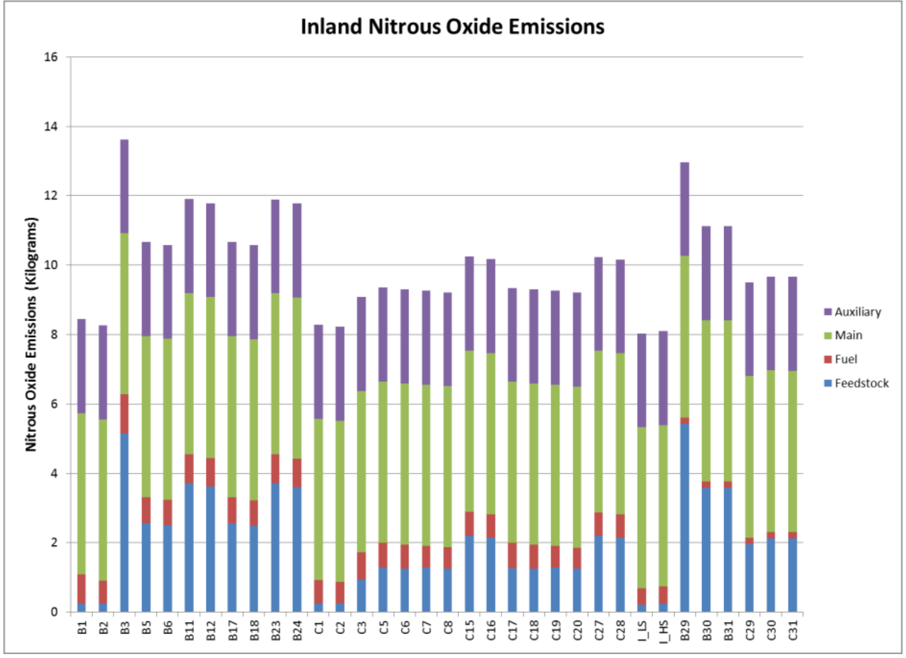


Figure 79 Breakdown of Inland River Case results for N_2O emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

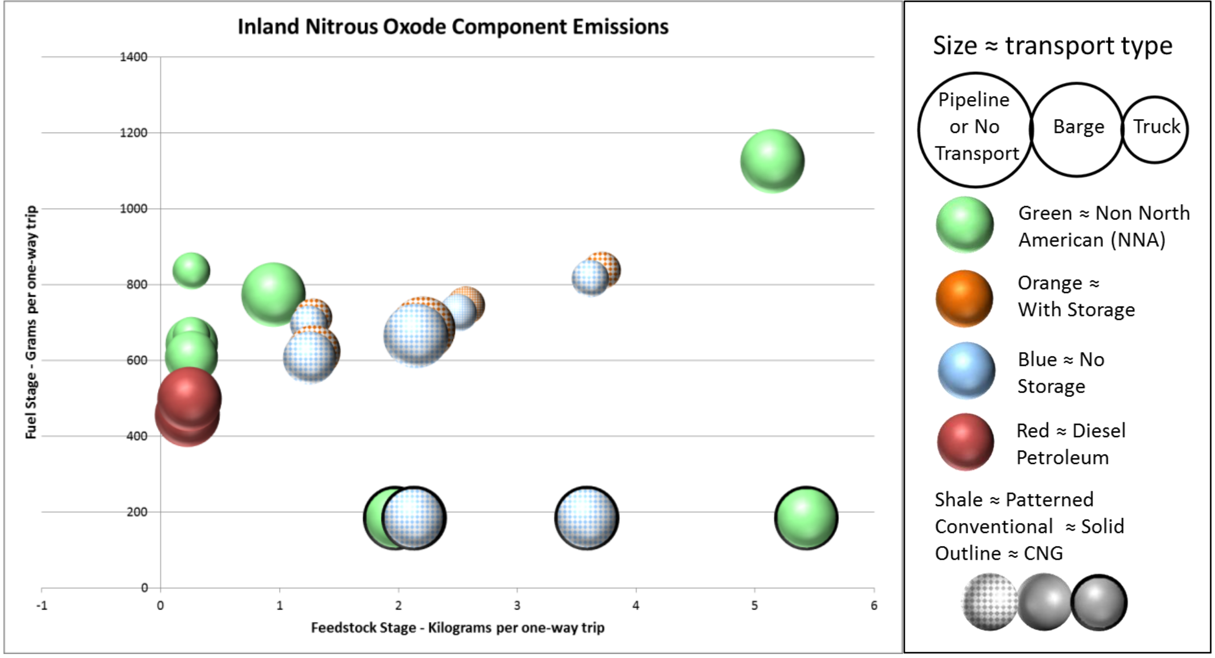


Figure 80 Inland River Case results for GHG emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

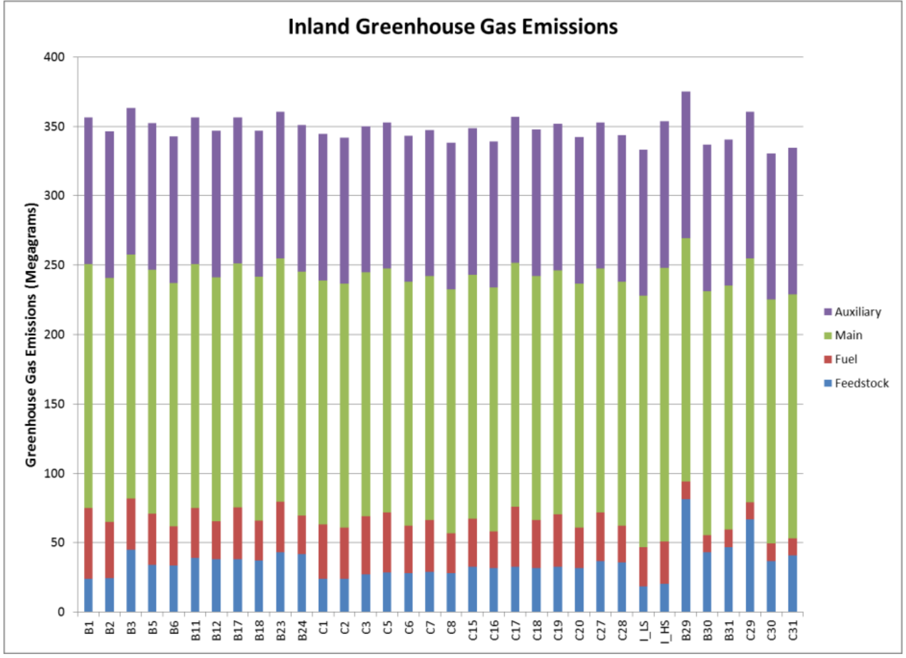


Figure 81 Breakdown of Inland River Case results for GHG emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

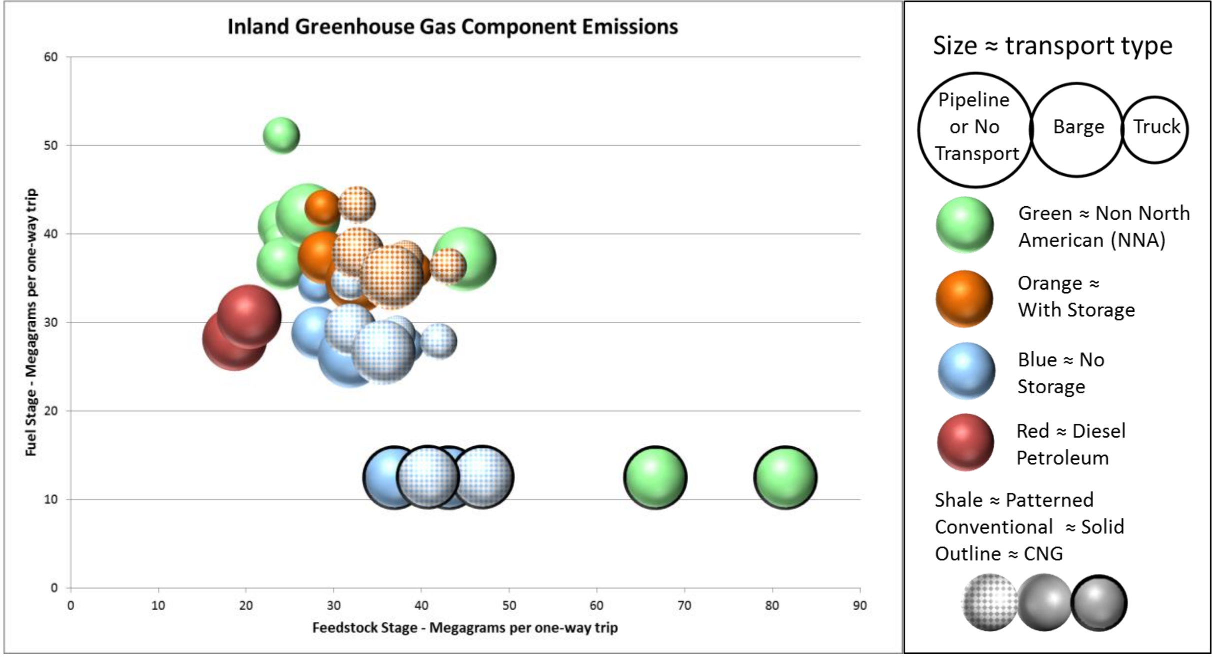


Figure 82 Inland River Case results for VOC emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

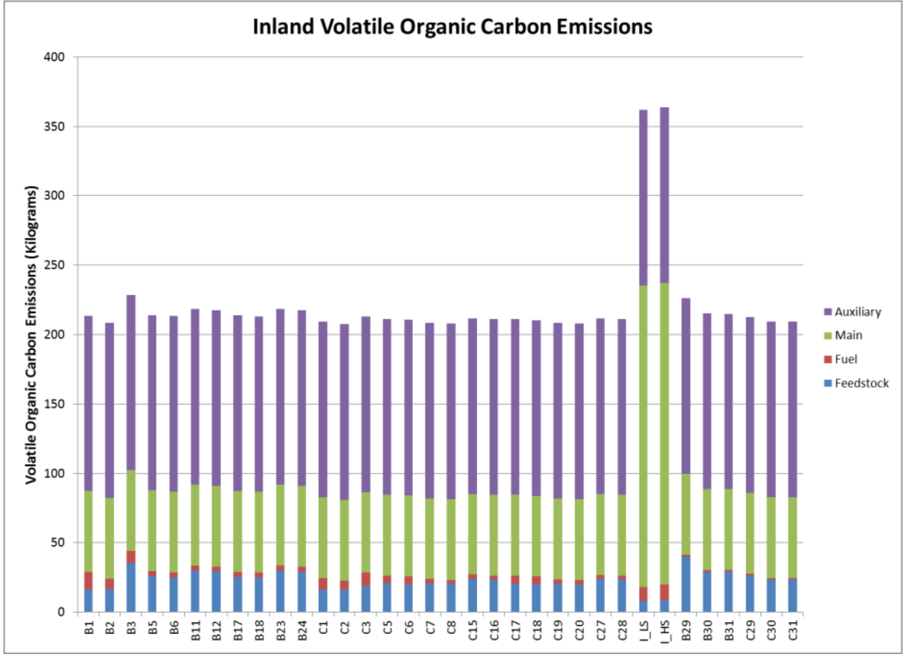


Figure 83 Breakdown of Inland River Case results for VOC emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

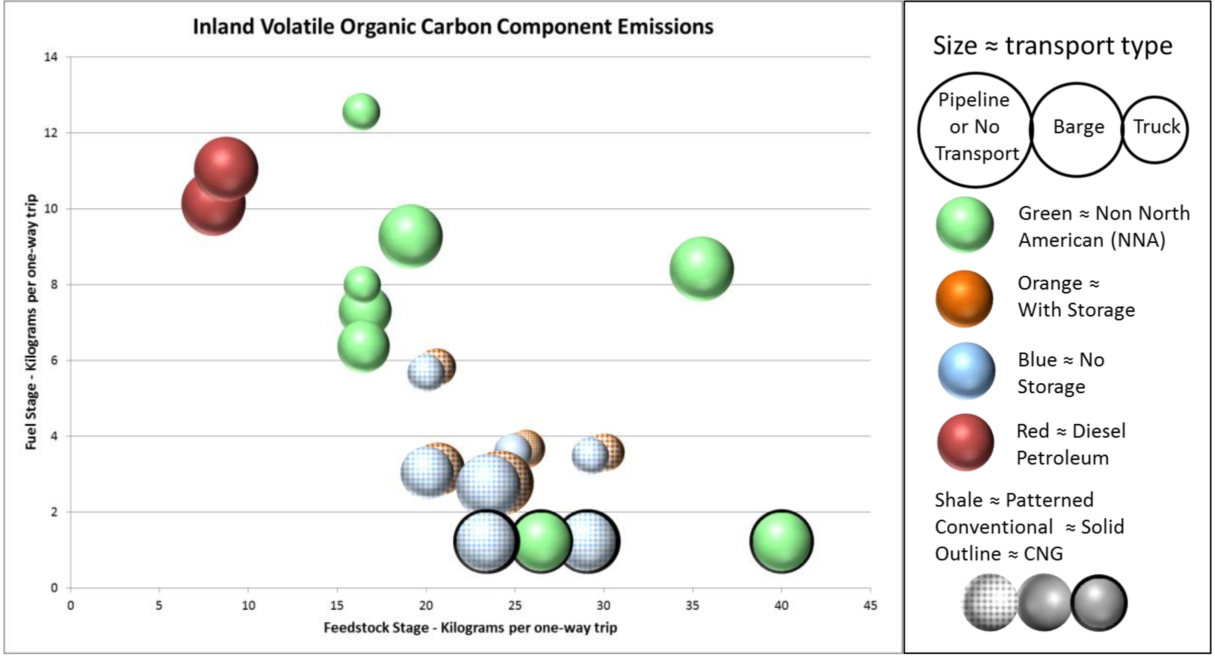


Figure 84 Inland River Case results for CO emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

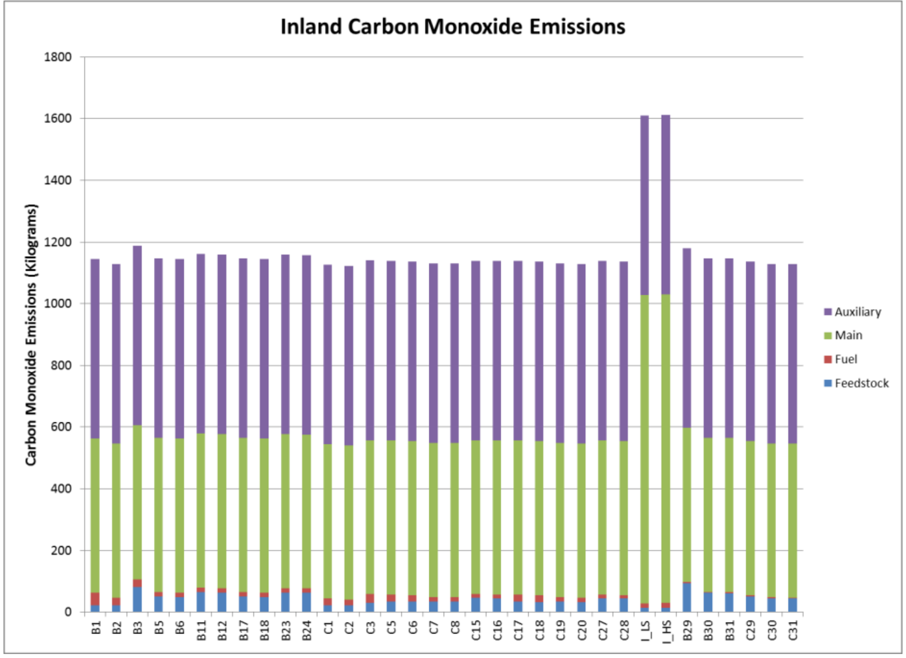


Figure 85 Breakdown of Inland River Case results for CO emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

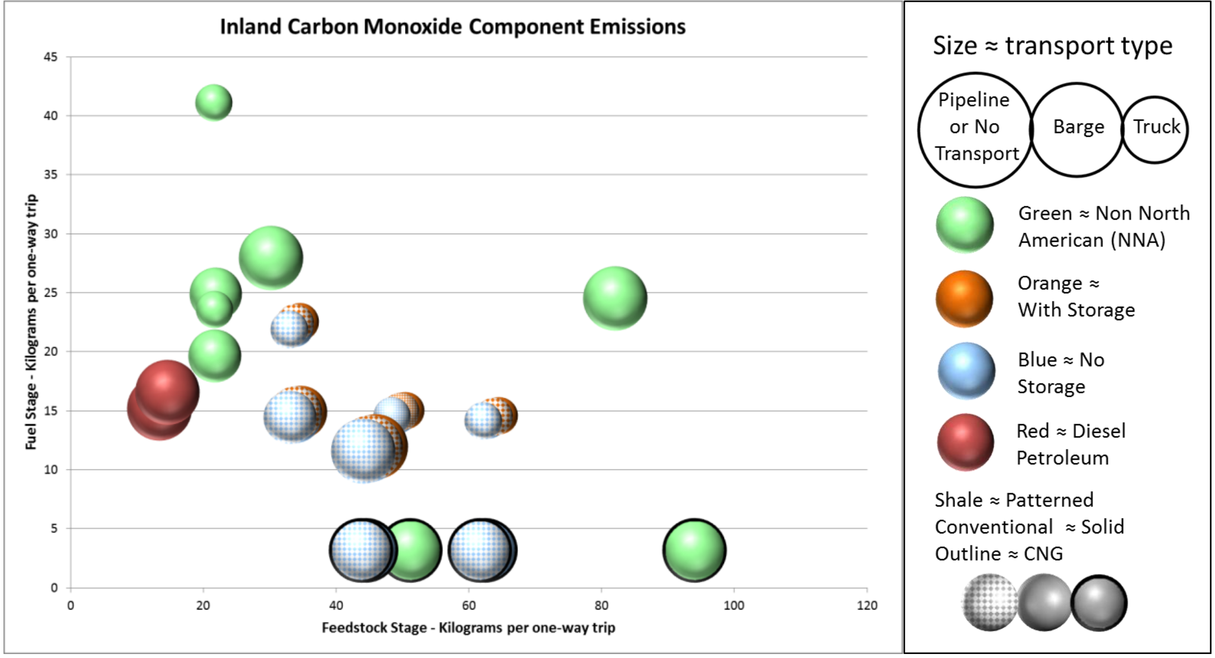


Figure 86 Inland River Case results for NO$_x$ emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

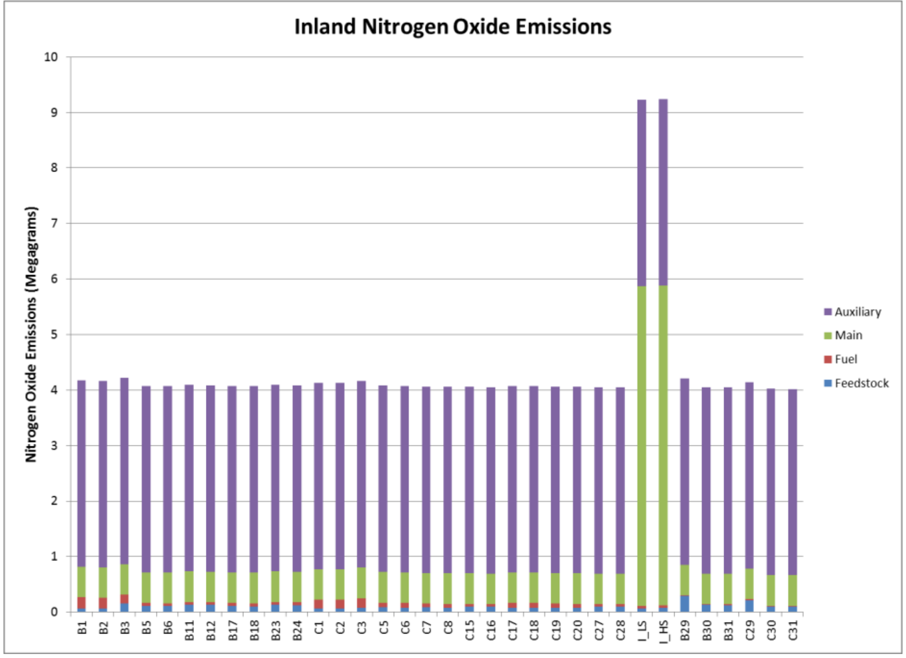


Figure 87 Breakdown of Inland River Case results for NO$_x$ emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

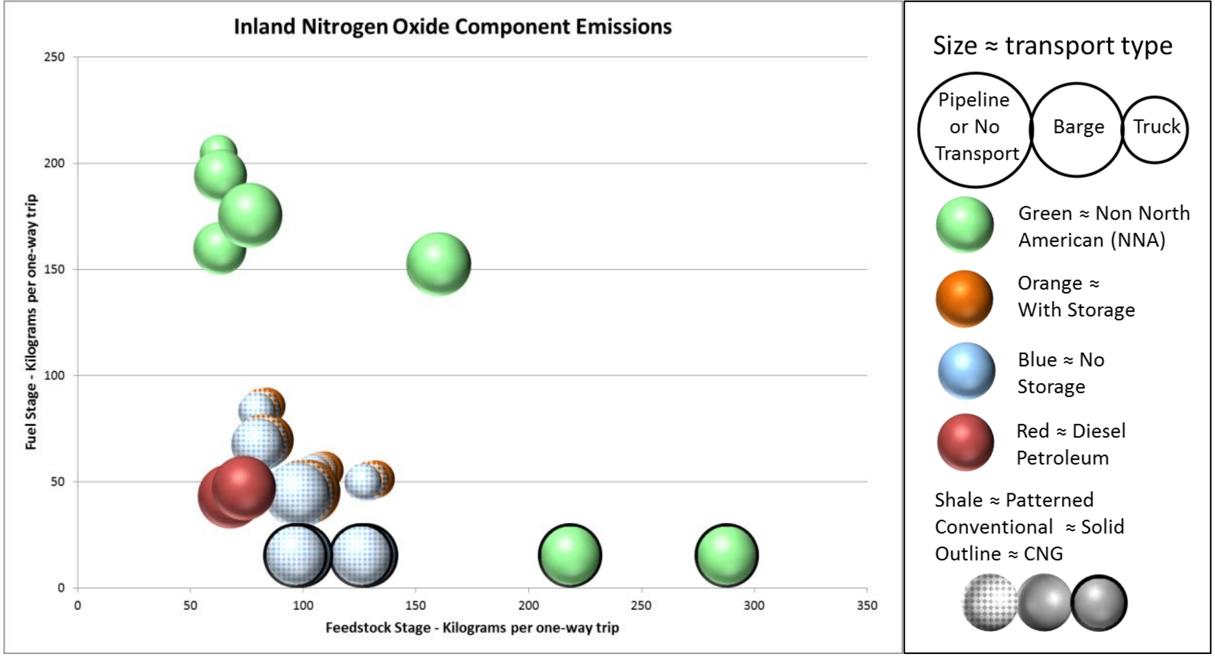


Figure 88 Inland River Case results for PM_{10} emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

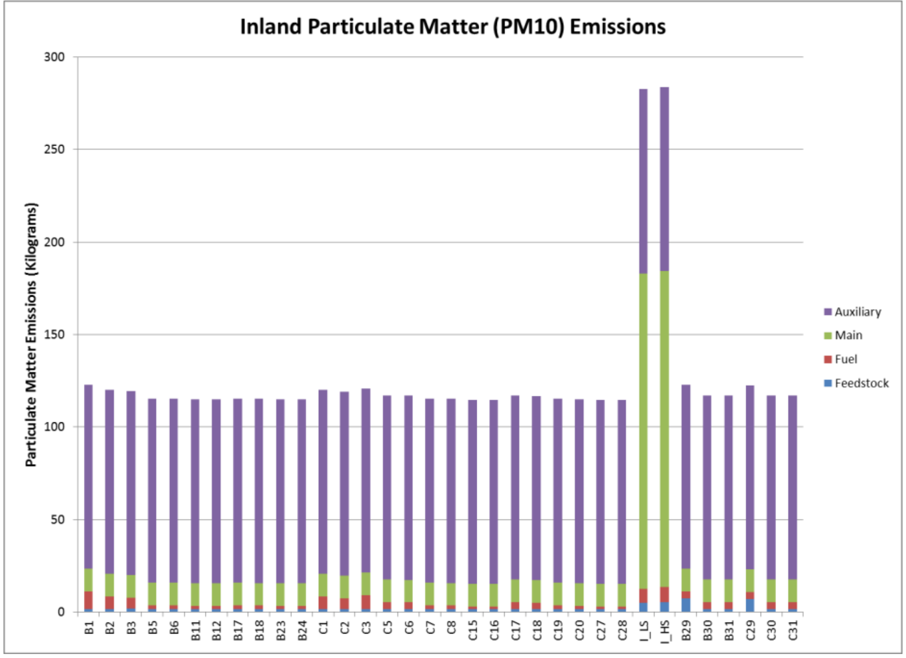


Figure 89 Breakdown of Inland River Case results for PM_{10} emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions

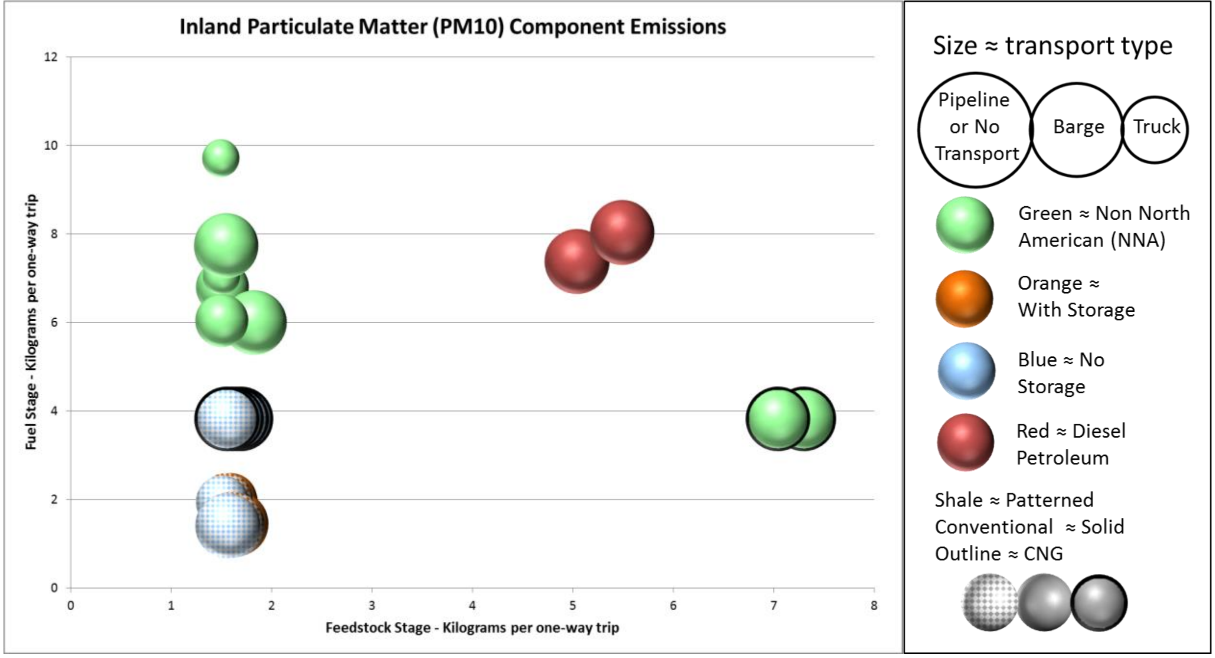


Figure 90 Inland River Case results for SO_x emissions for trip between Port of Peoria, IL and Port of New Orleans, LA; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

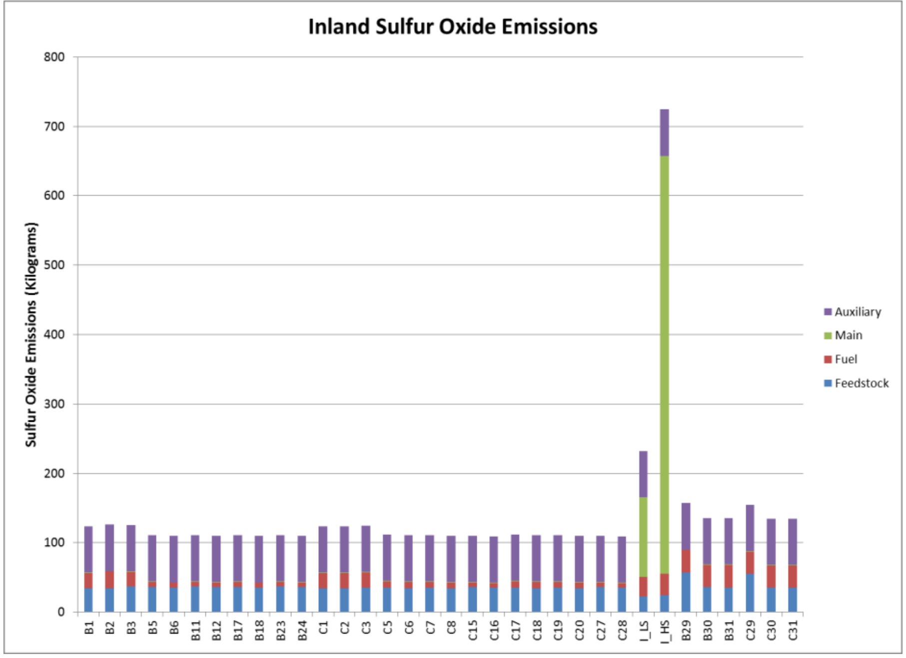
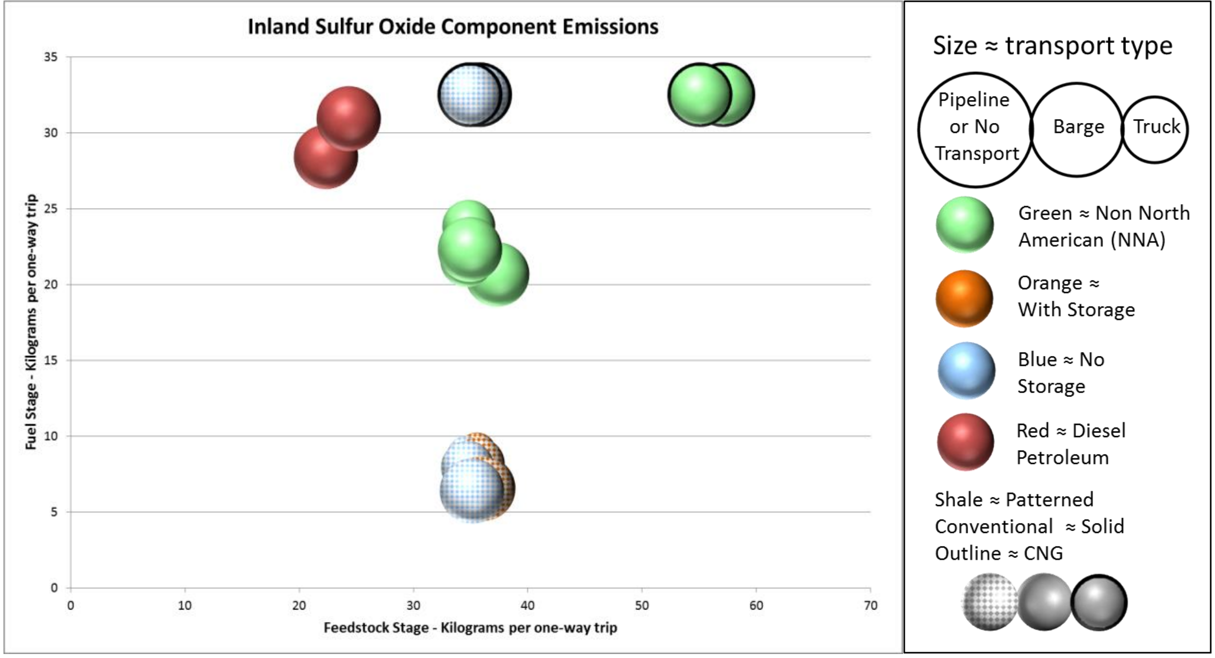


Figure 91 Breakdown of Inland River Case results for SO_x emissions for trip between Port of Peoria, IL and Port of New Orleans, LA showing how various pathway decisions affect upstream emissions



11 Appendix C East Coast Results

For each of the variables analyzed this report will be organized in the following manner. First there is a stacked bar chart showing how each of the four components (feedstock, fuel, main, and auxiliary) contribute to the overall emissions. Following that is a bubble chart showing how the variables that go into the feedstock and natural gas phases for natural gas affect the emissions.

Figure 92 East Coast Case results for total energy needed for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

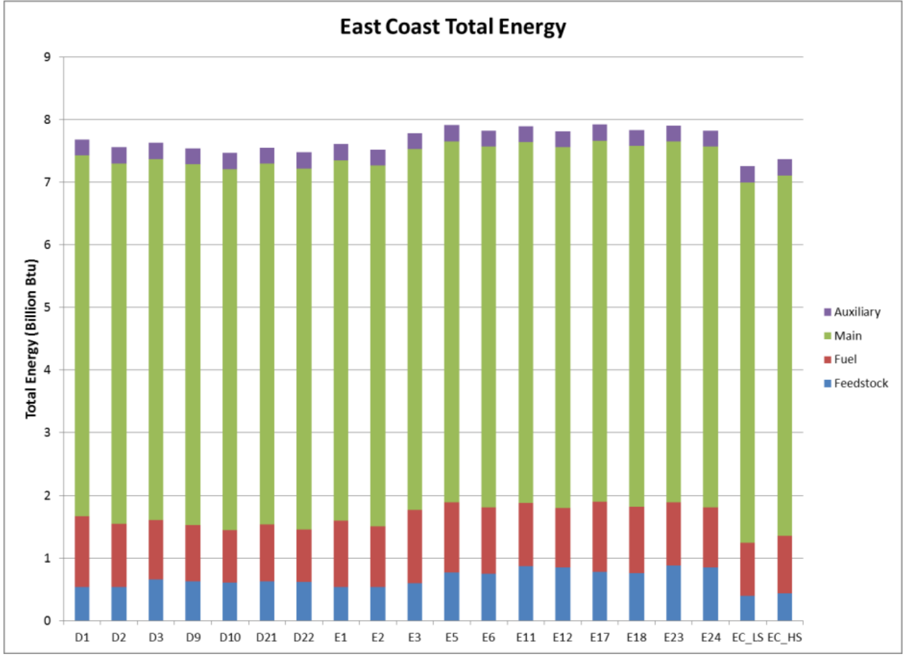


Figure 93 Breakdown of East Coast Case results for total energy for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

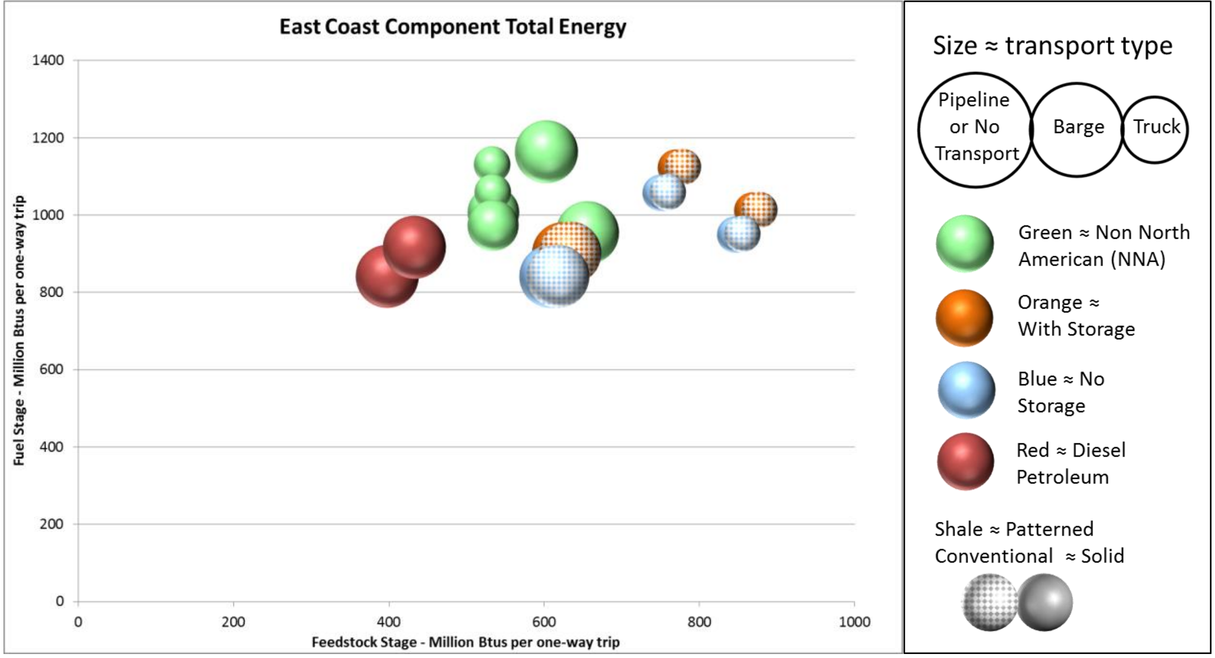


Figure 94 East Coast Case results for fossil fuel energy needed for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

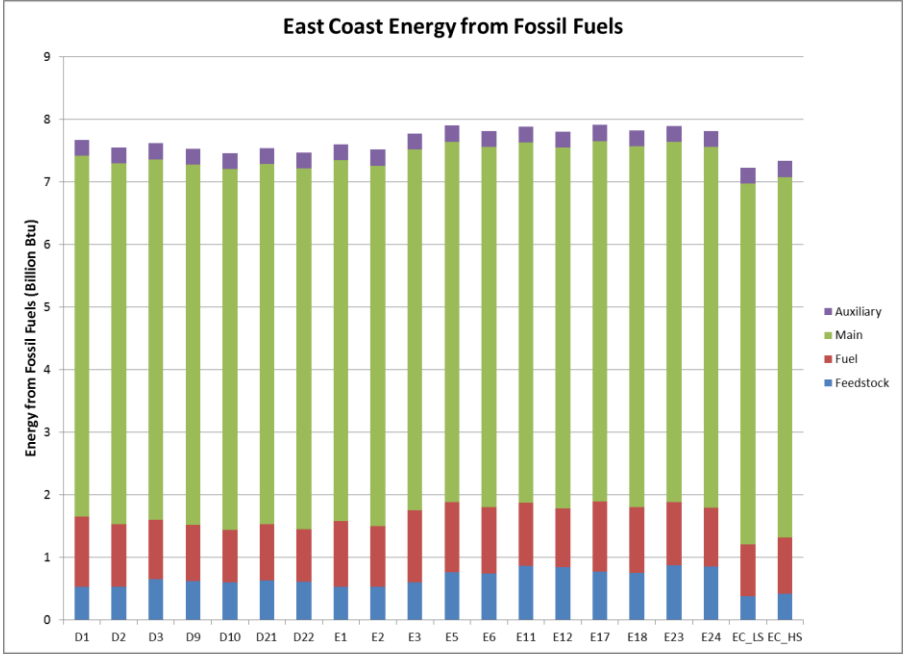


Figure 95 Breakdown of East Coast Case results for fossil fuel energy for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

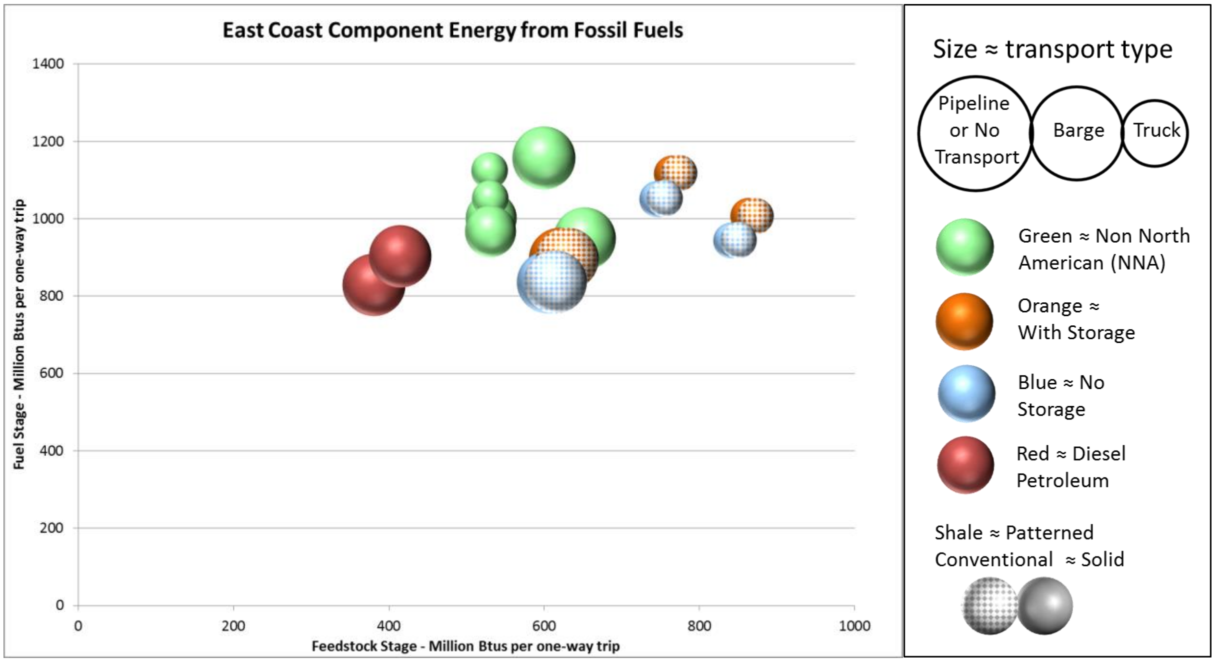


Figure 96 East Coast Case results for petroleum energy needed for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

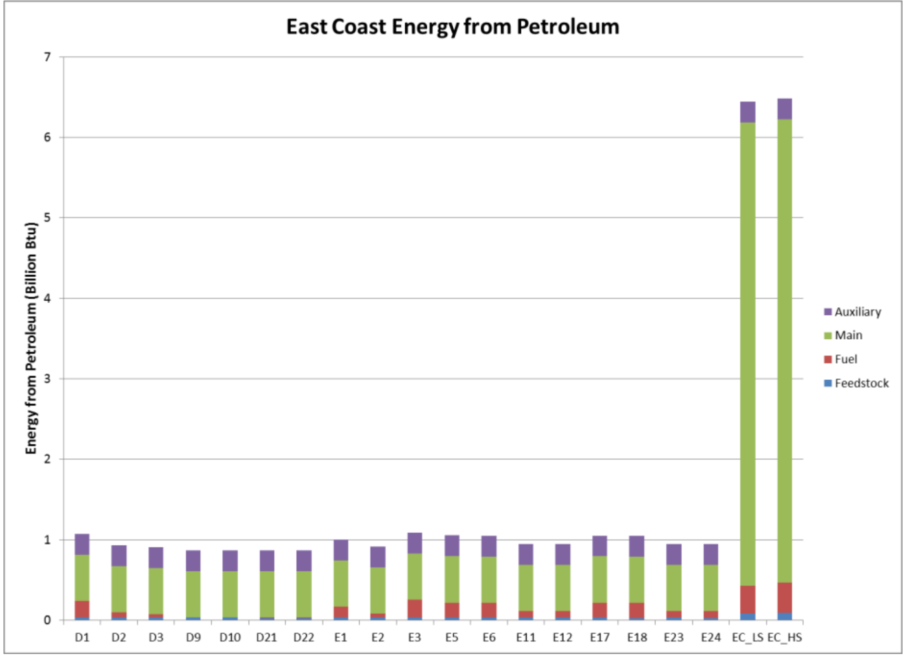


Figure 97 Breakdown of East Coast Case results for petroleum energy for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

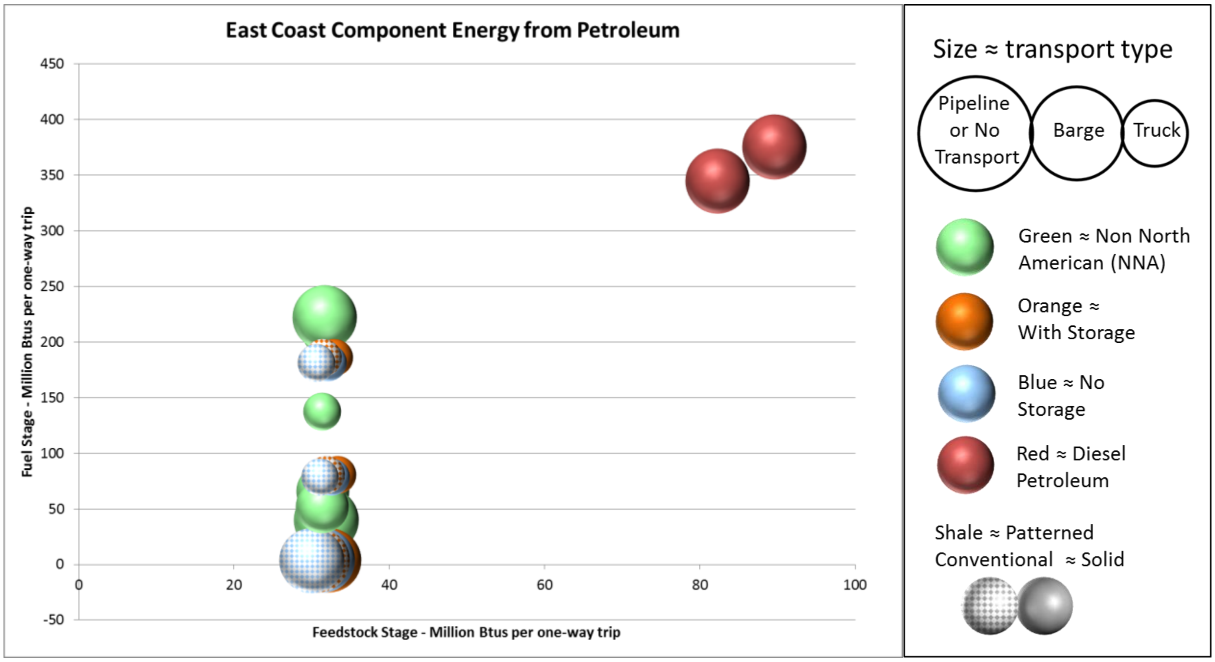


Figure 98 East Coast Case results for CO_2 emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

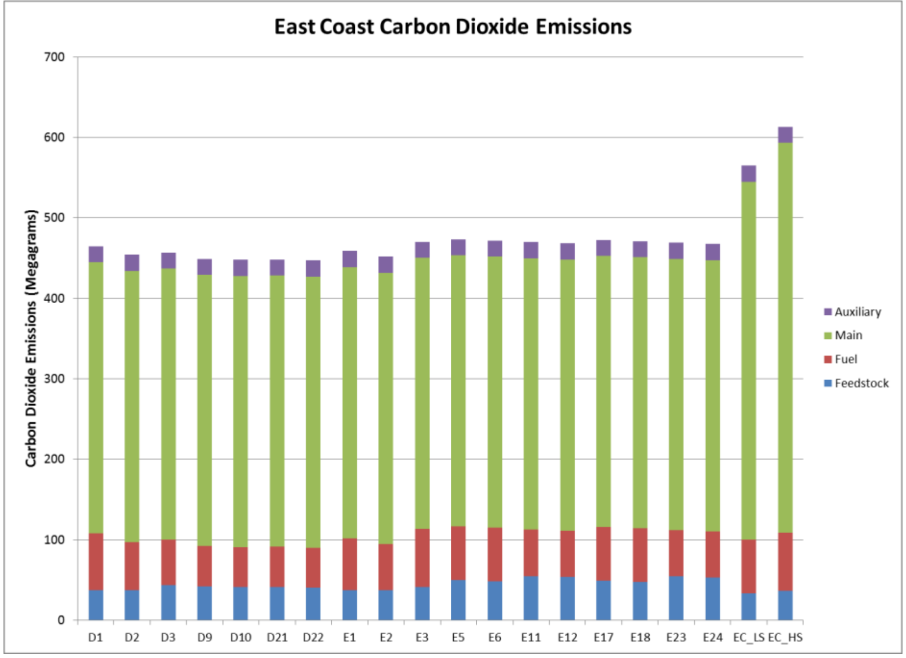


Figure 99 Breakdown of East Coast Case results for CO_2 emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

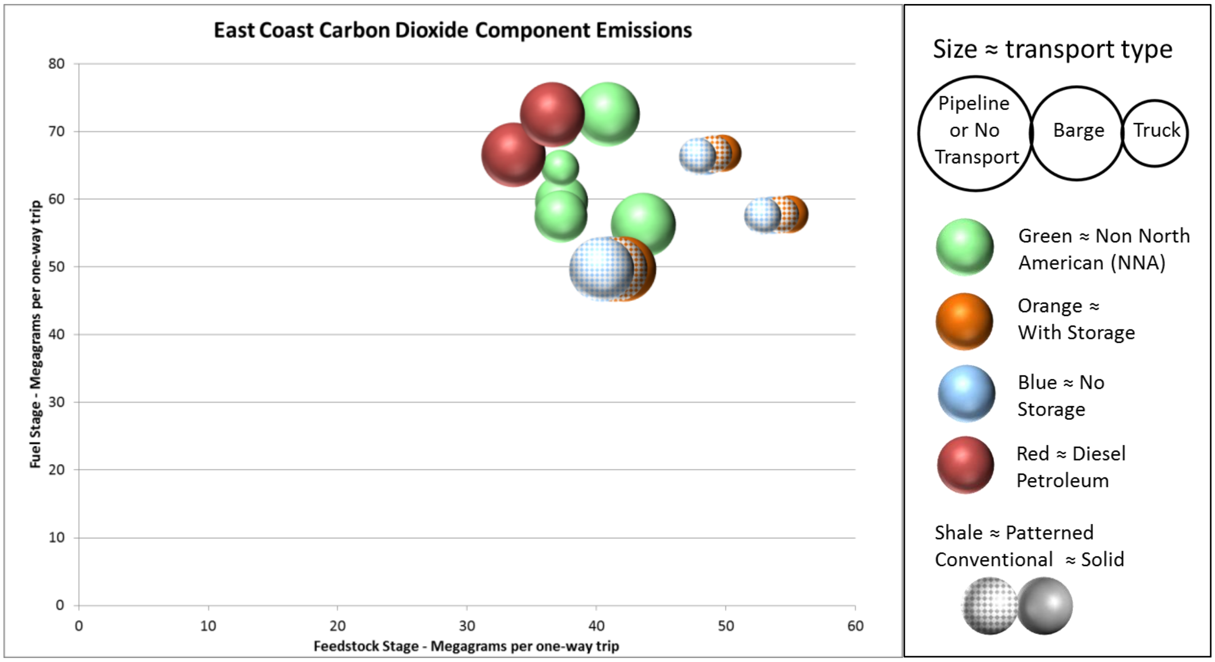


Figure 100 East Coast Case results for CH_4 emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

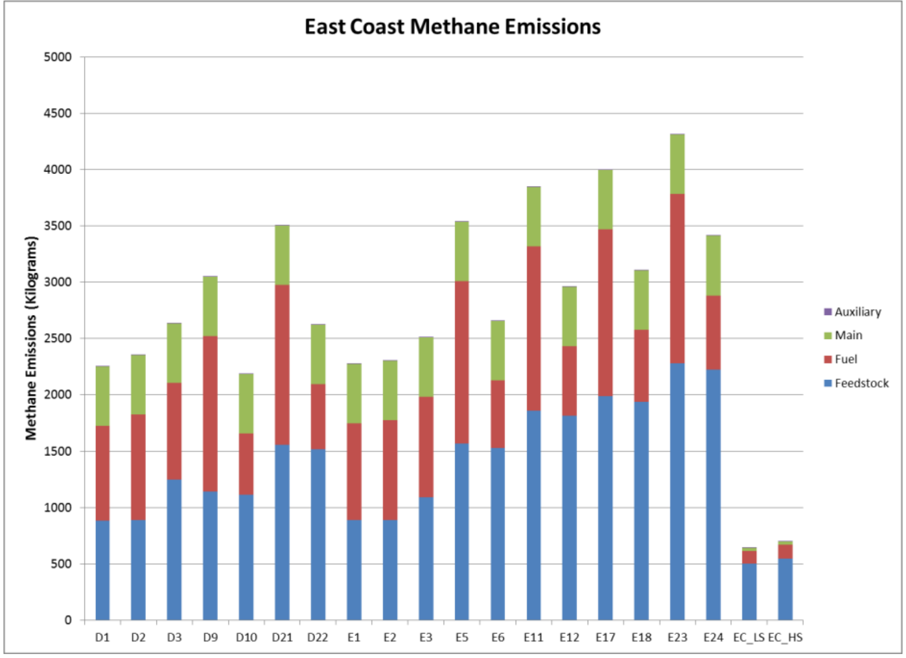


Figure 101 Breakdown of East Coast Case results for CH_4 emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

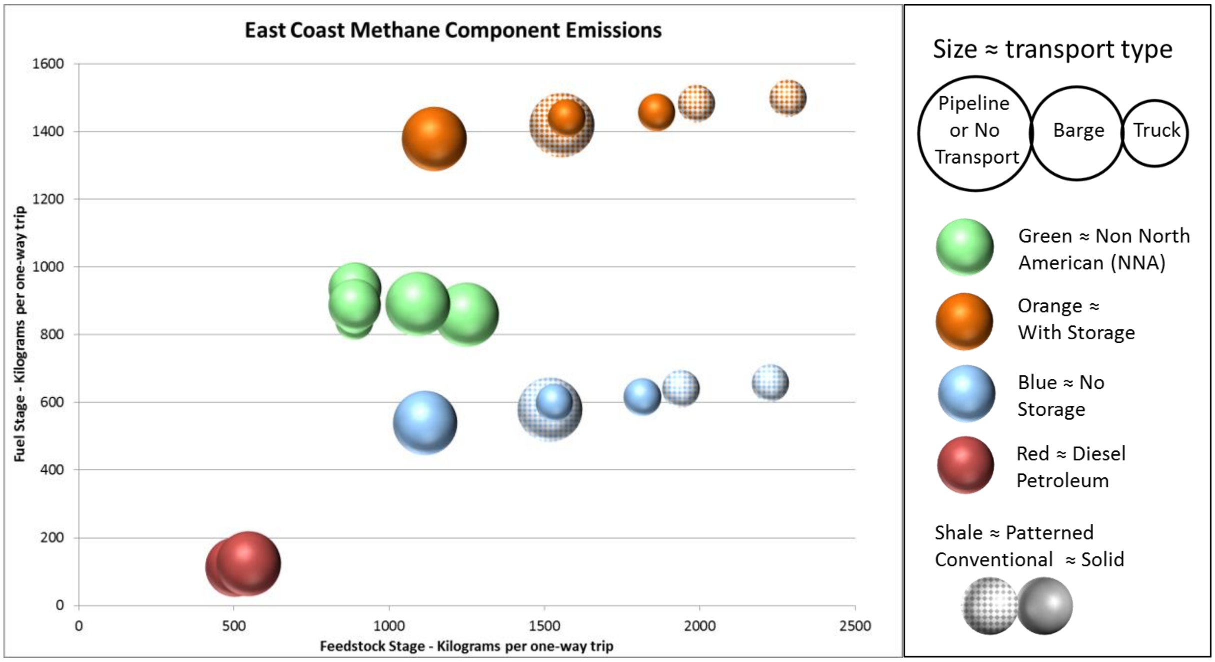


Figure 102 East Coast Case results for N_2O emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

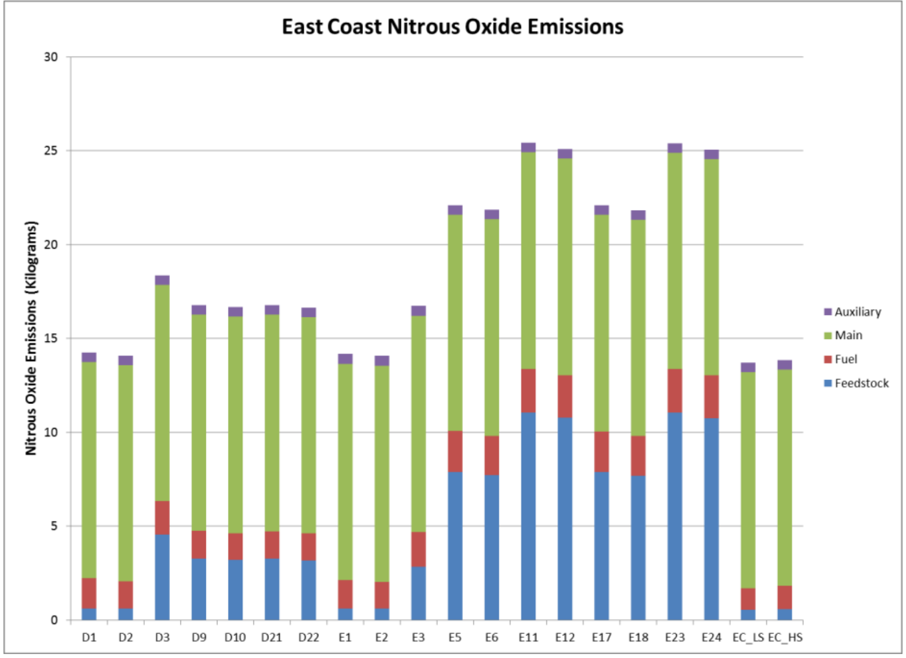


Figure 103 Breakdown of East Coast Case results for N_2O emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

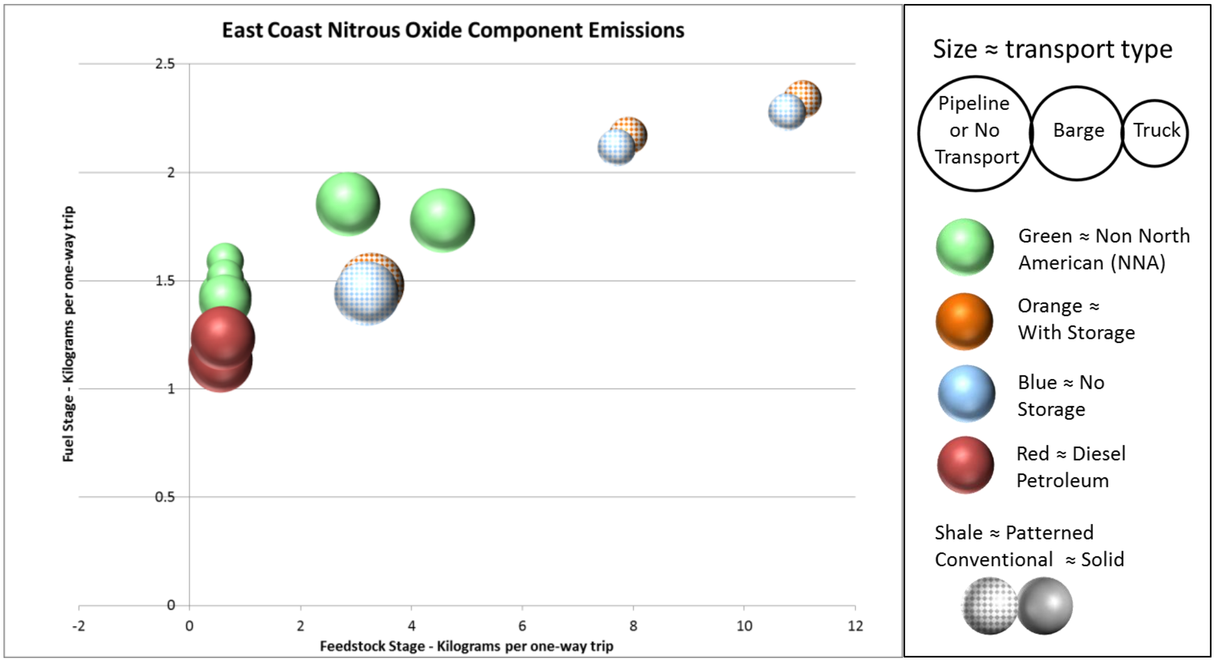


Figure 104 East Coast Case results for GHG emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

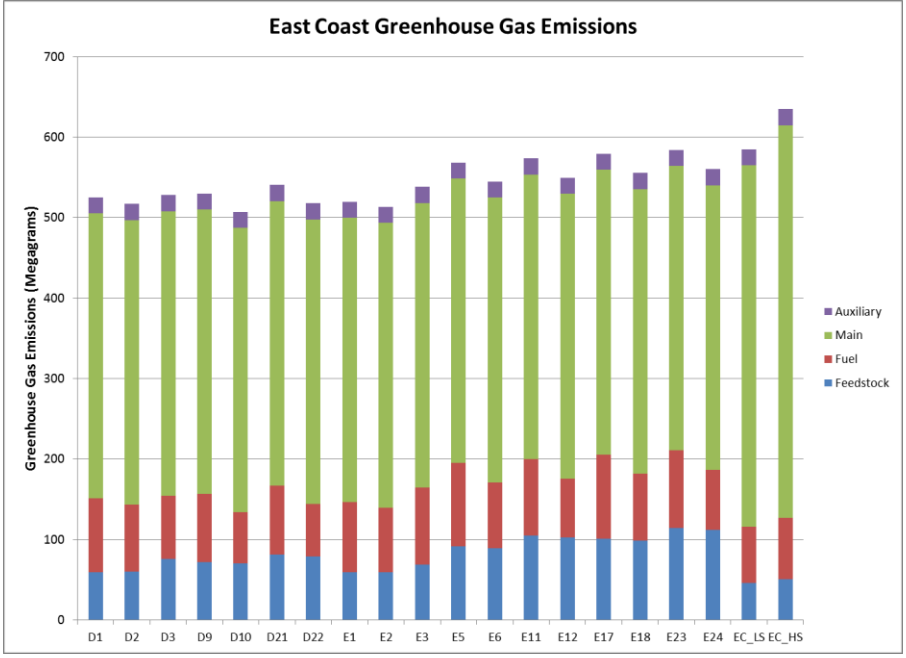


Figure 105 Breakdown of East Coast Case results for GHG emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

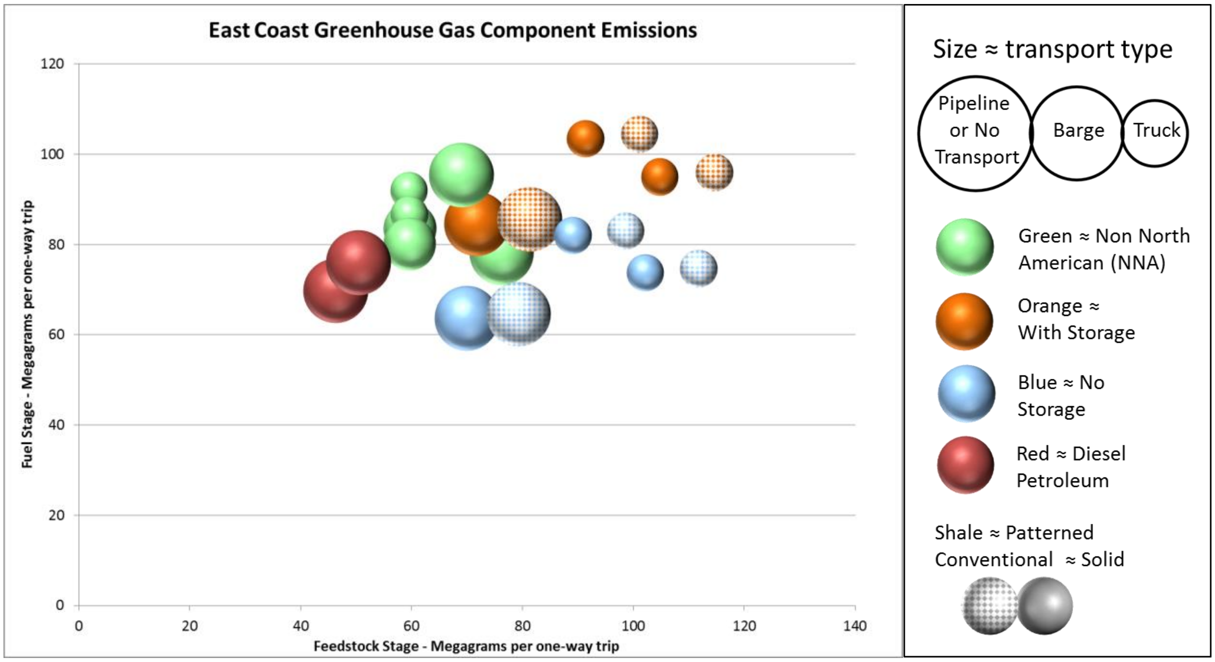


Figure 106 East Coast Case results for VOC emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

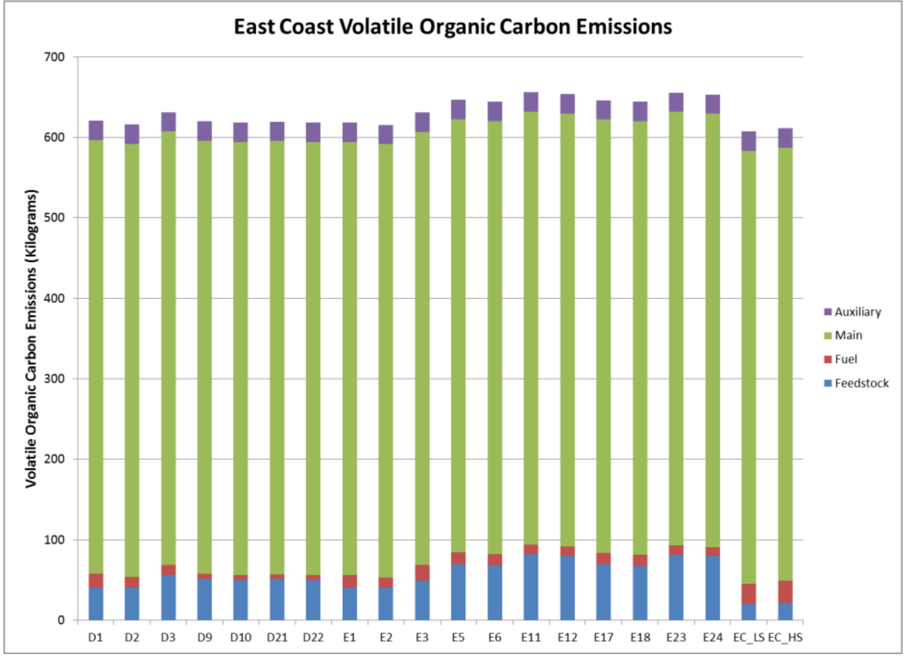


Figure 107 Breakdown of East Coast Case results for VOC emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

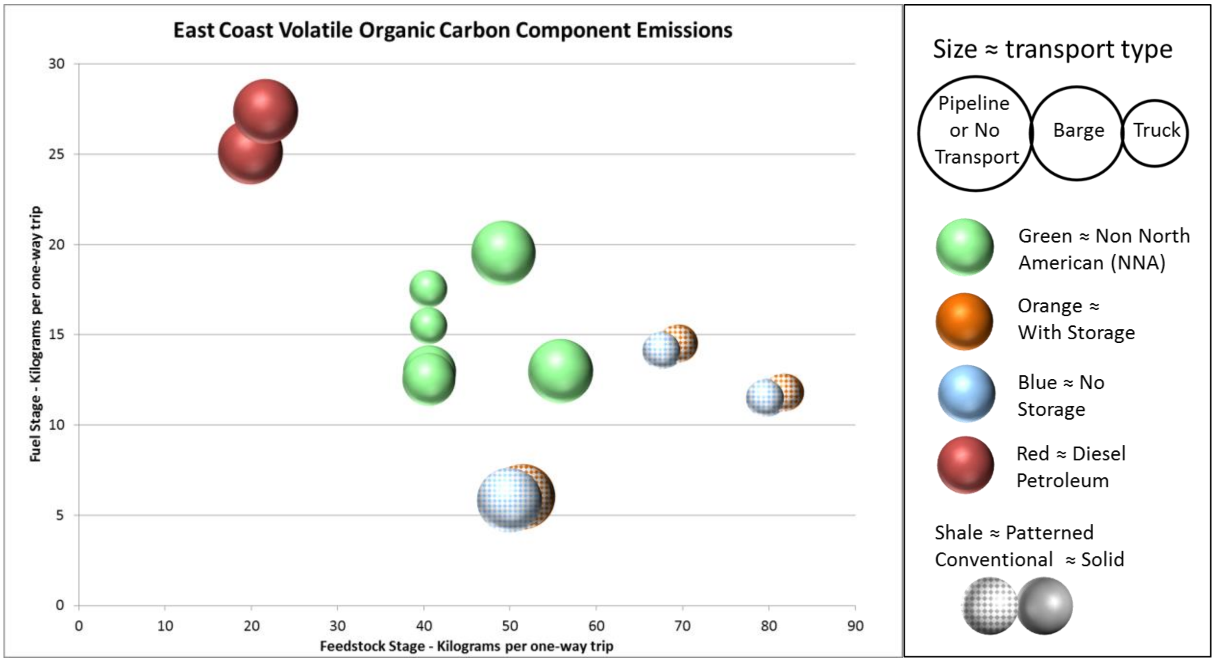


Figure 108 East Coast Case results for CO emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

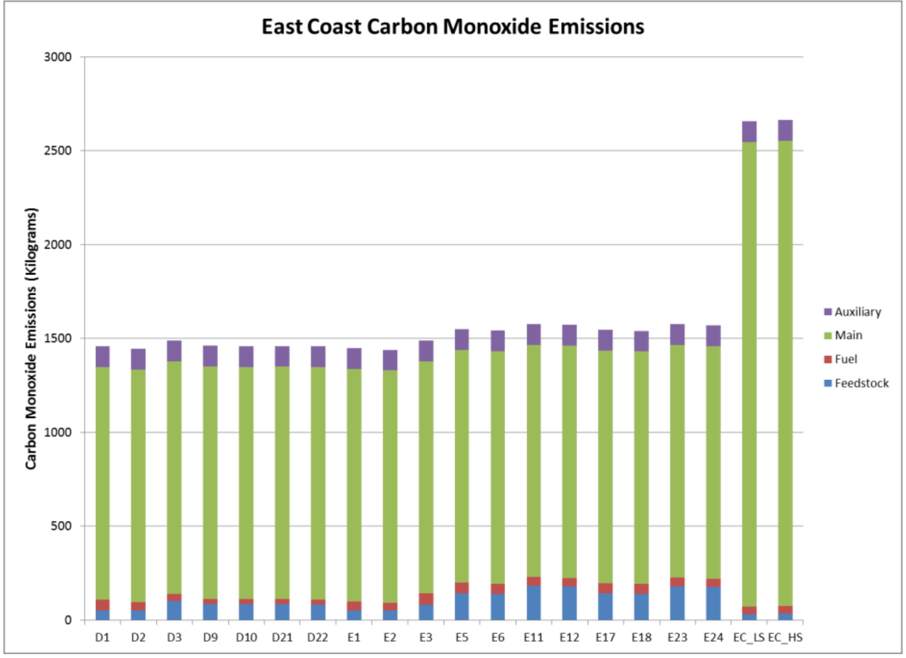


Figure 109 Breakdown of East Coast Case results for CO emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

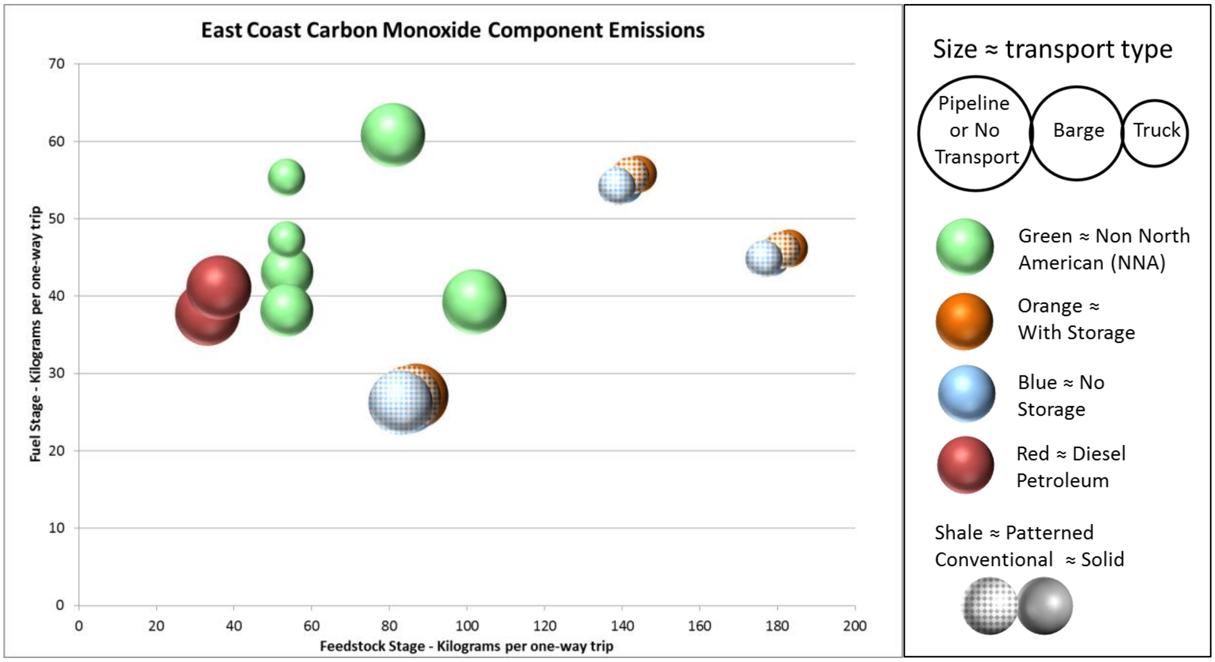


Figure 110 East Coast Case results for NO_x emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

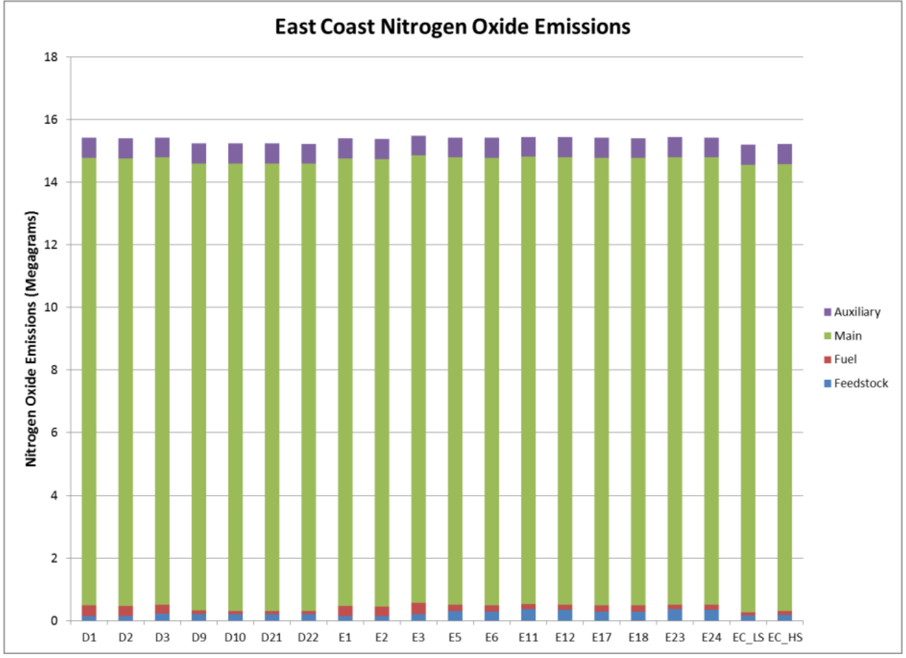


Figure 111 Breakdown of East Coast Case results for NO_x emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

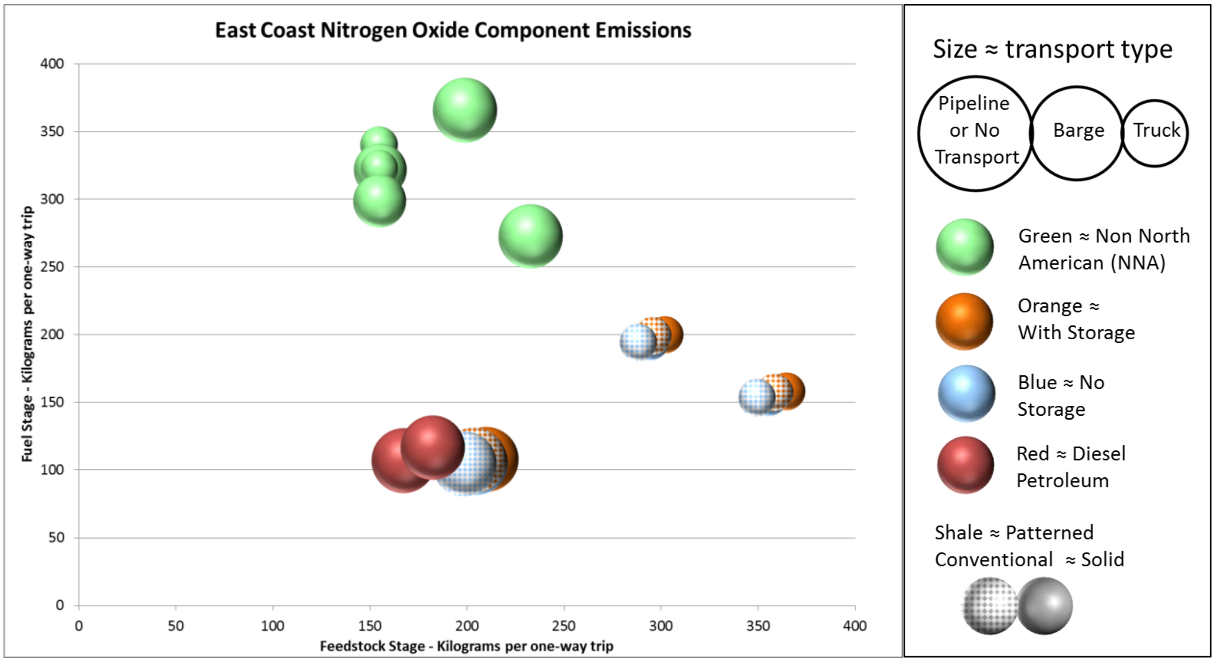


Figure 112 East Coast Case results for PM_{10} emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

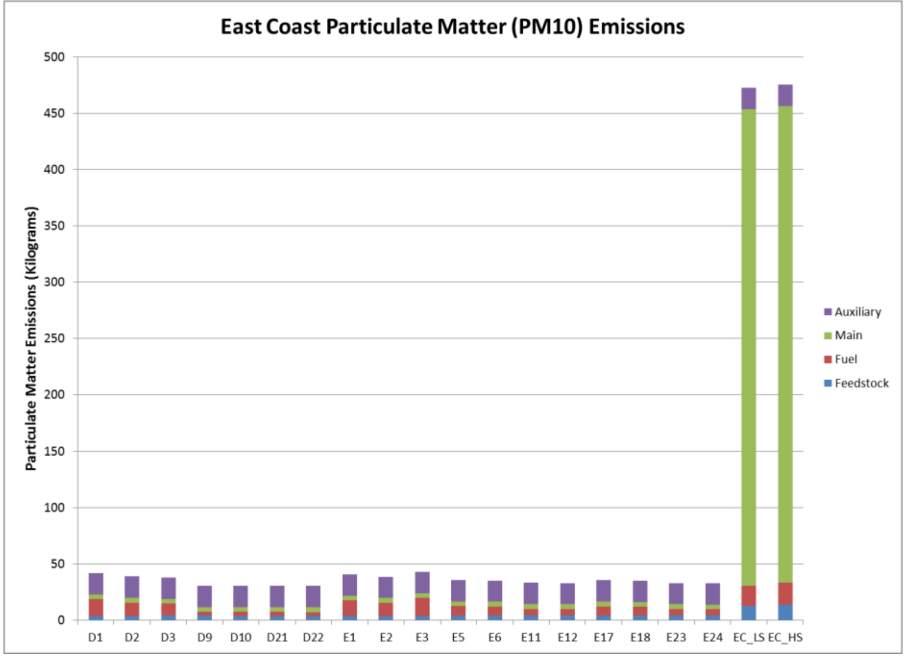


Figure 113 Breakdown of East Coast Case results for PM_{10} emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions

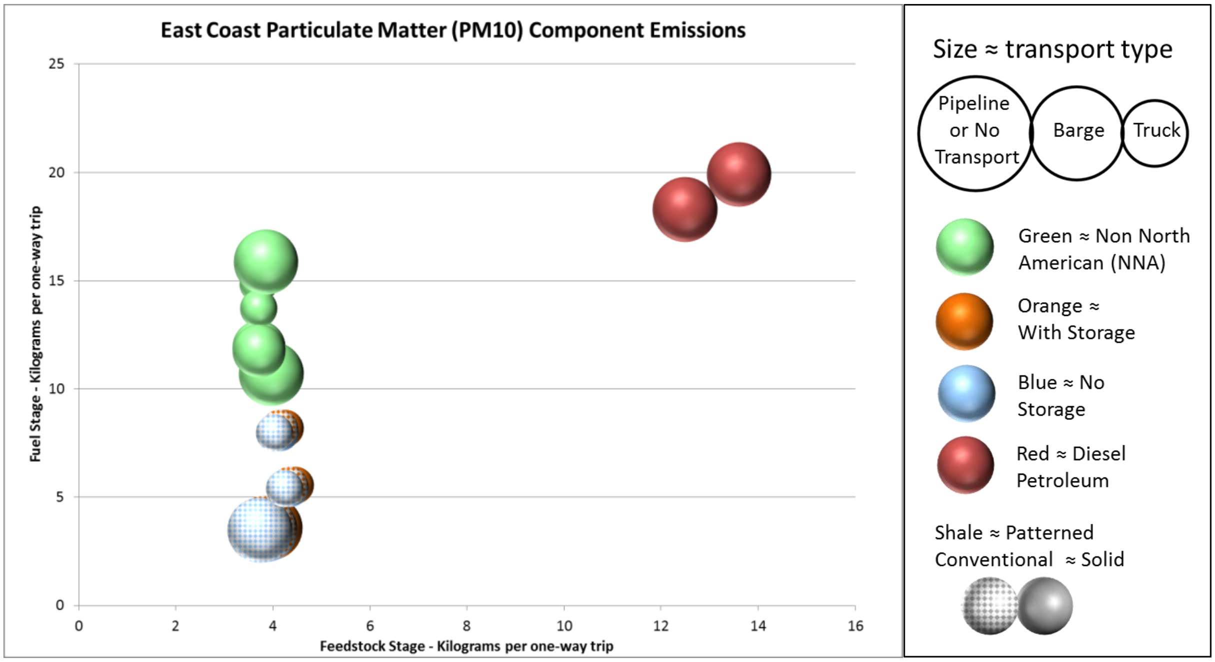


Figure 114 East Coast Case results for SO_x emitted for trip between Port Authority of New York / New Jersey (PANYNJ) and Port of Jacksonville, FL; each column is labeled by a Scenario Code corresponding to the port and pathway from Table 2

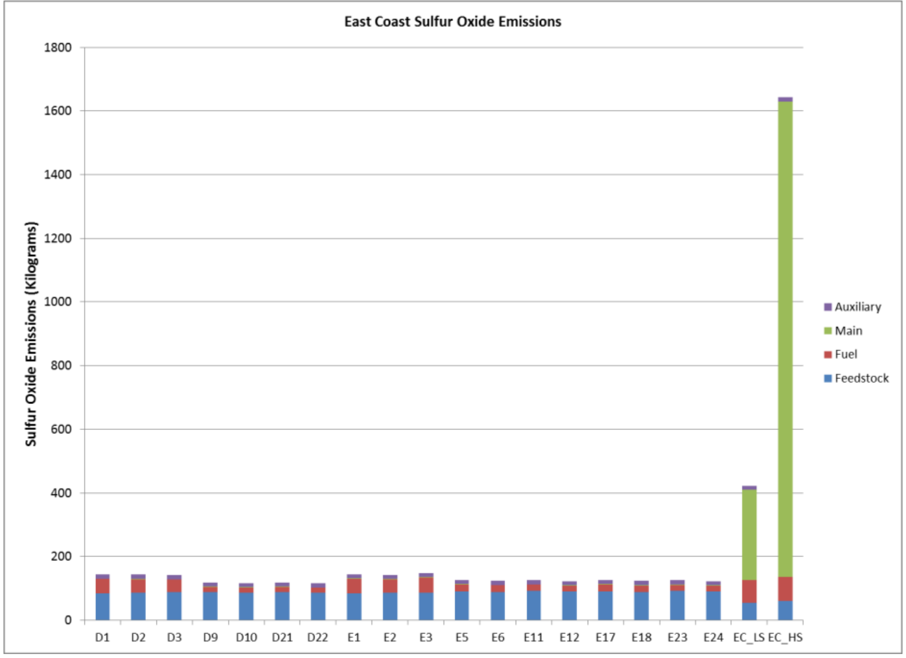


Figure 115 Breakdown of East Coast Case results for SO_x emissions for trip between Port Authority of New York / New Jersey and Port of Jacksonville, FL showing how various pathway decisions affect upstream emissions