Macroeconomic and Environmental Impacts of Port Electrification: Four Port Case Studies

Final Report

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Prepared by

Ellen Schenk, University of Delaware
Edward Carr, Ph.D., Energy and Environmental Research Associates
James J. Corbett, Ph.D. (Co-PI), University of Delaware
James J. Winebrake, Ph.D. (Co-PI), Rochester Institute of Technology

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Acronyms and Abbreviations

CHE	Cargo Handling Equipment
eGRID	Emissions & Generation Resource Integration Database
EIA	Energy Information Administration
ERCT	Electric Reliability Council Texas
FRCC	Florida Reliability Coordinating Council
GGL	Gross Grid Loss
GHG	Greenhouse Gas
Job-Year	Equivalent number of full-time jobs estimated from macroeconomic model
MT	Metric Tonne, equivalent to 1,000kg
NWPP	Northwest Power Pool
RFCE	Reliability First – East
RIO	Regional Input-Output
RTG	Rubber tire gantry crane, also eRTG, electric rubber tire gantry
SAM	Social Accounting Matrix
TEU	Twenty-foot Equivalent Unit (standard measure of a container)

Executive Summary of Potential Impacts of Port Electrification

This research focuses on cargo handling equipment (CHE), and on shore power for vessels during dockside hoteling. Four diverse U.S. ports were selected for case study: i) the Port of Baltimore; ii) Port Everglades; iii) the Port of Houston; and iv) the Port of Seattle. For this work, we focus on electrification of containerized cargo handling equipment and shore power during dockside hoteling. We assess:

1. Economic impacts of this conversion for the county and state in which a port operates;
2. Macroeconomic (jobs and economic growth) aspects of this conversion; and
3. Scenarios describing future-year potential benefits of electric technologies including regional economic activity and increased jobs at the state and county levels;
4. Environmental impacts of electrification by shifting from local diesel engine operation to regional electric grid power.

We use methods for input-output analysis that rely upon estimates of energy demand for current petroleum diesel fuels and potential electrification in ports. Macroeconomic benefits are estimated based solely on energy expenditures which recur over the long-term. Capital costs and other non-recurring spending are not considered in this study. Economic activity is in 2018 dollars, the most recent year of data available in IMPLAN. We use container throughput projections to estimate cargo handling and shore power energy demand in future years for diesel engine power and electrical power. This work relies upon published port data, fuel and electricity prices, and emissions data for diesel engines and regional electrical grid profiles. Combining net energy expenditures with macroeconomic factors, we estimate the direct and indirect regional economic and job output from spending on port electrification.

We produce three macroeconomic scenarios for each port based on zero electrification, fifty-percent electrification, and one-hundred percent electrification of cargo handling equipment and of shore power requirements for hoteling. For cargo handling equipment, we model the switch from regional spending on diesel fueled engines to electric power as a net change in expenditures within the region (state or county, respectively). For shore power, given that most vessels arrive with onboard fuel for auxiliary diesel power, modeling considers spending on shipboard fuel to produce no economic activity within the region. For each port case study, we use the change in emissions rates between diesel and electric power sources for cargo handling equipment to estimate the net emissions change (reduction or increase) and cost per change in emissions (cost per ton abated pollutant or cost associated with increased pollution). We do not evaluate the potential emissions changes from switching hoteling diesel emissions to shore power because assessing regional marine fuel qualities would require its own study.

Cargo handling electrification also reduces most annual air emissions at three of the four ports, with the exception of oxides of sulfur; moreover, the location of emissions from electric power generation reduces the near-port emissions concentrations. At the Port of Seattle emissions reductions are associated with cost savings because the price of electricity in the Northwest is lower than the diesel fuel price. Generally the costs per ton NOx abated fall within or below the cost-effectiveness estimates for reducing other mobile sources. The costs per greenhouse gas ton abated are generally high, similar to other freight GHG abatement costs, with the exception of the Port of Seattle.

Port electrification can produce increased economic output and employment in most regions. Port electrification in the base case doubles state and county economic activity between 2020 and 2050; in the high trend cases, port electrification increases economic activity 3.5 to ~5 times between 2020 and 2050 compared with the economic output of diesel-powered port operations. The Port of Seattle is unique among the four ports modeled. For the Port of Seattle, electrification is less expensive than continuing to use diesel fuel; therefore, it is the only port studies for which energy expenditures are lower under the electrification scenario. This results in net benefits from both emissions and port fiscal standpoints but lower economic output for the region.

Cargo handling electrification produces differing net results across ports, while shore power electrification produces more consistent, if often smaller results. Net economic changes associated with cargo handling equipment depend upon the transfer of expenditures from diesel- to electric-power. Regional economic output and employment produced by electrification are offset by the shift away from diesel-powered cargo handling. Most vessels not using shore power purchase fuel outside the region of study, so all expenditures related to recurring costs of shore power produce new regional economic activity and employment.

The relative share of economic output attributable to shore power and cargo handling electrification varies among the four port case studies. Shore power electrification accounts for about half of the net economic output for the ports of Baltimore (~46% shore power) and Everglades (~54% shore power). For the Port of Houston, shore power contributes ~26% to net economic output changes. The larger macroeconomic impact of cargo handling equipment electrification appears related primarily to Houston's acreage (more vast than other ports) and waterfront practices that utilize more cargo handling equipment; other influencing factors could include the regional economic multiplier and energy pricing differences. For the Port of Seattle, shore power contributes ~131% to changes in economic output; this is due to the lower energy pricing of electricity in the region.

Port electrification reduces port-based diesel-related emissions associated with air quality impacts in nearby port communities. Electrifying cargo handling equipment significantly reduces emissions of NOx and GHGs, and slightly increases emissions of SOx. This is mainly because of national policies setting stricter limits on fuel sulfur in onroad/nonroad diesel fuels, less strict limits on fuel sulfur for petroleum and coal fuels used in power generation; as power generation portfolios adopt more renewable energies and other low-sulfur fossil fuels, this may change (as discussed in Sections 5.5 and 6.4). These results reflect the current electric grid power generation profile, which is projected to shift to renewable sources (i.e., lower sulfur fuels) in coming decades. Generally, the costs per ton NOx abated fall within or below the cost-effectiveness estimates for reducing other mobile sources. The costs per ton greenhouse gas abated are generally high, similar to other freight GHG abatement costs, with the exception of the Port of Seattle.

This work identifies several important implications. First, cargo handling electrification produces differing net results across ports, while shore power electrification produces more consistent, if often smaller results. Second, electrifying ports with more container throughput and/or larger acres of cargo handling can result in greater economic benefits. Third, the relative pricing of diesel fuel and electricity, which vary by region, change relative expenditures and may influence electrification net economic impacts. Fourth, economic output multipliers in some port regions are typically higher than other regions (e.g., Houston versus Baltimore or Everglades). In other words, expenditures in some regions produce more output and may create more jobs. Fifth, the Port of Seattle provides an example where electrification saves money over diesel powered port equipment. These savings offer an opportunity for resources to be reinvested in other community activity that may produce more diverse macroeconomic benefits.

There are several important new research activities suggested by the results of these case studies. One key recommendation based on these four port studies would be to expand this work to help identify national level macroeconomic impacts of port electrification. This expansion could take one or a combination of three forms:

a. **Economic impacts of regionally expanded electrification.** In a regional follow-on study design, we could learn whether multiple regional ports could amplify economic and environmental benefits through coordinated electrification strategies;
b. **National scale economic impacts of port electrification.** In a national study design, we could evaluate nationwide macroeconomic impacts from port electrification – perhaps providing information to help prioritize those ports and regions with attractive combinations for ports (expenditures), regional economics (economic output and employment), and environmental performance (change in emissions); and
c. **Longitudinal effects of electric grid transitions renewables and cleaner energy.** A longitudinal study design could incorporate the expected changes in electrical grid power as renewables and cleaner energy are adopted to provide insights into the long-term changes in emissions associated with electrification.

1 Introduction

Opportunities and interests in electrification may provide a means to better stewardship. Electrification helps transition communities to more diverse energy options and can reduce dependence upon carbon-intensive petroleum fuels such as diesel. Centralized (or in some cases distributed) electric power generation capacity can take advantages of economies of scale in both fuel and technology options for cleaner, lower-GHG, and affordable power for industry and communities. These stewardship goals are increasingly part of the mission and master planning for the nation’s ports.

Electrification of our nation’s ports may also lead to improved economic performance. New and innovative investment can help modernize ports, transition ports to greater throughput efficiency, and advance integrated supply chains. Electrification of port operations might also provide community wide economic benefits in terms of expenditures that directly and indirectly increase regional economic activity. Greater economic activity within region is associated with increased employment in the region, even if these new jobs may relate to electricity generation, distribution, and related jobs beyond the gates of the port. Synergy between improving port operations and regional macroeconomic activity deserve more analysis.

Investment in port infrastructure, and infrastructure asset management in general, can be considered to be a choice of resource allocation to achieve beneficial outcomes. In the context of a firm, these outcomes arguably include cost reductions, value-added services, increased revenue, and corporate reputation. In the context of public assets or infrastructure that is co-invested or co-governed by regional or state authorities, beneficial outcomes include measures of welfare for the multiple and diverse communities that are impacted. It is in these contexts that this work evaluates port electrification.

Greater consensus on the economic and environmental benefits is needed to facilitate ports executing electrification projects. Currently, port electrification strategies are shown to achieve environmental benefits, and port infrastructure has also offered cost-effective pathways to achieve these environmental benefits. However, new investments to implement electrification strategies require resources, and costs can be a barrier. Adoption barriers may be overcome through regulatory mandates, such as California Shore Power rules for containerships and passenger cruise ships. Essentially requiring technologies or best practices sets implementation targets as corrections to market externalities. Another way is to address adoption barriers by demonstrating economic benefits that coincide with environmental stewardship strategies. If port businesses or the economic welfare of the region benefit from economic activity that implements environmental strategies, this can reduce the economic barrier(s) to community and business decisions to pursue port electrification. In conducting appropriate analyses on the environmental and economic (including macroeconomic) impacts associated with electrification. By demonstrating the potential benefits to the regional economy of port electrification, ports may better access funding from both the private and public sectors.

1.1 Project Scope

The purpose of this project is to evaluate the environmental and macroeconomic impacts of converting a variety of diesel-fueled port technologies to operate on electricity. This research focuses on cargo handling equipment (CHE) at US ports, and on shore power for vessels during dockside hoteling. Using appropriate modeling tools, we assess:

5. Economic impacts of this conversion for the county and state in which a port operates;
6. Macroeconomic (jobs and economic growth) aspects of this conversion; and
7. Scenarios describing future-year potential benefits of electric technologies including regional economic activity and increased jobs at the state and county levels;
8. Environmental impacts of electrification by shifting from local diesel engine operation to regional electric grid power.

The macroeconomic impacts of electrifying US ports could have a transformative effect on our nation's economy. Displacing petroleum with electricity may lead to significant economic activity and job growth – not only in the utility sector, but also across the entire economy due to fuel cost savings, emissions benefits, and reductions in petroleum imports, to name a few. This project will explore the macroeconomic and environmental impacts associated with a conversion to electric technologies at US ports. In particular, we will conduct environmental, microeconomic, and macroeconomic analysis to determine the regional and national impacts (jobs and economic growth) from converting these systems to electric using IMPLAN, an economic modeling software package.

This report studies four different ports across the United States: Port of Baltimore, Port Everglades, Port of Houston, and the Port of Seattle. These ports were chosen due to differing geographic location, data availability, port heterogeneity, and potential electrification. We consider this work to be a prototype for broader analyses that may consider multiple ports in a given region, may consider highly networked ports that may jointly modernize and convert to electric power for shared economic benefits, and ultimately for a national study how port electrification can be a factor in producing jobs, broader economic activity, and improve environmental performance.

1.2 Report Organization

The report presents a literature review (Section 2) that introduces research on electrification and a brief summary of port-specific studies for selected ports. Section 3 presents the methods for macroeconomic input-output analysis, how we develop port scenarios including future growth modeling with three levels of electrification (none, 50%, and 100%). Section 4 describes the data for energy pricing, cargo throughput trends, conversion of existing reports to estimates of energy per container (per TEU), net fuel usage and expenditures using petroleum pricing for the diesel base scenarios, environmental performance data for each case port's regional electrical grid power and port cargo handling emissions. Section 4 also describes the projected energy demand and expenditures using electricity pricing. Jointly, the expenditures for fuel and for electricity provide necessary inputs to estimate macroeconomic output and potential employment resulting from port electrification.

Section 0 reports results of each port case study for region specific economic output and jobs at both the county and state levels. These results are provided for electrification of cargo handling and for shore power of containerships during dockside hoteling. Also presented in Section 0 are estimates of emissions changes when ports shift cargo handling equipment from diesel to electricity power; these are presented for the year 2020 given available electric data. Section 0 discusses key findings, identifies major conclusions from this stage of the research, and recommends specific studies that could expand upon the insights of this work. In particular, future changes in electrical grid power generation to adopt more renewable energy could result in lower costs (more economic benefit) and better environmental performance (lower emissions of pollutants and greenhouse gases).

Section 7 provides references, and Section 8 provides data tables and other supporting information.

2 Literature Review

We summarize related research informing the scope of project, including summaries of similar study methods and findings. This review also identifies port-specific studies for the ports evaluated in this work. Lastly, this section presents an overview of relevant energy prices that informed macroeconomic cost inputs.

2.1 Research on Electrification of Port Infrastructure

The following studies compare economic and environmental benefits of electrification with respect to equipment. Yang and Chang compare rubber-tired gantries (RTGs) with electric rubber-tired gantries (E-RTGs) and find that E-RTGs have the potential to achieve 86.60% energy savings and reduce CO_2 emissions by 67.79% compared to RTGs (The Northwest Seaport Alliance, 2019; Yang & Chang, 2013). An important aspect of their study is the examination of RTG conversion systems, which include different methods such as bus bar, overhead conductor systems, and cable reel systems. The installation of the bus bar system includes power supply lines which allow E-RTGs to switch off their diesel generators when operating the area of the lines and switch off their electric power when moving to an area outside. RTG equipment powered by this bus bar system can reduce energy consumption by 60% and emissions by 95%. The system is a small project with a low cost and simply configuration. Overhead conductor systems allow RTGs to obtain electric power from overhead cables. When electric power is off, RTGs are still able to operate through their diesel engines. These systems allow for high mobility and flexibility; however, they require large investment costs. The cable reel systems include installation of cable reel RTGs which travel around a traffic lane, controlling speed, Advantages of this system include flexibility and minimal infrastructure investment, which means low maintenance costs (Yang & Chang, 2013).

Kim, Rahimi, and Newell provide a life-cycle assessment of yard tractors, specifically looking at the Port of Los Angeles due to their plan to reduce greenhouse gas emissions by 35% of 1990 levels by 2030 (Kim et al., 2012). This life-cycle assessment divides into three phases: production, use, and disposal. Based on assumptions about the amount of time tractors need to charge and hourly usage, the authors estimate the emission factors for electric tractors at 14 kg CO_{2e} per operating hour. Using prior studies to estimate emissions at each phase of the life-cycle, the authors determine the total emissions for both electric and diesel vehicles. Electric vehicles emit 327,000 kg/10-year lifetime for CO_{2e}, while diesel engines generate 781,000 (Kim et al., 2012). Another important aspect of the study is modeling changing in the number of tractors and their electrification. Kim et. Al. examine three adoption rates: 20%, 35%, 50%. Despite varying numbers of electric yard tractors in 2010, 2015, 2020, 2025, and 2030 for each rate, CO_{2e} emission rates exceed the projected target. As a result, there are no scenarios in which the target is met. However, there is still a drastic reduction in emissions as a result of electrification conversion (Kim et al., 2012)

Gillingham and Huang focus on shore power in their study of the US as a whole (Gillingham & Huang, 2019). They present three different scenarios of electrification with increasing decarbonization efforts that can be replicated using IMPLAN scenarios. The first scenario assumes that in 2019, marine vessels will increasingly use shore power at berth as opposed to fuel. In 2025, the scenario assumes that all vessels will use onshore electricity in port. The second scenario electrifies all fuel used within the boundary of the North American Emissions Control Area. The last scenario electrifies all fossil fuels in the entire marine sector that are attributed to the US energy system by electrifying all ship engines, including auxiliary. In all three scenarios, fuel consumption decreases dramatically along with CO_2 emissions. In the first scenario, emissions decline by 0.3% in 2030 and 1.2% in the second scenario. By 2050, the first scenario causes a 7 - 13% decrease in emissions while the second lowers emissions by 40%. The third scenario results in a 54% decrease in NO_x emissions and 34% decline in $PM_{2.5}$ in 2050 (Gillingham & Huang, 2019).

To project the change in emissions as a result of electrification, it is important to create or study an emission inventory for each port in order to have a baseline. While most ports that are to be analyzed in this study have an existing inventory, they should all use similar methodologies to ensure accuracy across our results. Browning and Bailey explain how to properly assess emissions from cargo handling equipment (CHE) and ocean-going vessels based on the level of detail needed, as well as providing equations and data necessary such as load factors and emissions factors (Browning & Bailey, 2006). For the ports in this study, Port Everglades, Port of Houston, and Port of Seattle have adequate inventories. The Port of Baltimore has an emissions inventory from 2016, but the report is lacking in methodology and only includes percent changes from 2012-2016. More information will need to be gathered from this port to generate a sufficient inventory.

The Port of Long Beach partnered with Long Beach City College as part of their efforts to obtain zero-emissions terminal equipment by 2030 and zero-emissions trucks by 2050 (Infusino et al., 2018). The report, *Zero-Emission Port Equipment Workforce* Assessment, details new job creation as a result of zero-emission efforts and skills and competencies needed to have an adequate workforce. The report estimates workforce needs and eRTGs adoptions as current RTGs are retrofitted. An estimated 50% reduction in maintenance is predicted compared to diesel equipment. Most of the workforce needed as ports convert to electrification from diesel will be in the infrastructure area. Maintenance will most likely be completed by retraining the existing workforce on new equipment (Infusino et al., 2018). This report may be useful to evaluate employment effects of shore power and additional electrification efforts, to see if new jobs will be added or people will simply be retrained on new equipment.

2.2 General approaches in prior studies

2.2.1 Vessel Electrification Shore Power Technology Assessment

The EPA shore report, *Shore Power Technology Assessment at US Ports* authored by the Eastern Research Group, Inc and Energy & Environmental Research Associates, LLC, provides a methodology for estimating emissions and energy use from shore power (Eastern Research Group & Energy & Environmental Research Associates, 2017). This methodology can be summarized with the following equation:

Where:

$$SPE = MEP * AEF * LF *^{j,k} *^{j,k} * SEF_{i,j,k\; j\; j\; j}\; yr\; call^{i,k}$$

$SPE_{i,j,k}$ = Shore power emissions for pollutant *i,*for vessel type *j*, in year *k*
MEP_j = Average main engine power, in kW, for vessel type *j*
AEF_j = Fraction of main engine power attributable to auxiliary engine power, in kW, for vessel type *j*
LF_j = Auxiliary engine hotelling load factor, in percent, for vessel type *j*
$C_{j,k}$ = Vessel calls for vessel type *j* in year *k*
$T_{j,k}$ = Hotelling hours at berth for vessel type *j* in year *k*
$SEF_{i,k}$ = Shore power emissions factor for pollutant *i* in year *k*

The next equation is used to estimate annual vessel emissions when using auxiliary power when hotelling is:

Where:

$$VE = MEP * AEF * LF *^{j,k} *^{j,k} * VEF_{i,j,k\; j\; j\; j}\; yr\; call^{i,j,k}$$

$VE_{i,j,k}$ = Vessel emissions for pollutant *i*, for vessel type *j*, in year *k*
MEP_j = Average main engine power, in kW, for vessel type *j*
AEF_j = Fraction of main engine power attributable to auxiliary engine power, in kW, for vessel type *j*
LF_j = Auxiliary engine hotelling load factor, in percent, for vessel type *j*
$C_{j,k}$ = Vessel calls for vessel type *j* in year *k*
$T_{j,k}$ = Hotelling hours at berth for vessel type *j* in year *k*
$VEF_{i,j,k}$ = Vessel type emissions factor for pollutant *i*, for vessel type *j*, in year *k*

Vaishnav et al. explains how to appropriate clean vessel call data and presents equations to determine costs and benefits of shore power (Vaishnav et al., 2015). The equations for the private benefit and environmental benefit are given by:

$$ben\_pvt_{i,j} = (m - e_j) * ener_{i,j} * o_{i,j}$$
$$ben\_env_{i,j} = ener_{i,j} * o_{i,j} * \sum_q (eim_q - \frac{eie_{q,j}}{1-t}) * sc_{q,j} * 10^{-6}$$

Where:

m is the cost of electric power generated from marine fuel in $/kWh
e_j is the average price of electricity in each state of port *j*
$ener_{i,j}$ is the amount of energy (kWh) that would be generated on shore
$o_{i,j}$ is a dummy variable, with the value of one if vessel i uses shore power at port j, zero otherwise
eim_q is the emission index, in grams/kWh, for pollutant k for marine diesel or gas oil
$eie_{q,j}$ is the state-average emissions in test in grams/kWh for pollutant k for the electricity generated in port j
t is the transmission and distribution loss, assumed to be 10%
$sc_{q,j}$ is the value, in dollars, of emitting pollutant k at port j

The costs are cst_ship_i, which is the annualized cost of retrofitting a ship, and cst_port_j,the annualized cost of retrofitting a port, defined as:

$$cst\_ship_i = r_i * p_i$$
$$cst\_port_j = c * k_j$$

Where:

r_i is a binary variable which takes the value of one if the ship is retrofitted and zero otherwise
p_i is the annualized cost of retrofitting a ship for shore power
k_j is a positive integer that represents the value of the number of berths that are retrofitted at port *j*
c is the sum of annualized cost of retrofitted a single berth to provide shore power and annual equipment operating and maintenance costs

Vaishnav, et. al. assumed that retrofitting each ship would cost $500,000 and installing an electrical distribution network and terminal substation would cost $1,000,000 and $500,000 respectively (Vaishnav et al., 2015). These costs are based off the 2004 Port of Long Beach Cold Ironing study. This report will be also useful to replicate the data cleaning of vessel call data.

2.2.2 Electrification Infrastructure Costs

Infrastructure costs are a large factor in determining costs of shore power. As stated above, Vaishnav, et. al. assumed retrofitting each ship to be adaptable to shore power would cost $500,000 (Vaishnav et al., 2015). Wang, et. al. estimates that shipside modifications could range from $300,000 to $ 2 million depending on the type of vessel and amount of retrofitted needed (Wang et al., 2015). The Port of Oakland allocated $60 million to install shore power infrastructure at their eleven berths on six terminals (Port of Oakland, 2013). The U.S, Navy, which has used shore power on their ocean-going vessels (OGV) for many years, estimates that daily electricity consumption for 14 vessels (35,000 kWh) costs $5,000 per day, or $0.146/kWh (Eastern Research Group & Energy & Environmental Research Associates, 2017). This is probably higher than normal OGV since they most likely will not draw as much power as navy vessels. Finally, the Port of Long Beach spent $185 million on dockside hookups and other infrastructure to allow ships to hook up to shore power (Port of Long Beach, 2017). It is clear that costs of infrastructure will differ based on the size of the port and number of berths.

2.3 Other Similar Freight and Heavy Duty Equipment Electrification Studies

There are similar studies that have been conducted related to electrification. Their methodologies can be adapted and modeled to fit the design of the analysis. The heavy-duty impact analysis by Goldberg is not related directly to ports but uses IMPLAN to examine the macroeconomic impacts that fuel efficiency has on employment, salary, and GDP (Goldberg, 2010). The study by EPRI of electric transportation in Ohio is again not specifically about ports but includes multiplier calculations and impacts on petroleum displacement, emissions, maintenance, and capital costs which relate to the scope of the study (Electric Power Research Institute, 2006).

Winebrake, et. al. look at electric forklifts and shore power (Winebrake et al., 2018). In order to accurately model the effects, they use different scenarios to evaluate the impacts of electrification. For shore power, the scenarios differ in who savings are passed onto. For forklifts, the scenarios are savings passed on to the consumer or to shippers. Under various scenarios, Winebrake and Green estimate that electric forklifts will displace 1.8 billion gallons of fuel per year in the United States by 2030, results in savings of $2.4 billion per year and 17,900 new jobs. From 2015-2030, they predict that impacts will be 156,000 cumulative job-years and an increased economic output of $36.4 billion. A benefit of this study is that the report models shifts in expenditures, specifically electricity and petroleum demand and consumption. These are important details of electrification that need to be considered in the analysis. For shore power, the report estimates that 945 million gallons of fuel per year will be displaced by 2030, saving $740 million and increasing employment by 14,600 jobs (Winebrake et al., 2018).

2.4 Port Specific Studies

This project scope identified four ports to evaluate macroeconomic impacts of cargo handling and vessel shore power electrification. This section provides a summary of available economic and environmental studies for the Port of Baltimore, Port Everglades, Port of Houston, and Port of Seattle.

2.4.1 Port of Baltimore

The 2017 economic impact report by Martin Associates evaluates the economic and employment impact of the cargo handling activity at the terminals at the Port of Baltimore (*THE 2017 ECONOMIC IMPACT OF THE PORT OF BALTIMORE IN MARYLAND*, 2018). The economic impact includes changes in personal income, revenue, and tax. The report found that port activity is responsible for 37,000 jobs (15,300 direct, 16,780 induced, and 5,190 indirect jobs), $3.3 billion in person income, $2.6 billion in business revenues, and 249,875 related jobs. Specifically looking at commodities, containerized cargo accounts for 4,169 direct Maryland

Port Authority (MPA) jobs and 11 private jobs, for a total of 4,179. This is the largest direct job impact for firms in the maritime sector. These jobs consist of longshoremen, trucking, warehousing and repair operations, and freight forwarder brokers. Containerized cargo also accounted for $558 million in revenue impact (*THE 2017 ECONOMIC IMPACT OF THE PORT OF BALTIMORE IN MARYLAND*, 2018). However, there is little detail about the methodology used to determine direct, indirect, and induced effects. More information is needed to determine the accuracy and validity of the results and if they can be used to guide this inventory.

2.4.2 Port Everglades

While no prior studies have evaluated Port Everglades electrification specifically, one study evaluated macroeconomic impacts of shore power for Florida (Winebrake et al., 2018). That study looked at twenty-five U.S. ports, including container ports and cruise ports. In Florida, the study considered Port Everglades and five other ports. While that study did not specifically break out statewide economic output and jobs resulting from shore power electrification, this work uses a consistent set of methods and extends that work to consider port-specific data and state/county level economic multipliers for Port Everglades.

2.4.3 Port of Houston

EPRI studies the Port of Houston and current electrification efforts along with identifying additional opportunities. The report looks at directly hooking up to the power grid for cranes, replacing combustion engines with electric motors powered by batteries, and using hybrids to replace other diesel engines. Costs for each would depend on whether equipment is retrofitted or purchased used or new. An electric forklift costs $7,700 more to operate annually than a diesel forklift (Electric Power Research Institute, 2006). The report states that if 100 forklifts were converted to electric, that would result in an emissions benefit of 64 tons of NO_x per year (van de Walle et al., 2013).

2.4.4 Port of Seattle

Similar to the study of the Port of Baltimore, the impact report looks at the impacts of cargo handling activities of the Port of Seattle and Port of Tacoma (The Northwest Seaport Alliance, 2019). Impacts, such as jobs, business output, and labor income, are broken out by types of cargo. Asa result of cargo activities in 2017, the Northwest Seaport Alliance (NWSA) was responsible for 58,400 total jobs. The NWSA imported its highest volume of containerized cargo TEUs in 2017 at 3.7 million TEUs. As a result of this activity, 14,900 direct jobs were supported, with the majority of jobs in the trucking, logistics, and warehousing sector. Total jobs from containerized cargo shipping through NWSA was 45,500. There is not much detail as to the methodology of the report, so that would need to be investigated further. In addition, the impacts include the Port of Tacoma as well as Seattle, so the independent impacts for the Port of Seattle are most likely less than what is in the report.

3 Methods

This section presents the study methods for macroeconomic input-output analysis, port specific scenarios for assessing effects of partial or full electrification of cargo handling equipment (CHE) and shore power, and for evaluating comparative changes in environmental performance between grid electric power and port-based diesel engine combustion.

3.1 Input Output Analysis

Pioneered by economist Wassily Leontief in the late 1930s, input-output (I-O) analysis is a theoretical framework for estimating the relationships within industries in an economy and the changes in demand for production inputs as a result of changes in demand for the final product (Miller & Blair, 2009). The basic Leontief model takes observed economic data from a region and quantifies the industries of interest that produce inputs and consume outputs from other industries. This is regional input-output analysis relies upon a Social Accounting Matrix (SAM), which is what will be used in this study. Using information about a direct effect (e.g. purchasing fuel), I-O analysis models the ripple effect this transaction has through the economy, quantified by indirect and induced effects (Christ, 1955). Indirect impacts are spending on local goods and services as a result of the initial direct effect, while induced effects are the impact of the indirect effects; in other words, the impact of increased household income from that increased local spending created by the direct effects (Hughes, 2018). The total effect is the sum of the direct, indirect, and induced effects.

Each economic activity, or event, is represented as a purchase or sale of inputs and outputs. I-O analysis details the inter-industry transactions that take place, linking different sectors together by their shared dollar flow (Miller & Blair, 2009).

I-O analysis is based on multiple assumptions to derive appropriate interindustry matrices (the visual representation of the linear equations that make up the analysis) and theoretical considerations. The first assumption is constant returns to scale, meaning that there is an equivalent increase in output when input (capital and labor) increases (IMPLAN, 2019a). I- O models also assume that all firms within a sector have a similar production process. There is assumed to be no adjustment in prices as a result of changes in supply constraints. This means that firms can increase inputs to meet additional demand (Bess & Ambargis, 2011). With respect to regional I-O analysis, local industries are assumed to make purchases outside of the region of interest, thus creating leakages (Bess & Ambargis, 2011).

The results of I-O analysis produce multipliers, a measure of how dollars added in an economy are distributed and produce additional economic activity, which are estimated for specific industries (Hughes, 2018). If, for example, if the multiplier for fuel sales is 1.25 and the multiplier for electricity is 0.33, this means that a $1 increase in local fuel sales will ultimately increase sales by local fuel by $1.25 and sales by local electricity by $0.33. Type I Multipliers includes those which exclude effects of household spending. This is the indirect effect divided by the direct effect. On the other hand, Type II Multipliers include effects of household spending, so the calculation is the indirect and induced effect divided by the direct (Hughes, 2018). There is also Type SAM multipliers, which are the direct, indirect, and induced effected divided by the direct effect.

IMPLAN is an economic impact assessment system that uses regional I-O analysis to develop models of inter-industry flows in a particular economy. IMPLAN accomplishes this by identifying the monetary value of inputs in a variety of sectors and translating that to indirect and induced impacts by sector, using local multipliers and purchase coefficients. There are 536 IMPLAN sectors representing private industries in the United States. IMPLAN displays multipliers for each sector, and may be constructed for output, employment, labor income, and value added (IMPLAN, 2019b). Output is the total output generated from an increase of one dollar of output in the industry of interest. Employment multipliers are the total jobs created as a result of one additional job in the target industry. The labor income details the additional income form a one-dollar increase. Finally, the value-added multiplier is the total dollars of value added as the result of one additional dollar. There are four different multiplier effects, as with impacts, direct, indirect, induced, and total, and their meanings are similar to the definition of the impacts with the same name (IMPLAN, 2019b).

For one the ports, we calculate an institutional spending pattern. These patterns "represent a general spending distribution for measuring broad institutional activity in the region" (Lucas, 2019). There are different options that this spending can be attributed to, including governments, capital, enterprises, and households. We attribute this spending to capital.

IMPLAN uses dollar amounts to calculate the output and employment impacts of increased or decreased spending in different sectors. Geography is also an important component of IMPLAN analysis. A spending pattern in geography may have different employment and output impacts than the same spending pattern in a different area of the country (French, 2018). Using IMPLAN, we modeled the impacts of $100,000 of spending at each port in the natural gas and crude petroleum sector as well as the electricity sector. Since IMPLAN accounts for regional differences that include differences in compensation and location of firms, we conducted analyses at both at the state-level (Maryland, Florida, Texas, and Washington) and at the county-level where the ports are located (Baltimore County, Broward County, Harris County, and King County). This spending pattern produced diesel and electric Type SAM multipliers at both the state and county level, which were ultimately used to determine changes in output (economic activity) and employment due to electrification. The output multipliers describe the total output in the study region resulting from one dollar of direct input.

Macroeconomic benefits are estimated based solely on energy expenditures which recur over the long-term. Capital costs and other non-recurring spending are not considered in this study. Economic activity is in 2018 dollars, the most recent year of data available in IMPLAN. Employment is reported as job-years. To use an example to define job-years, if an electricity provider employs 100 people to work full-time over five years, this is equivalent to 500 job-years (French, 2018).

3.2 Scenarios

We first develop our market penetration scenarios and collect relevant data in Section 4, which include:

- Energy prices for petroleum and electricity;
- Electric technology incremental costs and infrastructure costs; and
- Electricity mix assumptions.

Scenarios begin in 2020 and extend to 2050. Scenario development will include a baseline and high scenario. Building upon the data collection efforts in Task Market Penetration Scenario Development will include projections, estimates, or assumptions of the following, for each examined technology:

- Baseline Scenario market penetration levels and activity for conventional and electric technologies;
- Alternative Scenario market penetration levels and activity for conventional and electric technologies; and
- Energy prices for conventional and electric vehicle technologies ($/gallon or $/kWh).

Together these variables will be used to estimate the energy use, emissions, and expenditures associated with each scenario, which will then be employed as inputs in the next subtask—modeling macroeconomic impacts.

We next conduct a macroeconomic analysis of consumption and production shifts associated with large-scale replacement of petroleum powered technologies with electric-powered alternatives. A major component of the macroeconomic analysis will involve modeling the effects due to electricity replacing petroleum as a fuel through the use of input-output (I-O) analysis. The results of our scenarios are in Section 0.

3.2.1 Port Specific Scenarios

For each port, we conducted three different scenarios of electrification and projected the results from 2020 to 2050 in five-year increments. Each scenario has a baseline and high result, setting a minimum and maximum boundary for the results of the scenario. The first scenario was 0% electrification. This means that all economic activity and employment from energy consumption are in the diesel sector – there is no electrification. The next scenario was 50% electrification. In this scenario, 50% of the kWh comes from diesel fuel, and 50% comes from electricity. Finally, the 100% scenario models output and employment in the electricity sector as a result of all energy that the port uses coming from electricity.

3.3 eGRID Emissions Modeling

EPA's Emissions & Generation Resource Integrated Database (eGRID)[1] provides an inventory of electric power generation systems, including generator/plant attributes and environmental attributes, including emissions and emission rates. We use eGRID emission factors by subregion (Figure 1) to estimate the change in emissions from switching from diesel to electrification.

Specifically, we use emission factors from the following subregions, by port:

- Port of Baltimore: Reliability First – East (RFCE)
- Port Everglades: Florida Reliability Coordinating Council (FRCC)
- Port of Houston: Electric Reliability Council Texas (ERCT)
- Port of Seattle: Northwest Power Pool (NWPP)

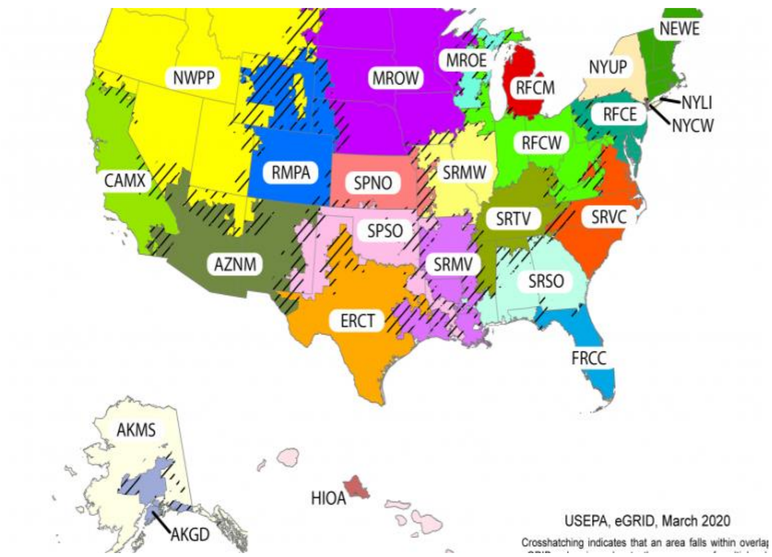

Figure 1: eGRID subregion map

Emissions from electricity generation are estimated using the emission factors multiplied by the estimate of energy usage in kWh, multiplied by the regional Grid Gross Loss (GGL) estimates from eGRID[2] (abbreviated in Table 1) to get emissions from total energy required. GGL accounts for line losses, power losses, and transmission and distribution losses, accounting for energy lost in the electricity supply system. For example, if 100 kWh of energy are required at the Port of Baltimore, in the eastern region, then 105.13 kWh of energy would need to be generated by the grid following (100 kWh / (1 - 0.0488)) in order to account for grid losses. Basing emissions on total energy generation rather than end user consumption requirements results in larger emissions estimates, but better reflects grid conditions and true emissions.

[1] https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

[2] https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid-questions-and-answers

Equation 1: Estimating total energy based on energy required and gross grid losses

$$Total\ Energy\ (kWh)\ =\frac{Energy\ Required\ (kWh)}{1-\ GGL}$$

Table 1: eGRID 2018 GGL estimates

Power Grid	2018 GGL %
ERCT	4.87
FRCC	4.88
NWPP	4.80
RFCE	4.88
U.S.	**4.87**

4 Data Inputs

In order to conduct our scenario, we gathered data about fuel prices, cargo throughout, and electricity at each port. Using this information, we calculated energy per TEU, projected fuel usage, and diesel and electricity consumption.

4.1 Energy Prices

Gasoline and diesel prices are updated weekly by the EPA, while electricity prices are supplied monthly based on the sector in which the electricity is used (US Energy Information Administration, 2019). The prices are broken out by state and city, so the data will differ depending on the port. The EPA also has historic data that can be downloaded and analyzed. Since this data changes weekly and monthly, amounts will need to be decided on that will be used for the duration of the project, whether based on the descriptive statistics below or forecasted prices. The graphs below show No 2 diesel prices historically since 1994, and wholesale and retail prices for residual fuel that is less than or equal to 1% sulfur. Prices have been increasing since 2016 after taking a sharp fall in 2014. The same pattern occurred in 2008, falling dramatically in 2009, and the price had slowly been recovering since then.

Electricity prices are also updated monthly by the Energy Information Administration. Prices can be broken out by geographical region, state, or city. The graph below shows the average yearly price in the US of electricity since 2001. Section 4.1.1 further shows electricity prices for the ports of interest, which are used as data inputs in our analysis.

This work uses pricing data for diesel fuel and electricity as it was provided publicly, namely as nominal prices. Averages use monthly fuel prices in nominal dollars from 2014 to 2019. Comparing this with the energy prices using constant dollars, average energy prices differ by less than 3% across all regions. Using nominal prices translates into a diesel fuel price difference of $0.05/gallon and an electricity price difference less than a quarter of a cent per kW. These differences fall within observed volatility of energy prices for diesel and electricity.

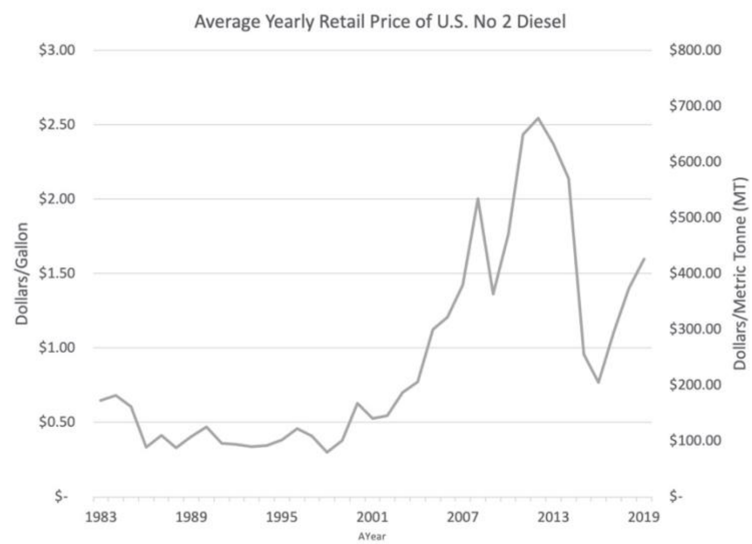

Figure 2: Average Yearly Retail Price of U.S. No 2 Diesel (U.S. Energy Information Administration, 2020b)

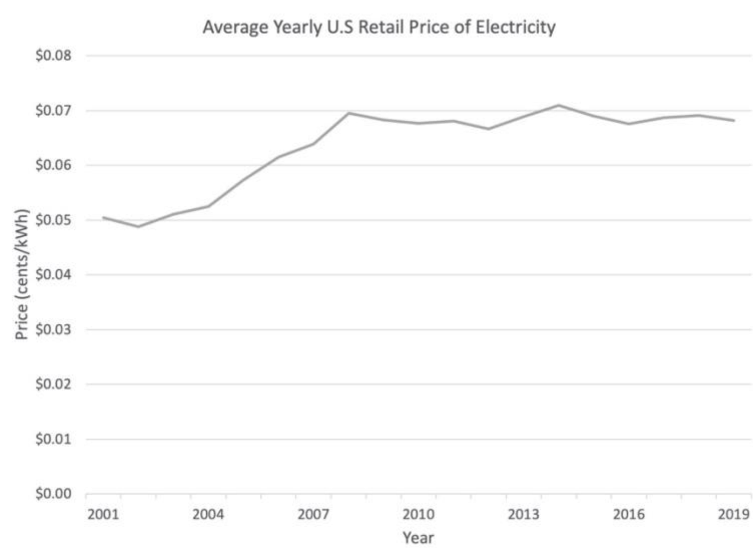

Figure 3: Average Yearly U.S. Retail Price of Electricity (U.S. Energy Information Administration, 2020a)

4.1.1 Diesel Fuel Prices

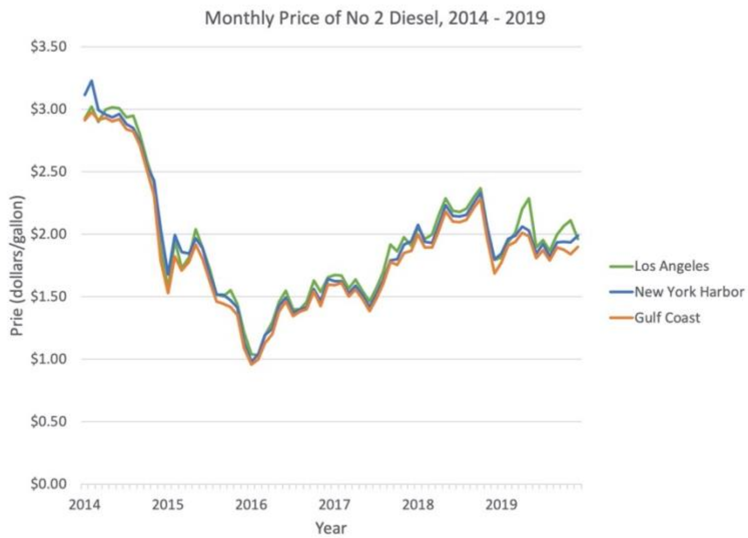

Figure 4: Monthly Price of No 2 Diesel (2014 - 2019) (US Energy Information Administration, 2020b) (US Energy Information Administration, 2020a)(US Energy Information Administration, 2020c)

To determine the fuel price of diesel for each port and ultimately determine the diesel expenditures based on energy consumption, we used the average monthly price of No. 2 diesel from 2014 – 2019. This data was not available for each port, but we used the prices at the Port of Los Angeles, New York Harbor, and the Gulf Coast to represent coastal prices for the ports. The Port of Baltimore and Port Everglades were assigned the east coast price average of $1.92/gallon from New York Harbor. The Port of Houston used the average from the Gulf Coast, which was $1.86/gallon The Port of Seattle used the average from the west coast from Los Angeles, or 1.95/gallon.

Table 2: Fuel Prices by Port

Port	Fuel Price ($/gallon)	Electricity Price ($/kWh)
Port of Baltimore	$1.92	$0.083
Port Everglades	$1.92	$0.078
Port of Houston	$1.86	$0.056
Port of Seattle	$1.95	$0.045

4.1.2 Electricity Prices

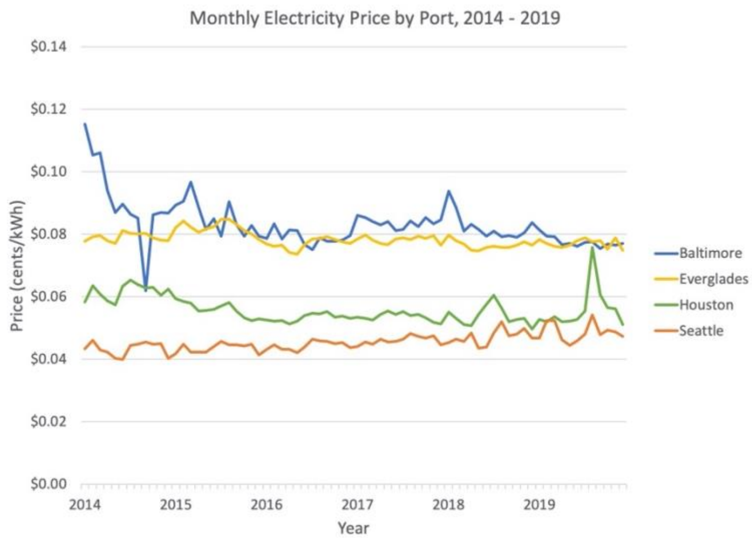

Figure 5: Monthly Electricity Prices by Port, 2014 - 2019

Electricity prices are from the Energy Information Administration. To get a price to use to calculate electricity expenditures, we took an average of the monthly electricity prices at each port from January 2014 to December 2019. The average price for the Port of Baltimore is $0.083; for Port Everglades, $0.078; the average price at the Port of Houston is $0.056; and finally, the Port of Seattle average price is $0.045. Although data were available through April 2020, we chose to only calculate the average through 2019 due to the volatility of the prices throughout the beginning of 2020.

4.2 Cargo Throughput

Using data from the US Army Corps of Engineers, we aggregated actual TEU cargo throughput from 2003 – 2018. The graph below shows TEU throughput yearly by port.

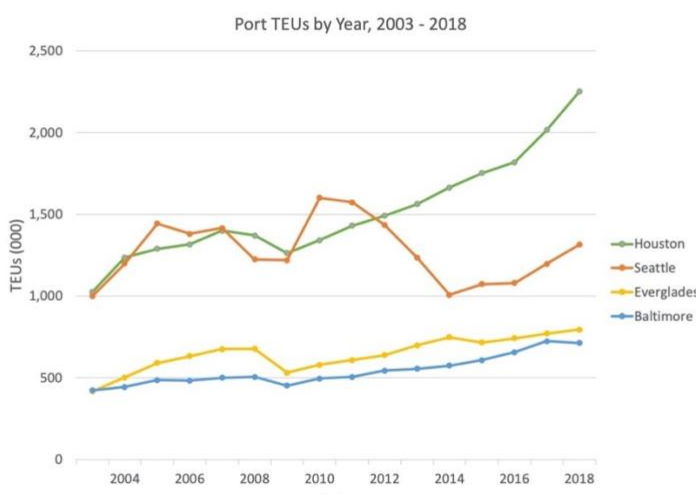

Figure 6: Port TEUs by Year, 2003 - 2018

Table 3: Port TEU Projection Growth Rates

Port	Baseline	High
Baltimore	3.00%	5.40%
Everglades	2.50%	4.30%
Houston	2.75%	4.75%
Seattle	2.75%	4.55%

To determine cargo throughput, or twenty-foot equivalent units (TEUs) per year, we looked at historic TEU throughput as well as the port master plans to calculate expected TEU throughput. For each port, we determined a baseline and high growth rate, which again, sets boundaries on our estimates. The Port of Houston master plan did not list a growth rate, so we took the average of the other three ports and their baseline and high numbers and used those numbers as growth rates for Houston. In addition, the Port of Seattle growth rates were listed in the master plan for both Seattle and Port of Tacoma, but we have just used Seattle TEUs in our analysis. The Port of Baltimore has the highest baseline and high growth rate at 3.00% and 5.40% per year respectively. We used the US Army Corps of Engineers Waterborne Container Traffic data to find the TEU throughput for 2018, and that number was the basis of the growth calculations for 2020 onward (United States Army Corps of Engineers, 2018). This is illustrated in Figure 7.

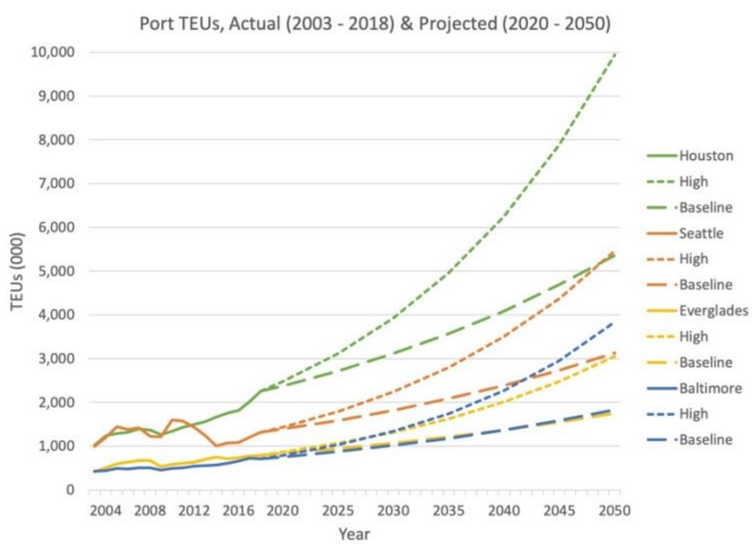

Figure 7: Port TEUs, Actual (2003 - 2018) & Projected (2020 - 2050)

4.2.1 Port of Baltimore

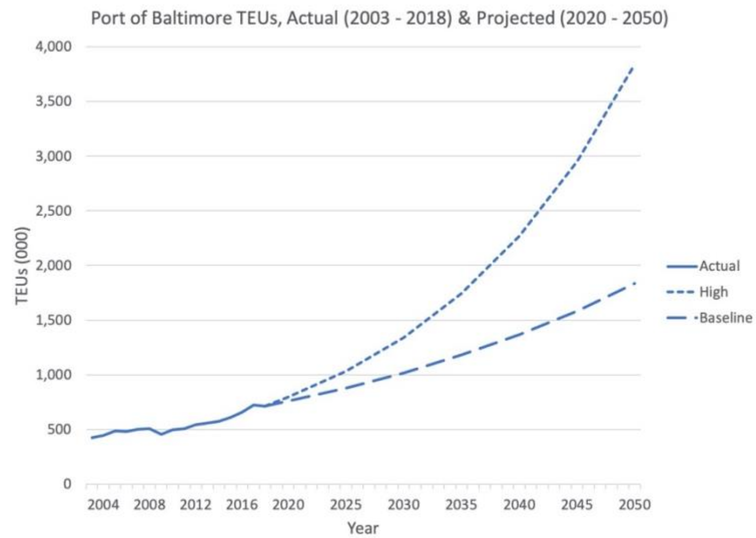

Figure 8: Port of Baltimore TEUs, Actual (2003 - 2018) & Projected (2020 - 2050)

The Port of Baltimore's estimated baseline growth rate is 3.00%, and the high growth rate is 5.40% (Maryland Port Administration, 2019). In 2020, the difference in the high and baseline projections is 35,671 TEUs. In 2050, the difference in the high and baseline projection is 2,001,477 TEUs. Aggregate TEU growth for the baseline scenario from 2020 – 2050 is 8,616,666, while for the high scenario, total TEU growth is 13,964,108.

4.2.2 Port Everglades

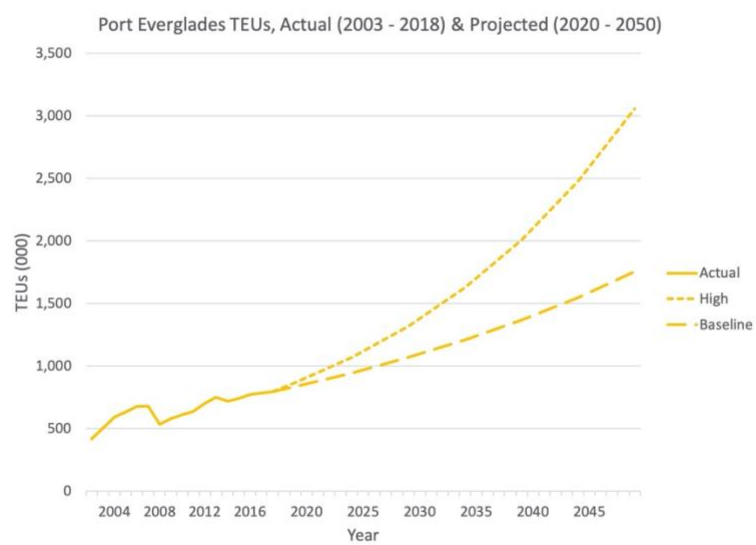

Figure 9: Port Everglades TEUs, Actual (2003 - 2018) & Projected (2020 - 2050)

Port Everglade's estimated baseline growth rate is 2.50%, and the high growth rate is 4.30% (Bermello Ajamil & Partners, 2018). In 2020, the difference in the high and baseline projections is 29,595 TEUs. In 2050, the difference in the high and baseline projection 1,306,278

TEUs. Aggregate TEU growth for the baseline scenario from 2020 – 2050 is 8,728,736 while for the high scenario, total TEU growth is 12,420,081.

4.2.3 Port of Houston

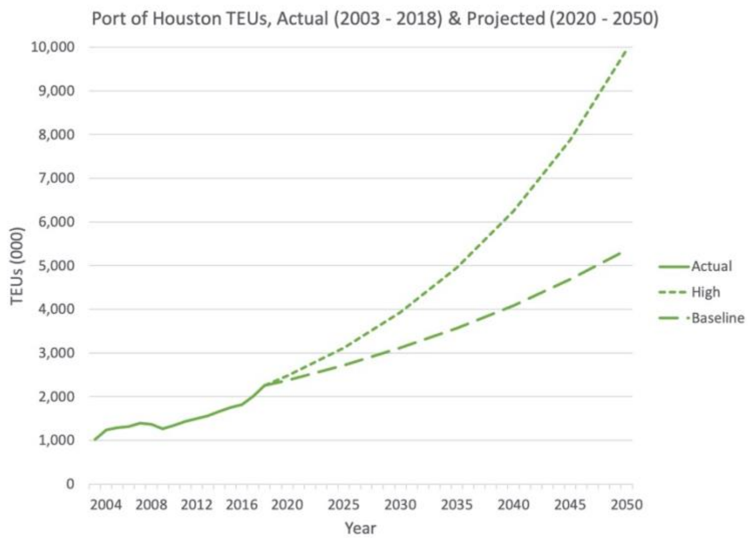

Figure 10: Port of Houston TEUs, Actual (2003 - 2018) & Projected (2020 - 2050)

Port of Houston's estimated baseline growth rate is 2.75%, and the high growth rate is 4.75%. In 2020, the difference in the high and baseline projections is 93,443 TEUs. In 2050, the difference in the high and baseline projection 4,576,607 TEUs. Aggregate TEU growth for the baseline scenario from 2020 – 2050 25,926,842 TEUs, while for the high scenario, total TEU growth is 38,545,455.

4.2.4 Port of Seattle

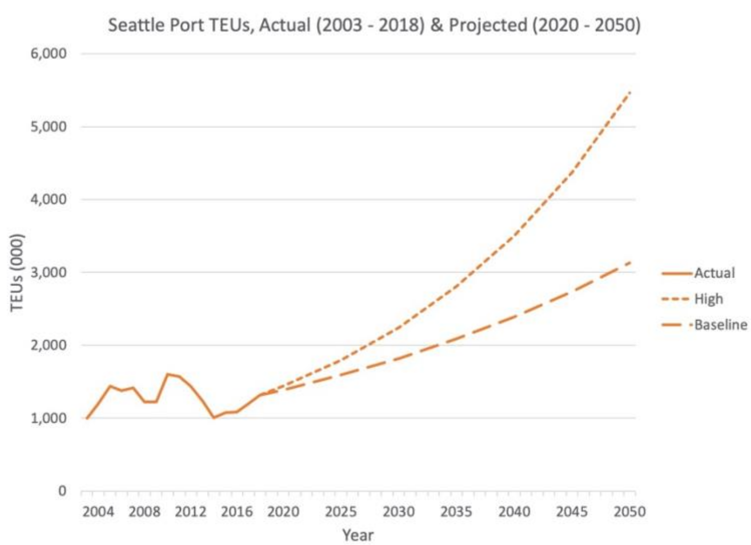

Figure 11: Port of Seattle TEUs, Actual (2003 - 2018) & Projected (2020 - 2050)

Port of Seattle's estimated baseline growth rate is 2.75%, and the high growth rate is 4.55% (The Northwest Seaport Alliance, 2015). In 2020, the difference in the high and baseline projections is 49,081 TEUs. In 2050, the difference in the high and baseline projection 2,329,013 TEUs. Aggregate TEU growth for the baseline scenario from 2020 – 2050 15,145,697 TEUs, while for the high scenario, total TEU growth is 21,616,417.

4.3 Energy/TEU

This section discusses how the cargo handling equipment (CHE) inventories for each port were used to calculate the energy/TEU throughput. At the time of this report, the Port of Baltimore does not have a detailed inventory of the cargo handling equipment and emissions for the port. As such, we used an average of the other three ports to calculate the number for Baltimore.

4.3.1 Energy Demand Derived by Combining TEU Throughput and Fuel Estimates per TEU

This section describes the approaches to derive energy demand for both cargo handling equipment (CHE) and oceangoing vessels at berth (for shore power demand) using convert best available data for containerized cargo throughput (TEUs) and fuel-based carbon dioxide (CO2) emissions. By grounding the energy demand on past and projected container throughput coupled with available activity-based CO2 inventory reporting, we estimate how much fuel demand would be considered to convert to electric power. These power estimates also inform the eGRID and environmental comparisons in Section 5.5.

4.3.1.1 Cargo Handling Equipment Energy Estimates

The Port of Seattle inventory did not have a breakdown of each cargo handling equipment emissions by inventory type. However, the inventory did detail the types of equipment in the Puget Sound, which includes a combination of the Port of Seattle and the Port of Tacoma. In general, the equipment matched the equipment from the Port of Houston inventory and Everglades inventory that we used for CO_2 emissions, so the emissions number for CO_2e that comes from Seattle and NWSA North Harbor are sufficient.

For the Port of Houston, the following cargo handling equipment were excluded from the calculation of CO_2e emissions because they do not directly relate to the TEU throughput activity in the port.

- Agricultural tractor
- Bulldozer
- Excavator
- Grader
- Pump
- Roller/Compactor
- Specialty vehicle carts
- Skid steer loader
- Tractor/loader/backhoe

This equipment only accounted for 3,649 tons of CO_2e emissions, which is less than 2.5% of the total emissions reported for Port of Houston. The exclusion of this equipment should not make a significant difference in our final results.

The excluded equipment for Everglades includes the excavator and skid steer loader. Similar to the Port of Houston, this equipment was not included because it does not directly impact throughput at the port. This equipment only made up 38 CO_2e emission tons, or less than .5% of total emissions for Everglades. Also, the Port of Everglades calculation of CO_2 equivalent emissions (CO_2e) is in metric tonnes/year, whereas the rest of the emissions are in tons per year.

After calculating CO_2 emissions in tons/year, we calculated CO_2 emissions per TEU. The year of TEU throughput that was used for this calculation was the same year of the port inventory. For Port Everglades, this was 2015; for the Port of Houston, this was 2013; and the Port of Seattle had the most recent inventory, completed in 2018. As mentioned above, since we did not have a detailed emissions inventory for the Port of Baltimore at the time of completing this analysis, we took the average of the other ports. As a result, the Port of Baltimore's CO_2 emissions/TEU was calculated to be 0.047.

Table 4: Cargo Handling CO_2 Emissions per TEU by Port

Port	CO_2 (tons/year)	TEU (Year)	CO_2 Emissions/TEU
Everglades	24691	716,182 (2015)	0.035
Houston	143863	1,563,060 (2013)	0.092
Seattle	15924	1,080,305 (2018)	0.015

As mentioned previously, Port of Baltimore did not have a sufficient emissions inventory to calculate CO_2 emissions/TEU. As a result, we took the average of the other three ports to get a value for the Port of Baltimore. Next, we converted CO_2 tons per TEU to CO_2 tonnes per TEU. We then converted this number to kg of CO_2/TEU, next to BTU/TEU, and finally to kWh/TEU. Section 4.4 further converts the kWh/TEU to gallons/TEU. We then multiply this by projected TEU throughput (Section 4.2) to get future energy consumption.

Table 5: Cargo Handling Fuel Use per TEU by Port

Port	Diesel (Gallons/TEU)	TEU (Year)	Diesel kWh/TEU
Everglades	3.39	716,182 (2015)	45
Houston	1.32	1,563,060 (2013)	18
Seattle	8.22	1,080,305 (2018)	110
Baltimore	4.20	713,191 (2018)	56

4.3.1.2 Shore Power Energy per TEU

Following a similar methodology using dockside hoteling, we developed shore power energy demand per TEU, as shown in Table 6.

Table 6. Shore Power Fuel Use per TEU by Port

Port	Containership (at Berth) kWh/TEU
Baltimore	36
Everglades	81
Houston	51
Seattle	37

4.4 Fuel Usage

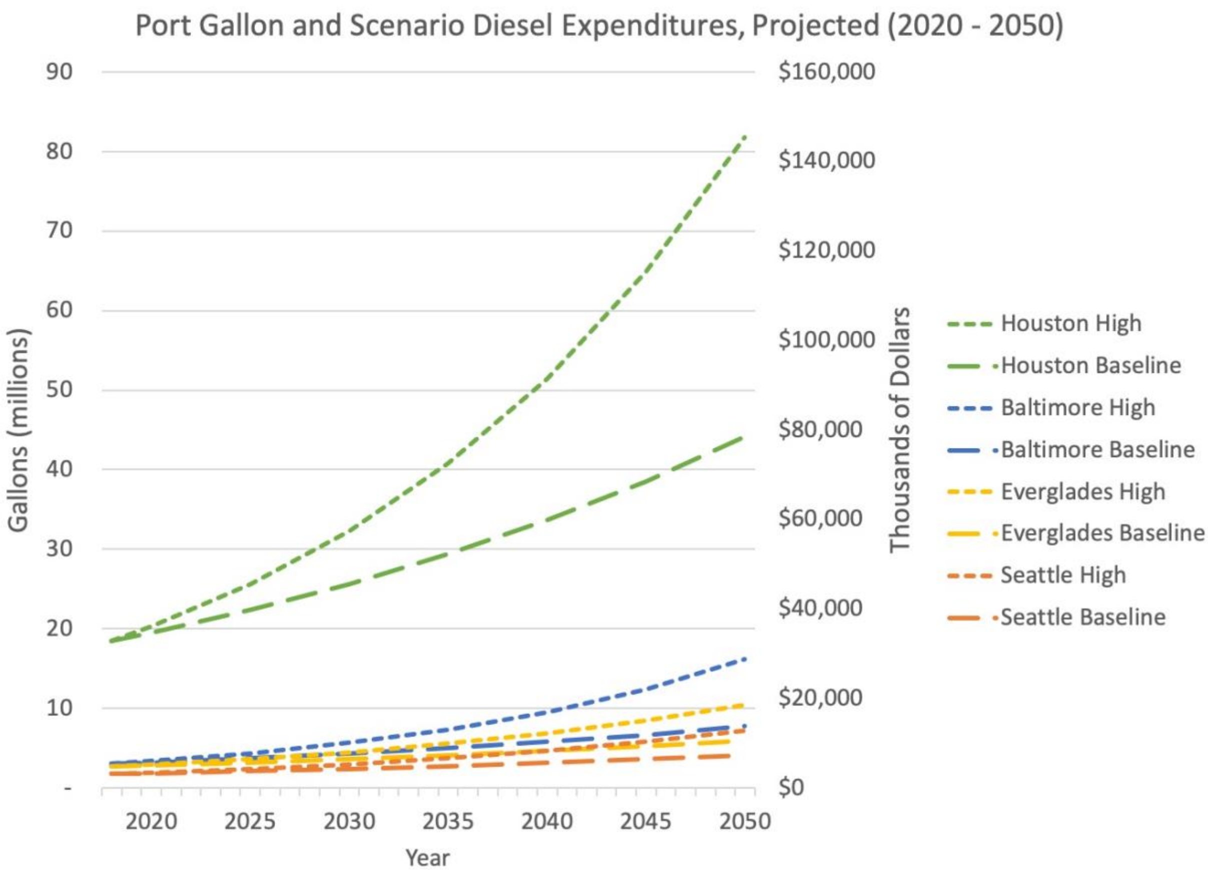

Figure 12: Port Gallon and Scenario CHE Diesel Expenditures by Year

Now that we have kWh/TEU for each port, we multiplied this number by the TEU projections calculated in Section 4.2. In order to project future fuel usage, we convert kWh to gallons. We then multiply gallons by dollars per gallon for each port to get diesel expenditures for each port. These diesel expenditures will be used in the 0% and 50% scenario. The sections below show the project diesel gallon consumption by port as well as tables for diesel expenditures. Graphs with diesel expenditures are in the appendix.

4.4.1 Port of Baltimore

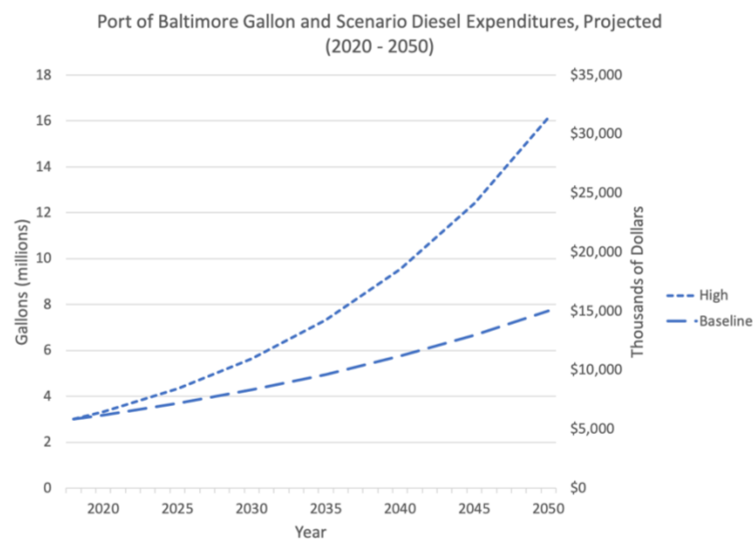

Figure 13: Port of Baltimore Gallon and Scenario CHE Diesel Expenditures by Year

Port of Baltimore projected gallon usage in 2020 for the baseline and high scenario range from 3,183,000 – 3,333,000. Corresponding expenditures are $6,110,000 to $6,398,000. In 2050, diesel consumption for the baseline scenario is 7,725,000, which would cost $14,832,000. The high scenario projects 16,143,000 gallons at $30,995,000.

4.4.2 Port Everglades

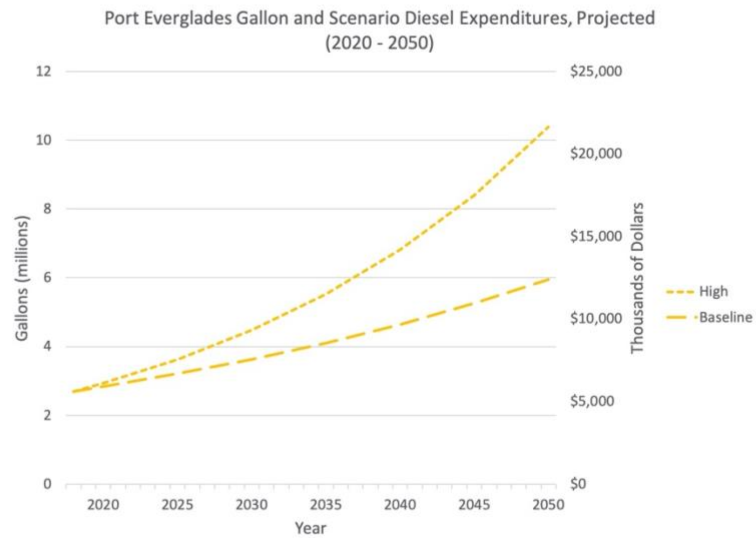

Figure 14: Port Everglades Gallon and Scenario CHE Diesel Expenditures by Year

Port Everglades projected gallon usage in 2020 for the baseline and high scenario range from 2,836,300 – 2,936,800. Corresponding expenditures are $5,446,000 to $5,639,000. In 2050, diesel consumption for the baseline scenario is 5,949,300, which would cost $11,423,000. The high scenario projects 10,384,900 gallons at $19,939,000.

4.4.3 Port of Houston

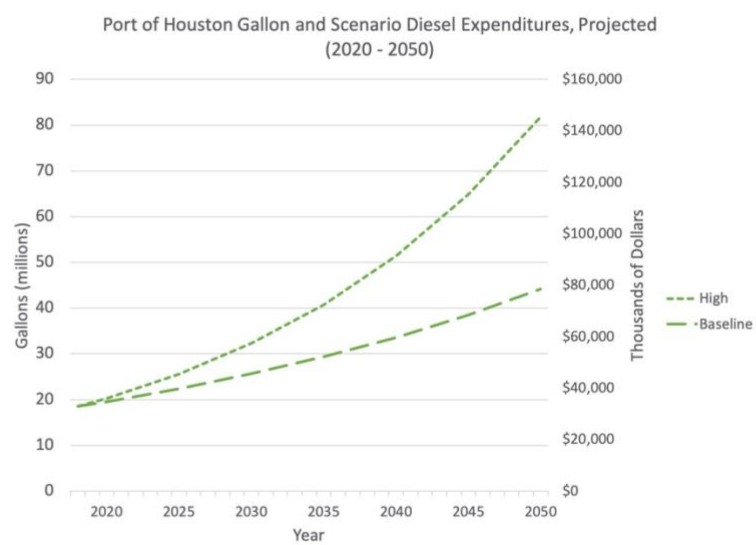

Figure 15: Port of Houston Gallon and Scenario CHE Diesel Expenditures by Year

Port of Houston projected gallon usage in 2020 for the baseline and high scenario range from 19,545,000 – 20,314,000. Corresponding expenditures are $36,354,000 to $37,783,000. In

2050, diesel consumption for the baseline scenario is 44,106,000 gallons, which would cost $82,037,000. The high scenario projects 81,735,000 gallons at $152,027,000.

4.4.4 Port of Seattle

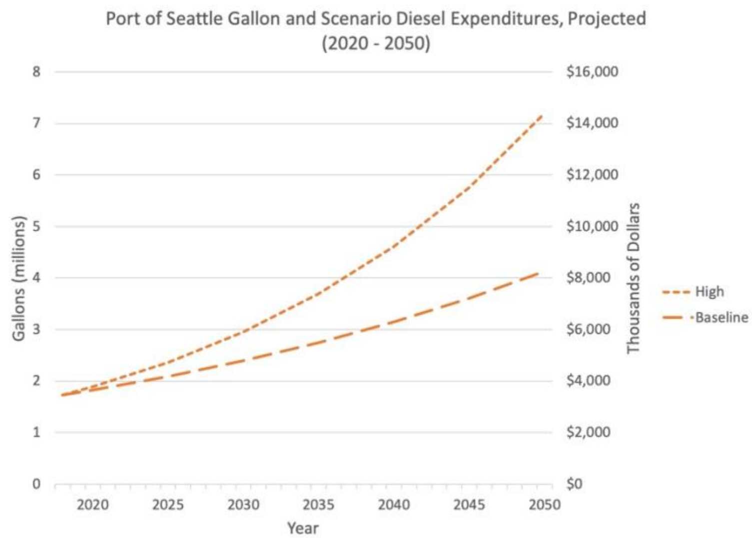

Figure 16: Port of Seattle Gallon and Scenario CHE Diesel Expenditures by Year

Port of Seattle projected gallon usage in 2020 for the baseline and high scenario range from 1,829,000 – 1,893,000. Corresponding expenditures are $3,566,000 to $3,692,000. In 2050, diesel consumption for the baseline scenario is 4,126,000, which would cost $8,046,000. The high scenario projects 7,193,000 gallons at $14,027,000.

4.5 Environmental Performance Data (Emissions)

4.5.1 eGRID Regional Data

As shown in Figure 1, and discussed in Section 3.3, we estimate emissions for four eGRID subregions, corresponding to the four ports studied. The criteria pollutant and GHG emission factors for these subregions are shown in Table 7.

Table 7: eGRID Subregion emission rates (eGRID2018)

		Total output emission rates (lb/MWh)						
Port	**eGRID subregion**	**CO_2**	**CH_4**	**N_2O**	**CO_2e**	**Annual NO_x**	**Ozone Season NO_x**	**SO_2**
Baltimore	RFCE	716.0	0.061	0.008	720.0	0.3	0.3	0.5
Everglades	FRCC	931.8	0.066	0.009	936.1	0.4	0.4	0.3
Houston	ERCT	931.7	0.066	0.009	936.1	0.5	0.6	0.8
Seattle	NWPP	639.0	0.064	0.009	643.4	0.6	0.6	0.4
	U.S.	**947.2**	**0.085**	**0.012**	**952.9**	**0.6**	**0.6**	**0.7**

4.5.2 Diesel Cargo Handling Equipment Emission Factors

Diesel cargo handling emission factors are shown in Table 8. Note that all pollutant emission rates are equivalent, except for NOx emission rates. These emission factors are based on those reported in Appendix B of the San Pedro Bay Ports emission inventory methodology (Starcrest Consulting Group, 2019). The Ports of Houston and Everglades included detail on the age/tier structure of their CHE in their latest inventories, and so the NOx values for those two ports are weighted based on the reported or projected engine tiers, and the corresponding emission factors. For the ports of Baltimore and Seattle, information on CHE tier structure was not available, so we assume CHE composition at these two ports based on the weighted average of CHE by engine tier combined across Port Everglades and the Port of Houston.

Table 8: Cargo handling equipment diesel emission factors (g/kWh)

	Diesel Emission Rates (g/kWh)					
	CO_2	CH_4	N_2O	CO_2e	Annual NO_x	SO_2
Everglades	762	0.048	0.02	769.304	3.94	0.07
Houston	762	0.048	0.02	769.304	8.24	0.07
Average	762	0.048	0.02	769.304	6.90	0.07

4.6 Cargo Handling Electricity Consumption

Using the TEU projections calculated and discussed in Section 4.2, we were able to project the future energy consumption of each port from 2020 – 2050 by multiplying the kWh/TEU by the TEU projection for that year. As seen from the graph below, the Port of Houston has the highest kWh projection, both for baseline and high cases, out of the four ports. The next graphs show kWh projections by port. We also calculate electricity expenditures by port by multiplying kWh projections by the electricity prices above. The tables for electricity expenditures are below; the graphs are in the appendix.

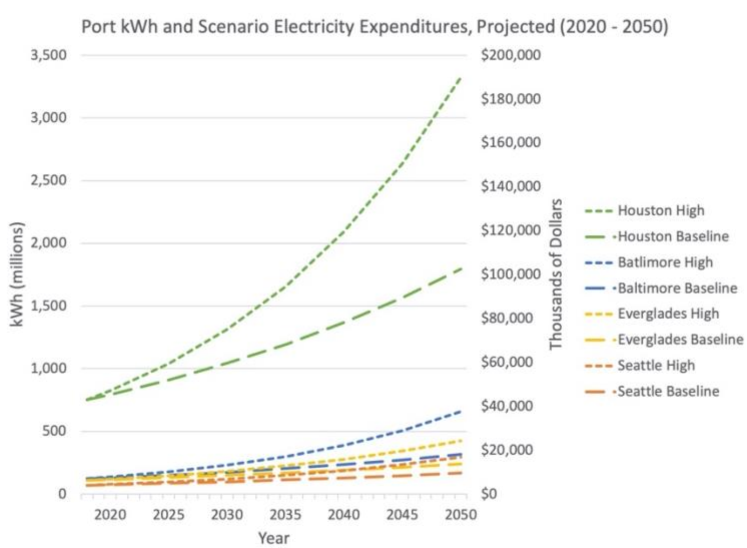

Figure 17: Port CHE Scenario kWh and Electricity Expenditures by Year, Projected (2020 - 2050)

4.6.1 Port of Baltimore CHE Electrification

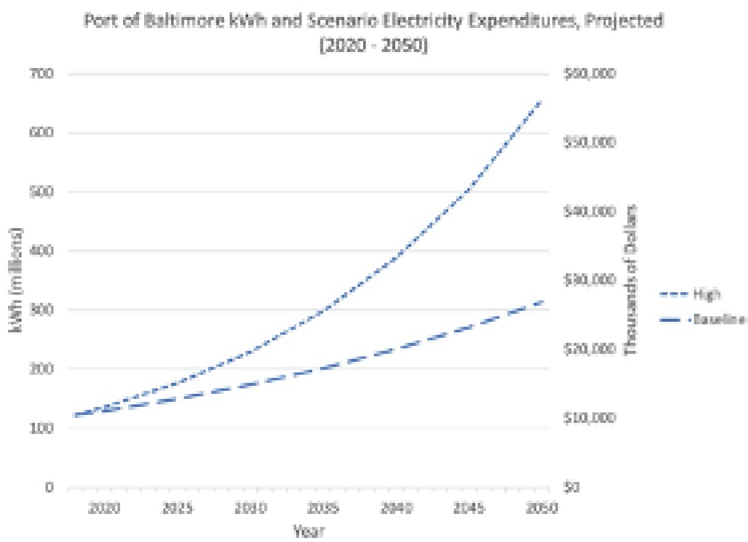

Figure 18: Port of Baltimore CHE kW and Scenario Electricity Expenditures by Year, Projected (2020 - 2050)

Table 9: Port of Baltimore CHE kWh Projections by Year

Year	Baseline kWh	High kWh
2018	121,944,000	121,944,000
2020	129,370,000	135,469,000
2025	149,975,000	176,215,000
2030	173,863,000	229,217,000
2035	201,555,000	298,160,000
2040	233,657,000	387,840,000
2045	270,872,000	504,494,000
2050	314,015,000	656,235,000

Table 10: Port of Baltimore CHE Scenario Electricity Expenditures

Year	Baseline	High
2018	$10,142,000	$10,142,000
2020	$10,759,000	$11,267,000
2025	$12,473,000	$14,655,000
2030	$14,460,000	$19,063,000
2035	$16,763,000	$24,797,000
2040	$19,432,000	$32,255,000
2045	$22,528,000	$41,957,000
2050	$26,116,000	$54,577,000

4.6.2 Port Everglades CHE Electrification

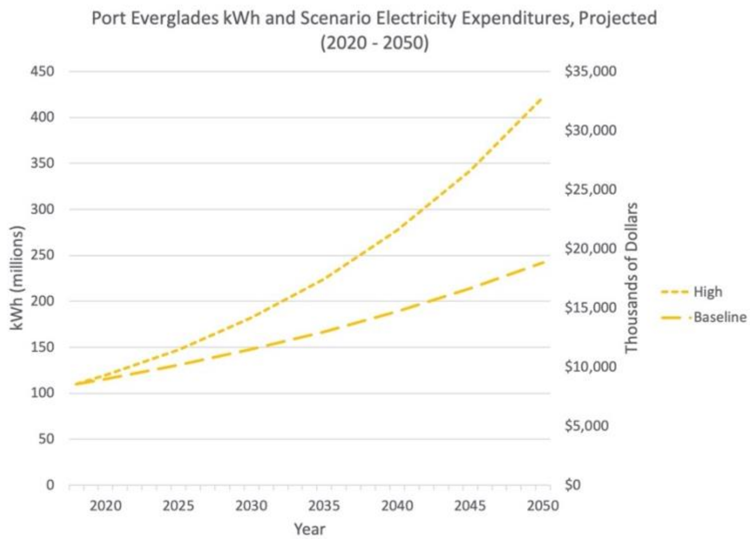

Figure 19: Port Everglades CHE kWh and Scenario Electricity Expenditures by Year, Projected (2020 - 2050)

Table 11: Port Everglades CHE kWh Projections by Year

Year	Baseline kWh	High kWh
2018	109,741,000	109,741,000
2020	115,297,000	119,382,000
2025	130,448,000	147,353,000
2030	147,589,000	181,878,000
2035	166,984,000	224,493,000
2040	188,927,000	277,092,000
2045	213,753,000	342,015,000
2050	241,842,000	422,150,000

Table 12: Port Everglades CHE Scenario Electricity Expenditures

Year	Baseline	High
2018	$8,594,000	$8,594,000
2020	$9,029,000	$9,349,000
2025	$10,215,000	$11,539,000
2030	$11,557,000	$14,243,000
2035	$13,076,000	$17,580,000
2040	$14,795,000	$21,699,000
2045	$16,739,000	$26,783,000
2050	$18,938,000	$33,058,000

4.6.3 Port of Houston CHE Electrification

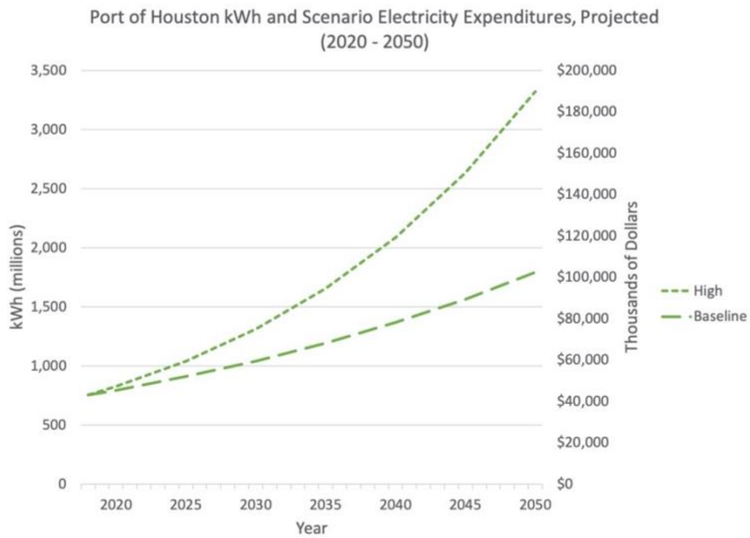

Figure 20: Port of Houston CHE kWh and Scenario Electricity Expenditures by Year, Projected (2020 - 2050)

Table 13: Port of Houston CHE kWh Projections by Year

Year	Baseline kWh	High kWh
2018	752,564,000	752,564,000
2020	794,524,000	825,756,000
2025	909,947,000	1,041,410,000
2030	1,042,139,000	1,313,385,000
2035	1,193,534,000	1,656,388,000
2040	1,366,922,000	2,088,970,000
2045	1,565,500,000	2,634,525,000
2050	1,792,925,000	3,322,558,000

Table 14: Port of Houston CHE Scenario Electricity Expenditures

Year	Baseline	High
2018	$41,894,000	$41,894,000
2020	$44,230,000	$45,968,000
2025	$50,655,000	$57,973,000
2030	$58,014,000	$73,114,000
2035	$66,442,000	$92,208,000
2040	$76,094,000	$116,289,000
2045	$87,148,000	$146,659,000
2050	$99,809,000	$184,960,000

4.6.4 Port of Seattle CHE Electrification

The Port of Seattle has the lowest projected kWh for the baseline and high scenario out of the four ports, as well as the lowest expenditures.

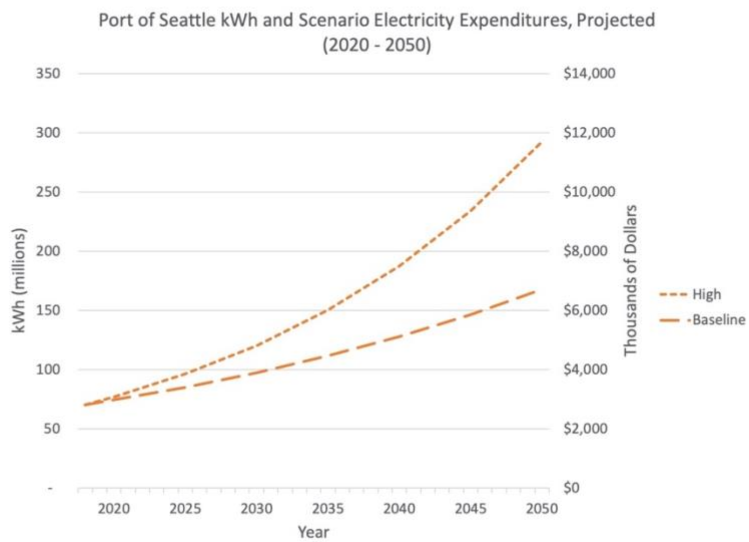

Figure 21: Port of Seattle CHE kWh and Scenario Electricity Expenditures by Year, Projected (2020 - 2050)

Table 15: Port of Seattle CHE kWh Projections by Year

Year	Baseline kWh	High kWh
2018	70,407,000	70,407,000
2020	74,333,000	76,960,000
2025	85,131,000	96,135,000
2030	97,498,000	120,089,000
2035	111,662,000	150,011,000
2040	127,884,000	187,389,000
2045	146,462,000	234,080,000
2050	167,739,000	292,405,000

Table 16: Port of Seattle CHE Scenario Electricity Expenditures

Year	Baseline	High
2018	$3,201,000	$3,201,000
2020	$3,380,000	$3,499,000
2025	$3,871,000	$4,371,000
2030	$4,433,000	$5,460,000
2035	$5,077,000	$6,821,000
2040	$5,815,000	$8,520,000
2045	$6,660,000	$10,643,000
2050	$7,627,000	$13,295,000

4.7 Shore Power Electricity Consumption

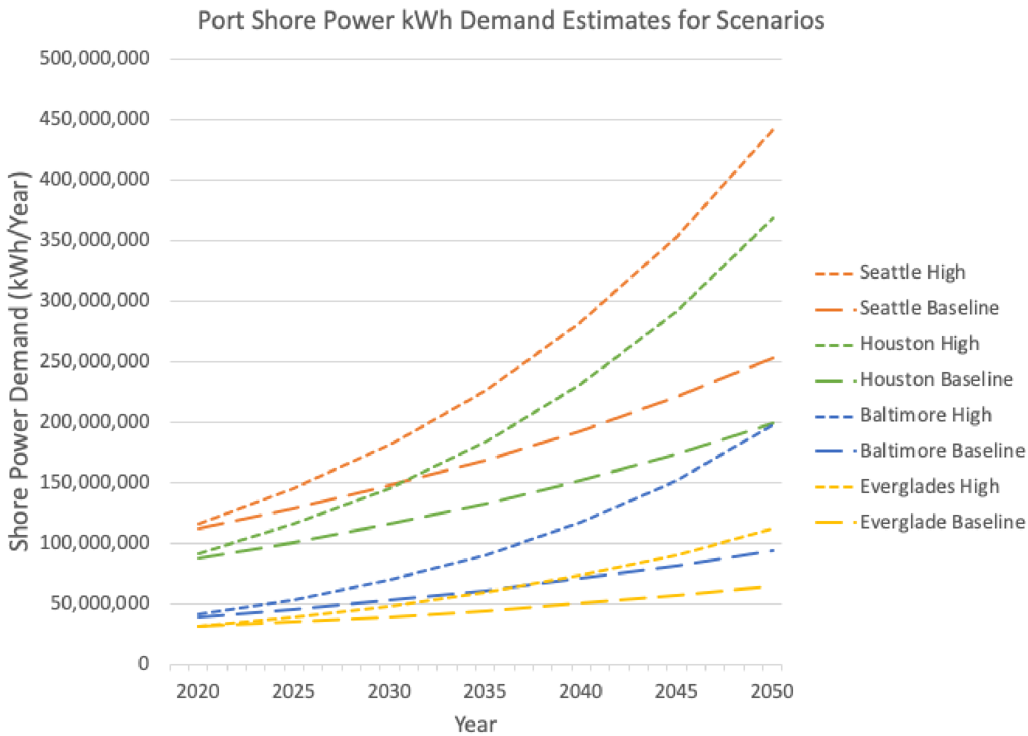

Figure 22. Port Shore Power kWh by Year, Projected (2020 - 2050)

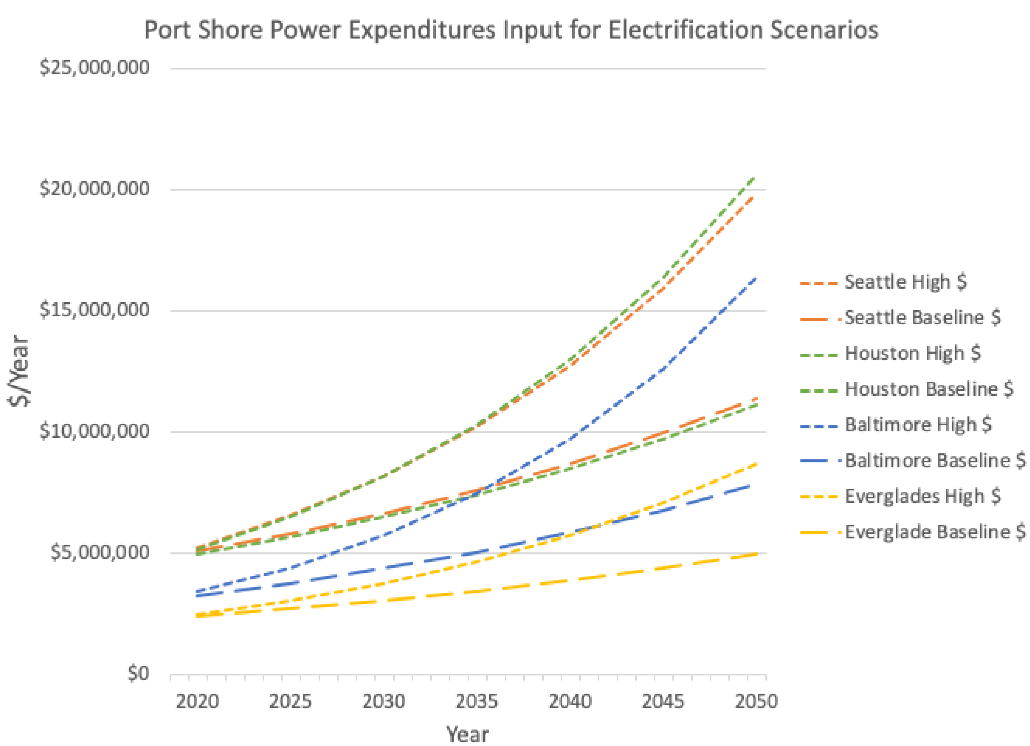

Figure 23. Port Shore Power Electricity Expenditures by Year, Projected (2020 - 2050)

4.7.1 Port of Baltimore Shore Power Electrification

Table 17: Port of Baltimore Shore Power kWh Projections by Year

Year	Baseline kWh	High kWh
2018	121,944,000	121,944,000
2020	129,370,000	135,469,000
2025	149,975,000	176,215,000
2030	173,863,000	229,217,000
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2040	233,657,000	387,840,000
2045	270,872,000	504,494,000
2050	314,015,000	656,235,000

Table 18: Port of Baltimore Shore Power Scenario Electricity Expenditures

Year	Baseline	High
2018	$10,142,000	$10,142,000
2020	$10,759,000	$11,267,000
2025	$12,473,000	$14,655,000
2030	$14,460,000	$19,063,000
2035	$16,763,000	$24,797,000
2040	$19,432,000	$32,255,000
2045	$22,528,000	$41,957,000
2050	$26,116,000	$54,577,000

4.7.2 Port Everglades Shore Power Electrification

Table 19: Port Everglade Shore Powers kWh Projections by Year

Year	Baseline kWh	High kWh
2018	109,741,000	109,741,000
2020	115,297,000	119,382,000
2025	130,448,000	147,353,000
2030	147,589,000	181,878,000
2035	166,984,000	224,493,000
2040	188,927,000	277,092,000
2045	213,753,000	342,015,000
2050	241,842,000	422,150,000

Table 20: Port Everglades Shore Power Scenario Electricity Expenditures

Year	Baseline	High
2018	$8,594,000	$8,594,000
2020	$9,029,000	$9,349,000
2025	$10,215,000	$11,539,000
2030	$11,557,000	$14,243,000
2035	$13,076,000	$17,580,000
2040	$14,795,000	$21,699,000
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2050	$18,938,000	$33,058,000

4.7.3 Port of Houston Shore Power Electrification

Table 21: Port of Houston Shore Power kWh Projections by Year

Year	Baseline kWh	High kWh
2018	752,564,000	752,564,000
2020	794,524,000	825,756,000
2025	909,947,000	1,041,410,000
2030	1,042,139,000	1,313,385,000
2035	1,193,534,000	1,656,388,000
2040	1,366,922,000	2,088,970,000
2045	1,565,500,000	2,634,525,000
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Table 22: Port of Houston Shore Power Scenario Electricity Expenditures

Year	Baseline	High
2018	$41,894,000	$41,894,000
2020	$44,230,000	$45,968,000
2025	$50,655,000	$57,973,000
2030	$58,014,000	$73,114,000
2035	$66,442,000	$92,208,000
2040	$76,094,000	$116,289,000
2045	$87,148,000	$146,659,000
2050	$99,809,000	$184,960,000

4.7.4 Port of Seattle Shore Power Electrification

The Port of Seattle has the lowest projected kWh for the baseline and high scenario out of the four ports, as well as the lowest expenditures.

Table 23: Port of Seattle Shore Power kWh Projections by Year

Year	Baseline kWh	High kWh
2018	70,407,000	70,407,000
2020	74,333,000	76,960,000
2025	85,131,000	96,135,000
2030	97,498,000	120,089,000
2035	111,662,000	150,011,000
2040	127,884,000	187,389,000
2045	146,462,000	234,080,000
2050	167,739,000	292,405,000

Table 24: Port of Seattle Shore Power Scenario Electricity Expenditures

Year	Baseline	High
2018	$3,201,000	$3,201,000
2020	$3,380,000	$3,499,000
2025	$3,871,000	$4,371,000
2030	$4,433,000	$5,460,000
2035	$5,077,000	$6,821,000
2040	$5,815,000	$8,520,000
2045	$6,660,000	$10,643,000
2050	$7,627,000	$13,295,000

5 Port Electrification Scenario Results

For each port, we generated a 0%, 50% and 100% electrification scenario. For the 50% and 100% electrification scenario for cargo handling, we calculated the difference in output and employment from the 0% scenario to demonstrate that for all but three ports, electrification increases output and jobs compared to the 0% scenario. When we displace 100,000 gallons of diesel at one port and replace it with the equivalent amount of electricity in kWh, locally priced electricity may be more expensive or less expensive than diesel. Where there were savings (results at the Port of Seattle only), we calculated an additional multiplier using an institutional spending pattern. Dollars are all in 2018 dollars, and employment is in job-years.

5.1 Regional Input-Output (RIO) Multipliers

Regional multipliers are ratios that describe the macroeconomic amplification of direct spending in a region. For example, if one unit of spending produces more than one unit of economic activity in the region, the multiplier ratio is greater than one; similarly if one unit of spending ($100k per year) produces more than one new jobs in the region, an employment multiplier ratio can estimate the relative change in expected employment in the region. The tables below detail the employment and output multipliers for diesel and employment for all ports, and the institutional spending multipliers for Port of Seattle.

Table 25: Port Multipliers for Diesel, Output and Employment

Port	Output		Employment (per $100k Expenditure)	
	State	County	State	County
Baltimore	1.91	1.59	2.16	1.70
Everglades	2.30	1.79	2.92	2.19
Houston	1.66	1.32	3.13	2.80
Seattle	1.99	1.84	2.19	1.91

The multipliers in the diesel sector for the state are larger than for the county, showing that a larger area of study has a larger economic impact because economic activity is not confined to the area nearest the ports. The interpretation of these multipliers at the county level for each port in the electric sector is as follows.

- Port of Baltimore: For every dollar of production in the electricity sector, $1.59 of activity is generated in the local economy, the original dollar and an additional $0.59. Every $100,000 in direct expenditures creates 1.70 jobs.
- Port Everglades: For every dollar of production in the electricity sector, $1.79 of activity is generated in the local economy, the original dollar and an additional $0.79. Every $100,000 in direct expenditures creates 2.19 jobs.

- Port of Houston: For every dollar of production in the electricity sector, $1.32 of activity is generated in the local economy, the original dollar and an additional $0.32. Every $100,000 in direct expenditures creates 2.80 jobs.
- Port of Seattle: For every dollar of production in the electricity sector, $1.84 of activity is generated in the local economy, the original dollar and an additional $0.84. Every $100,000 in direct expenditures creates 1.91 jobs.

Table 26: Port Multipliers for Electric, Output and Employment

Port	**Output**		**Employment (per $100k Expenditure)**	
	State	**County**	**State**	**County**
Baltimore	1.67	1.45	4.06	3.82
Everglades	1.79	1.75	4.98	2.21
Houston	1.99	1.67	4.95	4.00
Seattle	1.54	1.36	2.65	2.04

As with the diesel multipliers, the electric multipliers at the state-level are larger than those at the county level, showing that a larger area of study has a larger economic impact. We can also see from the electric multipliers for employment that they are bigger than the employment multipliers for diesel. There are more jobs created from $100,000 of spending in the electric sector than are created from $100,000 of spending in the diesel sector. These differences are attributed to the sectors that are connected with the different energy resources that result in different direct, indirect, and induced expenditures and employment. The difference between employment, with lower employment effects for diesel, is likely related to the in-region labor related to electricity generation and distribution.

Table 27 shows the institutional spending multipliers for Port of Seattle. Institutional multipliers are only needed in case studies where a switch from diesel to electric power saves money; then the savings are reinvested in our case design to other regional economic activity. The interpretation of institutional multipliers at the state level for each port in the electric sector is as follows.

- Port of Baltimore: For every dollar of production in the electricity sector, $1.67 of activity is generated in the local economy, the original dollar and an additional $0.67. Every direct job creates 4.06 jobs in the total economy, the original job and 3.06 addition jobs.
- Port Everglades: For every dollar of production in the electricity sector, $1.79 of activity is generated in the local economy, the original dollar and an additional $0.79. Every direct job creates 4.98 jobs in the total economy, the original job and 3.98 addition jobs.
- Port of Houston: For every dollar of production in the electricity sector, $1.99 of activity is generated in the local economy, the original dollar and an additional

$0.99. Every direct job creates 4.95 jobs in the total economy, the original job and 3.95 addition jobs.

- Port of Seattle: For every dollar of production in the electricity sector, $1.54 of activity is generated in the local economy, the original dollar and an additional $0.54. Every direct job creates 2.65 jobs in the total economy, the original job and 1.65 addition jobs.

Table 27: Institutional Spending Multipliers for Port of Seattle

Geography	**Multiplier**
State	1.791
County	1.505

5.2 Net Energy Expenditures

The estimated net direct energy expenditures for Cargo Handling Equipment, by scenario, based on estimates discussed in Sections 4.4 and 4.6 are shown in Table 28 for the years 2020, 2030, 2040, and 2050.

Table 28: Net CHE energy expenditures by port and scenario (values in parentheses are negative, representing net savings)

		Net Energy Costs by Year ($)			
Port	Scenario	2020	2030	2040	2050
Baltimore	50% Baseline	2,330,000	3,130,000	4,200,000	5,650,000
	50% High	2,440,000	4,120,000	6,980,000	11,800,000
	100% Baseline	4,650,000	6,250,000	8,410,000	11,300,000
	100% High	4,870,000	8,250,000	13,950,000	23,610,000
Everglades	50% Baseline	1,790,000	2,300,000	2,940,000	3,760,000
	50% High	1,860,000	2,830,000	4,310,000	6,570,000
	100% Baseline	3,590,000	4,590,000	5,880,000	7,530,000
	100% High	3,710,000	5,660,000	8,620,000	13,140,000
Houston	50% Baseline	3,950,000	5,190,000	6,800,000	8,920,000
	50% High	4,110,000	6,540,000	10,400,000	16,530,000
	100% Baseline	7,910,000	10,370,000	13,610,000	17,850,000
	100% High	8,220,000	13,070,000	20,790,000	33,070,000
Seattle	50% Baseline	(90,000)	(120,000)	(150,000)	(200,000)
	50% High	(90,000)	(140,000)	(220,000)	(350,000)
	100% Baseline	(180,000)	(230,000)	(310,000)	(400,000)
	100% High	(180,000)	(290,000)	(450,000)	(700,000)

For Shore Power, the study assumes all fuel used by vessels is purchased prior to arrival in the port, i.e., outside the region of study; this is a reasonable modeling assumption, particularly given the international nature of shipping and bunkering where fuels for vessels is typically purchased in an international market. Therefore, this study assigns zero regional macroeconomic effect to fuel used by vessels in port, and evaluates only the macroeconomic impact of provided electrified shore power to the vessel. The estimated net direct energy expenditures for Shore Power Electrification, by scenario, based on estimates discussed in Section 4.7 are shown in Table 29 for the years 2020, 2030, 2040, and 2050.

Table 29: Shore Power electrification expenditures by port and scenario

		Net Energy Costs by Year ($)			
Port	Scenario	2020	2030	2040	2050
Baltimore	50% Baseline	1,614,000	2,170,000	2,913,000	3,918,000
	50% High	1,689,000	2,859,000	4,839,000	8,188,000
	100% Baseline	3,229,000	4,341,000	5,827,000	7,835,000
	100% High	3,378,000	5,718,000	9,678,000	16,376,000
Everglades	50% Baseline	1,186,000	1,517,000	1,942,000	2,488,000
	50% High	1,229,000	1,868,000	2,847,000	4,341,000
	100% Baseline	2,371,000	3,034,000	3,884,000	4,976,000
	100% High	2,457,000	3,736,000	5,694,000	8,681,000
Houston	50% Baseline	2,464,000	3,234,000	4,242,000	5,564,000
	50% High	2,562,000	4,074,000	6,482,000	10,307,000
	100% Baseline	4,928,000	6,468,000	8,484,000	11,127,000
	100% High	5,124,000	8,148,000	12,964,000	20,613,000
Seattle	50% Baseline	2,525,000	3,312,000	4,343,000	5,697,000
	50% High	2,615,000	4,079,000	6,363,000	9,929,000
	100% Baseline	5,049,000	6,624,000	8,685,000	11,394,000
	100% High	5,229,000	8,159,000	12,726,000	19,859,000

5.3 Port Cargo Handling Electrification Scenario Results

This section discusses the results for each port case study electrification scenario Graphs are shown for the 0%, 50%, and 100% scenarios for both employment and economic activity. Additional graphs report expected gains in employment and changes in economic output from the 0% for both the 50% and 100% scenarios. As stated in the methods section, macroeconomic benefits are estimated based solely on energy expenditures which recur over the long-term. Capital costs and other non-recurring spending are not considered in this study.

5.3.1 Port of Baltimore Macroeconomic Effects of CHE Electrification

For the Port of Baltimore, the 0% CHE scenario shows the economic activity and employment effects of no electrification. All of the spending and job creation is in the diesel sector. As in all cases, state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $11,649,000 to $12,198,000, while county-level is between $9,726,000 and $10,184,000. Employment estimates at the state-level in 2020 range from 132 – 138 job-years. At the county-level, estimates are from104 – 109 job-years. In 2050, state-level output is between $28,275,000 to $59,089,000, while county-level output is $23,607,000 to $49,334,000. Employment in 2050 at the state-level is from 320 – 668 job-years, and at the county-level, from 252 – 527 job-years. This is illustrated in Figure 24.

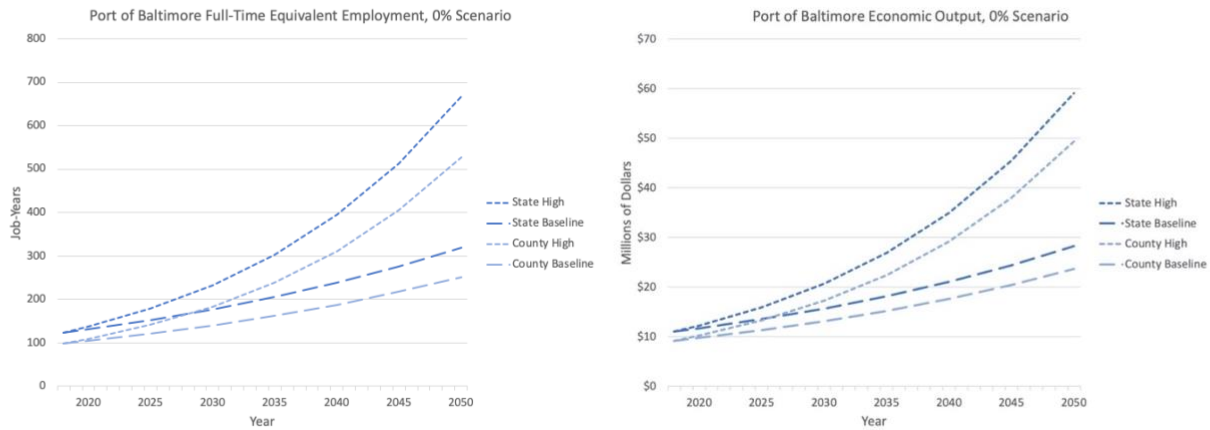


Figure 24: Port of Baltimore CHE 0% Scenario Results, Employment (left) & Economic Output (right)

For the Port of Baltimore, the 50% CHE scenario shows the economic activity and employment effects of partial electrification. 50% of energy consumption comes from electricity, and the other 50% comes from diesel fuel. Thus, expenditures and job creation are split 50% and 50% between the electricity and diesel sectors. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $14,830,000 to $15,529,000 while county-level is between $12,663,000 to $13,260,000. Employment estimates at the state-level in 2020 range from 284 to 298 job-years. At the county-level, estimates are from 257 to 270 job-years. In 2050, state-level output is between $35,996,000 to $75,225,000, while county-level output is $30,737,000 to $64,235,000. Employment in 2050 at the state-level is from 690 – 1443 job-years, and at the county-level, from 625 – 1306 job-years. This is illustrated in Figure 25.

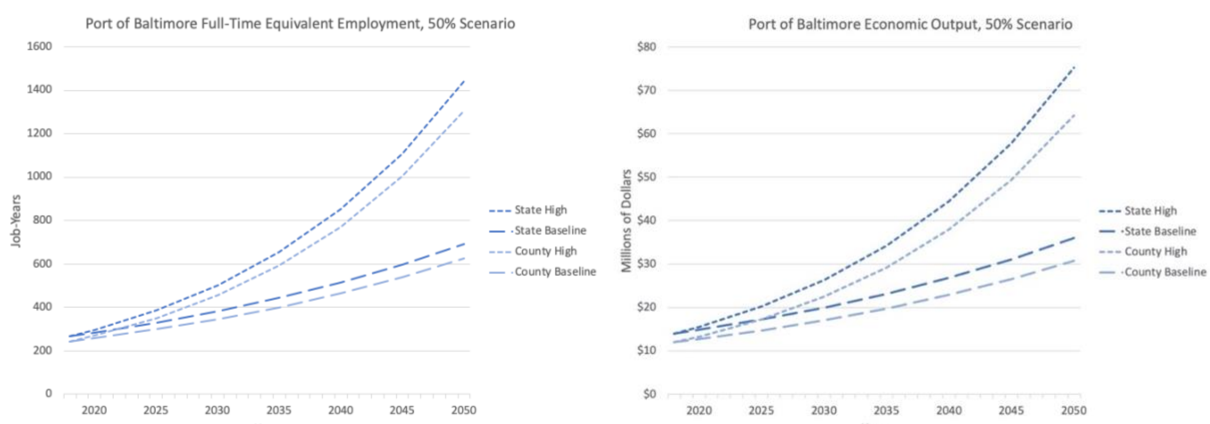


Figure 25: Port of Baltimore CHE 50% Scenario Results, Employment (left) & Economic Output (right)

For the Port of Baltimore, the 100% CHE scenario shows the economic activity and employment effects of complete electrification. All of the spending and job creation is in the electricity sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $18,011,000 to $18,860,000 while county-level is between $15,601,000 and $16,336,000. Employment estimates at the state-level in 2020 range from 437 to 457 job-years. At the county-level, estimates are from 411 to 430 job-years. In 2050, state-level output is between $43,718,000 - $91,362,000, while county-level output is $37,868,000 - $79,136,000. Employment in 2050 at the state-level is from 1061 – 2217 job years, and at the county-level, from 997 – 2084 job-years. This is illustrated in Figure 26.

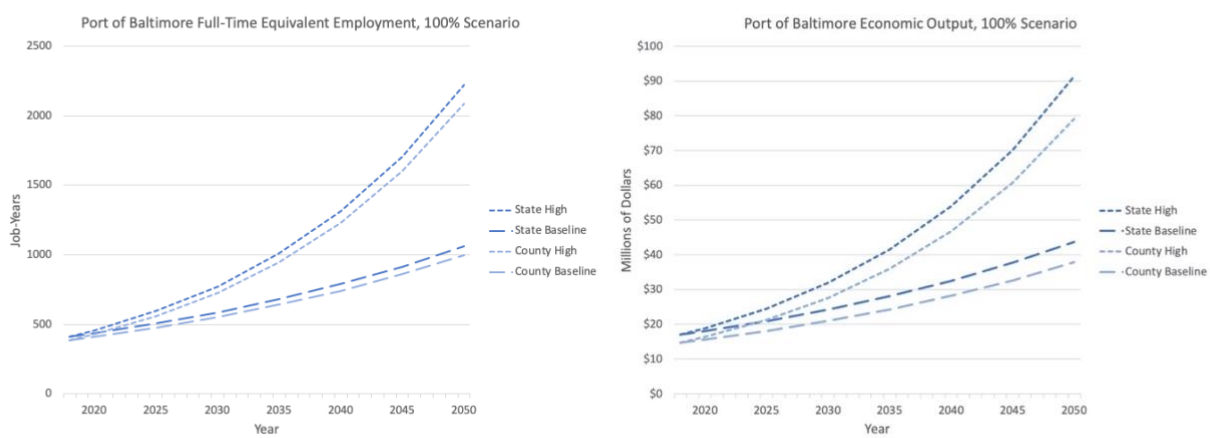


Figure 26: Port of Baltimore CHE 100% Scenario Results, Employment (left) & Economic Output (right)

Differences between the 0% CHE electrification scenario and the 50% and 100% CHE electrification scenarios indicate the change in economic activity for employment and economic output. In 2020, there is $3,181,000 - $3,331,000 more spending at the state-level in the 50% scenario and $6,362,000 - $6,662,000 more spending at the state-level in the 100% scenario. At the county level, there is between $2,938,000 and $3,076,000 more spending from CHE electrification in the 50% scenario and between $5,875,000 and $6,152,000 more spending in the 100% scenario. For 2020, the 50% CHE scenario creates 153 - 160 more jobs at the state-level and 154 to 161 more jobs at the county-level than the 0% scenario, while the 100% CHE scenario creates 305 to 320 more jobs at the state-level and 307 to 322 more jobs at the county-level compared to the 0% scenario. In 2050, there is $7,721,000- $16,136,000 more spending at the state-level in the 50% scenario and $15,443,000 to $32,273,000 more spending at the state-level in the 100% scenario. At the county level in 2050, there is between $7,130,000 and $14,901,000 more spending in the 50% CHE scenario and between $14,261,000 and $29,803,000 more spending in the 100% scenario. The 50% CHE scenario in 2050 creates 371 and 775 more jobs at the state-level and 373 and 779 more jobs at the county-level than the 0% scenario, while the 100% CHE scenario creates 741 – 1549 more jobs at the state-level and 745 and 1558 more jobs at the county-level compared to the 0% scenario. Figure 27 shows the county-level differences; the appendix includes tables that reveal state-level differences in employment and economic output.

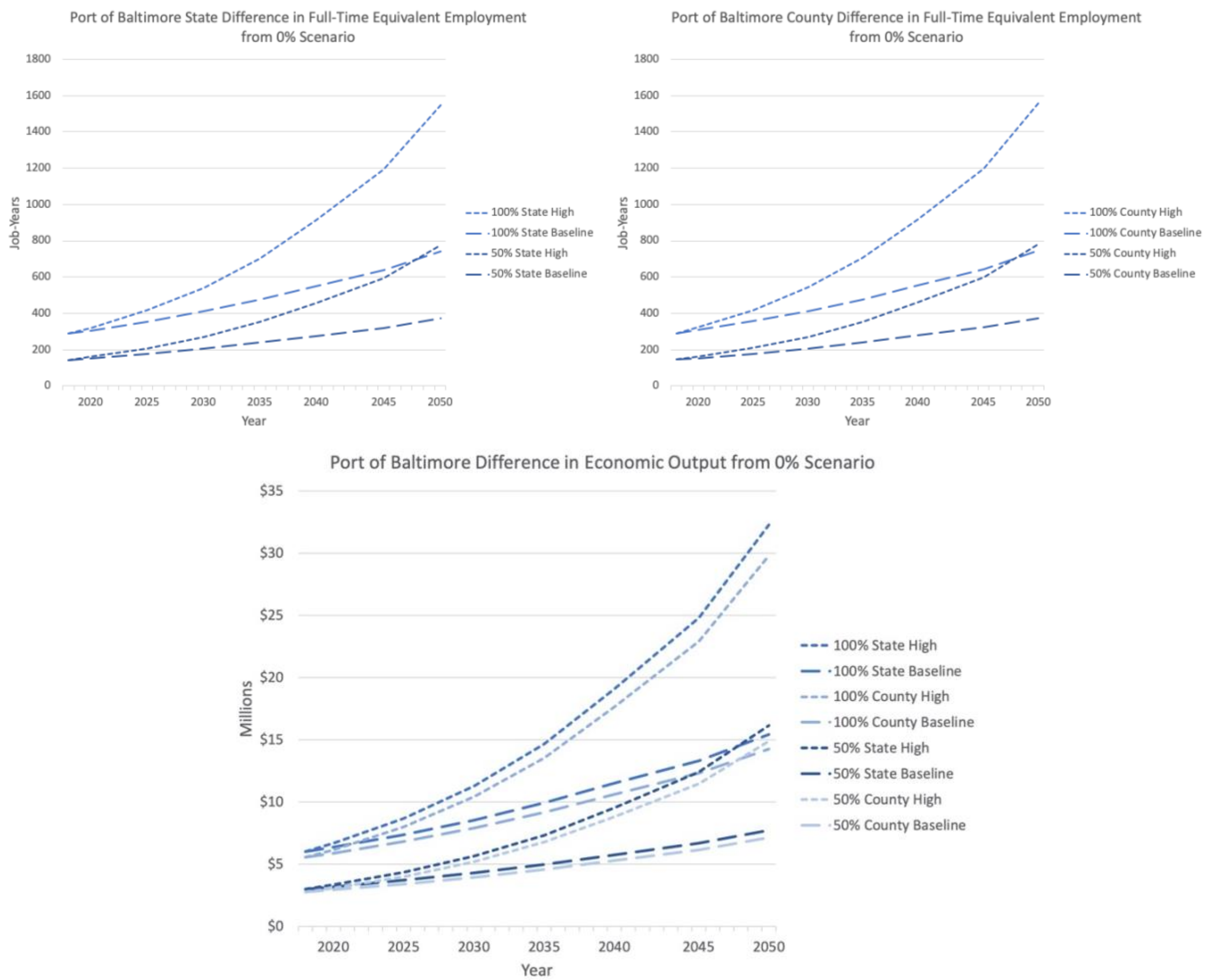


Figure 27. Port of Baltimore CHE Difference from 0% Scenario, Employment (left) & Economic Output (right).

5.3.2 Port Everglades Macroeconomic Effects of CHE Electrification

For Port Everglades, the 0% scenario shows the economic activity and employment effects of no electrification. All of the spending and job creation is in the diesel sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $12,531,000 to $12,975,000 while county-level is between $9,756,000 to $10,102,000. Employment estimates at the state-level in 2020 range from 159 – 165 job-years. At the county-level, estimates are from 119 – 123 job-years. In 2050, state-level output is between $26,284,000 - $45,881,000, while county-level output is $20,464,000 - $35,720,000. Employment in 2050 at the state-level is from 333 – 582, and at the county-level, from 250 – 436 job-years. This is illustrated in Figure 28.

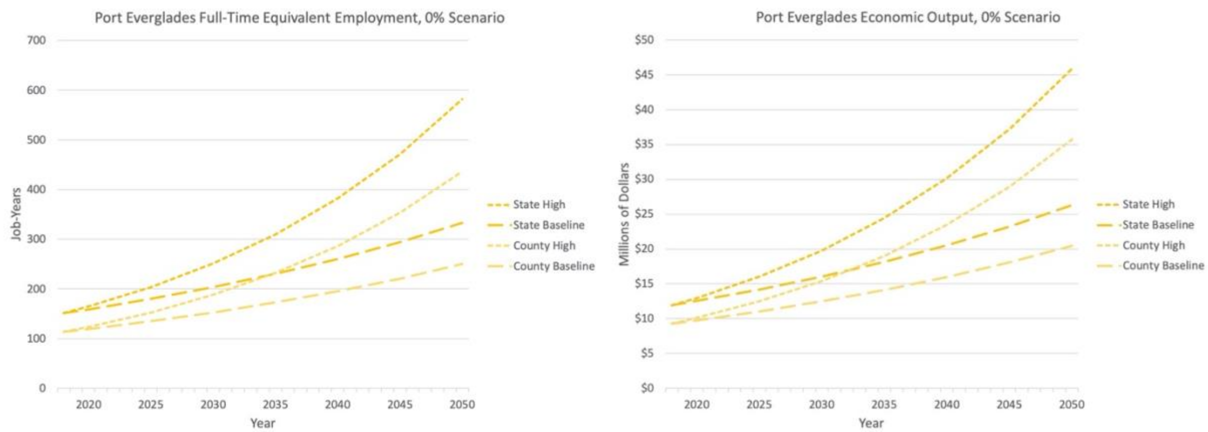


Figure 28: Port Everglades CHE 0% Scenario Results, Employment (left) & Economic Output (right)

For the Port Everglades, the 50% scenario shows the economic activity and employment effects of partial electrification. 50% of energy consumption comes from electricity, and the other 50% comes from diesel fuel. Thus, expenditures and job creation are split 50% and 50% between the electricity and diesel sectors. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $14,324,000 to $14,831,000 while county-level is between $12,755,000 and $13,207,000. Employment estimates at the state-level in 2020 range from 30.4 to 31.5 job-years. At the county-level, estimates are from 159 to 165 job-years. In 2050, state-level output is between $30,045,000 and $52,444,000, while county-level output is $26,755,000 to $46,703,000 Employment in 2050 at the state-level is from 638 – 1114 job-years, and at the county-level, from 334 – 584 job-years. This is illustrated in Figure 29.

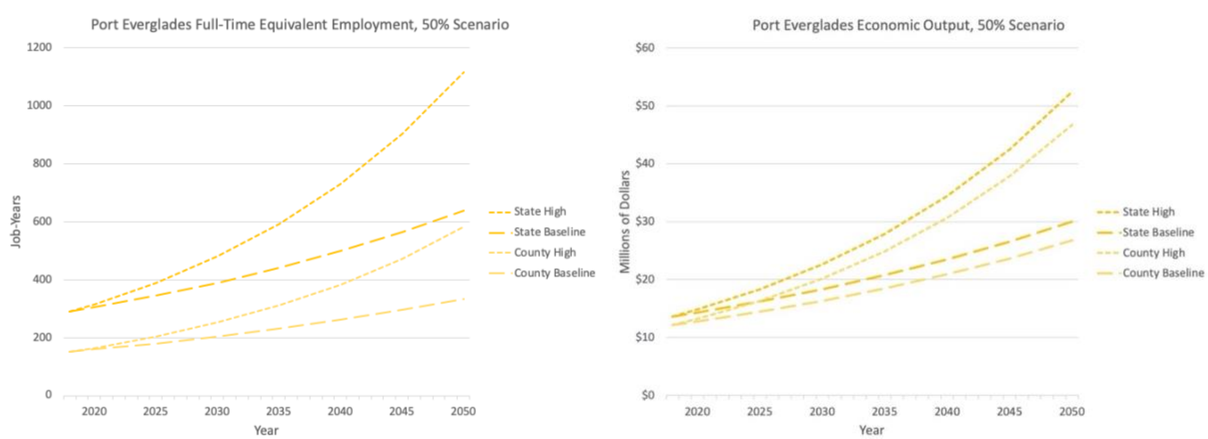


Figure 29: Port Everglades CHE 50% Scenario Results, Employment (left) & Economic Output (right)

For the Port Everglades, the 100% scenario shows the economic activity and employment effects of complete electrification. All of the spending and job creation is in the electricity sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $16,116,000 to $16,687,2000 while county-level is between $15,755,000 and $16,313,000. Employment estimates at the state-level in 2020 range from 450 – 466. At the county-level, estimates are from 200 – 207. In 2050, state-level output is between $33,805,000 - $59,008,000, while county-level output is $33,047,000 - $57,686,000. Employment in 2050 at the state-level is from 943 to 1647, and at the county-level, from 41.9 to 73.2. This is illustrated in Figure 30.

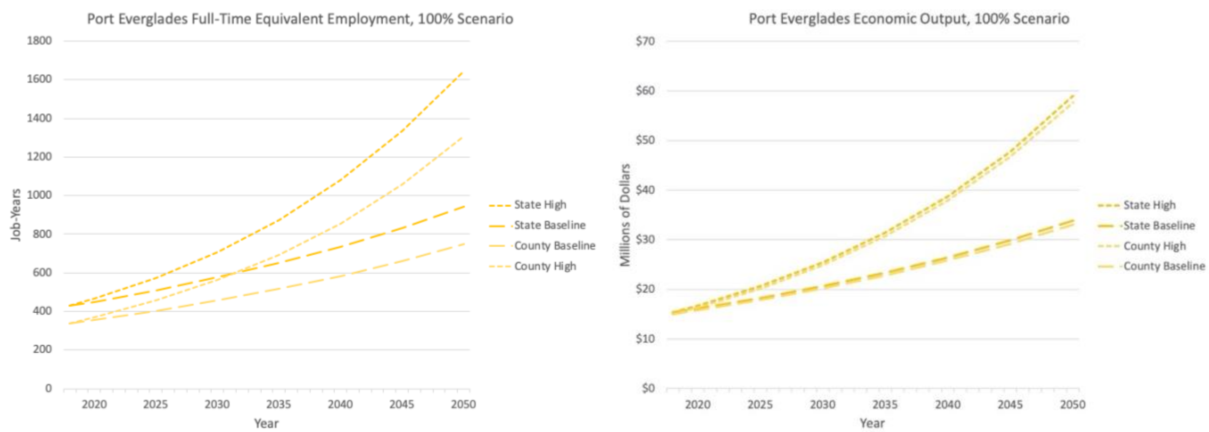


Figure 30: Port Everglades CHE 100% Scenario Results, Employment (left) & Economic Output (right)

Differences between the 0% CHE electrification scenario and the 50% and 100% CHE electrification scenarios indicate the change in economic activity for employment and economic output. In 2020, there is $1,793,000 - $1,856,000 more spending at the state-level in the 50% scenario and $3,585,000 - $3,712,000 more spending at the state-level in the 100% scenario. At the county level, there is between $3,000,000 and $3,106,000 more spending in the 50% scenario and between $5,999,000 and $6,212,000 more spending in the 100% scenario. The 50% scenario creates 145 – 151 more jobs at the state-level and 40 - 42 more jobs at the county-level than the 0% scenario, while the 100% scenario creates 291 – 300 more jobs at the state-level and 81 -84 more jobs at the county-level compared to the 0% scenario. In 2050, there is $3,760,000- $6,564,000 more spending at the state-level in the 50% scenario and $7,521,000 - $13,128,000 more spending at the state-level in the 100% scenario. At the county level, there is between $6,292,000 and $10,983,000 more spending in the 50% scenario and between $12,584,000 and $21,966,000 more spending in the 100% scenario. The 50% scenario creates 305 – 533 more jobs at the state-level and 85 – 148 more jobs at the county-level than the 0% scenario, while the 100% scenario creates 610 – 1065 more jobs at the state-level and 170 - 300 more jobs at the county-level compared to the 0% scenario. Figure 31 shows the county-level differences; the appendix includes tables that reveal state-level differences in employment and economic output.

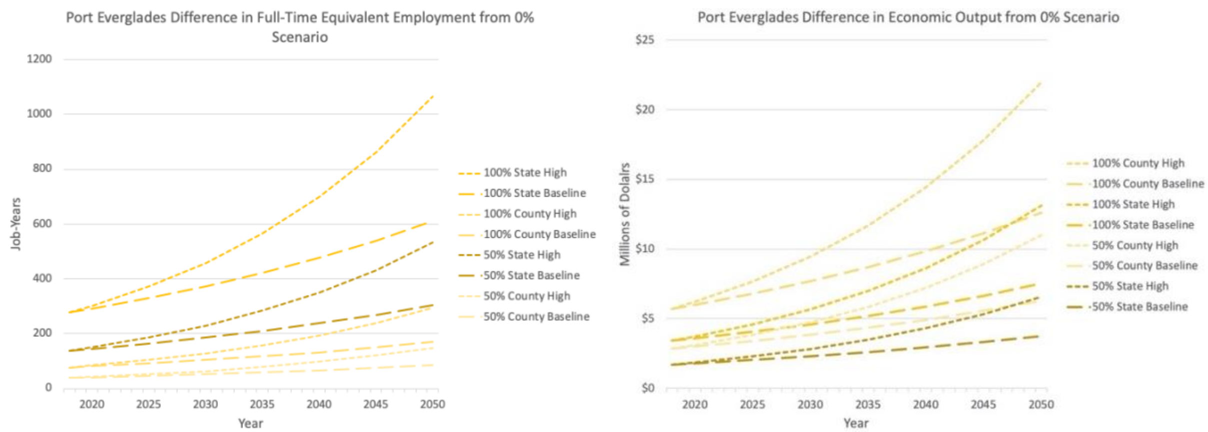


Figure 31: Port Everglades CHE Difference from 0% Scenario, Employment (left) & Economic Output (right)

5.3.3 Port of Houston Macroeconomic Effects of CHE Electrification

For the Port of Houston, the 0% scenario shows the economic activity and employment effects of no electrification. All of the spending and job creation is in the diesel sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $60,367,000 to $62,740,000 while county-level is between $47,945,000 and $49,829,000. Employment estimates at the state-level in 2020 range from 1136 – 1181. At the county-level, estimates are from 1016 – 1055. In 2050, state-level output is between $136,223,000 - $252,442,000, while county-level output is from $108,192,000 - $200,496,000. Employment in 2050 at the state-level is from 2564 – 4752, and at the county-level, from 2292 – 4247. This is illustrated in Figure 32.

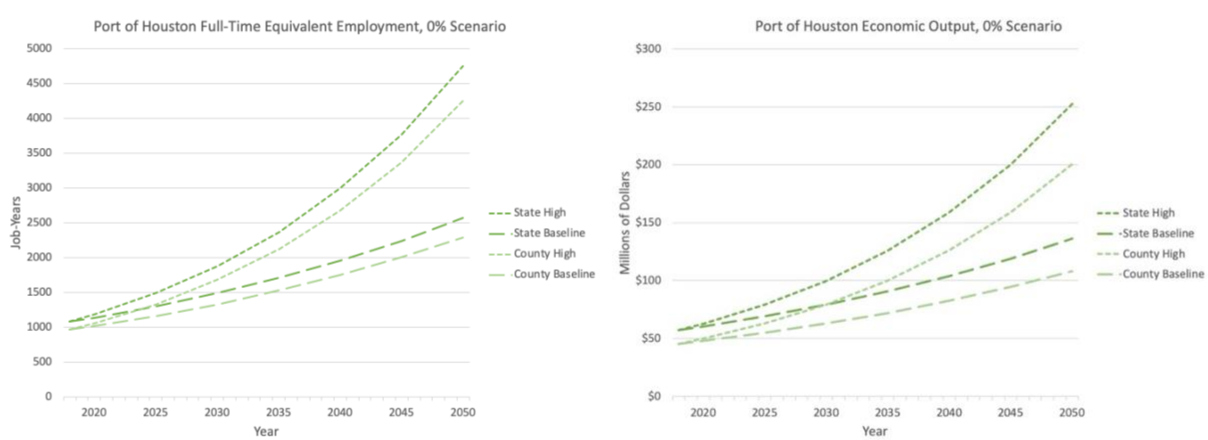


Figure 32: Port of Houston CHE 0% Scenario Results, Employment (left) & Economic Output (right)

For the Port of Houston, the 50% scenario shows the economic activity and employment effects of partial electrification. 50% of energy consumption comes from electricity, and the other 50% comes from diesel fuel. Thus, expenditures and job creation are split 50% and 50% between the electricity and diesel sectors. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $74,236,000 to $77,154,000 while county-level is between $60,993,000 to $63,390,000.

Employment estimates at the state-level in 2020 range from 1663 – 1729 job-years. At the county-level, estimates are from 1392 – 1447 job-years. In 2050, state-level output is between $167,521,000 and $310,442,000, while county-level output is $137,636,000 to $255,060,000. Employment in 2050 at the state-level is from 3754 – 6956 job-years, and at the county-level, from 3142 – 5822 job-years. This is illustrated in Figure 33.

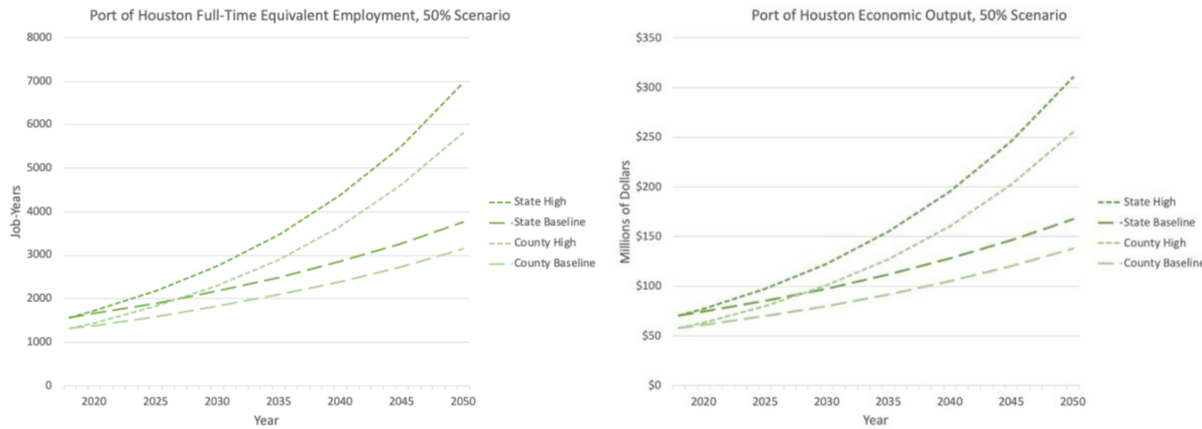


Figure 33: Port of Houston CHE 50% Scenario Results, Employment (left) & Economic Output (right)

For the Port of Houston, the 100% scenario shows the economic activity and employment effects of complete electrification. All of the spending and job creation is in the electricity sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $88,105,000 - $91,569,000 while county-level is between $74,040,000 and $76,951,000. Employment estimates at the state-level in 2020 range from 2191 – 2277 job-years. At the county-level, estimates are from 1769 – 1838 job-years. In 2050, state-level output is between $198,819,000 - $368,441,000, while county-level output is $167,080,000 - $309,624,000. Employment in 2050 at the state-level is from 4943 to 9160 job-years, and at the county-level, from 3992 to 7397 job-years. This is illustrated in Figure 34.

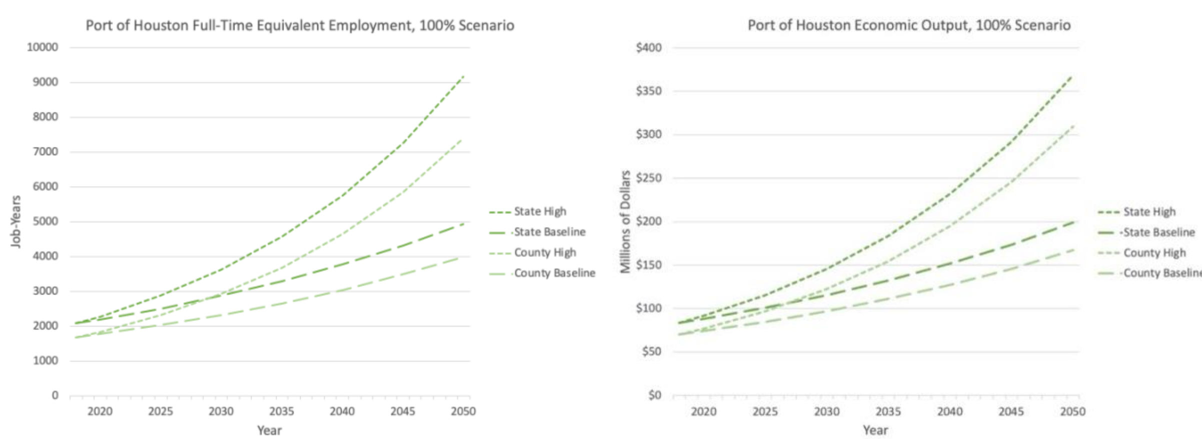


Figure 34: Port of Houston CHE 100% Scenario Results, Employment (left) & Economic Output (right)

Differences between the 0% CHE electrification scenario and the 50% and 100% CHE electrification scenarios indicate the change in economic activity for employment and economic output. In 2020, there is $13,869,00 - $14,415,000 more spending at the state-level in the 50% scenario and $27,739,000 - $28,829,000 more spending at the state-level in the 100% scenario. At the county level, there is between $13,048,000 and $13,561,000 more spending in the 50% scenario and between $26,096,000 and $27,122,000 more spending in the 100% scenario. The 50% scenario creates 527 – 550 more jobs at the state-level and 378 – 392 more jobs at the county-level than the 0% scenario, while the 100% scenario creates 1050 – 1096 more jobs at the state-level and 753 – 783 more jobs at the county-level compared to the 0% scenario. In 2050, there is $31,298,000 - $57,999,000 more spending at the state-level in the 50% scenario and $62,595,000 - $115,999,000 more spending at the state-level in the 100% scenario. At the county level, there is between $29,444,000 and $54,564,000 more spending in the 50% scenario and between $58,888,000 and $109,128,000 more spending in the 100% scenario. The 50% scenario creates 1189 – 2204 more jobs at the state-level and 850 – 1575 more jobs at the county-level than the 0% scenario, while the 100% scenario creates 2379 – 4408 more jobs at the state-level and 1700 – 3151 more jobs at the county-level compared to the 0% scenario. Figure 39 shows the county-level differences; the appendix includes tables that reveal state-level differences in employment and economic output.

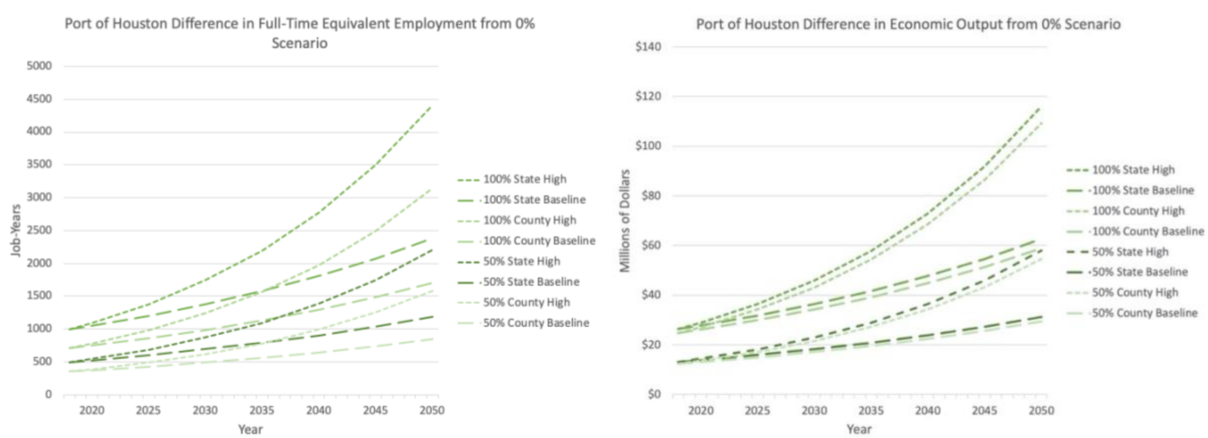


Figure 35: Port of Houston CHE Difference from 0% Scenario, Employment (left) & Economic Output (right)

5.3.4 Port of Seattle Macroeconomic Effects of CHE Electrifications

For the Port of Seattle, the 0% scenario shows the economic activity and employment effects of no electrification. All of the spending and job creation is in the diesel sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $7,092,000 to $7,342,000 while county-level is between $6,561,000 and $6,793,000. Employment estimates at the state-level in 2020 range from 78 – 81 job-years. At the county-level, estimates are from 68 to 71 job-years. In 2050, state-level output is between $16,003,000 and $27,896,000, while county-level output is $14,806,000 - $25,811,000. Employment in 2050 at the state-level is from 176 to 307 job-years, and at the county-level, from 154 to 268 job-years. This is illustrated in Figure 36.

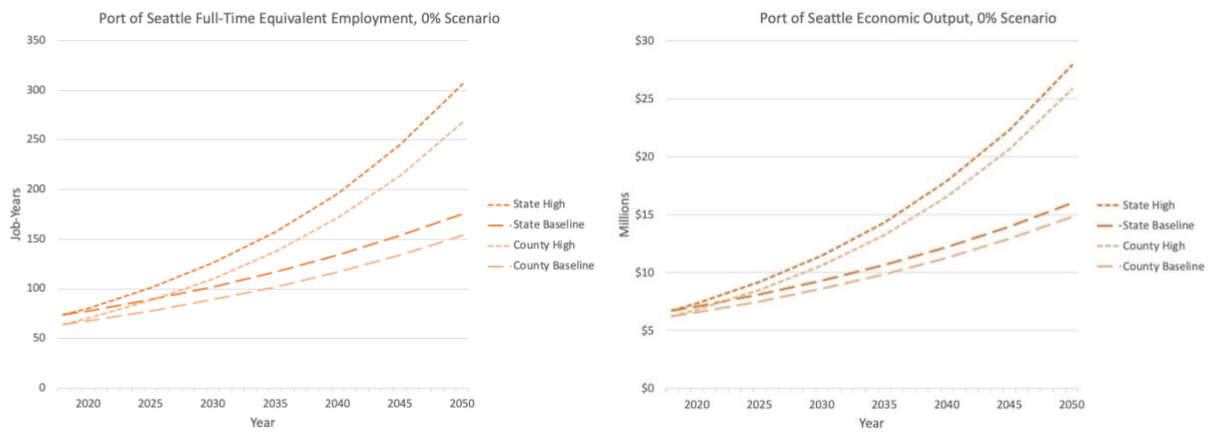


Figure 36: Port of Seattle 0% Scenario, Employment (left) & Economic Output (right)

For the Port of Seattle, the 50% scenario shows the economic activity and employment effects of partial electrification. 50% of energy consumption comes from electricity, and the other 50% comes from diesel fuel. Thus, expenditures and job creation are split 50% and 50% between the electricity and diesel sectors. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $6,167,000 to $6,384,000 while county-level is between $5,597,000 to $5,975,000. Employment estimates at the state-level in 2020 range from 84 – 87 job-years. At the county-level, estimates are from 68 to 71 job-years. In 2050, state-level output is between $13,890,000 and $24,199,000, while county-level output is $12,610,000 - $21,970,000. Employment in 2050 at the state-level is from 189 to 330 job-years, and at the county-level, from 155 to 270 job-years. While there are increases in employment, we can begin to see how because electricity is less expensive for the Port of Seattle and thus the port is spending less money in the economy, the output estimates for the 50% are less than the 0% scenario as some electrification begins. This is illustrated in Figure 37.

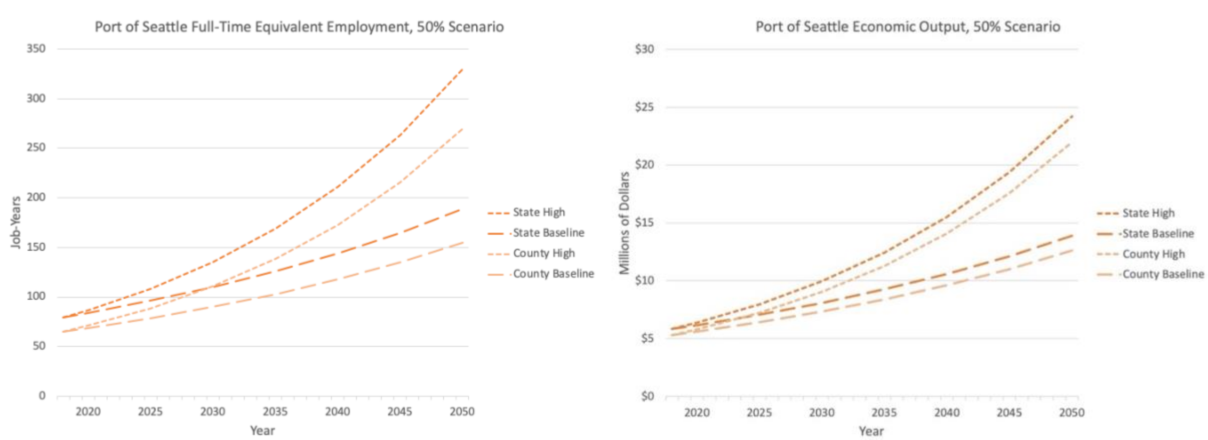


Figure 37: Port of Seattle 50% Scenario, Employment (left) & Economic Output (right)

For the Port of Seattle, the 100% scenario shows the economic activity and employment effects of complete electrification. All of the spending and job creation is in the electricity sector. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $5,241,000 to $5,425,000 while county-level is between $4,634,000 and $4,796,000. Employment estimates at the state-level in 2020 range from 90 – 93. At the county-level, estimates are from 70 to 72. In 2050, state-level output is between $11,778,000 and $20,502,000, while county-level output is $10,414,000 - $18,129,000. Employment in 2050 at the state-level is from 202 to 352, and at the county-level, from 156 to 272. Now with all spending in the electricity sector, output is significantly less at the 100% scenario than the 0%, but employment is still increasing. These results can further be seen in the graphs below showing the differences in employment and output from the 0% scenario to the 100% and 0% scenario. This is illustrated in Figure 38.

Figure 38: Port of Seattle 100% Scenario, Employment (left) & Economic Output (right)

Differences between the 0% CHE electrification scenario and the 50% and 100% CHE electrification scenarios indicate the change in economic activity for employment and economic output. For output, the differences are negative because there is less spending in the economy when the Port of Seattle shifts from diesel consumption to electricity consumption, as they are the only port where electricity expenditures are less than diesel expenditures. In 2020, there is $925,000 – $$958,000 less spending at the state-level in the 50% scenario and $1,850,000 - $1,917,000 less spending at the state-level in the 100% scenario. At the county level, there is between $964,000 to $999,000 less spending in the 50% scenario and between $1,928,000 and $1,997,000 less spending in the 100% scenario. The 50% scenario creates ~6 more jobs at the state-level and ~1 more jobs at the county-level than the 0% scenario, while the 100% scenario creates ~12 more jobs at the state-level and ~1 more jobs at the county-level compared to the 0% scenario. In 2050, there is $31,298,000 - $57,999,000 less spending at the state-level in the 50% scenario and $4,225,000 - $7,395,000 less spending at the state-level in the 100% scenario. At the county level, there is between $29,444,000 and $54,564,000 less spending in the 50% scenario and between $4,393,000 and $7,682,000 less spending in the 100% scenario. The 50% scenario creates 13 – 23 more jobs at the state-level and ~1 – 2 more jobs at the county-level than the 0% scenario, while the 100% scenario creates 25 - 46 more jobs at the state-level and 2 – 4 more jobs at the county-level compared to the 0% scenario. Figure 39 shows the county-level differences; the appendix includes tables that reveal state-level differences in employment and economic output.

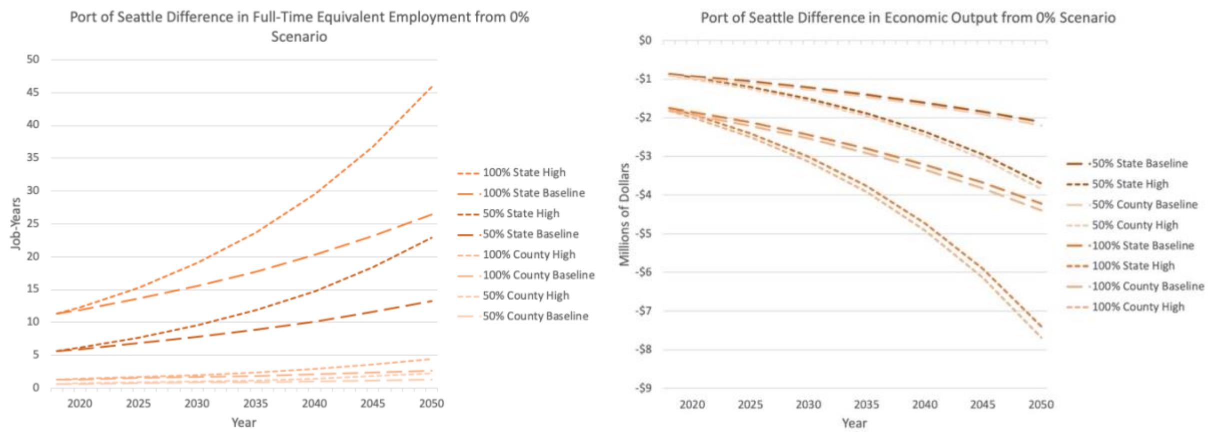


Figure 39: Port of Seattle Difference from 0% Scenario, Employment (left) & Economic Output (right)

5.4 Port Shore Power Scenario Results

This section discusses shore power electrification results for each scenario for each port. Graphs are shown for the 50%, and 100% scenario for both economic activity and employment. Given the expectation that most vessels not using shore power would have purchased fuel outside the region of study, there is no 0% scenario as in Section 5.3 because no expenditures or jobs are attributed to macroeconomic activity outside the region. Macroeconomic benefits are estimated based solely on electricity expenditures which recur over the long-term. As stated in the methods section, capital costs and other non-recurring spending are not considered in this study. There are also graphs showing the differences in employment and output for both the 50% and 100% scenario.

5.4.1 Port of Baltimore Macroeconomic Effects of Shore Power Electrification

For the Port of Baltimore, the 50% shore power scenario shows the economic activity and employment effects of partial electrification of vessels at berth. 50% of energy consumption comes from electricity, and the other 50% comes from fuel onboard vessels – not counted toward county or state economic activity. Thus, expenditures and job creation are only due to 50% electrification of vessel power at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $2,695,000 to $2,821,000 while county-level is between $2,341,000 to $2,449,000. Employment estimates at the state-level in 2020 range from 66 to 69 job-years. At the county-level, estimates are from 62 to 65 job-years. In 2050, state-level output is between $6,542,000 to $13,674,000, while county-level output ranges from $5,680,000 to $11,872,000. Employment in 2050 at the state-level is from 159 – 332 job-years, and at the county-level, from 150 – 313 job-years. This is illustrated in Figure 40.

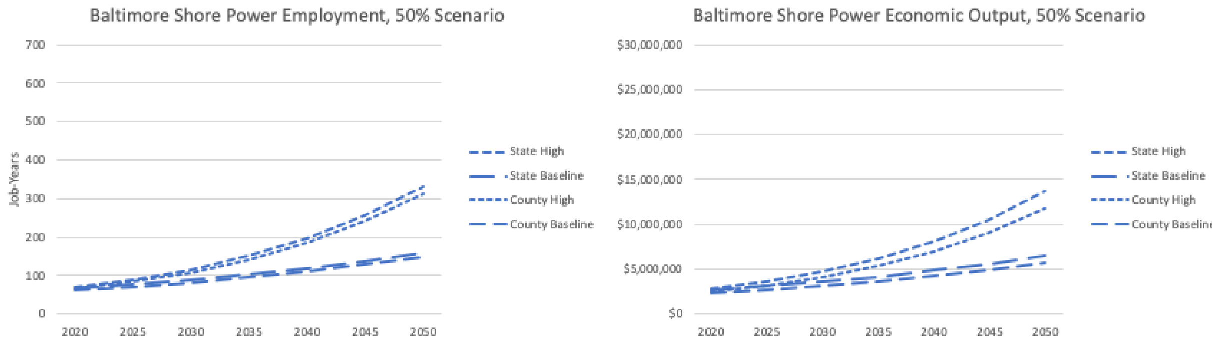


Figure 40. Port of Baltimore Shore Power 50% Scenario, Employment (left) & Economic Output (right)

For the Port of Baltimore, the 100% shore power scenario shows the economic activity and employment effects of complete electrification of vessels at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $5,392,000 to $5,641,000 while county-level is between $4,682,000 and $4,898,000. Employment estimates at the state-level in 2020 range from 131 to 137 job-years. At the county-level, estimates are from 123 to 129 job-years. In 2050, state-level output is between $13,085,000 - $27,348,000, while county-level output is $11,361,000 - $23,745,000. Employment in 2050 at the state-level is from 318 – 665 job-years, and at the county-level, from 299 to 626 job-years. This is illustrated in Figure 41.

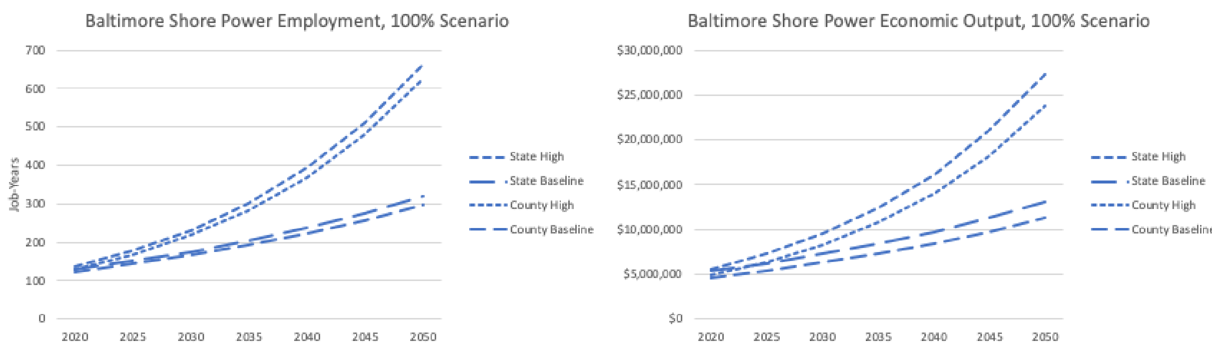


Figure 41. Port of Baltimore Shore Power 100% Scenario, Employment (left) & Economic Output (right)

5.4.2 Port Everglades Macroeconomic Effects of Shore Power Electrification

For Port Everglades, the 50% shore power scenario shows the economic activity and employment effects of partial electrification of vessels at berth. 50% of energy consumption comes from electricity, and the other 50% comes from fuel onboard vessels – not counted toward county or state economic activity. Thus, expenditures and job creation are only due to 50% electrification of vessel power at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $2,122,000 to $2,199,000 while county-level is between $2,075,000 to $2,150,000. Employment estimates at the state-level in 2020 range from 59 to 60 job-years. At the county-level, estimates are from 26 to 27 job-years. In 2050, state-level output is between $4,454,000 to $7,770,000, while county-level output ranges from $4,354,000 to $7,596,000. Employment in 2050 at the state-level is from 124 – 216 job-years, and at the county-level, from 55 – 96 job-years. This is illustrated in Figure 42.

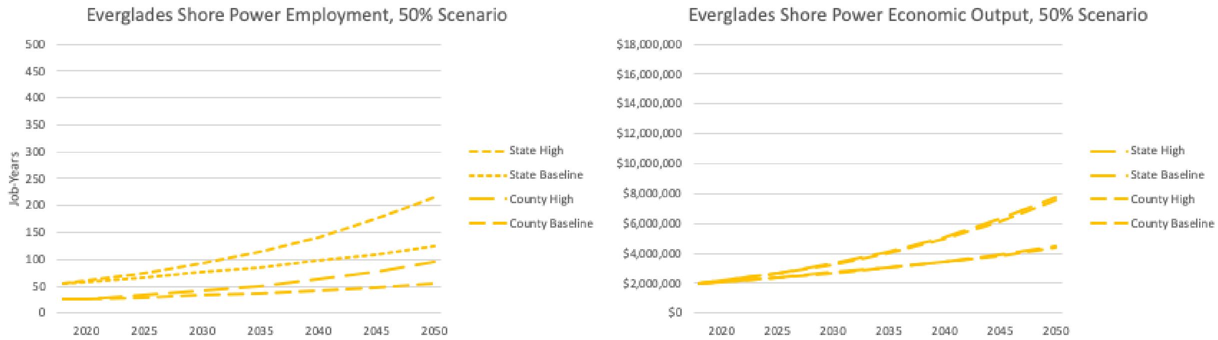


Figure 42. Port Everglades Shore Power 50% Scenario, Employment (left) & Economic Output (right)

For Port Everglades, the 100% shore power scenario shows the economic activity and employment effects of complete electrification of vessels at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $4,244,000 to $4,398,000 while county-level is between $4,150,000 and $4,300,000. Employment estimates at the state-level in 2020 range from 118 to 122 job-years. At the county-level, estimates are from 52 to 54 job-years. In 2050, state-level output is between $8,908,000 to $15,534,000, while county-level output is $8,709,000 and $15,192,000. Employment in 2050 at the state-level is from 248 to 432 job-years, and at the county-level, from 110 to 192 job-years. This is illustrated in Figure 43.

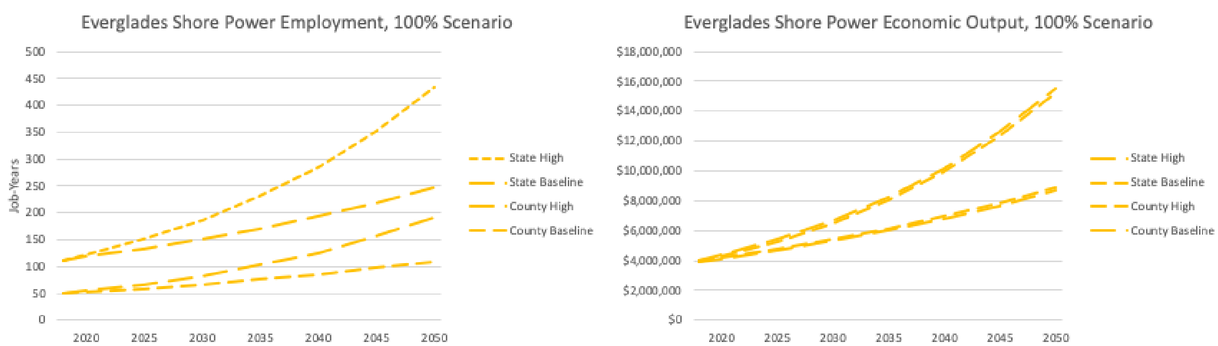


Figure 43. Port Everglades Shore Power 100% Scenario, Employment (left) & Economic Output (right)

5.4.3 Port of Houston Macroeconomic Effects of Shore Power Electrification

For the Port of Houston, the 50% shore power scenario shows the economic activity and employment effects of partial electrification of vessels at berth. 50% of energy consumption comes from electricity, and the other 50% comes from fuel onboard vessels – not counted toward county or state economic activity. Thus, expenditures and job creation are only due to 50% electrification of vessel power at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $4,903,000 to $5,098,000 while county-level is between $4,115,000 to $4,279,000. Employment estimates at the state-level in 2020 range from 122 to 127 job-years. At the county-level, estimates are from 99 to 102 job-years. In 2050, state-level output is between $11,072,000 to $20,511,000, while county-level output ranges from $9,291,000 to $17,212,000. Employment in 2050 at the state-level is from 275 – 510 job-years, and at the county-level, from 223 – 412 job-years. This is illustrated in Figure 44.

Figure 44. Port of Houston Shore Power 50% Scenario, Employment (left) & Economic Output (right)

For the Port of Houston, the 100% shore power scenario shows the economic activity and employment effects of complete electrification of vessels at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $9,807,000 to $10,197,000 while county-level is between $8,230,000 and $8,557,000. Employment estimates at the state-level in 2020 range from 244 to 254 job-years. At the county-level, estimates are from 197 to 205 job-years. In 2050, state-level output is between $22,143,000 to $40,021,000, while county-level output is $18,582,000 and $34,425,000. Employment in 2050 at the state-level is from 551 to 1020 job-years, and at the county-level, from 445 to 825 job-years. This is illustrated in Figure 45.

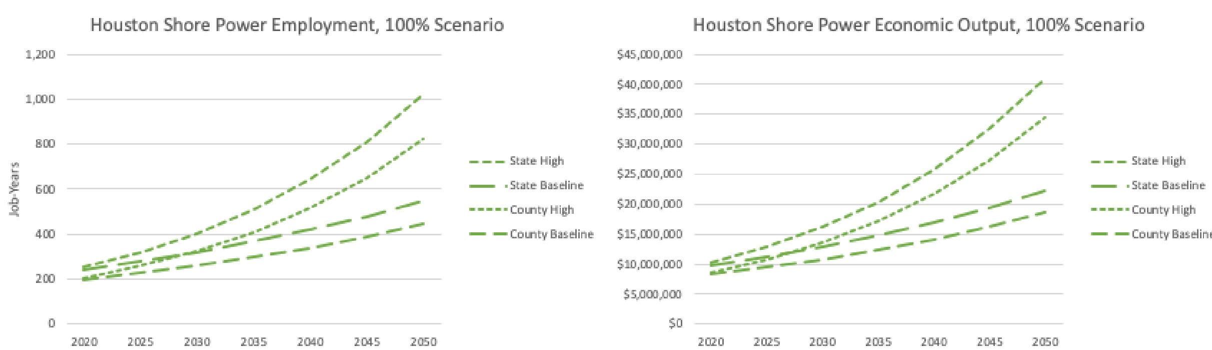


Figure 45. Port of Houston Shore Power 100% Scenario, Employment (left) & Economic Output (right)

5.4.4 Port of Seattle Macroeconomic Effects of Shore Power Electrification

For the Port of Seattle, the 50% shore power scenario shows the economic activity and employment effects of partial electrification of vessels at berth. 50% of energy consumption comes from electricity, and the other 50% comes from fuel onboard vessels – not counted toward county or state economic activity. Thus, expenditures and job creation are only due to 50% electrification of vessel power at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $3,888,000 to $4,026,000 while county-level is between $3,433,000 to $3,556,000. Employment estimates at the state-level in 2020 range from 67 to 69 job-years. At the county-level, estimates are from 51 to 53 job-years. In 2050, state-level output is between $8,774,000 to $15,291,000, while county-level output ranges from $7,748,000 to $13,504,000. Employment in 2050 at the state-level is from 151 – 263 job-years, and at the county-level, from 116 – 203 job-years. This is illustrated in Figure 46.

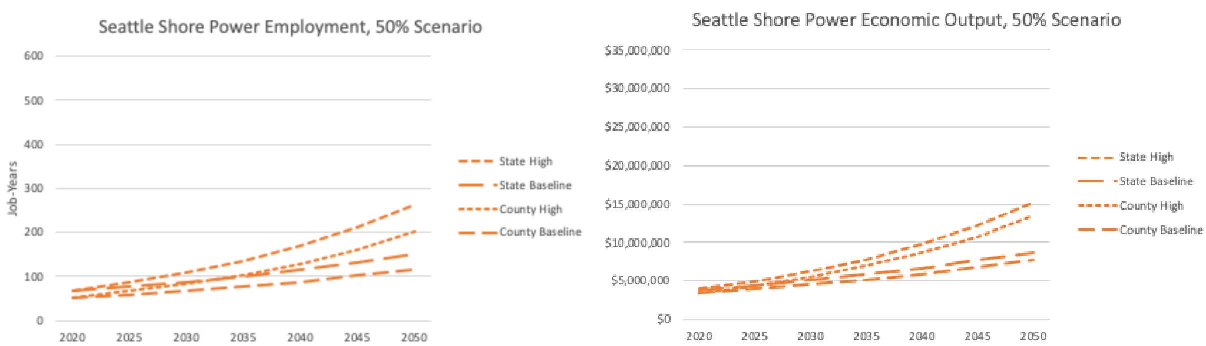


Figure 46. Port of Seattle Shore Power 50% Scenario, Employment (left) & Economic Output (right)

For the Port of Seattle, the 100% shore power scenario shows the economic activity and employment effects of complete electrification of vessels at berth. The state scenario for the output and employment impacts are higher than the county impacts. State-level output in 2020 ranges from $7,776,000 to $8,053,000 while county-level is between $6,867,000 and $7,111,000. Employment estimates at the state-level in 2020 range from 134 to 139 job-years. At the county-level, estimates are from 103 to 107 job-years. In 2050, state-level output is between $17,547,000 to $30,582,000, while county-level output is $15,496,000 and $27,008,000. Employment in 2050 at the state-level is from 302 to 526 job-years, and at the county-level, from 232 to 405 job-years. This is illustrated in Figure 47.

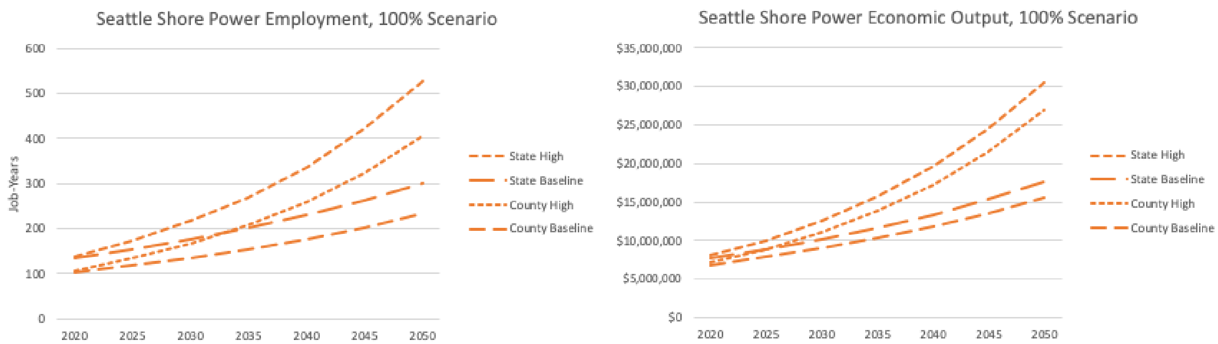


Figure 47. Port of Seattle Shore Power 100% Scenario, Employment (left) & Economic Output (right)

5.5 Emission Benefits of Cargo Handling Electrification (eGRID)

This section discusses Year 2020 emission benefits of electrifying cargo handling equipment. Current national policies set stricter limits on fuel sulfur in onroad/nonroad diesel fuels, and allow less strict limits on fuel sulfur for petroleum and coal fuels used in power generation. This will affect the emissions tradeoff for SOx emissions, even as the location of those emissions relocates to the electricity power generator location. We do not provide estimates for future years as the grid generation mix is in flux both nationally and regionally, with estimates of the share of electricity generation by source type falling outside the scope of this study. As power generation portfolios adopt more renewable energies and other low-sulfur fossil fuels, the relatively higher sulfur and PM emissions will change, along with additional changes to electricity grid emissions portfolios from potentially more or less strict pollution control requirements (see recommendation in Sections 6.4). Figure 48 provides an overview of the projected national-level grid mix from EIA.

We do not evaluate the potential emissions changes from switching hoteling diesel emissions to shore power for several reasons. First, the data necessary for this within port case studies was unavailable to this project. Second, studies have been done at both port-based and national levels that this report could not replicate within scope and budget. Third, international shipping uses a variety of marine fuels complying with North American ECA fuel sulfur – and more recently with global sulfur limits. Assessing regional marine fuel qualities would require its own study.

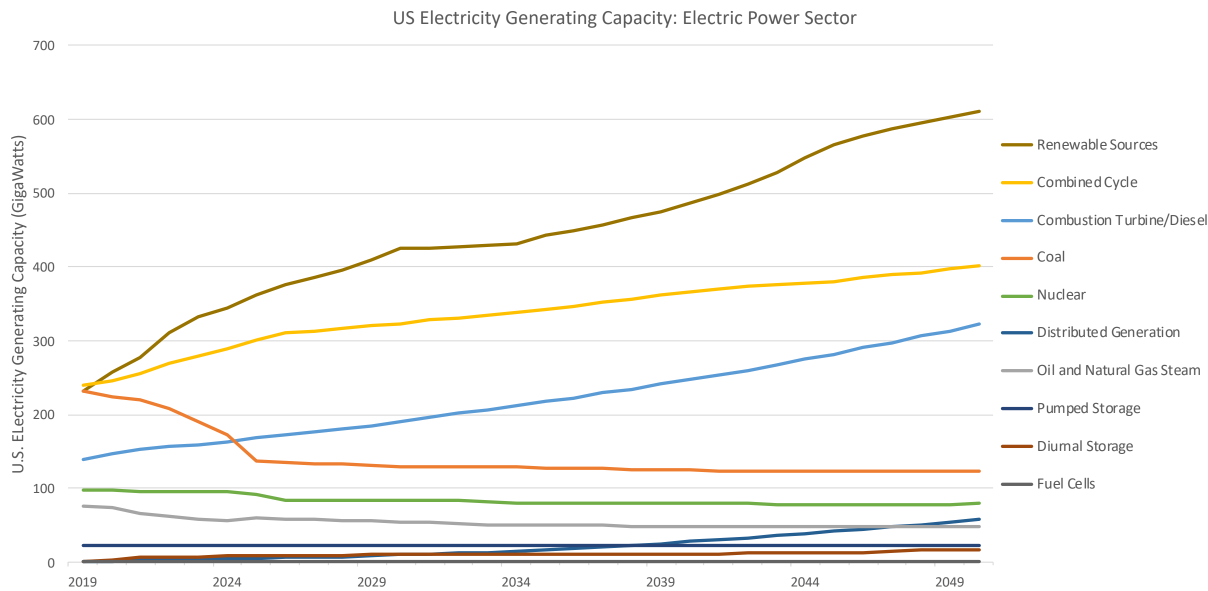


Figure 48: Projected U.S. electricity generating capacity by electric power sector. Source: EIA AEO

5.5.1 Port of Baltimore

Estimated emissions reductions for the Port of Baltimore are shown in Table 30. As with the other ports studied, NOx and GHGs are reduced in all scenarios, while SOx increases. Emission reductions increase with greater electrification and are greater under the high growth scenarios than under the baseline growth scenarios. Emission reductions for NOx range from 143 tonnes under the 50% electrification baseline to 300 tonnes under the 100% electrification high growth scenario. On the GHG side of things, CO_2e emission reductions from electrification range from 9,030 tonnes under the 50% baseline, to 18,900 tonnes under the 100% electrification high growth scenario.

Table 30: Difference in criteria and greenhouse gas pollutant emissions by scenario and market penetration in 2020 at the Port of Baltimore. (Values in parentheses are negative)

Metric Tons	NOx	SOx	CH4	N2O	CO2e
50% Baseline	(143.0)	3.57	(0.401)	(0.343)	(9,030)
50% High	(150.0)	3.74	(0.420)	(0.359)	(9,460)
100% Baseline	(287.0)	7.14	(0.802)	(0.686)	(18,100)
100% High	(300.0)	7.48	(0.840)	(0.719)	(18,900)

As discussed in Section 5.2, net expenditures increase under all scenarios at the Port of Baltimore, compared to the baseline. These increased expenditures result in reductions in pollutants, with the exception of SOx, which increases slightly. The net cost per unit pollution abated is shown in Table 31. The cost per MT NOx abated is around $16,270/MT, and the cost per unit CO_2 abated is $260/MT. SOx is estimated to increase slightly, resulting in high costs per MT of SOx emissions increased.

Table 31: Net energy cost per unit pollution abated ($/MT) at the Port of Baltimore. (Values in parentheses are negative, representing a cost per MT pollution increase)

	Net Energy Cost per Unit Pollution Abated ($/MT)				
	NOx	SOx	CH4	N2O	CO2e
50% Baseline	16,270	(651,830)	5,803,050	6,784,320	260
50% High	16,240	(651,530)	5,801,740	6,787,550	260
100% Baseline	16,220	(651,830)	5,803,050	6,784,320	260
100% High	16,240	(651,530)	5,801,740	6,778,110	260

5.5.2 Port Everglades

Estimated emissions reductions for Port Everglades are shown in Table 32. As with the other ports studied, NOx and GHGs are reduced in all scenarios, while SOx increases. Emission reductions increase with greater electrification and are greater under the high growth scenarios than under the baseline growth scenarios. Emission reductions for NOx range from 70.9 tonnes under the 50% electrification baseline to 147 tonnes under the 100% electrification high growth scenario. On the GHG side of things, CO_2e emission reductions from electrification range from 6,100 tonnes under the 50% baseline, to 12,600 tonnes under the 100% electrification high growth scenario.

Table 32: Difference in criteria and greenhouse gas pollutant emissions by scenario and market penetration in 2020 at Port Everglades. (Values in parentheses are negative)

Metric Tonnes	NOx	SOx	CH4	N2O	CO2e
50% Baseline	(70.9)	1.38	(0.312)	(0.297)	(6,100)
50% High	(73.4)	1.43	(0.323)	(0.307)	(6,320)
100% Baseline	(142.0)	2.76	(0.625)	(0.594)	(12,200)
100% High	(147.0)	2.86	(0.647)	(0.615)	(12,600)

As discussed in Section 5.2, net expenditures increase under all scenarios at Port Everglades, compared to the baseline. These increased expenditures result in reductions in pollutants, with the exception of SOx, which increases. The net cost per unit pollution abated is shown in Table 33. The cost per MT NOx abated is around $25,300/MT, and the cost per unit CO_2 abated is $290/MT. SOx is estimated to increase slightly at Port Everglades, resulting in high costs per MT of SOx emissions increased.

Table 33: Net energy cost per unit pollution abated ($/MT) at Port Everglades. (Values in parentheses are negative, representing a cost per MT pollution increase)

	Net Energy Cost per Unit Pollution Abated ($/MT)				
	NOx	SOx	CH4	N2O	CO2e
50% Baseline	25,300	(1,299,860)	5,749,370	6,039,740	290
50% High	25,300	(1,298,850)	5,750,330	6,050,020	290
100% Baseline	25,260	(1,299,860)	5,740,170	6,039,740	290
100% High	25,270	(1,298,850)	5,741,440	6,040,190	290

5.5.3 Port of Houston

Estimated emissions reductions for the Port of Houston are shown in Table 34. As with the other ports studied, NOx and GHGs are reduced in all scenarios, while SOx increases. Emission reductions increase with greater electrification and are greater under the high growth scenarios than under the baseline growth scenarios. Emission reductions for NOx range from 1,040 tonnes under the 50% electrification baseline to 2,170 tonnes under the 100% electrification high growth scenario. On the GHG side of things, CO_2e emission reductions from electrification range from 42,100 tonnes under the 50% baseline, to 87,400 tonnes under the 100% electrification high growth scenario.

Table 34: Difference in criteria and greenhouse gas pollutant emissions by scenario and market penetration in 2020 at Port of Houston. (Values in parentheses are negative)

Metric Tonnes	NOx	SOx	CH4	N2O	CO2e
50% Baseline	(1,040)	40.6	(2.15)	(2.05)	(42,100)
50% High	(1,080)	42.1	(2.24)	(2.13)	(43,700)
100% Baseline	(2,080)	81.1	(4.30)	(4.09)	(84,100)
100% High	(2,170)	84.3	(4.47)	(4.25)	(87,400)

As discussed in Section 5.2, net expenditures increase under all scenarios at Port Everglades, compared to the baseline. These increased expenditures result in reductions in pollutants, with the exception of SOx, which increases. The net cost per unit pollution abated is shown in Table 35. The cost per MT NOx abated is around $3,800/MT, and the cost per unit CO_2 abated is $90/MT. SOx is estimated to increase slightly at the Port of Houston, resulting in high costs per MT of SOx emissions increased.

Table 35: Net energy cost per unit pollution abated ($/MT) at the Port of Houston. (Values in parentheses are negative, representing a cost per MT pollution increase)

	Net Energy Cost per Unit Pollution Abated ($/MT)				
	NOx	SOx	CH4	N2O	CO2e
50% Baseline	3,800	(97,390)	1,839,060	1,928,770	90
50% High	3,800	(97,610)	1,834,550	1,929,290	90
100% Baseline	3,800	(97,510)	1,839,060	1,933,480	90
100% High	3,790	(97,490)	1,838,660	1,933,830	90

5.5.4 Port of Seattle

Estimated emissions reductions for the Port of Seattle are shown in Table 36. As with the other ports studied, NOx and GHGs are reduced in all scenarios, while SOx increases. Emission reductions increase with greater electrification and are greater under the high growth scenarios than under the baseline growth scenarios. Emission reductions for NOx range from 80.6 tonnes under the 50% electrification baseline to 167 tonnes under the 100% electrification high growth scenario. On the GHG side of things, CO_2e emission reductions from electrification range from 5,640 tonnes under the 50% baseline, to 11,700 tonnes under the 100% electrification high growth scenario.

Table 36:Difference in criteria and greenhouse gas pollutant emissions by scenario and market penetration in 2020 at Port of Seattle. (Values in parentheses are negative

Metric Tonnes	NOx	SOx	CH4	N2O	CO2e
50% Baseline	(80.6)	1.47	(0.213)	(0.191)	(5,640)
50% High	(83.4)	1.52	(0.221)	(0.198)	(5,840)
100% Baseline	(161.0)	2.94	(0.427)	(0.383)	(11,300)
100% High	(167.0)	3.04	(0.442)	(0.396)	(11,700)

As discussed in Section 5.2, the Port of Seattle is the only port for which there are estimated energy cost savings from electrification. Seattle is unusual in these results, as the port is estimated to generally achieve both reduced emissions and lower costs. These reduced expenditures result in reductions in pollutants, with the exception of SOx, which increases. As such, we estimate net *savings* per MT of pollution abated at the Port of Seattle. The net savings per unit pollution abated is shown in Table 37. The savings per MT NOx abated is around $1,110/MT, and the savings per unit CO_2 abated is around $20/MT. SOx is estimated to increase slightly at Port of Seattle.

Table 37: Net energy cost per unit pollution abated ($/MT) at the Port of Seattle. Note that costs are reduced at the Port of Seattle through electrification, thus the port receives lower emissions for reduced cost, with the exception of SOx, which increases slightly.

	Net Energy Cost per Unit Pollution Abated ($/MT)				
	NOx	SOx	CH4	N2O	CO2e
50% Baseline	(1,110)	60,670	(418,730)	(466,960)	(20)
50% High	(1,110)	60,750	(417,840)	(466,380)	(20)
100% Baseline	(1,110)	60,670	(417,750)	(465,750)	(20)
100% High	(1,110)	60,750	(417,840)	(466,380)	(20)

6 Discussion and Conclusion

This section discusses the macroeconomic impacts of port electrification of cargo handling equipment and shore power during dockside hoteling. We also discuss the environmental implications of port electrification in terms of changes when diesel emissions are replaced by electric grid emissions. We summarize general insights and recommend follow-on studies to support broader decision making with regard to the economic and environmental impacts of port electrification.

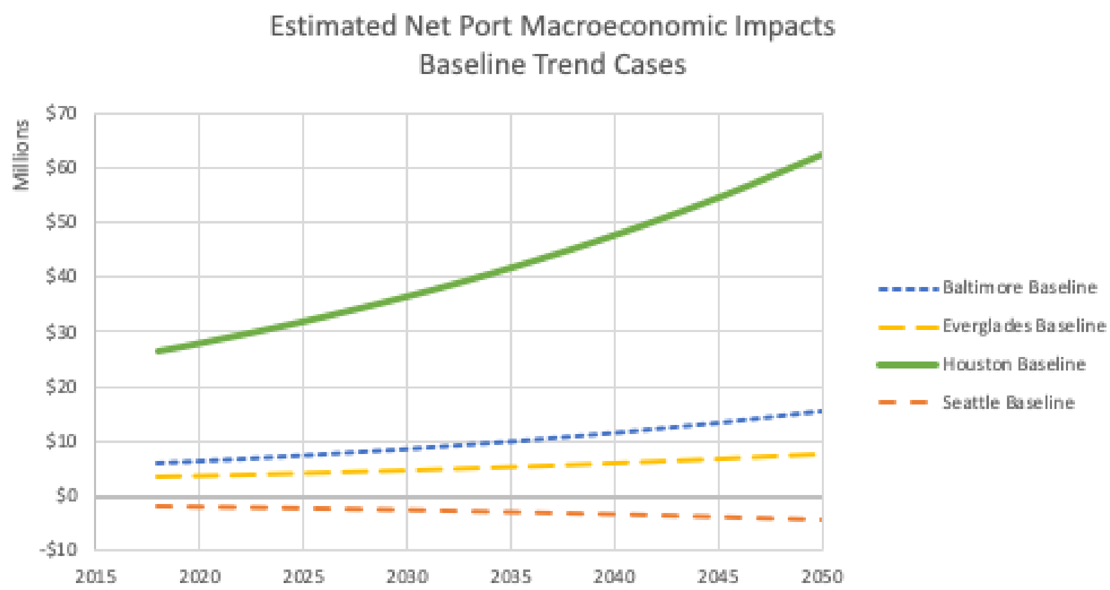
6.1 Macroeconomic Impacts of Electrification

Generally, port electrification changes cargo handling expenditures from diesel to electricity power, and adds new regional expenditures related to shore power for dockside vessels. These expenditures are associated with new direct and indirect jobs and other economic output in the region (state or county). Not all benefits are captured in this study, particularly where states are small, or electrification includes activity outside of the county/state (i.e., not aligned with electrical grid operations), or where other sector activity may include ex-county or ex-state employment and expenditures. Therefore, these results represent a conservative estimate of net economic impacts.

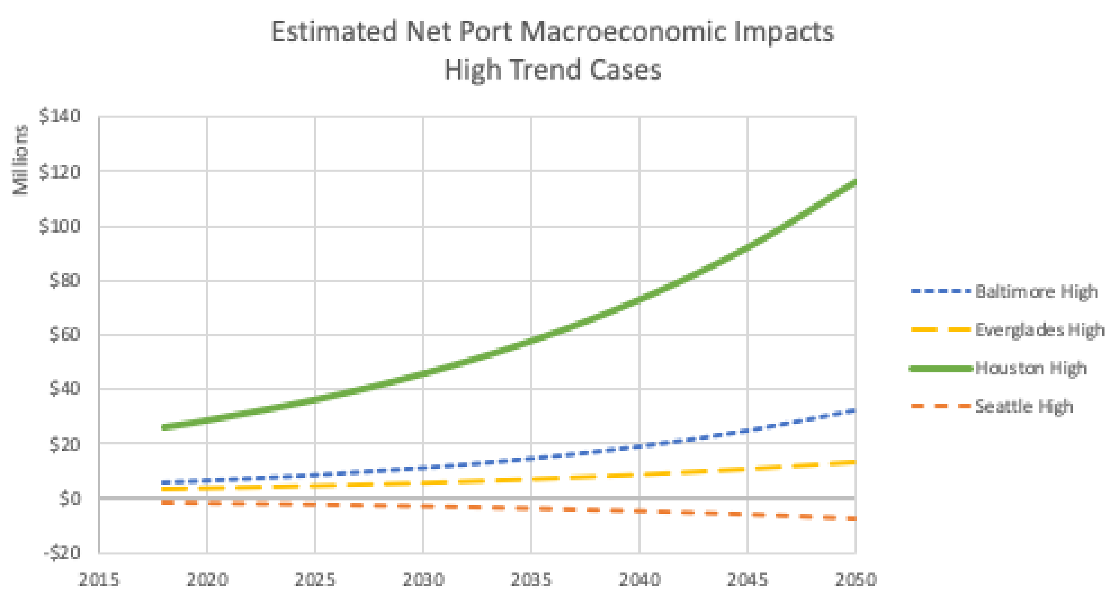
6.1.1 Port CHE Electrification Impacts on State Economic Output

State- and County-level net economic output between 2020 and 2050 changes by 2.1 to 2.4 times in base trend cases, and changes by 3.5 to 4.8 times in high trend cases across the ports. Importantly, economic output for the Port of Seattle cases declines because port CHE electrification saves money, thereby reducing expenditures associated with change in regional economic activity. This is illustrated in Figure 49.

Larger ports, with more activity, show greater net change in economic output. Ports in regions with higher economic multipliers receive greater impact for similar expenditures. And ports in regions where relative pricing ratios (see Table 2) are greater between petroleum diesel expenditures and electricity expenditures see greater economic impacts.



(a)



(b)

Figure 49. State-level Net Economic Output Related to Port CHE Electrification; (a) Baseline and (b) High Trend Cases

6.1.2 Port CHE Electrification Impacts on State Employment

State- and County-level net employment between 2020 and 2050 changes by 2.1 to 2.2 times in base trend cases, and changes by 3.7 to 4.8 times in high trend cases across the ports. (For the Port of Seattle, net employment impacts are small but positive.) In all cases, employment changes are positive, even though the job-year increase is quite modest for the Port of Seattle cases. This is illustrated in Figure 50.

Larger ports, with more activity, show greater net change in job-year employment. Ports in regions with higher employment multipliers receive greater impact for similar expenditures. And fewer employment benefits are observed in regions where net expenditures for port electrification are smaller (e.g., Port of Seattle).

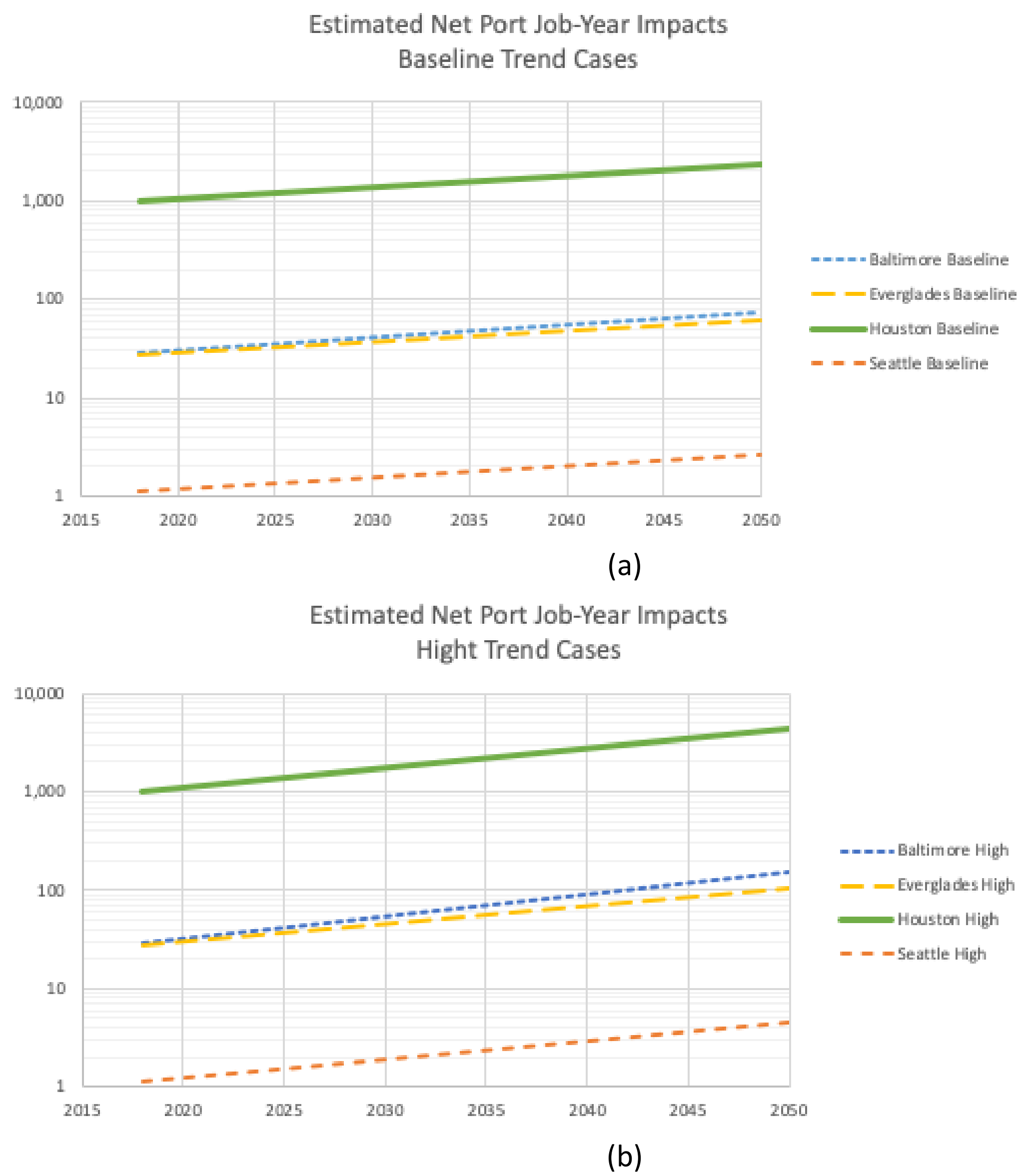


Figure 50. State-level Net Employment Change Related to Port CHE Electrification; (a) Baseline and (b) High Trend Cases

6.1.3 Port Shore Power Electrification Impacts on State Economic Output

In each port case study, economic output increases due to new shore power expenditures during dockside hoteling. This increases regional impacts compared with ex-region purchases for onboard auxiliary power fuels, even for the Port of Seattle cases. State- and County-level shore power related economic output between 2020 and 2050 changes by 2.1

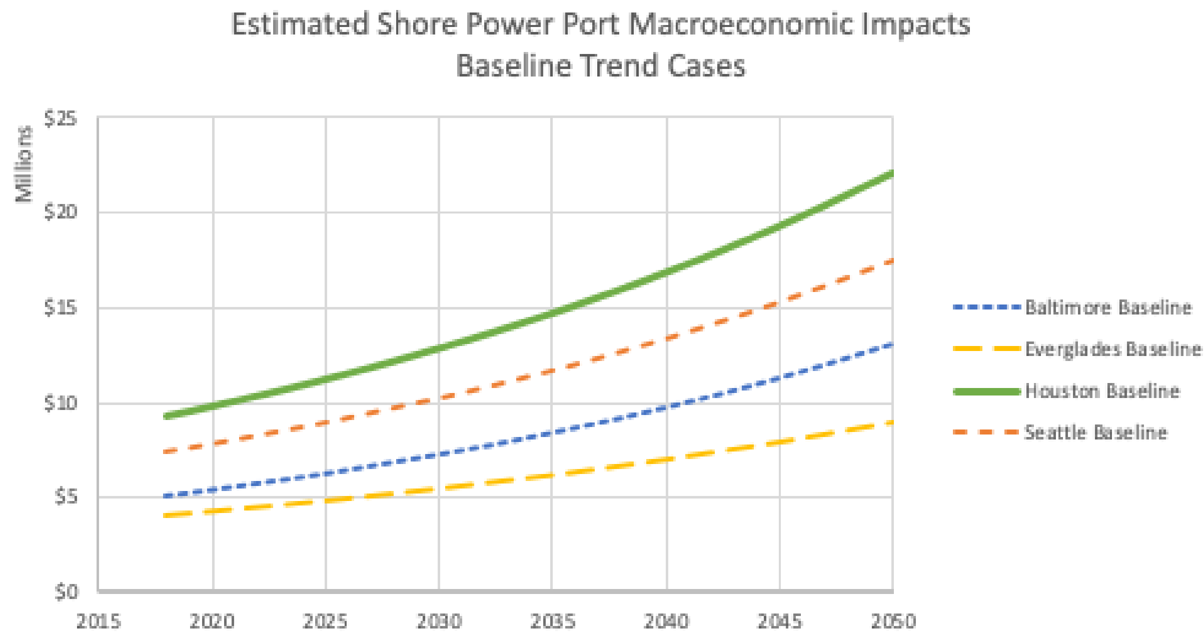
to 2.4 times in base trend cases, and changes by 3.5 to 4.8 times in high trend cases across the ports. This is illustrated in Figure 51.

At the ports of Baltimore and Houston, economic output from shore power expenditures are less than economic output from net CHE electrification expenditures; at Port Everglades and the Port of Baltimore, economic output from shore power expenditures are greater than economic output from net CHE electrification expenditures. This suggests that regional pricing differences between diesel-powered and electric-powered CHE can affect the net economic impact of CHE electrification. Larger ports, with more activity, show greater net change in job-year employment. Ports in regions with higher economic multipliers receive greater impact for similar expenditures. Economic benefits are generally proportional to port electrification expenditures for shore power.

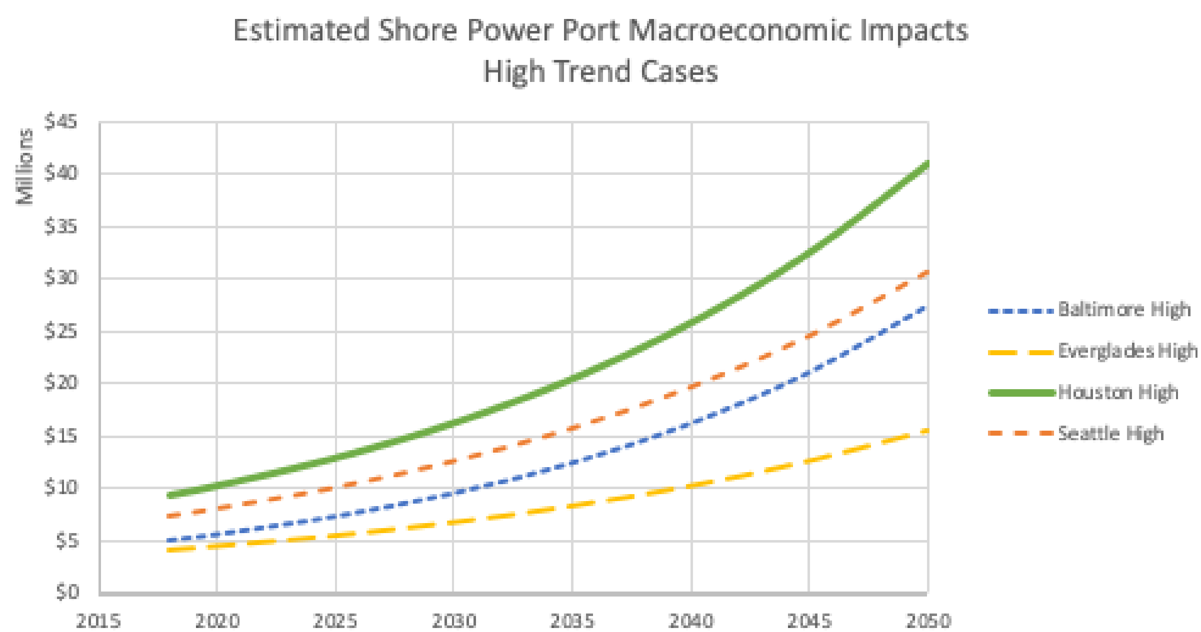
6.1.4 Port Shore Power Electrification Impacts on State Employment

In each port case, employment changes are positive due to new shore power expenditures during dockside hoteling. This increases regional impacts compared with ex-region purchases for onboard auxiliary power fuels, even for the Port of Seattle cases. State- and County-level shore power related employment between 2020 and 2050 changes by 2.1 to 2.4 times in base trend cases, and changes by 3.5 to 4.8 times in high trend cases across the ports. This is illustrated in Figure 52.

Job-benefits of port electrification increase when conversion includes shore power. At the Ports of Baltimore, Everglades and Seattle, employment benefits from shore power expenditures are greater than employment benefits from net CHE expenditures. For the Port of Houston, job-years resulting from net CHE electrification are larger than job-years resulting from shore power electrification. Larger ports, with more activity, show greater net change in job-year employment. Ports in regions with higher employment multipliers receive greater impact for similar expenditures. Employment benefits are generally proportional to port electrification expenditures for shore power.



(a)



(b)

Figure 51. State-level Economic Output Change Related to Port Shore Power Electrification; (a) Baseline and (b) High Trend Cases

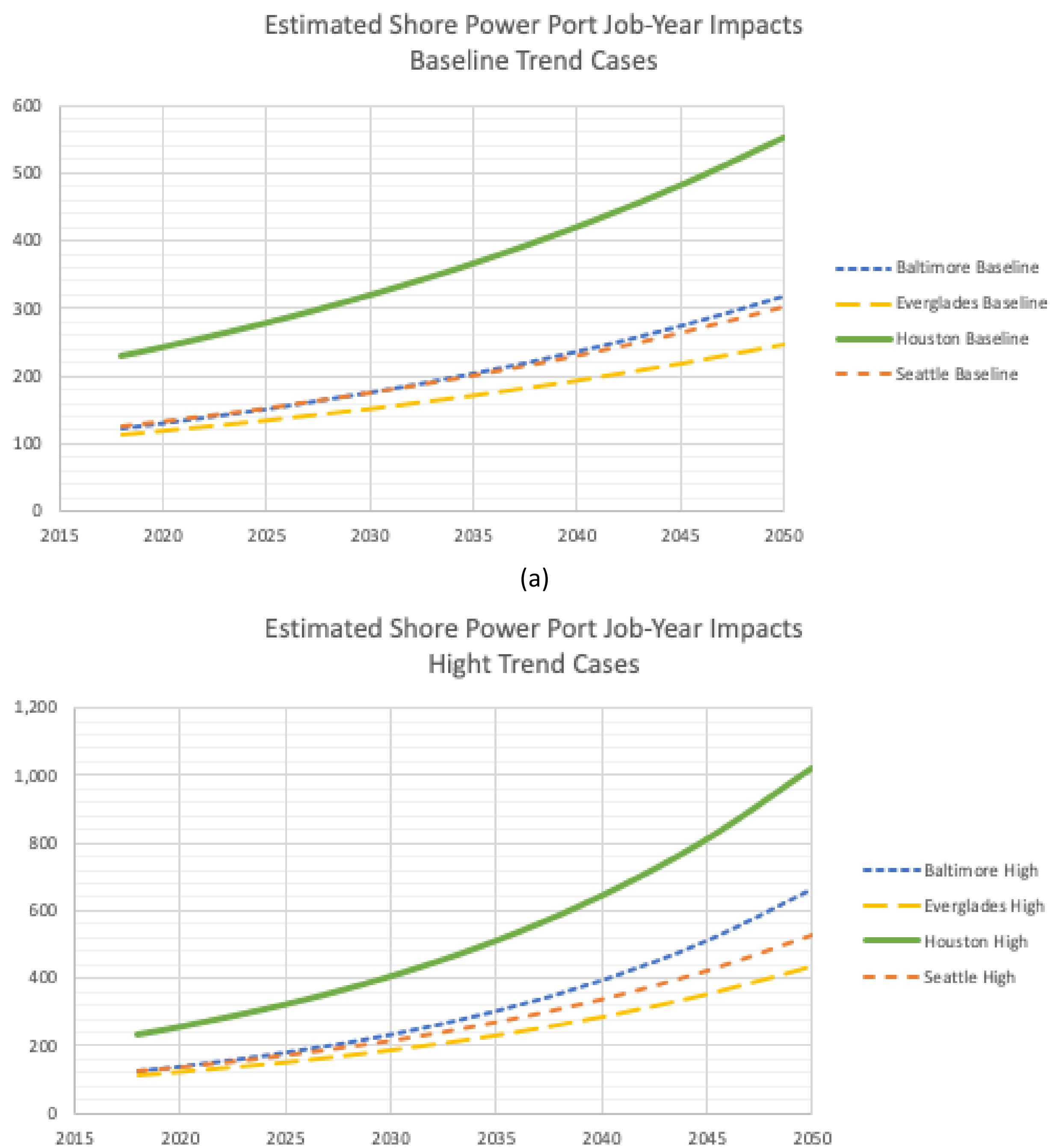


Figure 52. State-level Employment Change Related to Port Shore Power Electrification; (a) Baseline and (b) High Trend Cases

6.2 Environmental implications of electrification vary by port

Cargo handling electrification also result in general reductions in annual air emissions at three of the four ports, with the exception of oxides of sulfur; moreover, the location of emissions from electric power generation reduces the near-port emissions concentrations.

Current national policies set stricter limits on fuel sulfur in onroad/nonroad diesel fuels, and allow less strict limits on fuel sulfur for petroleum and coal fuels used in power generation. As power generation portfolios adopt more renewable energies and other low-sulfur fossil fuels, this may change (as discussed in Sections 5.5 and 6.4). While the magnitude of environmental benefits from CHE electrification vary by port, the patterns remain consistent. Generally, CHE electrification significantly reduces emissions of NOx and GHGs, and slightly increases emissions of SOx. Intuitively, the greatest net benefits in terms of emission reductions occur with 100% electrification in all ports.

The largest emission reductions from electrification occur in Houston, where GHG reductions range from 41,100 MT CO_2e to 87,400 MT CO_2e, and NOx reductions range from 1,040 MT to 2,170 MT depending on electrification and port growth scenario. While Houston has both the highest cargo throughput and the greatest emission reduction benefits (SOx excluded), the magnitude of emission reductions is not solely a function of port throughput. Baltimore ranks lowest in cargo throughput, but second in potential electrification emission reduction benefits due to the comparatively low CO_2e emission rates from electricity generation (Table 7). The 50% Baseline scenario emissions are summarized for the four ports in Table 38.

Table 38: Change in emissions from CHE electrification under the 50% Baseline scenario at the Ports of Baltimore, Everglades, Houston, and Seattle

Metric Tons	NOx	SOx	CH4	N2O	CO2e
Baltimore	(143.0)	3.57	(0.401)	(0.343)	(9,030)
Everglades	(70.9)	1.38	(0.312)	(0.297)	(6,100)
Houston	(1,040)	40.6	(2.15)	(2.05)	(42,100)
Seattle	(80.6)	1.47	(0.213)	(0.191)	(5,640)

Generally the costs per ton NOx abated fall within or below the cost-effectiveness estimates for reducing other mobile sources (Table 39). The costs per greenhouse gas ton abated are generally high, similar to other freight GHG abatement costs, with the exception of the Port of Seattle. The Port of Seattle is unique among the four ports modeled as it is the only port for which energy expenditures are lower under the electrification scenario, resulting in net benefits from both emissions and financial standpoints.

Table 39: Net energy cost per unit pollution abated ($/MT) at at the Ports of Baltimore, Everglades, Houston, and Seattle. (Values in parentheses are negative, representing a cost per MT pollution increase)

	Net Energy Cost per Unit Pollution Abated ($/MT)				
	NOx	SOx	CH4	N2O	CO2e
Baltimore	16,270	(651,830)	5,803,050	6,784,320	260
Everglades	25,300	(1,299,860)	5,749,370	6,039,740	290
Houston	3,800	(97,390)	1,839,060	1,928,770	90
Seattle[1]	(1,110)	60,670	(418,730)	(466,960)	(20)

1. Net savings for electrification produce net financial and emissions benefits, not abatement costs.

6.3 General Insights Regarding Port Electrification

Port electrification can produce increased economic output and employment in most regions. Port electrification in the base case doubles state and county economic activity between 2020 and 2050; in the high trend cases, port electrification increases economic activity 3.5 to ~5 times between 2020 and 2050 compared with the economic output of diesel-powered port operations.

Cargo handling electrification produces differing net results across ports, while shore power electrification produces more consistent, if often smaller results. Net economic changes associated with cargo handling equipment depend upon the transfer of expenditures from diesel- to electric-power. This means that economic activity associated with diesel powered cargo handling expenditures decline and are replaced by economic activity related to port electrification. Therefore, regional economic output and employment produced by electrification are offset by the shift away from diesel-powered cargo handling. Given the expectation that most vessels not using shore power would have purchased fuel outside the region of study, all expenditures related to recurring costs of shore power produce new regional economic activity and employment.

The relative share of economic output attributable to shore power and cargo handling electrification varies among the four port case studies. Shore power electrification accounts for about half of the net economic output for the ports of Baltimore (~46% shore power) and Everglades (~54% shore power). For the Port of Houston, shore power contributes ~26% to net economic output changes. The larger macroeconomic impact of cargo handling equipment electrification appears related primarily to Houston's acreage (more vast than other ports) and waterfront practices that utilize more cargo handling equipment; other influencing factors could include the regional economic multiplier and energy pricing differences. For the Port of Seattle, shore power contributes ~131% to changes in economic output; this is due to the lower energy pricing of electricity in the region.

Port electrification reduces port-based diesel-related emissions associated with air quality impacts in nearby port communities. Electrifying cargo handling equipment significantly reduces emissions of NOx and GHGs, and slightly increases emissions of SOx. These results reflect the current electric grid power generation profile, which is projected to shift to renewable sources (i.e., lower sulfur fuels) in coming decades. Generally, the costs per ton NOx abated fall within or below the cost-effectiveness estimates for reducing other mobile sources. The costs per ton greenhouse gas abated are generally high, similar to other freight GHG abatement costs, with the exception of the Port of Seattle.

The Port of Seattle is unique among the four ports modeled as it is the only port for which energy expenditures are lower under the electrification scenario, resulting in net benefits from both emissions and financial standpoints. For the Port of Seattle, electrification is less expensive than continuing to use diesel fuel. While input-output measures of economic activity for the Port of Seattle show decreased economic activity for cargo handling electrification, there are significant increases in economic activity associated with shore power electrification. Moreover, the environmental benefits of cargo handling electrification at the Port of Seattle are achieved with net savings to the port. This could suggest that port fiscal and public policy objectives would align to save money and reduce pollution through Port of Seattle electrification.

6.4 Recommended Next Studies

These four cases studies demonstrate that economic and environmental impacts related to port electrification are substantial. These cases also reveal that the benefits of port electrification vary among ports and regions, which motivates recommendations for further study. There are several important new research activities suggested by the results of these case studies.

One key recommendation based on these four port studies would be to expand this work to help identify national level macroeconomic impacts of port electrification. This expansion could take one or a combination of three forms: a) economic impacts of regionally expanded electrification; b) national scale economic impacts of port electrification; and c) next stage longitudinal effects of electric grid transitions to renewables and cleaner energy.

In a regional follow-on study design, we could learn whether multiple regional ports could amplify economic and environmental benefits through coordinated electrification strategies. In a national study design, we could evaluate nationwide macroeconomic impacts from port electrification – perhaps providing information to help prioritize those ports and regions with attractive combinations for ports (expenditures), regional economics (economic output and employment), and environmental performance (change in emissions). A longitudinal study design could incorporate the expected changes in electrical grid power as renewables and cleaner energy are adopted to provide insights into the long-term changes in emissions associated with electrification.

Installation and construction associated with electrification, even though non-recurring expenditures, will add economic activity and produce employment during transition. These impacts could be included in studies for ports that may be first to pursue electrification. A future study would help to identify these additional impacts, in support of port and port-community decision making.

With regard to environmental impact, we recommend evaluating the net reductions in $PM_{2.5}$ and PM_{10} (and consider including estimates for electricity grid emissions of VOC and CO) to better characterize the change in exposure to harmful air pollution. As power generation portfolios adopt more renewable energies and other low-sulfur fossil fuels, the relatively higher sulfur and PM emissions may change, along with additional changes to electricity grid emissions portfolios from potentially more or less strict pollution control requirements. This could be associated with regional models of air quality changes, and population related health benefits.

Additional work could also evaluate how port electrification may align with goals for improved air quality, specifically the emission effects of diesel trucks waiting to load or offload at the port, how electrification could include distributed power from port-based fuel cells, and how implementation strategies could include or join with such efforts in cost-effective strategies.

7 References

Bermello Ajamil & Partners. (2018). *Port Everglades Master/Vision Plan*.

Bess, R., & Ambargis, Z. (2011). *Input-Output Models for Impact Analysis: Suggestions for Practitioners Using RIMS II Multipliers*. bea.gov/system/files/papers/WP2012-3.pdf

Browning, L., & Bailey, K. (2006). *Current Methodologies and Best Practices for Preparing Port Emission Inventories*.

Christ, C. (1955). A Review of Input-Output Analysis. In *Input-Output Analysis: An Appraisal* (pp. 137–182). https://www.nber.org/books/unkn55-2

Eastern Research Group, I., & Energy & Environmental Research Associates, L. (2017). *Shore Power Technology Assessment at US Ports*.

Electric Power Research Institute. (2006). *Land-Side Equipment Electrification Opportunities: At the Port of Houston, Texas*.

French, T. (2018). *Interpreting Employment Impacts*. IMPLAN.

Gillingham, K., & Huang, P. (2019). *Long-run Environmental and Economic Impacts of Electrifying Ports in the United States*.

Goldberg, M. (2010). *National Heavy Duty Truck Transportation Efficiency Macroeconomic Impact Analysis*.

Hughes, D. (2018). *A Primer in Economic Multipliers and Impact Analysis Using Input-Output Models*. extension.tennessee.edu/publications/Documents/W644.pdf

IMPLAN. (2019a). *Key Assumptions of IMPLAN & Input-Output Analysis*. IMPLAN. https://implanhelp.zendesk.com/hc/en-us/articles/115009505587-Key-Assumptions-of-IMPLAN-Input-Output-Analysis

IMPLAN. (2019b). *Understanding Multipliers*. IMPLAN. https://implanhelp.zendesk.com/hc/en-us/articles/115009505707-Understanding-Multipliers

Infusino, M., Friez, D., & Boehm, M. (2018). *Zero-Emission Port Equipment Workforce Assessment*.

Kim, J., Rahimi, M., & Newell, J. (2012). Life-Cycle Emissions from Port Electrification: A Case Study of Cargo Handling Tractors at the Port of Los Angeles. *International Journal of Sustainable Transportation*, *6*(6), 321–337. https://doi.org/10.1080/15568318.2011.606353

Lucas, M. (2019). *IMPLAN Pro: Analysis-by-Parts Working with Government Institution Spending Patterns*. IMPLAN. https://implanhelp.zendesk.com/hc/en-us/articles/115009713228-IMPLAN-Pro-Analysis-by-Parts-Working-with-Government-Institution-Spending-Patterns

Maryland Port Administration. (2019). *Strategic Plan 2019*.

Miller, R., & Blair, P. (2009). *Input-Output Analysis: Foundations and Extentions* (2nd ed.). Cambridge University Press.

Port of Long Beach. (2017). *Shore Power*.

Port of Oakland. (2013). *Shore Power Fact Sheet 2013*.

Starcrest Consulting Group, L. (2019). *San Pedro Bay Ports Emissions Inventory Methodology Report*.

THE 2017 ECONOMIC IMPACT OF THE PORT OF BALTIMORE IN MARYLAND. (2018). www.martinassoc.net

The Northwest Seaport Alliance. (2015). *Strategic Business Plan*.

The Northwest Seaport Alliance. (2019). *Marine Cargo Economic Impact Analysis*. https://www.portseattle.org/sites/default/files/2019-01/CAI_NWSA_Marine_Cargo_Economic_Impacts_190122.pdf

U.S. Energy Information Administration. (2020a). *Average Retail Price of Electricity, Monthly*. https://www.eia.gov/electricity/data/browser/#/topic/7?agg=1,0&geo=000000000001&endsec=2&freq=M&start=200101&end=202001&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=

U.S. Energy Information Administration. (2020b). *U.S. No 2 Diesel Retail Price*. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emd_epd2d_pte_nus_dpg&f=a

United States Army Corps of Engineers. (2018). *U.S. Waterborne Container Traffic by Port/Waterway*. https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/1430

US Energy Information Administration. (2019). *Average Price of Electricity to Ultimate Customers by End-Use Sector*.

US Energy Information Administration. (2020a). *Los Angeles, CA Ultra-Low Sulfur CARB Diesel Spot Price*.

US Energy Information Administration. (2020b). *New York Harbor Ultra-Low Sulfur No 2 Diesel Spot Price*. https://www.eia.gov/dnav/pet/hist/eer_epd2dxl0_pf4_y35ny_dpgD.htm

US Energy Information Administration. (2020c). *U.S Gulf Coast Ultra-Low Sulfur No 2 Diesel Spot Price*. https://www.eia.gov/dnav/pet/hist/eer_epd2dxl0_pf4_rgc_dpgD.htm

Vaishnav, P., Fischbeck, P. S., Morgan, M. G., & Corbett, J. J. (2015). Shore Power for Vessels Calling at U.S. Ports: Benefits and Costs. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.5b04860

van de Walle, D., Ravallion, M., Mendiratta, V., & Koolwal, G. (2013). *Electrification at Ports: A Port of Houston, Texas Electrification Case Study and Options for Electric Cranes*.

Wang, H., Mao, X., & Rutherford, D. (2015). *Cost and Benefits of Shore Power at the Port of Shenzhen*.

Winebrake, J., Green, E., & Carr, E. (2018). *An Assessment of Macroeconomic Impacts of Medium- and Heavy-Duty Electric Transportation Technologies in the United States*.

Yang, Y. C., & Chang, W. M. (2013). Impacts of electric rubber-tired gantries on green port performance. *Research in Transportation Business and Management*. https://doi.org/10.1016/j.rtbm.2013.04.002

8 Appendix

8.1 TEU Throughput

Table 40: Port Actual TEU Throughput by Year

Year	Port of Baltimore	Port Everglades	Port of Houston	Port of Seattle
2003	423,482	416,559	1,024,755	999,946
2004	443,794	501,567	1,235,728	1,198,463
2005	486,798	591,375	1,289,818	1,442,969
2006	482,665	633,134	1,316,511	1,380,420
2007	501,332	676,385	1,399,927	1,416,054
2008	505,362	677,340	1,370,591	1,224,418
2009	453,125	531,546	1,262,816	1,219,345
2010	495,158	578,950	1,341,897	1,601,842
2011	505,636	608,355	1,430,907	1,573,558
2012	544,018	638,546	1,491,920	1,435,402
2013	555,407	698,673	1,563,060	1,236,727
2014	574,375	748,501	1,664,448	1,008,263
2015	609,186	716,182	1,753,047	1,072,946
2016	656,316	741,628	1,818,784	1,080,305
2017	724,807	771,015	2,016,072	1,198,177
2018	713,191	795,043	2,251,645	1,315,345

Source: United States Army Corps of Engineers. (2018). *U.S. Waterborne Container Traffic by Port/Waterway*. https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/1430

Table 41: Port of Baltimore TEU Projections

Year	Baseline	High
2018	713,191	713,191
2020	756,624	792,295
2025	877,134	1,030,599
2030	1,016,839	1,340,580
2035	1,178,795	1,743,797
2040	1,366,547	2,268,292
2045	1,584,202	2,950,544
2050	1,836,525	3,838,001

Table 42: Port Everglades TEU Projections

Year	Baseline	High
2018	795,043	795,043
2020	835,292	864,887
2025	945,056	1,067,532
2030	1,069,245	1,317,657
2035	1,209,752	1,626,387
2040	1,368,724	2,007,454
2045	1,548,585	2,477,805
2050	1,752,082	3,058,360

Table 43: Port of Houston TEU Projections

Year	Baseline	High
2018	2,251,645	2,251,645
2020	2,377,189	2,470,632
2025	2,722,531	3,115,862
2030	3,118,042	3,929,600
2035	3,571,010	4,955,854
2040	4,089,783	6,250,125
2045	4,683,919	7,882,407
2050	5,364,368	9,940,975

Table 44: Port of Seattle TEU Projections

Year	Baseline	High
2018	1,315,345	1,315,345
2020	1,388,684	1,437,764
2025	1,590,422	1,796,006
2030	1,821,468	2,243,510
2035	2,086,079	2,802,517
2040	2,389,131	3,500,809
2045	2,736,208	4,373,092
2050	3,133,706	5,462,718

8.2 Cargo Handling Emissions Inventory

Table 45: Port of Houston 2013 Cargo Handling Equipment Emissions, tons per year

Equipment Type	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	CO_2e
Aerial lift	0.74	0.70	0.00	0.08	0.08	127.00
Air compressor	0.01	0.00	0.00	0.00	0.00	1.00
Crane	374.24	86.82	0.26	27.36	26.54	28806.00
Forklift	344.76	150.42	0.40	30.05	29.15	43815.00
Front end loader	8.96	4.50	0.01	0.79	0.76	1328.00
Generator set	2.94	1.13	0.00	0.15	0.15	388.00
Light plant	0.04	0.02	0.00	0.00	0.00	4.00
Other industrial equip.	1.25	0.31	0.00	0.06	0.05	152.00
Railway maint. equip.	0.80	0.31	0.00	0.09	0.08	78.00
Rough terrain forklift	20.12	6.72	0.02	1.35	1.31	2753.00
RTG	192.84	54.90	0.18	7.21	7.00	19959.00
Sweeper/scrubber	0.69	0.73	0.00	0.06	0.06	84.00
Terminal tractor	345.60	117.62	0.42	28.10	27.08	46368.00
Total	**1,292.99**	**424.18**	**1.31**	**95.3**	**92.27**	**143,863**

Source: Eastern Research Group, Inc.. (2017). 2013 Good Movement Air Emissions Inventory at the Port of Houston.

Table 46: Port Everglades Cargo Handling Equipment Emissions, tons per year

Equipment Type	NO_x	CO	SO_2	PM_{10}	$PM_{2.5}$	CO_2e[a]
Aerial lift	0.16	0.12	0.00	0.02	0.02	17.00
Crane	13.72	4.89	0.02	0.70	0.68	2654.00
Empty container handler	1.24	0.27	0.00	0.06	0.06	141.00
Forklift	28.06	31.64	0.02	2.84	2.75	3240.00
Loader	0.07	0.03	0.00	0.01	0.01	12.00
Manlift	0.03	0.03	0.00	0.00	0.00	3.00
Power pack	22.90	7.85	0.01	1.08	1.04	1894.00
Reach stacker	1.28	0.29	0.00	0.04	0.04	554.00
RTG crane	0.12	0.08	0.00	0.00	0.00	239.00
Scissor lift	0.05	0.05	0.00	0.10	0.01	5.00
Sweeper	0.14	0.31	0.00	0.01	0.01	31.00
Top loader	74.01	18.43	0.06	2.67	2.59	8106.00
Truck	0.26	0.13	0.00	0.04	0.03	55.00
Yard truck	75.89	24.90	0.06	6.32	6.13	7740.00
Total	217.93	89.02	0.17	13.89	13.37	24691

[a] CO_2e is in tonnes/year

Source: Starcrest Consulting Group, LLC. (2016). Port Everglades 2015 Baseline Air Emissions Inventory.

Table 47: CO_2 Emissions per TEU to Diesel kWh per TEU Conversion

Port	CO_2 tpy/TEU	CO_2 tonnes/TEU	Kg of CO_2/TEU	BTU/TEU	kWh/TEU
Everglades	0.0345	0.034[a]	34.476	471,239	138
Houston	0.0147	0.013	13.369	182,742	54
Seattle	0.092	0.083	83.48	1,141,056	334
Baltimore	0.047	0.043	42.71	583,738	171

[a]CO_2 emissions/teu for Port Everglades was already in tonnes/year

Conversion	Factor
ton to tonnes	0.907
tonnes to ton	1.102
kg of co2 per gallon diesel	10.160
kg of CO2 per million BTU	73.160
BTU/kWh	3,414
Typical diesel efficiency (η)	0.328
Unconverted CO2 / kWh	0.250
kg CO2/kWh	0.762
CO2 per gallon diesel (power-out)	30.996
CO2 per million BTU (power-out)	223.199

Table 48 Conversion Factors for Table 47

8.3 Diesel Projections and Expenditures

Table 49: Port of Baltimore Gallon Projections by Year

Year	Baseline	High
2018	3,000,000	3,000,000
2020	3,183,000	3,333,000
2025	3,689,000	4,335,000
2030	4,277,000	5,639,000
2035	4,958,000	7,335,000
2040	5,748,000	9,541,000
2045	6,663,000	12,411,000
2050	7,725,000	16,143,000

Table 50: Port of Baltimore Scenario Diesel Expenditures

Year	Baseline	High
2018	$5,760,000	$5,760,000
2020	$6,110,000	$6,398,000
2025	$7,084,000	$8,323,000

2030	$8,212,000	$10,826,000
2035	$9,520,000	$14,083,000
2040	$11,036,000	$18,318,000
2045	$12,794,000	$23,828,000
2050	$14,832,000	$30,995,000

Table 51: Port Everglades Gallon Projections by Year

Year	Baseline	High
2018	2,699,600	2,699,600
2020	2,836,300	2,936,800
2025	3,209,000	3,624,900
2030	3,630,700	4,474,200
2035	4,107,800	5,522,500
2040	4,647,600	6,816,500
2045	5,258,300	8,413,600
2050	5,949,300	10,384,900

Table 52: Port Everglades Scenario Diesel Expenditures

Year	Baseline	High
2018	$5,183,000	$5,183,000
2020	$5,446,000	$5,639,000
2025	$6,161,000	$6,960,000
2030	$6,971,000	$8,590,000
2035	$7,887,000	$10,603,000
2040	$8,923,000	$13,088,000
2045	$10,096,000	$16,154,000
2050	$11,423,000	$19,939,000

Table 53: Port of Houston Gallon Projections by Year

Year	Baseline	High
2018	18,513,000	18,513,000
2020	19,545,000	20,314,000
2025	22,385,000	25,619,000
2030	25,637,000	32,309,000
2035	29,361,000	40,747,000
2040	33,626,000	51,389,000
2045	38,511,000	64,809,000

2050	44,106,000	81,735,000

Table 54: Port of Houston Scenario Diesel Expenditures

Year	Baseline	High
2018	$34,434,000	$34,434,000
2020	$36,354,000	$37,783,000
2025	$41,636,000	$47,651,000
2030	$47,684,000	$60,095,000
2035	$54,611,000	$75,790,000
2040	$62,545,000	$95,583,000
2045	$71,631,000	$120,545,000
2050	$82,037,000	$152,027,000

Table 55: Port of Seattle Gallon Projections by Year

Year	Baseline	High
2018	1,732,000	1,732,000
2020	1,829,000	1,893,000
2025	2,094,000	2,365,000
2030	2,398,000	2,954,000
2035	2,747,000	3,690,000
2040	3,146,000	4,610,000
2045	3,603,000	5,758,000
2050	4,126,000	7,193,000

Table 56: Port of Seattle Scenario Diesel Expenditures

Year	Baseline	High
2018	$3,377,000	$3,377,000
2020	$3,566,000	$3,692,000
2025	$4,084,000	$4,612,000
2030	$4,677,000	$5,761,000
2035	$5,356,000	$7,196,000
2040	$6,135,000	$8,989,000
2045	$7,026,000	$11,229,000
2050	$8,046,000	$14,027,000

8.4 Scenario Tables

8.4.1 Port of Baltimore

Table 57: Port of Baltimore Results, 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$10,980,000	$10,980,000	$9,167,000	$9,167,000
2020	$11,649,000	$12,198,000	$9,726,000	$10,184,000
2025	$13,504,000	$15,867,000	$11,275,000	$13,247,000
2030	$15,655,000	$20,639,000	$13,070,000	$17,232,000
2035	$18,148,000	$26,847,000	$15,152,000	$22,415,000
2040	$21,039,000	$34,922,000	$17,566,000	$29,157,000
2045	$24,390,000	$45,426,000	$20,363,000	$37,926,000
2050	$28,275,000	$59,089,000	$23,607,000	$49,334,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	124	124	98	98
2020	132	138	104	109
2025	153	179	120	141
2030	177	233	140	184
2035	205	303	162	239
2040	238	395	188	311
2045	276	514	217	405
2050	320	668	252	527

Table 58: Port of Baltimore Results, 50% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$13,979,000	$13,979,000	$11,936,000	$11,936,000
2020	$14,830,000	$15,529,000	$12,663,000	$13,260,000
2025	$17,192,000	$20,200,000	$14,680,000	$17,249,000
2030	$19,930,000	$26,276,000	$17,018,000	$22,437,000
2035	$23,105,000	$34,179,000	$19,729,000	$29,185,000
2040	$26,784,000	$44,459,000	$22,871,000	$37,963,000
2045	$31,051,000	$57,831,000	$26,514,000	$49,382,000
2050	$35,996,000	$75,225,000	$30,737,000	$64,235,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	268	268	243	243
2020	284	298	257	270
2025	330	387	298	350
2030	382	504	346	456
2035	443	655	401	593
2040	514	853	465	772
2045	595	1109	540	1004
2050	690	1443	625	1306

Table 59: Port of Baltimore Results, 100% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$16,977,000	$16,977,000	$14,705,000	$14,705,000
2020	$18,011,000	$18,860,000	$15,601,000	$16,336,000
2025	$20,880,000	$24,533,000	$18,086,000	$21,250,000
2030	$24,205,000	$31,912,000	$20,966,000	$27,642,000
2035	$28,061,000	$41,510,000	$24,306,000	$35,956,000
2040	$32,530,000	$53,996,000	$28,177,000	$46,770,000
2045	$37,711,000	$70,236,000	$32,665,000	$60,838,000
2050	$43,718,000	$91,362,000	$37,868,000	$79,136,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	412	412	387	387
2020	437	458	410	430
2025	507	595	476	560
2030	587	774	552	728
2035	681	1007	640	947
2040	790	1310	742	1232
2045	915	1704	860	1603
2050	1061	2217	997	2085

Table 60: Port of Baltimore Difference Between 50% and 0% CHE Scenarios

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$2,999,000	$2,999,000	$2,769,000	$2,769,000
2020	$3,181,000	$3,331,000	$2,938,000	$3,076,000
2025	$3,688,000	$4,333,000	$3,406,000	$4,001,000
2030	$4,275,000	$5,636,000	$3,948,000	$5,205,000
2035	$4,956,000	$7,332,000	$4,577,000	$6,770,000
2040	$5,745,0000	$9,537,000	$5,306,000	$8,807,000
2045	$6,661,000	$12,405,000	$6,151,000	$11,456,000
2050	$7,721,000	$16,136,000	$7,130,000	$14,901,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	144	144	145	145
2020	153	160	154	161
2025	177	208	178	209
2030	205	271	206	272
2035	238	352	239	354
2040	276	458	277	460
2045	320	595	321	599
2050	371	775	373	779

Table 61: Port of Baltimore Difference Between 100% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$5,997,000	$5,997,000	$5,538,000	$5,538,000
2020	$6,362,000	$6,662,000	$5,875,000	$6,152,000
2025	$7,376,000	$8,666,000	$6,811,000	$8,003,000
2030	$8,550,000	$11,273,000	$7,896,000	$10,410,000
2035	$9,912,000	$14,663,000	$9,154,000	$13,541,000
2040	$11,491,000	$19,073,000	$10,611,000	$17,614,000
2045	$13,321,000	$24,810,000	$12,302,000	$22,911,000
2050	$15,443,000	$32,273,000	$14,261,000	$29,803,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	288	288	289	289
2020	305	320	307	322
2025	354	416	356	418
2030	410	541	413	544
2035	476	704	478	708
2040	552	916	555	921
2045	639	1191	643	1197
2050	741	1549	745	1558

Table 62: Port of Baltimore Results, 50% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$2,543,000	$2,543,000	$2,208,000	$2,208,000
2020	$2,696,000	$2,821,000	$2,341,000	$2,449,000
2025	$3,123,000	$3,673,000	$2,714,000	$3,189,000
2030	$3,625,000	$4,775,000	$3,147,000	$4,146,000
2035	$4,200,000	$6,210,000	$3,647,000	$5,392,000
2040	$4,865,000	$8,081,000	$4,224,000	$7,016,000
2045	$5,641,000	$10,514,000	$4,898,000	$9,129,000
2050	$6,542,000	$13,674,000	$5,681,000	$11,872,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	62	62	58	58
2020	66	69	62	65
2025	76	89	71	84
2030	88	116	83	109
2035	102	151	96	142
2040	118	196	110	185
2045	137	256	129	240
2050	159	332	150	313

Table 63: Port of Baltimore Results, 100% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$5,087,000	$5,087,000	$4,417,000	$4,417,000
2020	$5,392,000	$5,641,000	$4,682,000	$4,898,000
2025	$6,251,000	$7,346,000	$5,428,000	$6,379,000
2030	$7,249,000	$9,550,000	$6,294,000	$8,292,000
2035	$8,400,000	$12,419,000	$7,293,000	$10,783,000
2040	$9,730,000	$16,162,000	$8,449,000	$14,032,000
2045	$11,283,000	$21,027,000	$9,796,000	$18,257,000
2050	$13,085,000	$27,348,000	$11,361,000	$23,745,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	124	124	116	116
2020	131	137	123	129
2025	152	179	143	168
2030	176	232	166	218
2035	204	302	192	284
2040	237	393	223	370
2045	274	511	258	481
2050	318	665	299	626

8.4.2 Port Everglades

Table 64: Port Everglades Results, 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$11,927,000	$11,927,000	$9,286,000	$9,286,000
2020	$12,531,000	$12,975,000	$9,756,000	$10,102,000
2025	$14,177,000	$16,015,000	$11,038,000	$12,468,000
2030	$16,040,000	$19,767,000	$12,488,000	$15,390,000
2035	$18,148,000	$24,399,000	$14,129,000	$18,996,000
2040	$20,533,000	$30,115,000	$15,986,000	$23,446,000
2045	$23,231,000	$37,171,000	$18,087,000	$28,940,000
2050	$26,284,000	$45,881,000	$20,464,000	$35,720,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	151	151	113	113
2020	159	165	119	123
2025	180	203	135	152
2030	203	251	152	188
2035	230	309	172	232
2040	260	382	195	286
2045	295	471	221	353
2050	333	582	250	436

Table 65: Port Everglades Results, 50% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$13,633,000	$13,633,000	$12,141,000	$12,141,000
2020	$14,324,000	$14,831,000	$12,755,000	$13,207,000
2025	$16,206,000	$18,306,000	$14,432,000	$16,302,000
2030	$18,335,000	$22,595,000	$16,328,000	$20,121,000
2035	$20,745,000	$27,889,000	$18,474,000	$24,836,000
2040	$23,471,000	$34,424,000	$20,901,000	$30,655,000
2045	$26,555,000	$42,489,000	$23,648,000	$37,838,000
2050	$30,045,000	$52,444,000	$26,755,000	$46,703,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	290	290	152	152
2020	304	315	159	165
2025	344	389	180	204
2030	390	480	204	252
2035	441	593	231	310
2040	499	731	261	383
2045	564	903	296	473
2050	638	1114	334	584

Table 66: Port Everglades Results, 100% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$15,340,000	$15,340,000	$14,996,000	$14,996,000
2020	$16,116,000	$16,687,000	$15,755,000	$16,313,000
2025	$18,234,000	$20,597,000	$17,825,000	$20,135,000
2030	$20,630,000	$25,423,000	$20,168,000	$24,853,000
2035	$23,341,000	$31,380,000	$22,818,000	$30,676,000
2040	$26,408,000	$38,732,000	$25,816,000	$37,864,000
2045	$29,879,000	$47,807,000	$29,209,000	$46,736,000
2050	$33,805,000	$59,008,000	$33,047,000	$57,686,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	428	428	190	190
2020	450	466	200	207
2025	509	575	226	255
2030	576	709	256	315
2035	651	876	289	389
2040	737	1081	327	480
2045	834	1334	370	593
2050	943	1647	419	732

Table 67: Port Everglades Difference Between 50% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$1,706,000	$1,706,000	$2,855,000	$2,855,000
2020	$1,793,000	$1,856,000	$3,000,000	$3,106,000
2025	$2,028,000	$2,291,000	$3,394,000	$3,834,000
2030	$2,295,000	$2,828,000	$3,840,000	$4,732,000
2035	$2,596,000	$3,491,000	$4,344,000	$5,840,000
2040	$2,938,000	$4,308,000	$4,915,000	$7,209,000
2045	$3,324,000	$5,318,000	$5,561,000	$8,898,000
2050	$3,760,000	$6,564,000	$6,292,000	$10,983,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	138	138	38	38
2020	145	151	40	42
2025	165	186	46	52
2030	186	229	52	64
2035	211	283	58	79
2040	238	350	66	97
2045	270	431	75	120
2050	305	532	85	148

Table 68: Port Everglades Difference Between 100% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$3,413,000	$3,413,000	$5,710,000	$5,710,000
2020	$3,585,000	$3,712,000	$5,999,000	$6,212,000
2025	$4,057,000	$4,582,000	$6,788,000	$7,667,000
2030	$4,590,000	$5,656,000	$7,679,000	$9,464,000
2035	$5,193,000	$6,981,000	$8,689,000	$11,681,000
2040	$5,875,000	$8,617,000	$9,830,000	$14,418,000
2045	$6,647,000	$10,636,000	$11,122,000	$17,796,000
2050	$7,521,000	$13,128,000	$12,584,000	$21,966,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	277	277	77	77
2020	291	301	81	84
2025	329	372	91	103
2030	372	459	103	127
2035	421	566	117	157
2040	477	699	132	194
2045	539	863	150	240
2050	610	1065	169	296

Table 69: Port Everglades Results, 50% Shore Power Scenario

		Output		
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$2,018,000	$2,018,000	$1,972,000	$1,972,000
2020	$2,122,000	$2,199,000	$2,075,000	$2,150,000
2025	$2,401,000	$2,709,000	$2,348,000	$2,648,000
2030	$2,716,000	$3,344,000	$2,655,000	$3,269,000
2035	$3,072,000	$4,133,000	$3,003,000	$4,040,000
2040	$3,477,000	$5,096,000	$3,399,000	$4,982,000
2045	$3,937,000	$6,297,000	$3,849,000	$6,156,000
2050	$4,454,000	$7,770,000	$4,354,000	$7,596,000

		Employment		
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	56	56	25	25
2020	59	61	26	27
2025	67	75	30	33
2030	76	93	34	41
2035	85	115	38	51
2040	97	142	43	63
2045	110	175	49	78
2050	124	216	55	96

Table 70: Port Everglades Results, 100% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$4,035,000	$4,035,000	$3,945,000	$3,945,000
2020	$4,224,000	$4,398,000	$4,150,000	$4,300,000
2025	$4,803,000	$5,417,000	$4,696,000	$5,296,000
2030	$5,431,000	$6,688,000	$5,310,000	$6,538,000
2035	$6,143,000	$8,265,000	$6,006,000	$8,081,000
2040	$6,953,000	$10,192,000	$6,798,000	$9,965,000
2045	$7,875,000	$12,594,000	$7,699,000	$12,312,000
2050	$8,908,000	$15,540,000	$8,709,000	$15,192,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	112	112	50	50
2020	118	122	52	54
2025	134	151	59	67
2030	151	186	67	83
2035	171	230	76	102
2040	193	284	86	126
2045	219	350	97	155
2050	248	431	110	192

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Table 71: Port of Houston CHE Results, 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$57,179,000	$57,179,000	$45,413,000	$45,413,000
2020	$60,367,000	$62,740,000	$47,945,000	$49,829,000
2025	$69,136,000	$79,125,000	$54,910,000	$62,843,000
2030	$79,180,000	$99,789,000	$62,887,000	$79,255,000
2035	$90,683,000	$125,850,000	$72,022,000	$99,953,000
2040	$103,856,000	$158,716,000	$82,485,000	$126,056,000
2045	$118,944,000	$200,167,000	$94,468,000	$158,977,000
2050	$136,223,000	$252,442,000	$108,192,000	$200,496,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	1076	1076	962	962
2020	1136	1181	1015	1055
2025	1301	1489	1163	1331
2030	1490	1878	1332	1679
2035	1707	2369	1525	2117
2040	1955	2988	1747	2670
2045	2239	3768	2001	3367
2050	2564	4752	2292	4247

Table 72: Port of Houston Results, 50% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$70,315,000	$70,315,000	$57,771,000	$57,771,000
2020	$74,236,000	$77,154,000	$60,993,000	$63,390,000
2025	$85,021,000	$97,304,000	$69,853,000	$79,945,000
2030	$97,372,000	$122,715,000	$80,001,000	$100,823,000
2035	$111,517,000	$154,764,000	$91,623,000	$127,154,000
2040	$127,718,000	$195,182,000	$104,933,000	$160,362,000
2045	$146,272,000	$246,156,000	$120,177,000	$202,242,000
2050	$167,521,000	$310,442,000	$137,636,000	$255,060,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	1576	1576	1319	1319
2020	1663	1729	1392	1447
2025	1905	2180	1594	1825
2030	2182	2750	1826	2301
2035	2499	3468	2091	2902
2040	2862	4373	2395	3660
2045	3278	5516	2743	4616
2050	3754	6956	3142	5822

Table 73: Port of Houston Results, 100% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$83,452,000	$83,452,000	$70,130,000	$70,130,000
2020	$88,105,000	$91,569,000	$74,040,000	$76,951,000
2025	$100,905,000	$115,483,000	$84,796,000	$97,047,000
2030	$115,564,000	$145,642,000	$97,115,000	$122,392,000
2035	$132,352,000	$183,678,000	$111,223,000	$154,356,000
2040	$151,579,000	$231,647,000	$127,381,000	$194,668,000
2045	$173,599,000	$292,145,000	$145,886,000	$245,507,000
2050	$198,819,000	$368,441,000	$167,080,000	$309,624,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	2075	2075	1675	1675
2020	2190	2277	1769	1838
2025	2509	2871	2026	2319
2030	2873	3621	2320	2924
2035	3291	4567	2657	3688
2040	3769	5759	3043	4651
2045	4316	7263	3485	5865
2050	4943	9160	3992	7397

Table 74: Port of Houston Difference Between 50% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$13,137,000	$13,137,000	$12,359,000	$12,359,000
2020	$13,869,000	$14,415,000	$13,048,000	$13,561,000
2025	$15,884,000	$18,179,000	$14,943,000	$17,102,000
2030	$18,192,000	$22,927,000	$17,114,000	$21,569,000
2035	$20,835,000	$28,914,000	$19,601,000	$27,202,000
2040	$23,861,000	$36,466,000	$22,448,000	$34,306,000
2045	$27,328,000	$45,989,000	$25,709,000	$43,265,000
2050	$31,298,000	$57,999,000	$29,444,000	$54,564,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	499	499	357	357
2020	527	548	377	392
2025	604	691	431	494
2030	691	871	494	623
2035	792	1099	566	785
2040	907	1386	648	990
2045	1039	1748	742	1249
2050	1189	2204	850	1575

Table 75: Port of Houston Difference Between 100% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$26,274,000	$26,274,000	$24,718,000	$24,718,000
2020	$27,739,000	$28,829,000	$26,096,000	$27,122,000
2025	$31,768,000	$36,358,000	$29,887,000	$34,205,000
2030	$36,384,000	$45,853,000	$34,229,000	$43,137,000
2035	$41,669,000	$57,829,000	$39,201,000	$54,403,000
2040	$47,723,000	$72,931,000	$44,896,000	$68,611,000
2045	$54,655,000	$91,978,000	$51,418,000	$86,530,000
2050	$62,595,000	$115,999,000	$58,888,000	$109,128,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	999	999	714	714
2020	1054	1096	753	783
2025	1207	1382	863	988
2030	1383	1743	988	1245
2035	1584	2198	1132	1570
2040	1814	2771	1296	1981
2045	2077	3495	1485	2498
2050	2379	4408	1700	3151

Table 76: Port of Houston Results, 50% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$4,647,000	$4,647,000	$3,900,000	$3,900,000
2020	$4,903,000	$5,098,000	$4,115,000	$4,279,000
2025	$5,617,000	$6,430,000	$4,713,000	$5,396,000
2030	$6,436,000	$8,107,000	$5,401,000	$6,804,000
2035	$7,366,000	$10,225,000	$6,182,000	$8,580,000
2040	$8,442,000	$12,899,000	$7,084,000	$10,825,000
2045	$9,667,000	$16,265,000	$8,113,000	$13,694,000
2050	$11,072,000	$20,511,000	$9,291,000	$17,212,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	116	116	93	93
2020	122	127	99	102
2025	140	160	113	129
2030	160	202	129	163
2035	183	254	148	206
2040	210	321	170	259
2045	240	405	194	327
2050	275	510	223	412

Table 77: Port of Houston Results, 100% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$9,294,000	$9,294,000	$7,800,000	$7,800,000
2020	$9,807,000	$10,197,000	$8,230,000	$8,557,000
2025	$11,233,000	$12,860,000	$9,427,000	$10,792,000
2030	$12,871,000	$16,215,000	$10,802,000	$13,607,000
2035	$14,732,000	$20,449,000	$12,363,000	$17,161,000
2040	$16,883,000	$25,798,000	$14,168,000	$21,650,000
2045	$19,335,000	$32,529,000	$16,226,000	$27,298,000
2050	$22,143,000	$41,021,000	$18,582,000	$34,425,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	231	231	187	187
2020	244	254	197	205
2025	279	320	226	258
2030	320	403	259	326
2035	366	509	296	411
2040	420	642	339	519
2045	481	809	389	654
2050	551	1020	445	825

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Table 78: Port of Seattle Results, 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$6,717,000	$6,717,000	$6,215,000	$6,215,000
2020	$7,092,000	$7,342,000	$6,561,000	$6,793,000
2025	$8,122,000	$9,172,000	$7,515,000	$8,486,000
2030	$9,302,000	$11,457,000	$8,606,000	$10,600,000
2035	$10,653,000	$14,312,000	$9,857,000	$13,242,000
2040	$12,201,000	$17,878,000	$11,288,000	$16,541,000
2045	$13,973,000	$22,332,000	$12,928,000	$20,662,000
2050	$16,003,000	$27,896,000	$14,806,000	$25,811,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	74	74	64	64
2020	78	81	68	70
2025	89	101	78	88
2030	102	126	89	110
2035	117	157	102	137
2040	134	196	117	172
2045	154	245	134	214
2050	176	307	154	268

Table 79: Port of Seattle Results, 50% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$5,842,000	$5,842,000	$5,303,000	$5,303,000
2020	$6,167,000	$6,384,000	$5,597,000	$5,795,000
2025	$7,059,000	$7,969,000	$6,408,000	$7,234,000
2030	$8,082,000	$9,950,000	$7,337,000	$9,033,000
2035	$9,253,000	$12,424,000	$8,400,000	$11,279,000
2040	$10,595,000	$15,515,000	$9,618,000	$14,085,000
2045	$12,131,000	$19,376,000	$11,013,000	$17,591,000
2050	$13,890,000	$24,199,000	$12,610,000	$21,970,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	79	79	65	65
2020	84	87	69	71
2025	96	108	79	89
2030	110	135	90	111
2035	126	169	103	139
2040	144	211	118	173
2045	165	264	135	216
2050	189	329	155	270

Table 80: Port of Seattle Results, 100% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$4,967,000	$4,967,000	$4,391,000	$4,391,000
2020	$5,241,000	$5,425,000	$4,634,000	$4,796,000
2025	$5,997,000	$6,767,000	$5,302,000	$5,983,000
2030	$6,863,000	$8,443,000	$6,067,000	$7,465,000
2035	$7,854,000	$10,537,000	$6,944,000	$9,317,000
2040	$8,989,000	$13,153,000	$7,947,000	$11,630,000
2045	$10,289,000	$16,420,000	$9,097,000	$14,519,000
2050	$11,778,000	$20,502,000	$10,414,000	$18,129,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	85	85	66	66
2020	90	93	69	72
2025	103	116	80	90
2030	118	145	91	112
2035	135	181	104	140
2040	154	226	119	175
2045	177	282	137	218
2050	202	352	156	272

Table 81: Port of Seattle Difference Between 50% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	-$875,000	-$875,000	-$912,000	-$912,000
2020	-$925,000	-$958,000	-$964,000	-$999,000
2025	-$1,062,000	-$1,202,000	-$1,106,000	-$1,252,000
2030	-$1,220,000	-$1,507,000	-$1,270,000	-$1,568,000
2035	-$1,400,000	-$1,887,000	-$1,456,000	-$1,962,000
2040	-$1,606,000	-$2,362,000	-$1,670,000	-$2,456,000
2045	-$1,842,000	-$2,956,000	-$1,916,000	-$3,072,000
2050	-$2,113,000	-$3,697,000	-$2,196,000	-$3,841,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	6	6	1	1
2020	6	6	1	1
2025	7	8	1	1
2030	8	10	1	1
2035	9	12	1	1
2040	10	15	1	1
2045	12	18	1	2
2050	13	23	1	2

Table 82: Port of Seattle Difference Between 100% and 0% CHE Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	-$1,750,000	-$1,750,000	-$1,824,000	-$1,824,000
2020	-$1,850,000	-$1,917,000	-$1,928,000	-$1,997,000
2025	-$2,125,000	-$2,404,000	-$2,213,000	-$2,503,000
2030	-$2,439,000	-$3,013,000	-$2,539,000	-$3,135,000
2035	-$2,799,000	-$3,774,000	-$2,913,000	-$3,925,000
2040	-$3,212,000	-$4,725,000	-$3,341,000	-$4,911,000
2045	-$3,684,000	-$5,912,000	-$3,831,000	-$6,143,000
2050	-$4,225,000	-$7,395,000	-$4,393,000	-$7,682,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	11	11	1	1
2020	12	12	1	1
2025	14	15	2	2
2030	16	19	2	2
2035	18	24	2	2
2040	20	30	2	3
2045	23	37	2	4
2050	26	46	3	4

Table 83: Port of Seattle Results, 50% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$3,683,000	$3,683,000	$3,523,000	$3,523,000
2020	$3,888,000	$4,026,000	$3,433,000	$3,556,000
2025	$4,453,000	$5,028,000	$3,932,000	$4,440,000
2030	$5,100,000	$6,282,000	$4,504,000	$5,548,000
2035	$5,839,000	$7,845,000	$5,156,000	$6,928,000
2040	$6,687,000	$9,799,000	$5,906,000	$8,654,000
2045	$7,661,000	$12,242,000	$6,766,000	$10,811,000
2050	$8,774,000	$15,291,000	$7,748,000	$12,504,000
Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	63	63	49	49
2020	67	69	51	53
2025	77	87	59	67
2030	88	108	68	83
2035	100	135	77	104
2040	115	169	89	130
2045	132	211	101	162
2050	151	263	116	203

Table 84: Port of Seattle Results, 100% Shore Power Scenario

Output				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	$7,367,000	$7,367,000	$6,506,000	$6,500,000
2020	$7,775,000	$8,053,000	$6,867,000	$7,111,000
2025	$8,905,000	$10,055,000	$7,864,000	$8,880,000
2030	$10,201,000	$12,564,000	$9,009,000	$11,096,000
2035	$11,677,000	$15,690,000	$10,312,000	$13,856,000
2040	$13,375,000	$19,598,000	$11,812,000	$17,307,000
2045	$15,322,000	$24,484,000	$13,531,000	$21,622,000
2050	$17,547,000	$30,582,000	$15,496,000	$27,008,000

Employment				
Year	**State Baseline**	**State High**	**County Baseline**	**County High**
2018	127	127	98	98
2020	134	139	103	107
2025	153	173	118	133
2030	176	216	135	166
2035	201	270	155	208
2040	230	337	177	260
2045	264	421	203	324
2050	302	526	232	405