Clean & Prosperous Washington

Low Carbon Prosperity Institute

WASHINGTON'S DECISIVE DECADE

AN EMERGING ROADMAP FOR TRANSPORTATION DECARBONIZATION & CLEANER AIR

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ABSTRACT

Meeting stringent 50% emissions reductions by 2030 requires an acceleration of low-carbon transportation solutions. With billions of dollars anticipated from the Climate Commitment Act (CCA) for the transportation-focused Carbon Emissions Reduction Account (CERA), state-directed investments are poised to play a major role in this acceleration, complementing other programs and funding sources. These investments can close the remaining emissions gap towards the state's greenhouse gas (GHG) limits by accelerating emerging technologies, riding cost-competitive technology waves, and supporting critical emerging technologies throughout this decisive decade. At the same time, transportation decarbonization can improve quality of life through air quality benefits while unlocking long-term fuel cost savings.

This report examines seven specific decarbonization approaches through a series of case studies which span off-road, on-road, freight, and marine transportation activities and focus on electrification strategies. Through these case studies, we offer two main contributions: First, we develop a methodological approach centered on key metrics that span costs and benefits of potential projects; Second, we use this methodology to evaluate a first batch of case studies and provide unique insights for each one, with an understanding that there are many more interventions that merit consideration with this methodology.

We focus on a set of data-driven metrics across these case studies, including net public health and climate benefits of reducing air pollution, cumulative GHG emissions avoided, abatement costs of emitting less GHGs, net present value lifetime costs of deploying the less polluting solution, and the potential value of credits earned under Washington's new Clean Fuel Standard program. The incremental upfront costs will unlock lower carbon pollution, long-term fuel cost savings, and significant air quality benefits. If designed well and deployed strategically, these investments will also catalyze reduced inequity of pollution exposure and harms.

Scaled to the broader market, these strategies have a combined potential of billions of dollars of investment opportunities, while representing a range of outcomes and justifications for investment. All require additional, upfront investment over a higher pollution alternative. Some provide net savings over their lifetime, some have benefits that outweigh their increased lifetime costs, and others require more substantial investments but can catalyze the broader market. All have potential to reduce pollution exposure to overburdened communities, although some more than others. There is compelling justification to pursue any of these technologies, but the priorities and trade-offs should be considered against desired goals and outcomes.

> IN EXAMINING THESE SPECIFIC DECARBONIZATION STRATEGIES, THIS REPORT OFFERS A DATA-DRIVEN APPROACH THAT CAN BE REPLICATED ACROSS A BROADER SOLUTION SET.

EXECUTIVE SUMMARY

The seven case studies evaluated in this report cover a broad scope of transportation emissions including off-road, on-road (both heavy-duty and light-duty), marine, and freight applications. While broad in scope and scalable to match available funding, the specific decarbonization solutions examined consider only a subset of transportation decarbonization strategies. These strategies focus on switching from liquid fossil fuels to electricity, covering a range of investment needs and potential impacts. They are not one-size fits all, but rather range in terms of overall cost-effectiveness and impacts on air quality.
Each of these strategies offers the potential for public health benefits and reduced fuel costs that pay back at least a portion of upfront costs over time. Cost-effectiveness should not be the only consideration. Even without long-term cost savings or net benefits, investments can stimulate technology in harder to decarbonize--but necessary--sectors of the economy and address environmental health disparities.

This report centers on data-informed insights and a framework that can inform investment strategies by evaluating important metrics: estimated cost-effectiveness, public health benefits from improved air quality, and GHG emissions reduction potential for each technology considered. Other insights include the potential value of Clean Fuel Standard (CFS) credits and the implications of upfront capital costs as a barrier to technology access and adoption. There is not a one-size fits all narrative that cleanly captures these case studies, although all require an upfront premium to transition. Each technology has unique merits and returns different benefits and costs. These merits are influenced by proximity to population centers and are accompanied by different investment dynamics given the different use cases and technological maturity. To help contextualize these merits, we consider four broad categories:

- Long-term cost savings, with additional benefits. Example: Ferry System Electrification.
- Long-term net financial costs, but net benefits are greater than the net costs. Example: Ocean-Going Vessel Shore Power.
- Costs that are greater than benefits, but may play important market transformation role. Example: Electric Motor Coaches and other On-road Heavy-Duty Vehicles.
- Difficult to quantify net costs and benefits, but necessary to accelerate the market. Example: EV Charging Infrastructure.

With the transportation focused *Carbon Emissions Reduction Account (CERA)* under the Climate Commitment Act's Cap-and-Invest program slated for more than $5.2 billion in investments before 2040, these case studies could require a substantial portion of the investments. There are different strategies for prioritizing use of these funds, mapping to the four broad categories we highlighted above. The investment dynamics are different for each case study, but in all of them, some level of state-directed public investment is necessary to deliver potential benefits and meet statewide GHG limits. Leveraged investments will be a major component of decarbonizing our transportation system, meaning the state's funding can be multiplied by unlocking additional private and federal funding. Although financial performance is one relevant consideration, non-financial barriers may dampen the uptake of cost-effective approaches. Access to capital, consumer awareness through education and outreach, and the design of incentives factor into both the rate of uptake and the distribution of impacts.

While some of these investments have limited additional scale (electric ferries, shore power), others operate within markets that are potentially orders of magnitude larger than the scope of the case study. These case studies are not intended as a specific package or portfolio, and should be carefully considered on various program goals and merits. Considering the general scalability and performance of these types of decarbonization strategies may provide useful framing. Assuming that the on-road vehicle strategies in particular scale to a broader market over the next 10 years, total private-public investment needs scale well into the billions of dollars. Financing this, and unlocking the associated benefits, will require substantial contributions from many sources: state, federal, private, and utility among them.

CASE STUDY CATEGORIES

MARINE & FREIGHT

FERRY SYSTEM ELECTRIFICATION

The transition of the Washington State Ferry fleet to primarily battery-electric propulsion. The scope of this case study includes the conversion of three existing ferries to electric-hybrid, new builds of eight hybrid-electric ferries, and terminal electrification projects at five ferry terminals to allow for charging of ferries during regular operation.

OCEAN-GOING VESSEL SHORE POWER

Infrastructure investments at Terminal 18 in the Seattle Harbor, operated by the Northwest Seaport Alliance, that would allow for Ocean-Going Vessels to use electricity rather than auxiliary engines for ship power needs while docked.

CARGO-HANDLING EQUIPMENT

This case study considers infrastructure investments at Seattle and Tacoma Port operations covering several categories of emerging technologies for cargo-handling equipment. Adoption of electric and hybrid equipment leads to early retirement of older equipment and reduced use of diesel for moving goods at the ports.

VEHICLES

DRAYAGE TRUCKS

Drayage trucks are on-road, heavy-duty trucks that transport containers and bulk freight to and from ports. This case study considers early retirement (scrapping) of older drayage trucks and replacement with new, battery electric trucks and charging infrastructure.

MOTOR COACHES (Heavy-Duty Vehicles)

Motor Coaches are a class of on-road, heavy-duty passenger vehicles traveling a variety of routes (fixed, commute, on-demand trips). This case study considers a private fleet of motor coaches with annual travel demand of 35,000 miles per vehicle.

PASSENGER VEHICLES

The passenger electric vehicle market is rapidly evolving in both models offered and pricing. This case study considers two vehicle classes and two purchase years to span a range of near-term price premiums and payback periods for new vehicle purchases.

ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

EV Charging Infrastructure is an essential precursor to widespread adoption of electric vehicles This case study summarizes needs assessments and installation costs based on studies in California and Oregon and applies this to Washington's market and ambition for electrifying heavy-duty and light-duty transport.

These case studies demonstrate some of the potential impacts associated with decarbonizing our transportation system, combining programs that deliver net benefits at affordable costs or cost-savings with other programs that can help stimulate market readiness in harder to decarbonize sectors. Initial costs and access to ongoing cost savings are real barriers to deployment. Adept investment strategies can mobilize net benefits that exceed net system costs while improving equity from pollution exposure. Even without attempting to cost-optimize this set of case studies, incorporate sustained price declines in electric vehicle costs, or consider strategies that payback or moderate the upfront EV charging infrastructure costs, a simplified, scaled-up version of these case studies offers:[1]

- 16 million tCO_2e of avoided GHGs
- Public health and climate benefits that balance 80% of the net costs (220% of net costs before charging infrastructure for LDVs is factored in)
- Abatement costs of \$120/tCO_2e (\$40/tCO_2e before charging infrastructure for LDVs is factored in)
- Clean Fuel Standard revenue potential that is greater than the net costs

The combined capital costs from a hypothetical, scaled-up version of these case studies is on the order of \$4 to \$5 billion, leading to net present value (NPV) costs of \$0.5 to \$1.3 billion. These costs would be shared between various parties, both public and private. How major EV charging infrastructure needs are funded is a critical component to the ultimate cost-benefit assessment. In this hypothetical example, we have not attempted to quantify anything related to EV infrastructure aside from the upfront capital costs, although we would expect some level of payback on those investments.

Investments highlighted in the case studies will need to be complemented with additional investments in other decarbonization strategies such as public transit and non-motorized mobility that reduces vehicle-miles traveled and additional sector-specific interventions including aviation and liquid fuels. Whatever form the portfolio of programs ultimately takes, new funding sources designated for emissions reductions should not be tapped to sustain ongoing programs. New funding is designed to enable additional programs and infrastructure that create additional and durable benefits rather than to maintain the status quo of ongoing programs at current levels of funding. An example of this funding approach is paying only the additional, incremental costs of electrifying new ferries and terminals rather than the full costs which would have largely been required whether the ferry system was electrified or not. There are existing VMT-reduction, public transit, and EV incentives that represent a baseline standard of action. Those programs should be continued without reallocation of newly approved funding sources, although scaling those programs could provide additional impact beyond the status quo.

EXECUTIVE SUMMARY FOOTNOTES

[1] *We make a rough estimate of what scaling these case studies to a broader market would look like through the 2020s. We consider the following scaling from the individual case studies: Drayage Trucks from 10 to 500, Motor Coaches or similar HDV from 60 to 1,000, Light-duty vehicles to 300,000 total, Cargo-Handling Equipment to one-third of the current equipment at the Seattle and Tacoma Ports, and Shore Power to a nearly doubling (90% increase) of impact by extension to three additional terminals (Terminal-30, PCT – Pierce County Terminal, and WCT – Washington United Terminals) based on relative emissions reduction potential reported in the Terminal 18 Shore Power Grant update (item 8D, second table on page 3) from September 2021 NWSA meeting materials. t.ly/YIRi Ferry system electrification has modest scaling potential on the timeframe considered, so only use the totals from the case study. For EV infrastructure, HDV charging infrastructure is considered within the respective case studies but for LDVs additional public charging infrastructure beyond the vehicle-specific case study is needed. Public EV infrastructure for LDVs alone totals over \$800 million in NPV by 2030 assuming a growing stock of electric LDVs to reach 1 million electric LDVs.*

INTRODUCTION

PURPOSE OF THIS REPORT

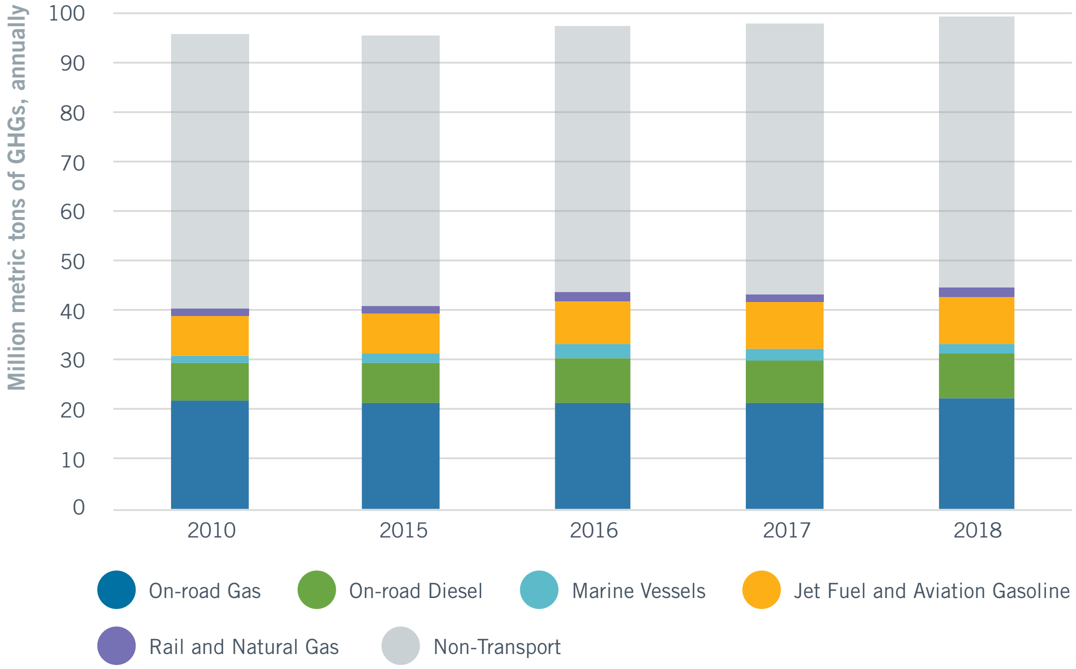
This report examines a set of seven specific opportunities to spur rapid decarbonization of our transportation system throughout this decisive decade. These case studies were completed in partnership with motivated businesses, entrepreneurs, and thought-leaders. Comprising nearly half of Washington state's annual GHG emissions, transportation is inextricably linked with meeting our emissions targets, increasing the well-being of our residents, and overall economic productivity. This inextricable link means that the investments enabled by the Climate Commitment Act--more than $5 billion dollars for transportation decarbonization prior to 2040--must be deployed strategically. This strategic use will include a return on investment that captures priority co-benefits to improve quality of life, leverages federal and private capital, and integrates with other state-directed programs.

In examining these specific decarbonization strategies, this report offers a data-driven approach that can be replicated across a broader solution set. It is important to understand various perspectives that capture not only the net present costs, but the benefits and distributional impacts of those benefits. These metrics must also be placed in context, considering factors like the impact of other programs, the scale of the overall market that can be catalyzed, and the relative market transformation opportunity of the technologies being considered.

The decarbonization strategies evaluated here encompass both public and public-private partnership approaches, although the financial returns in certain cases may motivate private investment alone. While there is detailed modeling work behind our results, including the ability to easily test key assumptions, this analysis should not be viewed as comprehensive, nor any of the following: a full life-cycle emissions assessment, an engineering study of the technical feasibility, a comprehensive guide to transportation decarbonization, or a full accounting of net benefits. This report endeavors to provide a useful framework, adaptable approach, and examples that increase our understanding of the important opportunities for near-term decarbonization of the transportation system.

THIS REPORT CAN ENHANCE OUR UNDERSTANDING OF THE POTENTIAL OF INTERVENTIONS TO REDUCE PERVASIVE SOURCES OF AIR POLLUTION ON OUR ROADS, IN OUR PORTS, AND ACROSS OUR WATERWAYS THAT IMPACT BOTH LOCAL AND GLOBAL COMMUNITIES AND OUR ECONOMIC EFFICIENCY.

Figure 1: Washington statewide Transportation emissions by source (2010-2018)



REPORT CONTEXT

The 2021 legislative session in Washington state provided powerful new tools to achieve state-mandated deep decarbonization targets in 2030 that can blaze the trail towards deeper reductions in 2040 and a net-zero emissions economy by 2050. At the same time, significant opportunities to improve public health and make equitable progress are tied to the evolution of how we move people and goods. Transportation activities are a growing source of state-wide emissions, up to 45 million metric tons of carbon dioxide equivalents (tCO_2e) in the latest inventory year of 2018, equal to 45% of statewide emissions.[2] Both total emissions and the share from transportation sources have been on the upswing through at least 2018, a trend that may very well persist through the 2020s without concentrated and significant effort.

Previous work[3] conducted by our organization in partnership with Climate XChange demonstrated how a low-carbon, pollution-reducing, job-creating portfolio of investments can pave the path to a more prosperous and equitable future. That *Building Back Better: Investing in A Resilient Recovery for Washington* report emphasized a portfolio of programs and investments that can push beyond the status quo and provide economic benefits across multiple sectors of the economy. These programs collectively offer positive net benefits that outweigh the upfront costs—let alone the costs of inaction—on the pathway to deep decarbonization alongside resilient lands and ecosystems. That report was written in the context of the early months of the COVID-19 pandemic and recently updated greenhouse gas emissions (GHG) limits for Washington state (HB 2311): 45% reduction in 2030 emissions relative to 1990 levels, 70% reduction in 2040, and 95% reduction including net-zero emissions by 2050. Since that report, evidence has continued to grow surrounding major environmental inequities in exposure to air pollution and climate change.

By contrast, this report takes a deeper dive into the cost-effectiveness, public health benefits, and climate benefits of a subset of transportation decarbonization investments. While this report seeks to provide quantifiable insights into the overall scope and scale of a variety of transportation decarbonization strategies, we do not propose that it is in any way comprehensive. For example. the interventions contained in this report do not cover critical levers such as low carbon liquid fuels, public transit capacity, or other vehicle-miles-travelled (VMT) focused strategies—although our previous research did touch on some of those additional levers. This report also lacks any quantifiable outputs about the distribution of impacts or benefits and how this may translate into net equity impacts, although that is a critical consideration.

While reducing pollution is a necessary precursor to addressing environmental inequities, it is the design and implementation of programs that will determine how the benefits are distributed. It is our hope that this study can serve as an important input to that conversation, and we look forward to exploring all avenues and partnerships to make this report useful to pushing system outcomes in a direction that aligns with policy intention and existing community knowledge. This includes leveraging the processes supported in 2021's Healthy Environment for All (HEAL) Act.[4]

What has also emerged since our original *Building Back Better* analysis is a dramatically more ambitious policy landscape. Building upon previous legislative efforts to increase ambition in our GHG reduction limits (HB 2311, 2020[5]); drive electricity sector emissions to net-zero by 2030 and zero without offsets by 2045 under the Clean Energy Transformation Act (CETA) (SB 5116, 2019[6]); and, establish a zero-emissions vehicles mandate aligned to requirements in California, including Advanced Clean Truck efforts (SB 5811, 2020[7]), the 2021 legislature advanced two major pieces of legislation to directly address emissions from the transportation sector:

- The Climate Commitment Act (CCA) (SB 5126[8]), an economy-wide Cap & Invest program[9], largely covering transportation fuel distributed within the state. The CCA requires economy-wide emissions reductions by leveraging a price on carbon, which will generate at least $5.2 billion over 16 years for transportation-specific decarbonization purposes through the *Carbon Emissions Reduction Account (CERA)*. The CERA-directed investments may not be spent for highway purposes other than alternative fuel infrastructure, reduced VMT, freight transportation, and maritime and port activities. These funds are also subject to investment minimums for communities overburdened by air pollution (35% minimum with a goal of 40%) and Tribal Nation supported projects (10%, may be additional to or within the 35%), totalling up to half of the investment allocation.
- A Clean Fuel Standard (CFS) (HB 1091[10]), which institutes a cap-and-trade style program on the carbon emissions intensity of transportation fuels. The CFS incentivizes producers of cleaner transportation fuels, including renewable fuels and electricity, by up to $200 per tCO_2e reduced. This is measured over the full life-cycle of the fuel, not just tailpipe emissions. The reduction in carbon intensity of fuels is set to reach 10% by 2031, and increase again in 2033 to eventually reach 20% by 2038.

Despite these policy frameworks, a gap still remains in meeting our emissions targets (and the potential jobs and public health multipliers that accompany them) without the additive impact of investing in solutions.[11] If deployed strategically, the CCA investment mechanism has the potential to close much, if not all, of this remaining gap while achieving substantial co-benefits. These investments are not being made in isolation, but extend to deliberations, including state--notably a new transportation budget--and federal levels--notably passage of the Bipartisan Infrastructure Framework (BIF) and ongoing consideration of the *Build Back Better* (BBB) package. For all these reasons, it is critical to enhance our understanding through data-driven assessments. Doing so, and placing this into a framework that balances priorities and leverages other opportunities can enhance outcomes of emissions reduction, public health, and broadly shared economic prosperity.

ENVIRONMENTAL JUSTICE PROVISIONS AND 2021'S NEW CLIMATE POLICY TEMPLATE

Introduced and championed by 37th District Senator Rebecca Saldaña, the bill implements many of the recommendations from the state's Environmental Justice Task Force[12] and "set[s] a new standard for inclusive, effective policymaking in Olympia, touching down in every corner of the state."[13] The Environmental Justice Task Force issued a report of recommendations which was completed with input from community leaders and listening groups. The recommendations codified by the HEAL Act include:

- Forming the Environmental Justice Council to provide designations and definitions for overburdened communities and vulnerable populations, as well as integrating guidance and accountability within state agencies incorporating environmental justice into their work
- Defining Environmental Justice in state law as a process of both bringing impacted communities into government processes and equitably distributing the benefits of policy and government investments
- Requiring state agencies to conduct Environmental Justice analysis to evaluate benefits and harms within overburdened communities when developing policy, writing regulations, and planning transportation and capital projects
- Maintaining the Environmental Health Disparities map tool to inform future investments and progress on alleviating the health burdens of pollution on communities

The Climate Commitment Act also includes many Environmental Justice provisions that complement and utilize the HEAL Act provisions.[14] These include:

- Giving oversight authority to the HEAL Act's Environmental Justice Council in all phases of program design and revenue allocation
- Requiring Environmental Justice review such as air quality monitoring and, as necessary, additional authority to improve local air quality to meet defined limits
- Requiring a minimum of 35%, and up to 50%, of investments to deliver "direct and meaningful benefits to vulnerable populations within the boundaries of overburdened communities" or projects formally supported by a resolution of a tribe
- Creating opportunities for formalized community engagement, including capacity grants for participation, an Assistance Program for Offsets on Tribal Lands, and a Small Forestland Owners Work Group
- Directly addressing low-income utility cost impacts and fuel use through bill assistance, rebates, energy efficiency, and other demand and emissions reduction approaches
- Forming a Residential Heating Assistance Program to mitigate cost burdens for households using home heating fuels other than electricity and natural gas

Throughout these programs, first priority use is given to low-income customers to help reduce cost burdens and ensure equitable access to clean energy.

REPORT MOTIVATION

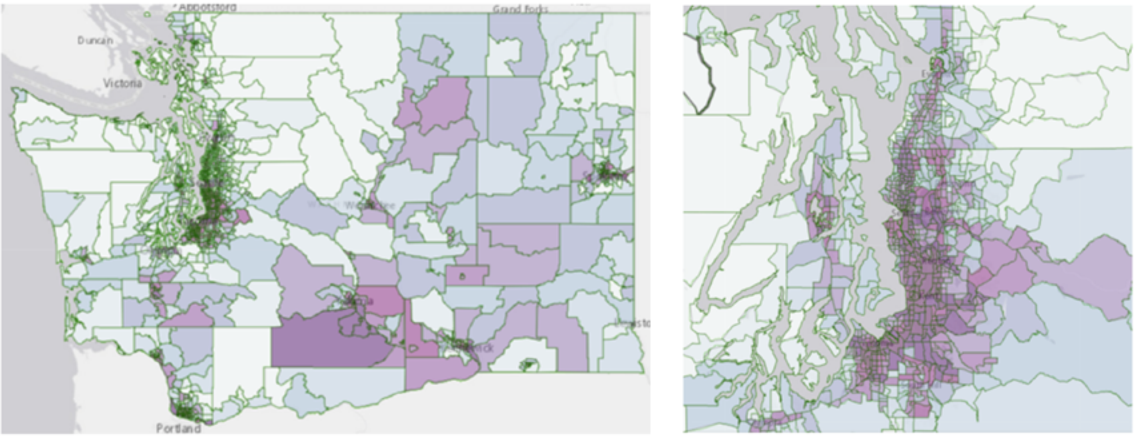
This report is motivated by the opportunity and need to address transportation sector pollution in the decisive decade of the 2020s. Addressing GHG emissions from transportation, whether utilizing Washington's cap-and-invest dollars, leveraging federal spending, harnessing the market signal of the Clean Fuel Standard, or by other means, will benefit the state in a multitude of ways. Reducing fossil fuel use has huge implications for well-being and overall prosperity and equity. Sources that emit fossil fuels also emit air pollutants, such as Volatile Organic Compounds (VOCs),[15] nitrous oxides (NO_x), and outdoor fine particulate matter ($PM_{2.5}$) that each cause significant damages from health impacts. The release of $PM_{2.5}$ results in as many as 200,000 premature deaths each year and is known to cause cardiovascular and respiratory diseases[16] such as asthma. Evidence of health impacts from $PM_{2.5}$, including the neurodegenerative effects linked to exposure, continues to accumulate.[17]

Proximity to pollution sources matters. In King County[18], marginal damages from $PM_{2.5}$ have been calculated to vary by a factor of more than 100, reaching as high as $890,000 per ton depending on the location and nearby population. Half of health damages from these toxic pollutants occur within 32 km (20 miles) of the source[19], with road and mobile sources as major sources of ground-level $PM_{2.5}$, NO_x, and VOC concentrations.

Systemic inequality is deeply-rooted in patterns of exposure to pollutants and co-location with pollution sources. A 2021 study[20] determined that nearly all major sources of fine particulate air pollution disproportionately affect people of color in the United States. Pervasive disparities are widespread rather than isolated to a small number of highly polluting activities. The study finds that people of color are exposed to 14% higher levels of $PM_{2.5}$ than the national population average and 25% higher than the white population, on average. Another study determined those in poverty face an average 35% greater pollution burdens than the overall population.[21] Light-duty gasoline vehicles and heavy-duty diesel vehicles are two of the largest contributors to these disparities.

In Washington state, the Environmental Health Disparities Mapping tool was developed in 2018. The mapping analysis demonstrated that census tracts with lower-incomes and higher percentages of people of color were more likely to experience higher environmental health disparities, and the tool identified nine clusters (ranking 9 or 10 on a scale of 10) of highly impacted communities across the state: Urban locations (South Seattle, Kent, Tacoma, Vancouver, and Spokane) as well as rural areas (Centralia, Longview, Yakima Valley, and the Tri–Cities).[22]

Figure 2: State and Puget Sound corridor Environmental Health Disparities



Source: V1.1 captured from online Information By Location (IBL) viewer: t.ly/a8fm

Reducing GHG emissions in the transportation sector could go a long way towards improving these inequities, and would certainly boost overall public health outcomes. This can likely be accomplished with net benefits, as the Lancet 2021 Countdown on Health and Climate Change report[23] indicated strong supporting evidence that air quality improvements and the associated health benefits are likely comparable to or even greater than the costs of control. That report points to a variety of existing research, including prior work indicating that greater health benefits are associated with a quicker and more equitable transition away from fossil fuels.[24]

In addition to health impacts, the job creation potential of clean transportation investments is compelling. A growing body of research shows that cleaner industries have greater jobs potential than incumbent, heavier-polluting industries. Our Washington *Build Back Better* Report[25], co-authored with Climate XChange, found that a Resilient Recovery Portfolio creates 10.1 full-time equivalent (FTE) jobs per million dollars invested, compared to just 4.3 FTE jobs created in the state's largest industries and 7.4 FTE jobs created in the broader state economy. Clean Transportation investments specifically outperform the state average economy in both annual wages per FTE job and job creation efficiency while keeping more money in the local economy. In Massachusetts, another Climate XChange report[26] found Clean Transport and Development to have high job creation potential while returning substantial physical activity, time savings, and fuel cost benefits plus additional avoided traffic accidents and air pollution health benefits. Totaling $2.60 returned for each dollar invested, the benefits were led by strong outcomes from low carbon buses, active mobility, and ferry electrification. Electric Ferries were one of the highest performing programs for health and climate benefits in the initial Washington study, while also projecting the highest average wages of the 14 potential investment programs evaluated.

While some specific transportation-focused programs showed greater potential, not all had strong anticipated public health and climate benefits. In the Washington *Build Back Better* report, on-road programs were projected to deliver between $0.17 to $0.32 in benefits per dollar invested,[27] while rail-focused and Transit-Oriented Development programs were projected to return $0.03 to $0.12 in benefits per dollar invested. The Massachusetts report found similar relative air pollution and climate benefits from a set of seven clean transportation programs, but expanded the scope to additional benefits in physical activity health, time-savings, avoided fuel costs, and avoided traffic fatalities to demonstrate a more comprehensive set of benefits.[28]

STUDY APPROACH

INTRODUCTION

This report is constructed around a series of case studies focusing on a range of opportunities to decrease fossil fuel consumption, greenhouse gas emissions, and the associated release of criteria pollutants. These case studies were completed with stakeholder support from various industry leaders, businesses, and non-governmental organizations. This support enabled robust data collection and a deeper understanding of the technologies being considered. While stakeholder support and feedback provided valuable input, the findings in this report are those of the study authors and are based on our direct assessment of the best available information.

The case studies contained in this report are based on detailed modeling and data-gathering about technology capital costs; fuel and electricity costs; fuel and electricity consumption; fuel and electricity emissions intensity; operational costs; and more. This approach provides robust feedback on key questions around certain substantial transportation decarbonization investments. It also establishes an overarching methodology, supported by accessible modeling tools with transparency of key assumptions, to allow for deeper investigation. This deeper investigation is intended to be nimble, offering insights from the perspectives of both the public sector (policy-makers or program administrators) and the private sector (businesses or individuals) ultimately deploying the technology.

In framing these case studies, we focus on several critical pieces of information, including:

- **NET PRESENT VALUE (NPV) COSTS** across equipment lifetime and with the perspective of a 4% discount rate on present and future costs (both upfront and ongoing). Additional equipment lifetimes or discount rates are discussed in certain cases
- **PUBLIC HEALTH BENEFITS**, communicated as a monetized present value based on avoided criteria air pollutants ($PM_{2.5}$, NO_x, VOCs, and in some cases SO_2) and an estimate of the damages associated with each metric ton of those emissions
- **AVOIDED GHG EMISSIONS** in metric tons of carbon dioxide equivalent (tCO_2e) and the monetized value of climate benefits through the social cost of carbon
- **ABATEMENT COSTS ($/TCO$_2$E)**, a measure of the relative cost-effectiveness in reducing GHG emissions through the intervention

We extend these results to additional sensitivity and discussion based on unique characteristics of the various decarbonization strategies. Among further perspectives applied across the case studies are the ratio of benefits to net costs and total costs of ownership (TCO) through the interim stages of a technology's life.

IT ALSO ESTABLISHES AN OVERARCHING METHODOLOGY, SUPPORTED BY ACCESSIBLE MODELING TOOLS WITH TRANSPARENCY OF KEY ASSUMPTIONS, TO ALLOW FOR DEEPER INVESTIGATION.

METHODOLOGICAL OVERVIEW

A full overview of key modeling parameters is described in the supporting Appendix to this report. Here, we briefly cover some of the overarching assumptions and the general methodological approach.

- Our central estimates of net present value, abatement costs, public health benefits, and climate benefits rely on the discounting of future costs and benefits at a rate of 4% per year. A 4% discount rate results in costs and benefits being weighed 4% lower every subsequent year. For example, year 2 is 96% of year 1, while year 3 is 96% of year 2 (or 92.2% of year 1).
  - *Net Present Value* is the difference between the lower GHG option and the higher GHG option of the present value cost of all capital investments plus all ongoing operation (mainly fuel) and maintenance costs.
  - *Abatement costs* are the net present value divided by the avoided emissions (also discounted to net present value) over a selected timeframe.
- Upfront capital costs are typically estimated as incremental costs against the baseline, higher-emissions technology. To the extent information is available, this includes both the equipment cost and any associated

infrastructure costs (e.g. charging equipment installation). In certain cases, financing the upfront costs over multiple years is included.

- Ongoing costs center on relative fuel costs of the lower GHG approach relative to the baseline, higher GHG approach. Estimates of future costs of fuels and electricity both with and without estimated impacts of various climate policies (CETA for electricity, CFS and CCA for liquid fuels) can be utilized. To the extent that information is available for a given case study, ongoing maintenance, fees, and residual end-of-life values are considered. In certain cases, the additional fuel cost of public versus private charging is considered.
- Emissions intensities (GHGs per unit of fuel) are designed to allow for incorporating compliance with CFS (up to 20% emissions intensity reduction by 2038) and CETA 100% Clean Power Plan (net-zero emissions by 2030, zero total emissions by 2045). Upstream emissions (sometimes known as "Well-to-Tank") are typically excluded from the emissions intensity and avoided GHG emissions. An exception is for estimating the potential value of Clean Fuel Standard credits which are, by definition, based on full life-cycle emissions that include upstream emissions. Emissions intensity varies depending on the source of electricity, such as Seattle City Light or Puget Sound Energy.
- There are no incentives, rebates, or other monetary provisions considered in determining the abatement cost ($/tCO$_2$e), although those are important considerations from the perspective of each stakeholder and have a significant effect on the likelihood that a technology is deployed or not.
- Beyond significant community health benefits, there are additional benefits to reducing greenhouse gas emissions, reflected through the social cost of carbon. The economic value of avoided damages stemming from climate change incorporates impacts such as reduced agricultural production, damages from extreme weather events, and property loss. A social cost of carbon estimate from the U.S. Interagency Working Group finds that avoided emissions have a societal benefit of $52 per metric ton of carbon dioxide and our valuation of climate benefits is based on this estimate.[29]
- The value of public health benefits is based on methodology developed for the *Building Back Better: Investing in a Resilient Recovery for Washington State* report. The EPA's national emissions inventory (NEI) underpins this, and has not been updated since our previous work although we expect it to be updated soon. Based on that work, emissions from the power sector are estimated to produce $16 in public health damages for each tCO$_2$e emitted, which is relatively invariable between coal and natural gas power plants (Table 7.1). The public health benefits are based on the ratio of criteria pollutants to GHGs for each case study, and the following multipliers which are the average, state-wide values:

Table 2: Public health damages per metric ton of criteria pollutants

Criteria Pollutant	$/metric ton
$PM_{2.5}$	$282,051
SO_2	$38,081
NO_x	$13,235
NH_3	$174,952
VOC	$13,317

- We also consider the potential value of Clean Fuel Standard (CFS) credits, which is potentially substantial. There is great uncertainty at this early stage of rule-making about which party can access these for a given project, if that party will actually access these credits, and the potential volume and value of CFS credits. Therefore, while we assess the potential magnitude of CFS credits, no CFS credits are assumed in our central estimates of NPV or abatement costs.

INTRODUCTION FOOTNOTES

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[25] Kurman-Faber, J., Tempest, K., & Wincele, R. (2020). Building Back Better: Investing in a Resilient Recovery for Washington State. Low Carbon Prosperity Institute. t.ly/Btwv

[26] Wincelle, R., Kurman-Faber, J., & Shimberg, N. (2021). Investing in a Better Massachusetts: An Analysis of Job Creation and Community Benefits from Green Investments. Climate XChange. t.ly/3x6H

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[28] While these cost-effectiveness metrics focus on system costs, to the degree that these investments decrease the need for car ownership, there could be substantial net savings for at least the segment of the population which can transition off car-ownership. This impact is described in scenario analysis released by Climate Solutions: The Big Issues: Transforming our Transportation. t.ly/LZ6F

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FERRY SYSTEM ELECTRIFICATION

PROJECT BACKGROUND

The Washington State Department of Transportation operates Washington State Ferries (WSF), the largest ferry system in the US and one of the highest-use ferry systems in the world. Combined, the WSF vessels consume over 18 million gallons of diesel per year, the largest fuel consumer in the state government.[30] While the WSF fleet increased the share of biofuels in its fuel mix from 5% to 10% by early 2020,[31] by far the largest impact moving forward on avoided diesel consumption, fuel costs, and emissions is WSF's System Electrification Plan.[32] This plan is the cornerstone of meeting WSF's emissions goals of decreasing GHGs by more than 70% and air toxic emissions by nearly 60% by 2040.

Ferries and ferry terminals are a long-lived infrastructure investment, with anticipated useful lives of 60 years for new vessels and at least 60 years for terminal infrastructure. Diesel engines for ferry boats, whether for existing vessels or new builds that must meet cleaner engine tiers, are among the more pollution-intensive mobile sources of toxic criteria pollutants today. Based on the public health multipliers developed for our previous report: *Build Back Better: Investing in a Resilient Recovery for Washington State*, a gallon of diesel used by a ferry is expected to lead to many times greater health damages than a comparable gallon burned in an on-road vehicle.[33]

This high local air pollution impact combined with the proximity of these ferry routes and terminals to population corridors that include many communities at highest risk for environmental health disparities indicates that limiting diesel consumption has a strong nexus to environmental justice outcomes. Research has shown that 50% of damages from air pollution tend to be concentrated within 20 miles of the release point, and that relative proximity of population to pollution sources can result in much greater public health damages than the baseline assumed in this analysis.[34]

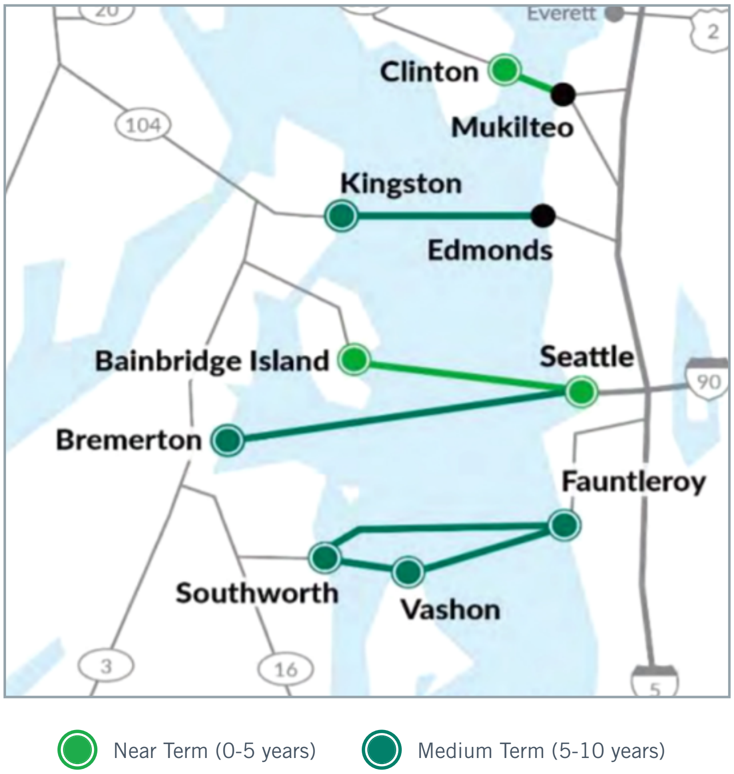
PROJECT DESCRIPTION

In this case study, we examine a full transition from diesel-powered to plug-in hybrid electric ferries along four central Puget Sound routes: Seattle-Bainbridge, Seattle-Bremerton, Edmonds-Kingston, and Clinton-Mukilteo.[35] The transition on these routes is forecast to take place through 2033.[36] Reaching the maximum feasible and practical amount of electric miles on these routes calls for the construction of 11 total plug-in capable ferries: 3 retrofits of the largest vessels in the fleet (Tacoma, Wenatchee, and Puyallup) plus 8 newly built ferries. The electrification plan calls for 5 ferry terminal charging infrastructure projects: Seattle, Bainbridge, Bremerton, Kingston, and Mukilteo.

Combined, the four routes considered in this case study consume nearly 13 million gallons of diesel annually, equal to 29,000 new Ford F-150 Turbo-Diesel Trucks travelling 10,000 miles per year.[37] Decreasing diesel consumption is primarily dependent on the ability to recharge vessel batteries using shore power.[38] On two of the four routes examined, Seattle-Bainbridge and Edmonds-Kingston, the shore power capability is projected to lag the first electric-hybrid vessel by approximately two years.

FERRY SYSTEM ELECTRIFICATION PROJECTS CONSIDERED FOR THIS REPORT

Year	Projects
2022	JMII Retrofit (Wenatchee)
2023	Clinton Terminal Electrification / JMII Retrofit (Tacoma) / HEO #1 (Mukilteo-Clinton)
2024	Bainbridge Terminal Electrification / Seattle Terminal Electrification / JMII Retrofit (Puyallup)
2025	HEO #2 (Mukilteo-Clinton)
2026	Kingston Terminal Electrification / Bremerton Terminal Electrification / HEO #3 (Seattle-Bremerton)
2027	HEO #4 (Seattle-Bremerton)
2028	
2029	HEO #5 (Backup)
2030	
2031	144-Car #1 (Edmonds-Kingston)
2032	144-Car #2 (Edmonds-Kingston)
2033	144-Car #3 (Edmonds-Kingston)



Total capital investments in the Washington State Ferries (WSF) fleet to continue running these routes at the necessary capacity are projected to be $1.9 to $2.0 billion. However, most of that will be incurred whether the fleet is electrified or not. The marginal costs of electrifying this central Puget Sound portion of the WSF fleet, including both vessel and terminal costs, is between $275 to $310 million, or roughly 14-16% of the total capital expenditure. The long lifetimes of these vessels, combined with the significant public health implications of reduced diesel consumption, means that WSF electrification has both short and long-term implications for delivering pollution reduction and meeting WSF's pollution reduction targets.

RESULTS SUMMARY

Table 3: Summary of ferry system electrification results

Time Frame	2022-2094 (60-year vessel lifetimes)
Average Public Health Benefits Multiplier ($/tCO$_2$e emitted)	$280
Cumulative Avoided Emissions (million metric tons CO$_2$e)	4.4 (2.1 through 2050)
NPV Public Health and Climate Benefits ($, M)	$510 ($390 through 2050)
NPV costs ($, M)	$-140 (-$30 through 2050)
NPV Abatement Cost ($/tCO$_2$e)	-$90 (-$20 through 2050)
NPV CFS Credit potential ($, M)	$205 ($180 through 2050)

Once shore power is installed and in use, fuel consumption on each of the four ferry routes is expected to be reduced by 85% to 95% relative to current levels, a system-wide reduction of 11.5 million gallons of diesel per year. This is the greenhouse gas equivalent of removing over 26,000 diesel F-150 trucks from the road. In terms of public health impacts of air quality, we estimate that each gallon of diesel avoided from a retrofit Jumbo Mark II vessel (Tier 1 engine) avoids $3.47 in public health damages, equivalent to $341 for each metric ton of diesel GHG emissions released. Newer diesel ferry engines with stricter engine requirements (Tier 4) are the likeliest alternative to electrifying the fleet. While cleaner burning than the Jumbo Mark II vessels, these Tier 4 engines are still projected to result in $1.63 in public health damages per gallon (equivalent to $161 per metric ton of diesel GHG emissions released).[40] Combined across the 11 vessels considered, the average public health benefits are $280 for each metric ton of diesel GHG emissions reduced.

The public health benefits greatly outweigh the incremental costs of electrifying these ferry routes, even without considering the long-term savings on fuel and maintenance. Present-value public health benefits (at a 4% discount rate) for improved air quality alone are projected to reach $100 million by 2030, $330 million by 2050, and $430 million over the full-lifetime of these four routes.[41] With 2.1 million tCO$_2$e in avoided emissions through 2050 and 4.4 million tCO$_2$e avoided across the vessel lifetimes, the climate benefits reach a present value of $60 million by 2050 and $84 million over the full lifetime of all vessels. Combined with long-term fuel savings, these public health and climate benefits push the

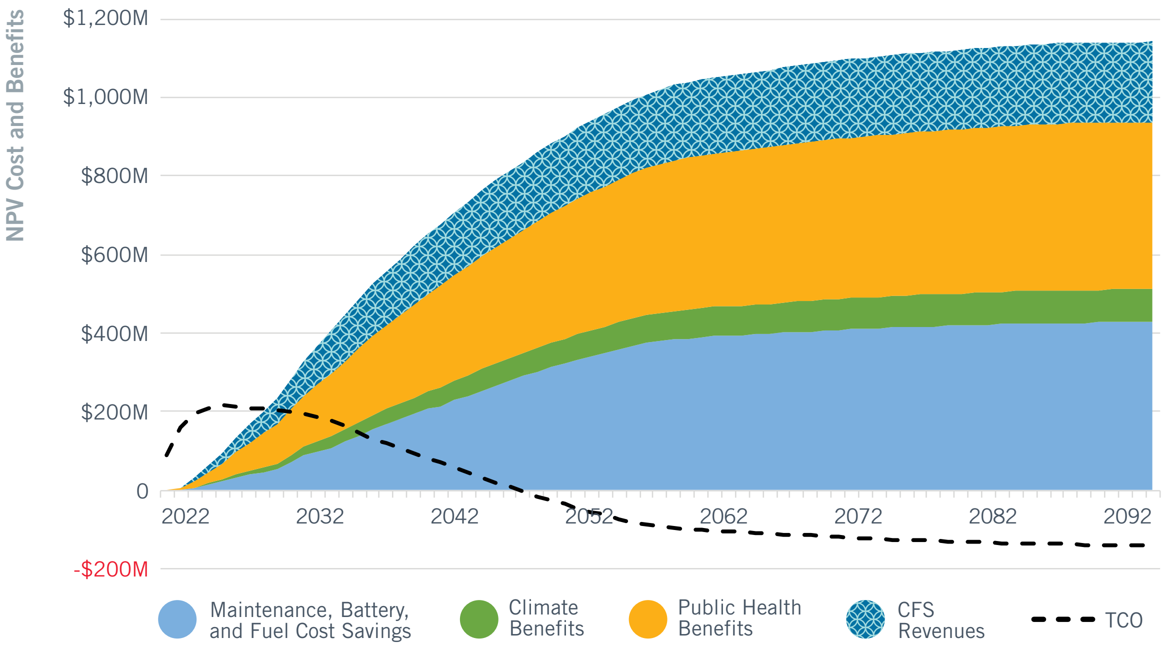
BUILD IN WASHINGTON

Existing Washington law known as Build in Washington requires all new ferries in the system to be built in-state. Vigor (formerly Todd Shipyards) has a long track-record of building WSF ferries, and the Legislature authorized an extension of Vigor's existing contract to build the first five new electric-hybrid ferries called for in WSF's Long Range Plan, although funding has not been fully authorized.[39] Additionally, WSF is expected to release a Request For Proposal shortly for the conversion of existing Jumbo Mark II class ferries to hybrid-electric. Previous work from our organization estimated the jobs impacts of fleet electrification and shore power installation, finding strong wage characteristics for these jobs (20% greater than the state average) and much greater job creation efficiency (full-time equivalent jobs per million dollars) than that of the state's largest industries. Ferry Electrification also projected to contribute higher value added to the state economy than either the statewide average or the average of the state's ten largest industries.

NPV of system electrification (net benefits minus net costs) into positive values in 2034 - timing consistent with the final vessel electrification along these central Puget Sound routes.

Even without considering public health and climate benefits, the electrification strategy pays for itself before 2050, and continues to generate longer-term net savings. Primarily as a result of the ongoing fuel cost savings, the present value net *savings* are $27 million dollars by 2050, growing to nearly $140 million over the full lifetime of the vessels. Considering the 2.1 million tCO_2e avoided emissions through 2050 and 4.4 million tCO_2e avoided across the vessel lifetimes,[42] ferry electrification marginal costs are *negative* $20/$tCO_2e$ through 2050 and *negative* $90 dollars per/$tCO_2e$ across the full lifetime of these vessels.

Figure 3: Cumulative net present value of benefits associated with the electric ferries project over time compared with total cost of ownership (TCO) of the project



We also project the potential value of clean fuel standard credits on the basis of the modeled GHG emissions reductions. The credits depend not only on the market value but also on the annual emissions reductions associated with the switch to electrification. Because of the uncertainty of CFS credits, including whether the power utility or the vessel operator would ultimately receive the credit value, we separate clean fuel credits from the overall assessment of cost-effectiveness. In addition, the long-term nature of the ferries themselves is a unique consideration.[43] Our central estimate is for a present value of approximately $180 million in potential clean fuel credits through 2050 and $205 million through the full lifetime of all vessels.

DISCUSSION

Previous research demonstrated that, on a per gallon of diesel basis, Washington State Ferries create significantly more public health damages than most other transportation fuels.[44] This more comprehensive analysis, which accounts for newer and cleaner engines, supports those initial findings while indicating that the public health and climate benefits of ferry electrification alone are very likely to significantly outweigh the upfront costs.

Compared to most cases of transportation electrification, the ferry system plan may be uniquely positioned for maximum return on investment. Because the ferry routes are fixed, multi-daily routes, the batteries are utilized to nearly their full capacity and capability. Even with an accelerated battery replacement schedule compared to on-road vehicles (once every four years on most routes), ferries are able to deploy their battery capacity multiple times per day, whereas a typical vehicle uses a fraction of its battery capacity daily. The fuel savings unlocked as a ratio of the overall battery capacity, therefore, are much greater than most, if not all, on-road applications.

The net benefits of the system remain clearly positive even if considering a uniquely pessimistic and unlikely set of assumptions that lead to lower avoided emissions estimates (2.5 million tCO_2e rather than 4.4 million tCO_2e) and higher system costs (from *negative* \$150 million to \$140 million).[45] While GHG abatement costs in this scenario are \$320/tCO_2e over the system lifetime, net climate and public health benefits are very likely to outweigh net costs by 2043 and reach nearly sixty percent greater (\$222 million) over the project lifetime. More optimistic scenarios that track more closely to current projected ferry terminal costs without extra contingencies, align shore power availability directly with hybrid-electric boat availability, and anticipate slightly higher diesel costs align to lifetime abatement costs approaching negative \$180/tCO_2e, \$290 million in net savings, and over \$530 million in net public health and climate benefits.[46]

When considering potential funding allocation through the Carbon Emission Reduction Account (CERA) for transportation decarbonization established within the Climate Commitment Act, it is important to note the difference between total investment needs of up to \$2.0 billion and the incremental costs of ferry electrification of around \$300 million. The latter, smaller, incremental costs are what unlocks reduced pollution and could represent most of a single-year of allocation to the CERA. It is this incremental cost that makes the most sense to finance from CERA. The larger number would be nearly 40% of the fixed CERA allocation of \$5.2 billion into the late 2030s, with the majority of that cost necessary whether electrifying the system or not. It is our recommendation that this be taken into consideration when determining what portion of the cost of ferry electrification be provided by CERA and what additional funding may be provided by other sources, including additional State and Federal capital funds.

SHORE POWER

An opportunity to maximize near-term benefits

A unique question presented by the system rollout deals with right-timing shore power availability to the degree possible. With shore power availability, the reduction in diesel fuel consumption is at least 5 times greater than with no shore power. While not necessarily a major lifetime or long-term concern, the impacts in the initial years of the program are nonetheless considerable. Simply moving our central estimates to assuming no delay in shore power for the Seattle-Bainbridge or Edmonds-Kingston routes unlocks enough avoided fuel costs for the project to more than pay for itself and save a net \$3 million dollars through 2026. The net benefits of this shift forward in shore power availability are estimated at an additional \$19 million, including over 35 thousand additional tons of avoided GHG emissions through 2026. This equals a savings of \$90 for each ton of CO2e avoided, a win-win that reduces both total costs and GHG emissions. Whether this timeline adjustment might be feasible is an open question, however the near-term benefits of fully utilizing the capabilities of each vessel as it comes online have a clear impact on the near-term benefits of ferry electrification.

FERRY SYSTEM ELECTRIFICATION FOOTNOTES

[30] *Washington State Ferries System Electrification Plan. (2020). Washington State Department of Transportation. t.ly/mjEV*

[31] *Washington State Ferries Energy Performance Plan. (2021). Washington State Ferries. t.ly/0gAp*

[32] *Washington State Ferries System Electrification Plan. (2020). Washington State Department of Transportation. t.ly/mjEV*

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[34] *Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D., & Marshall, J. D. (2019). Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. Proceedings of the National Academy of Sciences, 116(18), 8775-8780. t.ly/6oHF*

[35] *While the long-term strategy involves running electric, shore powered ferries along all routes in the system, we consider this subset based on current availability of engineering studies and cost projections. In particular, while some of the investment towards Vashon Island routes is anticipated to be made in the timeframe considered here, assessments of those vessels are not yet available for consideration.*

[36] *The first vessels, retrofits of current Jumbo Mark II class ferries on the Seattle-Bainbridge route are currently delayed relative to the original timeline which may have implications for the overall timeline.*

[37] *Within that nearly 13 million gallons, blended biodiesel is nearly 1.3 million gallons.*

[38] *Without shore power, the expected emissions reductions rely exclusively on the hybrid engine efficiency and are only expected to be in the 10-15% range, far short of the emissions reductions targets of WSF and not in line with long-term statewide goals.*

[39] *Hanley, S. (2020, July 2). Vigor chooses ABB battery electric power for new ferries in Washington. CleanTechnica. t.ly/QqtK*

[40] *By comparison, a model year 2023 drayage truck results in roughly $40 in public health damages for each metric ton of diesel emissions.*

[41] *Health damages are only assigned to fossil fuel diesel and not to replacement fuels to comply with the Clean Fuel Standard requirements for the baseline of a diesel ferry. This likely underestimates the overall public health benefits, as biofuels and renewable fuel replacements for diesel may show some improvement in smokestack emissions but would still have some residual emissions of criteria pollutants.*

[42] *The abatement cost calculation requires equal discounting of net costs and net emissions. The present value of avoided emissions for determining the $/tCO$_2$e avoided is 1.1 million tCO$_2$e through 2050 and 1.5 million tCO$_2$e over the vessel lifetimes.*

[43] *We assume that the value of clean fuel credits falls to a floor price of $50 per tCO$_2$e avoided, which is reached in 2048 and held constant beyond.*

[44] *Building Back Better: Investing in a Resilient Recovery for Washington State projected $334 in public health benefits for each tCO$_2$e avoided in fuel consumption by the existing ferry fleet, several times higher than the existing on-road diesel or gasoline impacts per gallon of fuel. In this research, we account for newer ferry engines as a point of comparison for new builds, such that the public health benefits are somewhat lower, at an average of $280/tCO$_2$e.*

[45] *8% discount rate for future costs and benefits, no improvement in Puget Sound Energy emissions intensity for power, much lower diesel cost savings as carbon pricing programs have no net impact, shore power delays for the two routes project to be doubled from 2 to 4 years.*

[46] *There are several reasons to suspect the public health benefits presented here are, if anything, an underestimate. (1) as more research comes out about the impacts of various air pollutants, the public health damages are being revised upwards (reference back to David Roberts and article he wrote about); (2) point-sources in proximity to population centers may have several times higher than average public health implications (Tessum et al.); (3) We scale-reduced public health impact 1:1 with reduced carbon intensity of BAU diesel consumption as a clean fuel standard takes effect. However, criteria pollution is unlikely to scale 1:1 with a reduced fossil fuel diesel share, so we likely overestimate the public health benefits.*

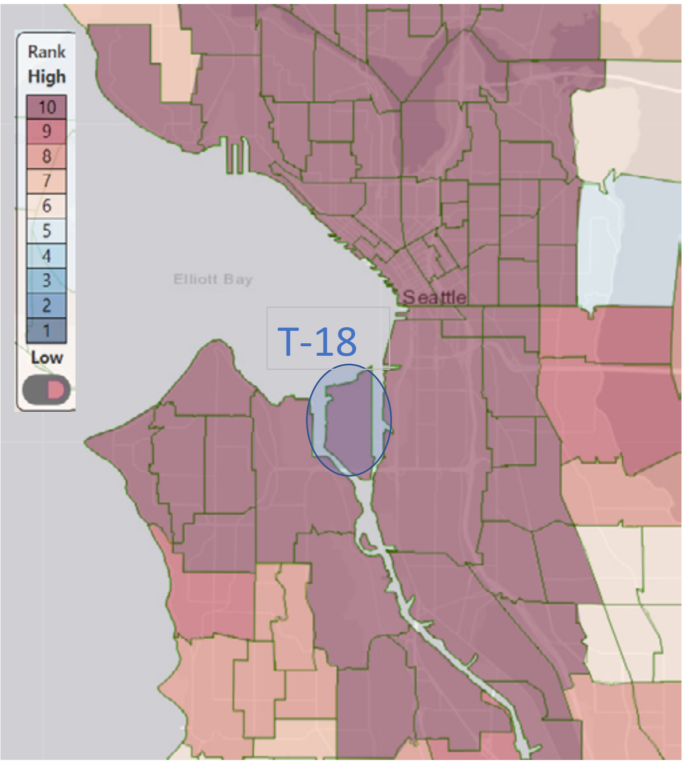
SHORE POWER

PROJECT BACKGROUND

Shore power has been identified as an important emission reduction strategy due to the magnitude of emissions from ocean-going vessels (OGV) that call at the Northwest Seaport Alliance (NWSA) operated terminals and the location of those emissions relative to sensitive populations. Shore power at the largest container terminals is a key priority of the NWSA under the Northwest Ports Clean Air Strategy and the NWSA's 2021-2025 Clean Air Implementation Plan,[47] both of which have been unanimously adopted by the NWSA's Managing Members (10 port commissioners from Seattle and Tacoma). The Terminal 18 (T-18) project on Harbor Island is planned as the third of six major international container terminals to allow for shore power and, due to the volume of OGV port calls, offers the largest potential emissions benefit.

Based on the 2016 Puget Sound Maritime Air Emissions Inventory, Ocean Going Vessels (OGVs) are the largest source of both diesel particulate matter (PM) and GHG emissions within the Northwest Seaport Alliance's (NWSA) operational scope, largely due to in-transit emissions.[48] Hoteling of OGVs at dock accounts for 8% of diesel PM and 10% of GHG emissions associated with the NWSA's operations, but occur close to major population centers and sensitive populations. Due to the location of vessel hoteling emissions, among other factors, air modeling using Washington State University's AIRPACT-5 tool indicated that controlling emissions from OGVs at berth is one of the most impactful means of reducing the population impacts of PM2.5 from port-related sources. That modeling found that OGVs are the largest contributor to population-health impacts among the sources considered.

Figure 4: Environmental Health Disparity rankings NOx-Diesel Emissions Environmental Exposure, using the Information-by-Location (IBL) tool of the Environmental Health Disparities Map[49]



Therefore, strategies to mitigate emissions from docked vessels are among the best health-impact strategies.

Motivated by this potential to significantly reduce toxic air pollutants and greenhouse gas emissions, the NWSA plans to install shore power at its six major international container terminals in Seattle and Tacoma by 2030. Located on Harbor Island at the mouth of the Duwamish Waterway, the T-18 project census tract and nearby communities all rank 10/10 in terms of Diesel Pollution Burden based on the Environmental Health Disparities Map (Figure 4).[50] For overall Environmental Health Disparities, the community around the eastern Port of Seattle ranks 10/10 and the community including the western Port of Seattle ranks 7/10. Thus, reducing pollution from the ports' operations constitutes an opportunity to address environmental inequities, especially with regard to transportation pollution exposure. These health impacts include improved working conditions, especially for crane operators that sit directly above the ship stacks while loading and unloading cargo.

In 2020, there were 1,663 OGV vessel calls at ports, split between the Tacoma (810) and Seattle (853) harbors.[51] Of these, the largest share were container ships with 1,055 calls. The provision of shore power through a grid-connected power cable to an OGV provides a cheaper, cleaner option to provide much of the energy requirements while in port. Nearly 30% of container volumes in the ports of Tacoma and Seattle pass through T-18, the highest number of vessel calls of any terminal.

Marine terminal regulations in California and infrastructure installations in Asian ports have begun to influence ocean carriers serving the region to install equipment that allows for shore power to substitute for diesel-burning auxiliary engines while in port. This is an important lever, given that ports have limited influence on OGV emissions since they are privately owned and operated, and regulated under international law by the International Maritime Organization. Leveraging the increasing prevalence of ocean carriers that are shore power capable is an opportunity for the NWSA to enable emissions reductions that reduce local health impacts and avoid GHG emissions.

PROJECT DESCRIPTION

T-18 has the largest footprint of any container terminal in the Pacific Northwest, a large on-dock rail yard serviced by both Class 1 railways (Burlington Northern Santa Fe and Union Pacific), 1,250 plug-in points for refrigerated containers, 10 ship-to-shore cranes, and 24 truck lanes. This project would include the power distribution elements required to bring electricity from the customer-side substation to the connection points on the dock for ships to plug into.

The NWSA's Capital Investment Plan includes $1 million in 2022 for the design of the T-18 shore power project and subsequent capital costs. The project would include dedicated shore power switchgear for each berth, transformers, underground power distribution, power distribution vaults, recessed connection point vaults, and upgrades to the electrical service entry point to accommodate the additional shore power load at 6.6 kV. The NWSA currently has $2 million in grant funds from the Washington State Department of Ecology to support the project, but will need significantly more funding to move forward with construction.

A 2020 analysis by the NWSA indicated that 55% of container ship calls across the Tacoma-Seattle marine gateway were shore power capable, with a slightly lower share of 49% estimated to be shore power capable at T-18.[52] This works out to 197 annual shore power-capable calls at T-18 currently. Based on NWSA data, the average duration of a shore call is 32 hours. As shore power infrastructure installations across the Pacific Rim become more widespread, the container vessel fleet is becoming increasingly shore-power capable, and this trend is expected to continue.

KEY ASSUMPTIONS

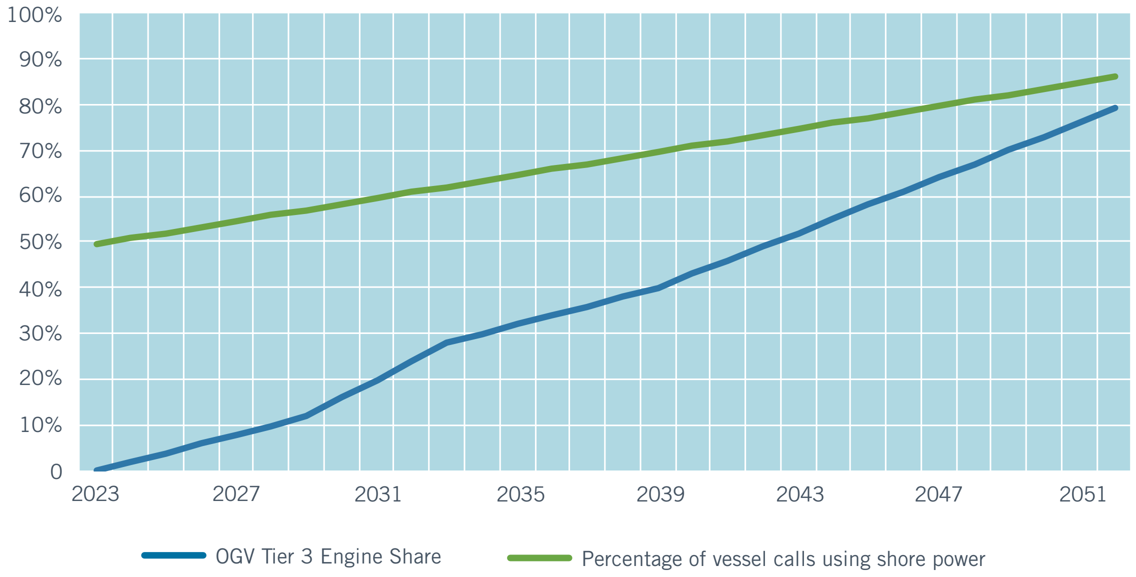
For this project, the lifetime of the electrical infrastructure is assumed to be at least 30 years without significant maintenance needs. Total development costs are assumed to be $28.6 million, which includes design and construction.

An important assumption for the overall project impact is the proportion of port calls made by shore power capable vessels. While providing shore power as an option can help improve the economics of a vessel switching to shore power compatible equipment, the rate of conversion or uptake is ultimately beyond the control of the NWSA. However, the expectation is that the share of OGVs that are shore power capable will increase over time to take advantage of shore power resources and comply with marine regulations at various ports along shipping routes. We are not aware of any projections of the change in shore power capable dockings. However, based on the expectation of increased access, demand, and fuel savings, we include an assumption that the share of shore power-capable dockings will grow by 5 per year to reach 86% of dockings by year 30, the final year considered (Figure 5).

The average shore power draw is estimated to be 34.7 MWh. This is based on an average port call of 32 hours, which includes an hour each to connect and disconnect and an average auxiliary load of 1,139 kW. The GHG emissions from diesel are 23.7 tCO_2e per call under the assumption of a fully fossil fuel source. Our central estimate does not include reductions in emissions intensity of the fuel based on the CFS requirements, as these marine sources are unlikely to be covered under the program except on a voluntary basis. Based on the near-zero electricity mix of Seattle City Light, electricity emissions associated with each shore power call are 0.03 tCO_2e.

The criteria pollutant benefits from moving to shore power are dependent on the engine characteristics of the ships at port. Engine classes for OGVs are rated from Tier 0, the highest polluting class, to Tier 3, the lowest polluting class. Based on NWSA estimates (personal communication), the share of OGVs by engine tier is approximately 20% Tier 0, 65% Tier 1, 15% Tier 2, and 0% Tier 3. For this analysis, we assume all newer ships will be Tier 3, so that the ship fleet slowly turns over from that initial share to a year 30 ratio of 79% Tier 3 (Figure 5).[53]

Figure 5: Assumed share of Tier 3 OGV engines and vessels using shore power over time



SUMMARY OF RESULTS

Fuel costs savings, which would not be realized by the port but instead passed through to the OGV operator, are based on an initial price point of $598 per metric ton and scaled to projected changes in diesel fuel price from the US EIA's 2021 Annual Energy Outlook.[54] Shore power costs from electricity consumption are estimated to start at $3,735 and increase to just over $4,000 per port call, based on Seattle City Light usage and capacity rates. Shore power costs for diesel start at just over $5,000 and increase over the project lifetime as the market price of fuel rises and additional costs related to carbon intensity of fuel are incurred for any diesel used.

Table 4: Summary of shore power case study results

Time Frame considered	30 years
Average Public Health Benefits Multiplier ($/tCO$_2$e emitted)	$250
Cumulative Avoided Emissions (million metric tons CO$_2$e)	0.19
NPV Public Health and Climate Benefits ($, M)	$33
NPV costs ($, M)	$8.9
NPV Abatement Cost ($/tCO$_2$e)	$90
NPV CFS Credit potential ($, M)	$16

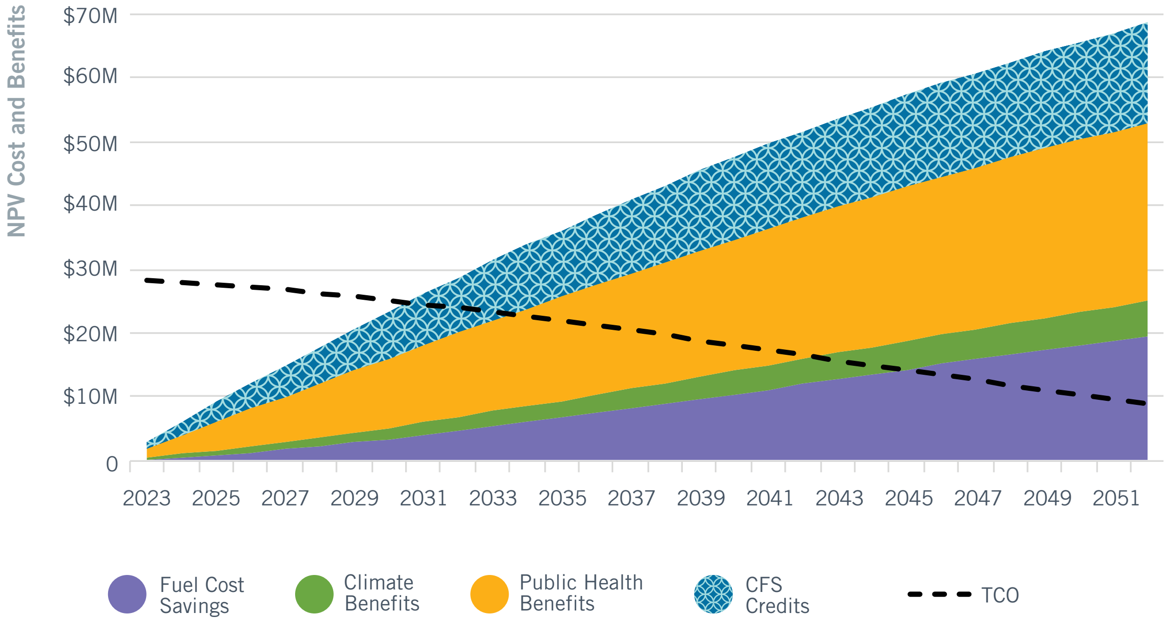
Over a 30-year project lifetime, T-18 shore power is projected to avoid over 190,000 tCO$_2$e emissions. The average annual reduction grows over time as more vessels are assumed to have shore power capability. Due to the high prevalence of toxic air pollutants from OGV auxiliary engines, the cumulative public health benefits are substantial, reaching $28 million over 30 years, including $22 million over the first 20 years. With an additional $5.4 million in climate benefits over 30 years ($4.0 million over 20 years), the net present benefits outweigh the projected costs by 16% over 30 years, reaching 91% of the upfront cost over 20 years. The fuel cost savings ($20 million over 30 years) and potential CFS credits ($16 million over 30 years, including $13.5 million in the first 20 years) are also substantial, although it remains unclear how those savings and credits would be distributed amongst the various parties involved.

It is clear that a primary motivation for this project is to limit the release of toxic air pollutants from the port into surrounding neighborhoods. The public health benefits alone are roughly equivalent to the upfront capital costs over 30 years. With no discounting of future benefits, the public health benefits are 70% higher than the upfront costs. The net project cost-effectiveness on a GHG abatement basis is $90/tCO$_2$e. This includes fuel cost savings of nearly $20 million dollars (which the NWSA is unlikely to realize), but does not include CFS credits of nearly $16 million dollars (which the NWSA would likely retain some portion of if not the full value).

DISCUSSION

Large marine vessels have significant public health considerations associated with their fuel consumptions while docked. Using a broad average estimate of damages, the public health benefits are nearly equal to the upfront costs, even when discounting the value of future avoided damages. Given the immediate proximity of these pollution sources to workers and to communities with the highest environmental health risks, using a broad average for public health benefits may significantly underestimate both the equity impacts and the total value of avoided health damages.[55]

Figure 6: Cumulative net present value of benefits associated with the shore power project over time compared with TCO of the project



This project is an example where the public benefits likely outweigh the capital costs, but the financial costs alone do not justify it as a business case. These project characteristics are clearly shown in Figure 6. Shore power is a good candidate for public funding that ensures the project gets done and secures long-term benefits for local residents. Based on the high initial and long-term costs, external funding would be required to move forward with construction of the project.

While it is beyond the scope of this project to assess the likelihood of fuel switching by OGVs over the next 30 years, some progress in moving to lower carbon fuels can be expected. However, the likelihood of fuel switching may also be impacted by the higher costs of these fuels, resulting in a greater financial benefit of shifting to shore power. A potential proxy for this shift across the industry is to include a CFS pathway assumption of a 20% reduction in fuel emissions intensity by 2038. Under this assumption, avoided CO_2e emissions are 160,000 metric tons rather than 190,000 metric tons. Additional considerations regarding fuel costs and criteria pollutant emission factors from alternative fuels are beyond the scope of this analysis. Therefore, we refrain from further reporting any additional findings on the net costs, abatement cost, or total public health benefits. However, we would expect the relative changes in these factors to be proportionally smaller than the change in CO_2e emissions.

To the degree that OGVs increase shore power capabilities at a more rapid pace or older vessels with lower engine tiers remain in service longer than assumed, the relative impacts of shore power at T-18 would be greater. Conversely, if the share of OGVs with shore power capability were to remain stagnant, ship turnover or engine replacement to higher tiers were to be accelerated, or lower carbon fuels were to be integrated into auxiliary engine use, the relative impacts of shore power at T-18 would be lower.

SHORE POWER FOOTNOTES

[47] *t.ly/RToQ*

[48] *Starcrest Consulting Group LLC. (2018). Puget Sound Maritime Air Emissions Inventory. Puget Sound Maritime Air Forum. t.ly/ZjCa*

[49] *University of Washington Department of Environmental & Occupational Health Sciences. Washington Environmental Health Disparities Map: technical report. Seattle; 2019. t.ly/a8fm*

[50] *Ibid*

[51] *Table 11 of t.ly/RToQ*

[52] *See Table 2 of the Northwest Ports Clean Air Strategy 2021-25 Implementation Plan (November 2021). t.ly/RToQ*

[53] *Tier 0 ships are phased out from Year 1 through Year 11, Tier 1 ships start phasing out in Year 8 and remain at 19% in Year 30, and Tier 2 ships start phasing out in Year 18 and remain at 2% in Year 30.*

[54] *North America bunker fuel prices today, IFO 380, IFO 180, MGO prices per ton. (n.d.). OilMonster. Retrieved October 28, 2021, from t.ly/kxKX*

[55] *Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D., & Marshall, J. D. (2019). Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. Proceedings of the National Academy of Sciences, 116(18), 8775-8780. t.ly/6oHF*

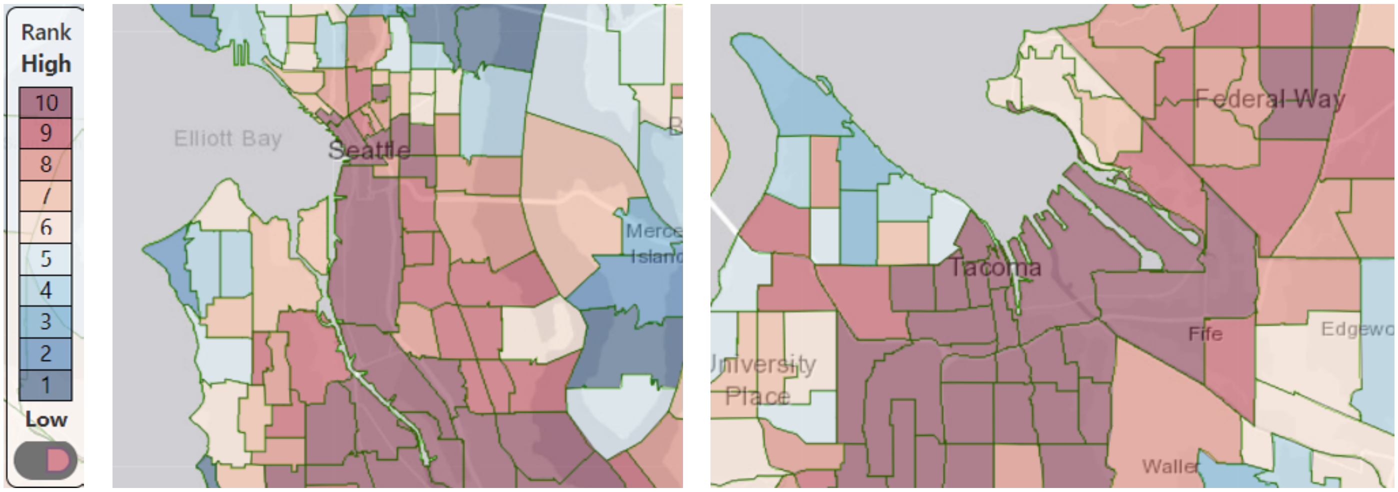
DRAYAGE TRUCKS

PROJECT BACKGROUND

Drayage trucks are on-road, heavy-duty Class 8 diesel trucks that transport containers and bulk cargo from ports and railyards to another location such as a regional distribution center or warehouse. These trucks are integral to the operations of a port, but, as a result of the diesel fuel they consume for their activities, they are also a significant source of GHGs and other toxic air pollutants. As in many other urban areas around the country, diesel exhaust presents the greatest public health risk of all toxic air pollutants in the Tacoma/Seattle area.[56]

Both the Seattle and Tacoma harbors are surrounded by near-port communities facing significant environmental health burdens. According to the Washington DOH's Health Disparities Map,[57] both the ports and many of the typical drayage truck routes are in close proximity to neighborhoods with the highest environmental disparities risks, largely as a result of diesel and particulate matter exposure.[58] Census tracts at and around the Tacoma harbor all score either a 9/10 or 10/10 for Environmental Health Disparities. In these census tracts, the percentage of persons below the poverty line is more than double the rate in Pierce County as a whole and the rest of the state, and the life expectancy is five years lower than the state average. The Tacoma harbor is in close proximity to Downtown, East Side, Hilltop, and Northeast Tacoma, as well as the City of Fife, which are all disproportionately impacted by air pollution due to their proximity to the port industrial complex and the I-5 corridor. Located near the mouth of the Duwamish Waterway, the Seattle harbor location and nearby communities all rank 10/10 in terms of Diesel Pollution Burden based on the Environmental Health Disparities Map.[59] For overall Environmental

Figure 7: Census tracts near the harbors of Seattle (left) and Tacoma (right) by Environmental Health Disparities rank[60]



Source: V1.1 captured from online Information by Location (IBL) viewer.

Health Disparities, the community around the eastern Seattle harbor ranks 10/10 and the community including the western Seattle harbor ranks 7/10.

In addition to nearby communities, port workers themselves often bear a disproportionate burden of the health impacts associated with diesel exhaust working in or near diesel equipment. Many of the truck's owner operators are new Americans and people of color who often both live and work in communities disproportionately impacted by diesel pollution. Furthermore, many NWSA and Port of Tacoma properties lie within the boundaries of the Puyallup Indian Reservation, thereby impacting indigenous communities as well. Many of the distribution centers and warehouses that drayage trucks service and base out of are also within or adjacent to high environmental health disparity communities, such as the SODO industrial area and the Kent Valley, with travel to and from the port occurring primarily along main transport corridors that are disproportionately adjacent to highly impacted communities. Thus, this drayage zero-emission demonstration, which prioritizes scrappage of older diesel trucks, would reduce diesel pollution in environmental justice communities away from the port's industrial complex as well as those within the immediate vicinity.

PROJECT DESCRIPTION

Roughly 4,000 diesel trucks conduct business at the Northwest Seaport Alliance's (NWSA) international container terminals in Seattle and Tacoma. An additional 500-600 trucks conduct business around the Port of Tacoma, at NWSA's TOTE[61] and West Sitcum[62] domestic container terminals. Collectively, these ~4,500 drayage trucks represent the second largest source of GHG emissions in NWSA's scope of operations,behind ocean-going vessels, accounting for roughly one-quarter of the NWSA's emissions in the 2016 emissions inventory.[63]

To explore opportunities to reduce these emissions, the NWSA is planning an electric truck pilot program with ten battery electric class-8 drayage trucks.[64] These trucks are expected to replace the operating hours of model year 2007 trucks, which are then assumed to be scrapped.[65] Due to their age, the trucks planned for scrappage do not meet 2010 clean-diesel emissions standards for Particulate Matter (PM) or NOx emissions.

The port itself does not own or operate drayage trucks. Instead, these trucks are owned by a large number of different trucking companies that vary in size from small, independent owner-operators with fleets as small as one truck to large logistics companies with expansive fleets. As such, the NWSA expects the project to be a collaboration between the port, a trucking company, and a zero-emission truck manufacturer. According to the most recent Northwest Ports Clean Air Strategy Implementation Plan, the port expects to contribute 5% of funds for the Zero-Emission Drayage Truck Demonstration, with 20% of funding coming from the trucking company and the remaining 75% coming from external funds that the port will help to secure in collaboration with other project partners.[66] This initial 10 truck project can serve to inform the NWSA on the feasibility of electrifying a larger portion of the drayage fleet and provide relevant lessons for other vehicle classes and truck operators throughout the region.

KEY ASSUMPTIONS

For this project, the lifetime of a new electric truck is assumed to be 12 years, including a capital cost for each new drayage truck of $290,194 and electric infrastructure costs of $68,698 per vehicle.[67] Across a 10-truck project, total capital outlay is $3.6 million.[68]

While a program could focus on vehicle turnover at the point of new purchase, this program specifically focuses on early retirement of higher-polluting, existing diesel drayage trucks. While a new diesel truck is projected to cost $180,126, we assume that the baseline vehicle being replaced in this scenario is a used drayage truck at an average purchase price of 30% of a new truck. The initial used truck (a 2007 model) is assumed to have 3 years of useful life remaining, after which time a subsequent used truck must be purchased.

In order to model the most likely real-world scenario, this analysis compared the cost of the new electric trucks with the cost of continued usage of the 2007 diesel trucks through the end of their useful life (roughly 15-18 years) and subsequent replacement with later model year used diesel drayage trucks. Two used truck replacements were assumed over a 12-year comparison period based on a California Air Resources Board (CARB) estimate for the useful life of a battery-electric truck. Based on information provided by the NWSA, this Drayage Truck case study uses a central estimate of 41,000 annual Vehicle Miles Traveled (VMT). Trucks running on diesel are assumed to comply with Clean Fuel Standard requirements, which grow to a 12% reduction in emissions intensity of fuel over the time duration considered for this project.

Relative maintenance costs can be readily analyzed, spanning a range of values according to an NREL study[69] on the Total Cost of Ownership (TCO) of new class-8 and class-4 trucks. We assume the widest range of maintenance costs due to a baseline of an older, and therefore likely higher maintenance, diesel vehicle. The maintenance cost savings are projected to be $0.13/mile for electric drayage trucks relative to diesel drayage trucks. Finally, the model assumed scrappage of the old diesel vehicle, and thus no residual value after the useful lifetime of the diesel trucks. The electric drayage trucks are assumed to have relatively little residual value, roughly $8,000 per truck, after 12 years.

The electricity providers for the NWSA's port operations in both harbors, Seattle City Light and Tacoma Power, have have near-zero carbon (less than 10 gCO_2e/kWh). Both values are less than 1% of the national average emissions intensity. Thus, this demonstration project serves as a potential leading case study to evaluate the effects on public health benefits, climate benefits, and cost effectiveness of drayage truck decarbonization. However, many of the drayage trucks may be home-based and are likely to be charged within Puget Sound Energy (PSE) territory. While emissions from PSE electricity are required to reach net-zero by 2030 and drop substantially by 2025 through transitioning away from coal power as required by the Clean Energy Transformation Act,[70] the emissions intensity of PSE power is currently much higher than that of either Seattle City Light or Tacoma Power, at around 400 gCO_2e/kWh. This is expected to fall by nearly 50% by 2025. Therefore, our summary results include perspectives on both near-zero emissions electricity used for charging, and PSE territory based charging.

SUMMARY OF RESULTS

Table 5: Summary of 10-vehicle drayage truck fleet results

Time Frame	12-year vehicle lifetime
Public Health Benefits Multiplier ($/$tCO_2e$ emitted)	$80 to $90
Cumulative Avoided Emissions (million tCO_2e)	0.0072 to 0.0081
NPV Public Health and Climate Benefits ($, M)	$0.80 to $0.85
NPV costs ($, M)	-$0.041 to -$0.055
NPV Abatement Cost ($/$tCO_2e$)	-$10
NPV CFS Credit potential ($, M)	$0.97 to $1.1

We project an average avoided emissions per drayage truck across the 12-year project life of 720 to 810 metric tons of CO2e (tCO_2e), depending on the electricity provider. Initially, savings are 61 to 79 tons per year compared to an earlier model drayage truck.

As the baseline drayage truck is replaced by newer models that require more stringent clean fuel standard compliance, the annual avoided emissions drop to 52 tons by year 12 in both cases as electricity emissions intensity falls to net-zero emissions. Across the 10-truck sample, total emissions savings are 7,200 to 8,100 tCO_2e over 12 years.

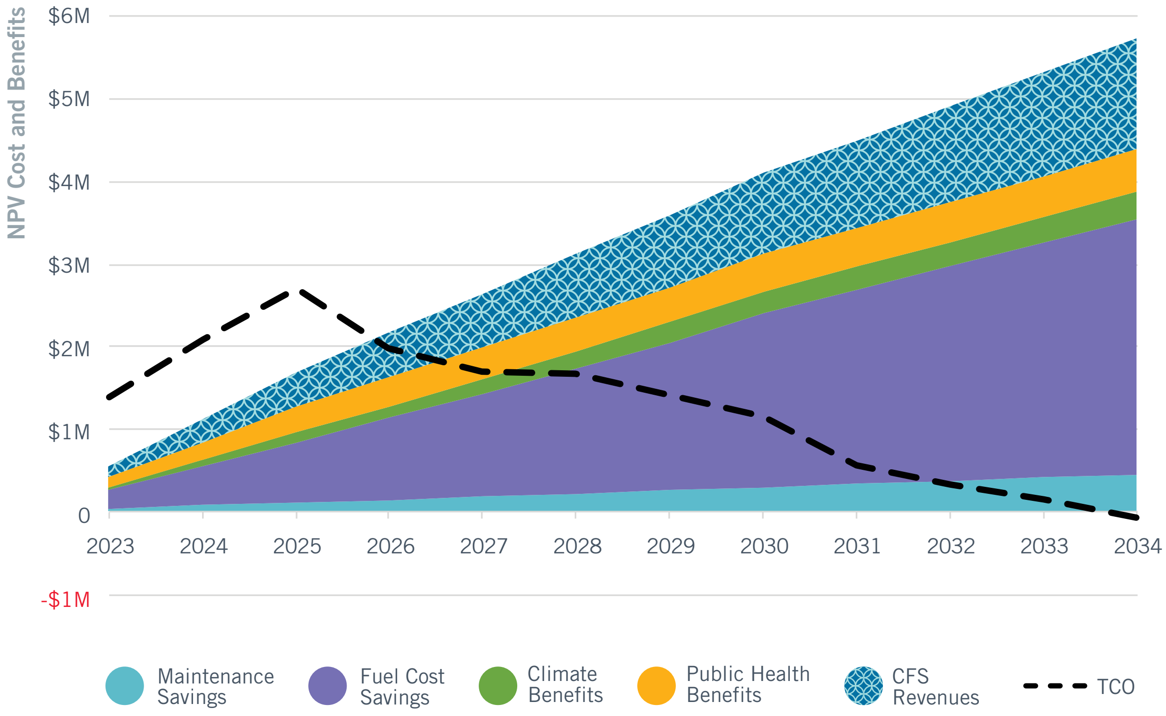
As higher upfront capital costs are partially recouped through lower fueling and maintenance costs and avoided future used vehicle purchases, the cumulative abatement costs decrease each subsequent year to around negative $10 per tCO_2e after 12-years.[71]

Climate benefits of the project start at between $31,000 and $40,000 in year one, rising to a cumulative total of between $300,000 and $340,000 over a 12-year project life. Public health benefits of the project start at around $110,000 in the first year and reach a cumulative total of around $500,000 over the 12-year lifespan.

The cumulative NPV cost of the project in year 12 is negative $41,000 to negative $55,000. Comparing net benefits (public health and climate) against net costs, the total net benefit of the project over the 12-year lifetime ranges from $840,000 to $900,000--or $84,000 to $90,000 per truck.

We can also project the potential value of Clean Fuel Standard (CFS) credits on the basis of the modeled GHG emissions reductions. The credits depend not only on the market value and the annual emissions reductions associated with the switch to electrification, but also on ownership and ability to access the credits. Because of these complicated considerations, we do not include CFS credits in the overall assessment of cost-effectiveness. However, we do estimate a potential cumulative value of CFS credits at around $1 million dollars, or between $97,000 and $110,000 per drayage truck.

Figure 8: Cumulative net present value of benefits associated with the drayage truck project (near-zero emissions electricity scenario) over time compared with TCO of the project



DISCUSSION

Overall climate and public health benefits as well as net lifetime savings scale with annual VMT, but also vary depending on the model year of the truck that is ultimately displaced. Targeting the highest possible VMT use cases would result in greater climate and public health benefits, as well as more net savings through avoided fuel and maintenance costs. Identifying trucks for this pilot program that travel frequently through the highest environmental health disparity communities and are owned and/or operated by members from these communities would be one way to maximize the positive community impact of this program and should be considered as a metric for grants or incentives to facilitate completion of this project and broader heavy-duty fleet incentives.

This specific project is a demonstration including 10 trucks, but a project at a larger scale would likely have a lower infrastructure cost per vehicle, making the electric trucks more cost-efficient. Simply scaling this pilot project projection across the full range of 4,500 drayage trucks active at the port yields projected benefits of around 3.4 million tCO_2e avoided; $140 million in climate benefits; and $220 million in public health benefits. These totals are likely constrained by the limited inventory of earlier models, meaning less-efficient and higher polluting trucks, as is assumed for this case study.[72]

Many fleet operators make capital investment decisions within the constraints of shorter-term payback periods than a full truck lifetime. This perspective helps inform incentive structure in California's programs targeting heavy-duty vehicles. Here we present the 3-year, 5-year, and 7-year TCO values for our central scenario alongside the full, 12-year lifetime (Table 6). These dollar amounts represent the additional cost of owning a battery electric truck when compared with a diesel truck over different time intervals. The potential value of CFS credits are estimated at around $40,000 per truck in the first three years, $60,000 in the first five-years, $75,000 in the first seven-years of the program, and around $100,000 over the full 12-year life (Table 6). Which party, if any, utilizes the CFS credits is not clear.

Table 6: TCO premium over various time periods for an electric truck (near-zero electricity) compared to a diesel truck

TCO premium per drayage truck	No CFS Credits	With CFS Credits
3-year	$270,000	$230,000
5-year	$170,000	$110,000
7-year	$140,000	$65,000
12-year (full life)	-$5,500	-$110,000

The values in Table 6 are indicative of the total anticipated out-of-pocket cost to the purchaser across three different timeframes. One possible framing for incentives would be to decrease the TCO premium to near-zero over a specified time-period. In California, under their Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP), drayage capable tractor trucks currently can receive a $120,000 incentive.[73] This works out to around 6-years to break even if CFS credits are available and longer if CFS credits are not available to the vehicle purchaser. Washington has recently adopted Advanced Clean Truck requirements, although the impact of this regulation is currently unknown.

Capital costs are rapidly changing and the charging infrastructure costs are not well documented. An MJ Bradley & Associates report on clean trucks[74] projects regional-haul truck cost premiums to fall by over $90,000 between 2020 and 2025 and continue sharp price drops beyond that. Infrastructure costs will vary quite substantially depending on whether slower, Level 2 charging overnight is sufficient or more rapid and frequent DC Fast Charging is needed. Projections range from as little as $5,500 per vehicle for a single-unit truck[75] to $92,000 for DC Fast Charging.[76]

Alternatively, a cost comparison of new diesel vehicles with new electric vehicles results in a lower incremental cost for the electric trucks, since the cost of a new diesel truck is significantly higher than that of a used diesel truck. However, because the new diesel trucks do not pollute as much as 2009 and earlier models, this comparison also results in lower overall climate and public health benefits from switching to the electric trucks.

A longer lifetime usage of the vehicle would result in stronger overall cost-effectiveness and net impacts. In the final year alone, the abatement cost falls by over $30/tCO$_2$e while climate benefits increase by around $1,700 per vehicle and public health benefits increase by over $1,300 per vehicle. Any need to purchase a replacement battery would reverse cost-effectiveness improvements.

This program is a partnership example - the NWSA does not own the trucks and does not realize the fuel or maintenance savings. NWSA may not necessarily assume responsibility for the charging infrastructure costs if their charging requirements are satisfied off-site. The question of who would have access to the value of CFS credits under the new statewide program is open. They could go to the utilities servicing the charging, the vehicle or fleet owner, or the port (assuming the charging infrastructure is on-site). Adding the CFS credits as a source of revenue significantly decreases the incremental cost of the project and increases the cost-effectiveness of reducing pollution.

DRAYAGE TRUCKS FOOTNOTES

[56] *2010 Study of Air Toxics inTacoma and Seattle. (2010). Puget Sound Clean Air Agency. t.ly/LhhW*

[57] *University of Washington Department of Environmental & Occupational Health Sciences. Washington Environmental Health Disparities Map: technical report. Seattle; 2019. t.ly/a8fm*

[58] *Ibid*

[59] *Ibid*

[60] *Ibid*

[61] *TOTE maritime Alaska terminal. (n.d.). Northwest Seaport - Port of Tacoma. t.ly/h0Gc*

[62] *West Sitcum terminal. (n.d.). Northwest Seaport - Port of Tacoma. t.ly/XPRs*

[63] *Table 9.44. Starcrest Consulting Group LLC. (2018). Puget Sound Maritime Air Emissions Inventory. Puget Sound Maritime Air Forum. t.ly/ZjCa*

[64] *Hydrogen-powered drayage trucks are also a consideration, but anticipated initial interest is expected to be greater for battery electric trucks due to cost.*

[65] *This could be done by direct replacement of a 2007 truck or a two-step approach to directly replace a more recent truck which would subsequently be used to displace and scrap an older truck.*

[66] *Port share of cost burden percentages assume a total cost of the project at $8.4 million (Draft Implementation Plan t.ly/f5Sh), whereas our model relying on published projections for California's Advanced Clean Truck rule forecast a much lower capital cost.*

[67] *Table 18. Appendix H Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document. (2019). California Air Resources Board. t.ly/JDQW*

[68] *A recent program at the Port of Oakland had a higher capital outlay ($5.1 million total for 10 trucks and $1.7 million for 10 electric chargers) (source: t.ly/zYXZ). These are well above anticipated prices for drayage trucks in upcoming years (California Air Resources Board rulemaking: t.ly/JDQW) and the typical fast-charger installation cost (around $100,000 per charger according to California Energy Commission's CALeVIP DC Fast Chargers Data: t.ly/zkZY), but represent a real-world data point. A full-sensitivity analysis would incorporate these as a high-end estimate of future costs with a total outlay of $6.7 million. This is nearly double the capital outlay assumed for our central case, which translates to 3 to 4 times higher NPV and abatement costs:around $160-$270/tCO$_2$e.*

[69] *Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). Spatial and temporal analysis of the total cost of ownership for class 8 tractors and class 4 parcel delivery trucks. t.ly/lsx4*

[70] *Clean energy transformation act. (2021, November 4). Washington State Department of Commerce. t.ly/Tv0Z*

[71] *Assumes a 4% discount rate. At no present discounting (0% discount rate), abatement costs are $ to negative $30.*

[72] *As a point of reference, comparing the impacts of purchasing a new EV drayage truck rather than a new diesel truck ($180,000 purchase price) is projected to save money by year 11 of operation, but result in nearly 20% less GHG emissions avoided and 60% fewer public health benefits.*

[73] *Tractor. (n.d.). Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project | California HVIP. t.ly/fMfJ*

[74] *Lowell, D., Saha, A., Freeman, M., MacNair, D., Seamonds, D., & Langlois, T. (2021). Clean Trucks Analysis: Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks. MJ Bradley and Associates. t.ly/fGfi*

[75] *Ibid*

[76] *Alexander, M., Crisostomo, N., Krell, W., Lu, J., & Ramesh, R. (2021). Electric vehicle charging infrastructure assessment - AB 2127. California Energy Commission. t.ly/bY8V Per vehicle cost estimate assumes 9 connectors for every 10 trucks and costs above and beyond the charging unit itself representing over $^{2}/_{3}$ of the total cost.*

MOTOR COACHES

PROJECT BACKGROUND

Motor coaches are large passenger buses used for a variety of routes, from fixed daily commutes to group trips, intercity routes, and more. This case study focuses on a motor coach fleet operating throughout the Puget Sound and northwest region of Washington state. Starline Luxury Coaches owns and operates a fleet with 82 motor coaches and minibuses. Collectively, these vehicles travel nearly 2.4 million miles and consume nearly 320,000 gallons of fuel each year. Over 90% of this fuel consumption is from motor coaches, which are the focus of this case study. There are large uncertainties about the incremental costs of electrifying motor coaches and installation of sufficient charging infrastructure. Vehicle costs are trending downwards as a result of battery cost declines,

In order to reduce motor coach emissions, incentive programs are often necessary. California's HVIP is financed through revenue raised in the California Cap & Trade Program. Incentives in the HVIP program range from $22,250 for a retrofit Step & Panel Van to $240,000 for a hydrogen fuel cell heavy-duty transit bus. Vouchers for new battery-electric vehicle purchases are the main category of available incentives. The highest battery-electric incentives are set to $198,000 for certain school bus options, but $120,000 is a more typical incentive for a motor coach. Through HVIP, hybrid and natural gas vouchers have claimed 30% of vouchers to date, but new vouchers are no longer available for either type of vehicle. Zero-emissions vehicles (ZEVs), which are almost exclusively battery electric to date, have become the clear focus of the current program. These ZEVs make up the largest category of vouchers assigned (37%) as well as the predominant share of vouchers awaiting redemption (91%).

California also has programs in place that are focused on scrappage of older heavy-duty vehicles, such as the Carl Moyer Heavy-Duty Voucher Incentive Program and the Funding Agricultural Replacement Measures for Emission Reductions (FARMER) program. The modeling tool described below is initially developed with a focus on assessing new-for-new vehicle purchase decisions, but it can also be deployed to evaluate scrappage or early retirement focused opportunities.

PROJECT DESCRIPTION

This case study considers Starline's fleet of 60 motor coaches with an average annual distance travelled of 35,000 miles. This equates to an average daily trip of 141 miles if driven for 250-days per year use case or 107 miles average daily trip if driven for 330-days per year. Vehicles are assumed to last for 15 years (~530,000 miles) and require charging infrastructure to be installed at their home-base to satisfy most of the charging requirements for annual travel.

KEY ASSUMPTIONS

The large uncertainties in heavy-duty vehicle (HDV) price trends and charging infrastructure needs lead us to deploy a unique framing for this case study, rather than assuming a single, central case. To do this, we have developed a new modeling tool, building additional metrics and sensitivities onto the CARB Low Carbon Transportation Program On-Road Consumer-Based Incentives Project Calculator Tool.[77] The CARB Calculator Tool provides efficiency and criteria pollutant values across 44 unique vehicle classes and a wide-range of model years. The vehicle classes range from motorcycles and passenger vehicles to many varieties of heavy-duty tractor trucks and utility trucks. This broad functionality means the potential applications of this tool are substantial. Using the CARB Calculator, we select a 2024 Motor Coach as the point of comparison. A 2024 model year (MY) diesel Motor Coach is projected to get 8.2 mpg. The comparative electric motor coach option is projected to travel 0.84 miles per kWh.[78]

Fuel prices are assumed to reflect price impacts of the CFS and Climate Commitment Act (CCA) for diesel fuel as well as a high price impact on electricity stemming from the Clean Energy Transformation Act (CETA) compliance in the Puget Sound Energy service area. It is assumed that 95% of charging is done at the home base of the fleet, which is a lower cost option of fueling than public charging.[79] Maintenance savings are assumed on a per mile travelled basis, with a central estimate of $0.14 per mile saved in an electric motor coach compared to a diesel motor coach.

Cost premiums of motor coaches, particularly in future years, are sparsely documented and highly uncertain. This also goes for infrastructure costs for vehicle charging. Therefore, we consider three price premiums: high, medium, and low. These are loosely based on incremental vehicle cost projections from two recently released charging infrastructure estimates from MJ Bradley & Associates and the California Energy Commission.[80,81,82] We use cost-premium estimates for a low, mid, and high case as described in the table below, with an overarching assumption that vehicle cost premiums in 2024 generally follow long-term trends of lower battery pack costs to lower overall cost premiums than today. For private fleets, we assume that vehicles are financed over 5 years with no down payment and a 2% loan rate. No battery replacement is assumed over the 15-year lifetime.

Table 7: Electric Vehicle Cost Premium Scenario Values

Cost Premium Scenario	Vehicle Cost Premium[83]	Charging Infrastructure Cost Premium[84]
Low	$160,000	$20,000
Mid	$240,000	$70,000
High	$320,000	$100,000

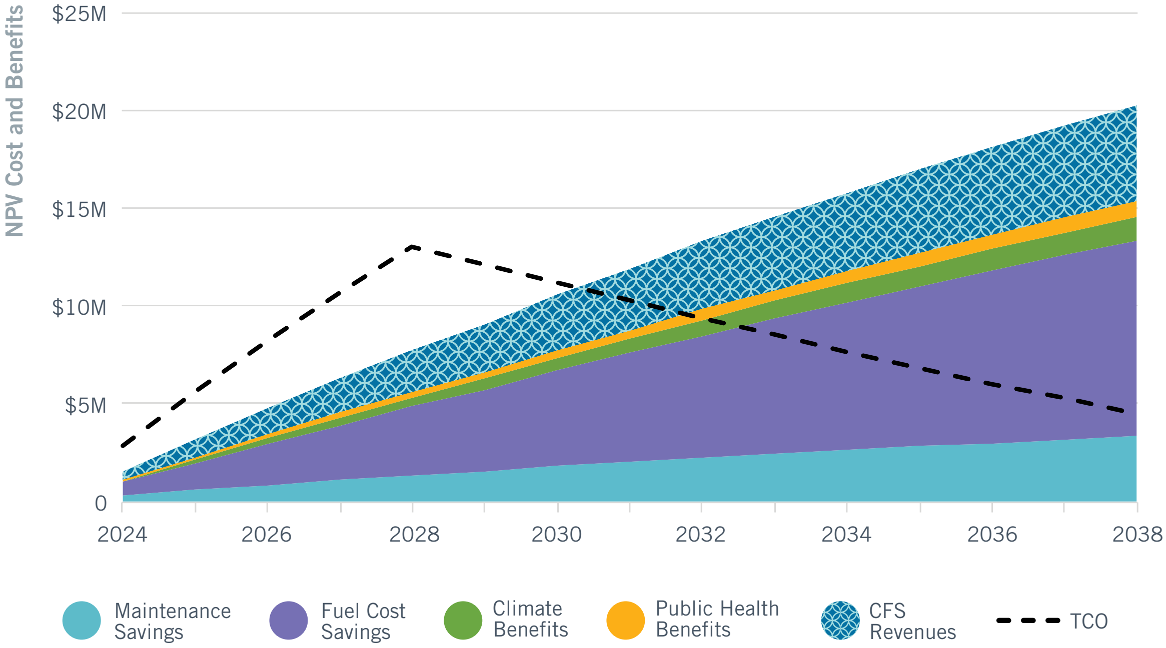
SUMMARY OF RESULTS

Table 8: Summary of 60-vehicle motor coach fleet results

Time Frame considered	15-year vehicle lifetime (2024-2038)
Average Public Health Benefits Multiplier ($/tCO$_2$e emitted)	$32
Cumulative Avoided Emissions (million metric tons CO$_2$e)	0.032
NPV Public Health and Climate Benefits ($, M)	$2.0
NPV costs ($, M)	**-$3.0** (low) / **$4.5** (mid) / **$10.8** (high)
NPV Abatement Cost ($/tCO$_2$e)	**-$130** (low) / **$190** (mid) / **$460** (high)
NPV CFS Credit potential ($, M)	$4.8

The projected lifetime emissions savings per motor coach is 530 tCO_2e, leading to net climate benefits of $20,000 and associated public health benefits of over $13,000. Cumulative maintenance savings are estimated at $55,000 and fuel cost savings are nearly $170,000. There is uncertainty about whether the power provider or the charging station owner could claim first rights on CFS credits, as well as the possibility that credits go unclaimed. Potential CFS credits of $80,000 per motor coach are therefore not factored into the NPV abatement costs.

Figure 9: Cumulative net present value of benefits associated with the motor coach project (mid-case) over time compared with TCO



An important perspective for fleet owners and managers is the TCO relative to a diesel motor coach. This consideration is typically weighted towards shorter time frames rather than a full vehicle lifetime. Shorter time frames align to financing periods of new vehicles. The number of years that it takes to reach a breakeven TCO relative to a diesel HDV is the payback period. The payback period is one factor that can be used to help inform incentive structure. In the table below, a range of TCOs of purchasing an electric rather than new diesel motor coach are shown across the three cost-premium scenarios and four time frames ranging from 3 to 15 years. A perspective both without and with assumed revenues from the CFS credit are included.

Table 9: Net, per vehicle, costs of different timeframes under various cost-premium and CFS credit scenarios

Net Cost Timeframe	Low - no credits	Low - w/credits	Mid - no credits	Mid - w/credits	High - no credits	High - w/credits
3-year	$59,000	$36,000	$136,000	$114,000	$202,000	$180,000
5-year[85]	$92,000	$57,000	$217,000	$181,000	$322,000	$287,000
7-year	$62,000	$14,000	$186,000	$139,000	$292,000	$245,000
15-year	-$50,000	-$131,000	$75,000	-$6,000	$180,000	$100,000

Vehicles with stronger use cases (e.g., greater VMTs or a smaller price differential between diesel and electricity) would have a more compelling financial case to switch, while vehicles with weaker use cases (e.g., lower VMTs or a smaller price advantage of electricity relative to diesel) would have a less compelling financial case to switch.

DISCUSSION

An August 2021 report from MJ Bradley & Associates[86] indicates the total current market size in Washington state as Class 7-8 trucks traveling 2.7 billion miles annually and consuming nearly 400 million gallons of fuel. Extending to smaller trucks (Class 3-8) adds another 2.45 billion miles annually and 302 million gallons of fuel. This total market potential represents nearly 80% of Medium and Heavy-Duty on-road fuel consumption in the state. Scaling the findings of this study to the full market size yields a rough market potential of 70 million tCO_2e and nearly $4.4 billion in climate and public health benefits for the current fleet.[87]

We also suggest two perspectives for this case study: a vehicle-owner or fleet-owner/operator or an incentive program designer or administrator perspective. From a vehicle owner or fleet manager perspective, the approach helps to establish the expected net costs or savings over various timeframes, including how the availability of various financial incentives impacts breakeven periods and TCO. Alternatively, from a public policy or budget allocation perspective, the model can provide useful insights into how financial incentives can be aligned to various program outcomes such as total vehicles incentivized, GHG emissions impact, public health and climate benefits impact, or the influence on breakeven costs for new technology.

Consider the perspective of a 5-year timeframe in the previous table, which is aligned with the financing period assumptions for this case study. Under the low cost-premium scenario, the 5-year TCO is $92,000 per vehicle without any CFS credit value realized ($57,000 with CFS credit value factored in). Net incentives would need to be set somewhere within that $57,000 to $92,000 range to help make the electric vehicle achieve payback over that time period for this use case. Tracking to higher cost premiums align 5-year payback to $181,000 to $217,000 in the mid-cost premium scenario and $287,000 to $322,000 in the high-cost premium scenario. By setting incentives to match those values and linked to real-world price premiums, fleets may decide what level of risk and payback is suitable for their situation. Under California's HVIP program, the largest battery-electric incentives are currently $198,000 for certain school bus makes, rising to $240,000 for certain hydrogen fuel-cell vehicles.

In general, longer payback periods require lower incentives. Incentives may be combined or additive such that any combination--including federal, vehicle focused, air quality focused, infrastructure focused, utility-based, or other--that hit the necessary price point could tip the scales to the purchase of the cleaner technology. Climate and public health benefits and net lifetime savings both scale with annual VMT. Targeting the highest possible VMT use cases would result in greater climate and public health benefits as well as greater net savings through avoided fuel and maintenance costs, thereby allowing for lower incentive prices to unlock similar or shorter payback periods.

While the TCO is presented primarily from the vehicle owner's perspective, this logic can be applied from the perspective of meeting specific goals of an incentive program such as: enabling specific GHG reductions to be met, financing a specific number of vehicles, matching the value of net climate and public health benefits, or tracking to specific cost-effectiveness metrics. Cost-effectiveness is a strategic consideration for states promoting technologies that are early in their adoption and uptake curves, such as heavy-duty electric vehicles. Pilot programs or demonstration projects often focus on market transformation, covering high cost-premiums and creating market growth and learning opportunities for new and evolving technologies. Larger and more immediate emissions reduction potential would emphasize stricter cost-effectiveness metrics while accounting for the actual impact of incentives on purchase decisions. California has included both of these types of programs through their Climate Investments and Greenhouse Gas Reduction Fund strategies. The approach Washington takes should be informed by California's approach while also noting key differences such as the emissions intensity of electricity, the relative economic clout and market transformation potential, and more.

The model developed for this case study can be used to query appropriate incentive points based on program priorities and vehicle use cases. Setting incentives based on a specific and realistic use case establishes a threshold above which a policy or program would facilitate faster deployment or market transition. Incentives may be structured on any range of priorities, many of which can be quantified. In our modeling approach, three main factors can be adjusted to identify a target incentive price:

1. The $/tCO$_2$e the program desires to make the particular use case viable. A $10/tCO$_2$e target would be a cost-effective intervention for which an incentive may not have a great influence on purchase decisions, whereas a $1,000/tCO$_2$e target would clearly be more focused on market transformation or ensuring that any incentives offered would create emissions reductions that would not otherwise occur
2. The time period over which the incentive should ensure a net present value breakeven cost (e.g. 3 years for a relatively quick payback, or the full lifetime of the equipment for the longest possible payback, which is less likely to overcome other barriers such as access to capital)
3. Whether or not other incentives or revenue streams, such as CFS credits, should be factored in

To illustrate this, we provide two examples of how this approach might be applied to determining an initial incentive point for an on-road decarbonization opportunity:

EXAMPLE 1: HIGH-USAGE HDV, INTERSTATE TRACTOR TRUCK

Under a use-case of a 75,000 mile per year tractor truck with a 15-year lifetime, a targeted abatement cost of $10/tCO$_2$e is achieved for a price premium of $405,000. Selecting a 5-year payback period to set the incentive translates into a breakeven cost of $244,000 ($185,000 with CFS credits). Given a $244,000 incentive, operators who anticipate utilizing CFS credits, drive greater annual mileage that can be achieved with an electric vehicle, or tolerate longer payback periods, would be financially motivated to utilize the incentive. The net benefits from this tractor truck being an EV instead of a diesel truck are 880 tCO$_2$e avoided and $59,000 in net public health and climate benefits.

EXAMPLE 2: MODERATE MILEAGE, LOCAL USAGE BUS

A relatively high cost-premium vehicle class with relatively low annual usage -- such as an 8,000 mile per year bus, with a targeted abatement cost of $1,000/tCO$_2$e over 15-years translates to a cost-premium of $110,500. In order for this investment to be cost effective on a 5-year payback period, an incentive of $91,000 ($85,000 with CFS credits) would be required, with an expected net benefit of 90 tCO$_2$e and $9,000 in climate and public health benefits.

At 100 times the lifetime cost-premiums of the high-usage tractor truck, the lower mileage bus benefits and avoided emissions are very unlikely to be realized without a strong incentive. This is largely dictated by the low annual fuel use. On both a per vehicle and per dollar deployed basis, the avoided emissions and net benefits are much lower for the hypothetical bus in Example 2 than the hypothetical tractor truck in Example 1. At the same time, the lower overall impacts from the bus are more likely to depend directly on financial assistance than in the truck example. With the potential for CFS credits, more aggressive use cases, or greater tolerance for longer payback periods to be cost-effective, it is difficult to assess whether the truck incentive is ultimately a deciding factor.

However, the 5-year net costs in these two hypothetical situations are substantially greater for the truck than for the bus at the assumed price premiums. This indicates that if the biggest barrier is actually upfront costs and not total lifetime costs, the greater long-term savings of the truck would be more likely to be influenced by upfront financial assistance than the lower long-term savings of the bus.

Any incentives would be most impactful if aligned to technology trends and vehicle costs. To the extent that access for different segments of the population or geographies is essential, impacts of incentives will need to assess whether barriers to access exist and if they are being addressed. In the tractor truck example, a 5-year payback is achieved even without incentives at a cost-premium of $150,000. Key information indicating market maturity, program demand and access, and the relevance of non-cost barriers to deployment can be factored in to adjust incentive amounts and increase access. In the truck example, if program demand at the 5-year breakeven of $244,000 consistently outstrips available funds, the program is very likely too generous and may be resulting in additional profits for recipients rather than additional vehicles on the road and emissions avoided. Who is receiving the incentives is also a critical consideration. Under the opposite scenario (cost premiums are much higher OR incentives are consistently under-utilized), program demand outstripping available funds indicates that a higher incentive is necessary and/or barriers other than total costs need to be addressed.

MOTOR COACHES FOOTNOTES

[77] *Draft On-Road Consumer-Based Incentive Draft Calculator Tool. (n.d.). California Air Resources Board. Retrieved October 28, 2021, from t.ly/CX4x*

[78] *While the CARB calculator suggests a value of 1.09 mi/kWh (based on an Energy Efficiency Ratio, or EER) of 5.0 for an electric bus versus a diesel bus, more recent data collected in California for the Advanced Clean Truck Rule (CARB. Battery-Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles t.ly/KAQm) indicates an EER rating that is dependent on average speed. We assume an average speed of 30 mph for the motor coaches, which results in a lower EER of 3.8 for the electric motor coach relative to a diesel motor coach. An EER of 3.8 relative to an 8.2 mpg fuel economy calculates to 0.84 mi/kWh.*

[79] *Electricity rates are assumed to start at $0.118/kWh and rise over time to $0.156/kWh. Initial power rates are based on the announced schedule rate (WA UTC Puget Sound Energy Electric Customer Rates Increasing Slightly t.ly/qD6t) increase where an average residential customer would pay a monthly rate of $98.30 based on 900 kWh of usage plus anticipated rate increases (used in Electric Ferries study) and price impacts of CETA as emissions reductions become more stringent. Bulk or commercial rates could be substantially lower, as the Electric Ferries analysis indicates a rate of around $0.07/kWh in PSE's service area.*

[80] *Lowell, D., Saha, A., Freeman, M., MacNair, D., Seamonds, D., & Langlois, T. (2021). Clean Trucks Analysis: Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks. MJ Bradley and Associates. t.ly/fGfi*

[81] *California electric vehicle infrastructure project (CALeVIP) cost data. (2021). California Energy Commission. t.ly/uuFj*

[82] *See Charging Infrastructure Case Study for more information.*

[83] *MJ Bradley (t.ly/fGfi) estimate for a 150 kWh battery shuttle bus premium in 2023, multiplied by 2, 3, and 4 respectively to represent a larger vehicle and battery pack.*

[84] *Based generally off of Low: MJ Bradley projected charging needs (t.ly/fGfi) for a transit bus (50 kW home-depot charging, 20% at 500 kW public charging) with $650-$700/kW infrastructure costs; Mid: Advanced Clean Truck Drayage Truck Estimates as in the drayage truck case study (t.ly/oiHR); High: California Energy Commission DC-Fast Charging costs per station (t.ly/zkZY) with an assumed 0.87 chargers required per vehicle (more than one vehicle shares a single charger, on average).*

[85] *The 5-year TCO is greater than the 3-year due to the 5-year financing period, which spreads the upfront capital costs across a 5-year time period in this specific use case.*

[86] *Washington Clean Trucks Program. (2021). Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks. t.ly/93KG*

[87] *The 60-vehicle case study assumes replacing 320,000 gallons of current fuel consumption. Scaling this case studies cumulative findings to 700 million gallons gives the values reported here.*

PASSENGER VEHICLES

PROJECT BACKGROUND

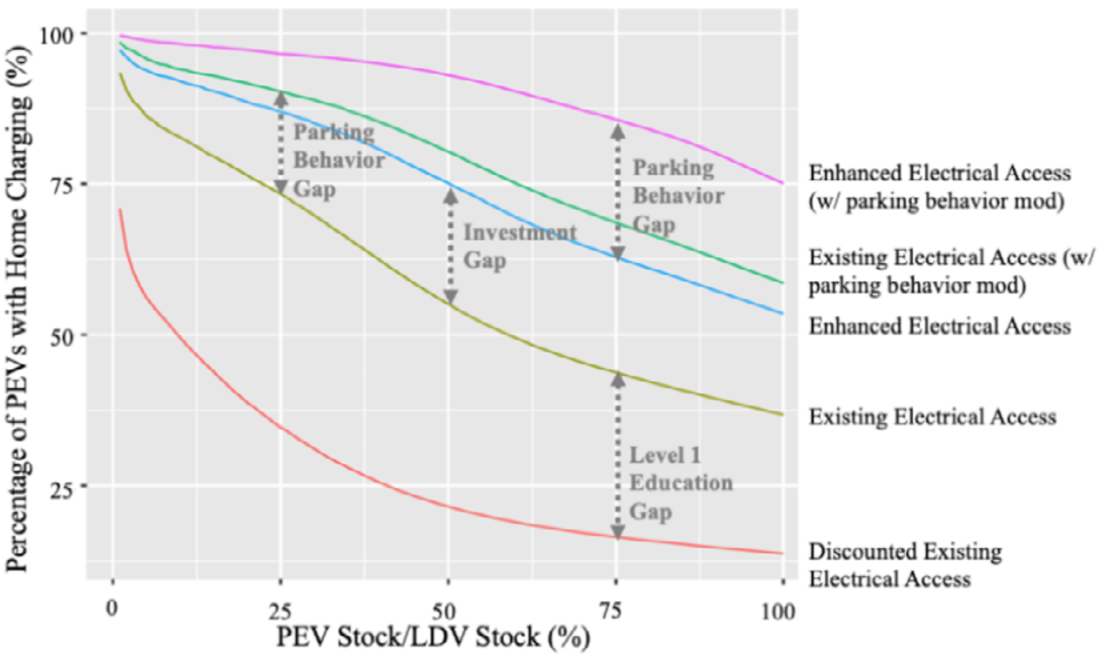
Electrification of passenger or light-duty vehicles (LDVs) is a central plank of meeting statewide GHG emissions limits. Deep decarbonization modeling scenarios suggest at least 22% of new LDV sales need to be electric vehicles (EVs) by 2025, 85% by 2030, and 100% by 2035, reaching a total fleet of 1.0 million electric LDVs by 2030, and 2.3 million by 2035.[88] This market growth for electric LDVs operates within an evolving landscape that includes increased variety and availability of electrified passenger cars, falling battery costs, and shifting incentive programs. At the international COP-26 climate meetings in November, Governor Inslee announced an executive order to transition all state-owned vehicles to zero-emission technology by 2035 for LDVs and 2040 for medium- and heavy-duty vehicles.[89] A December 2021 announcement under the Governor's strategic climate agenda aimed at implementing point-of-sale rebates totalling $100 million per year to bring upfront buying costs of EVs on par with gasoline vehicles.[90] Rebates proposed include additional incentives for low-income customers and rebates for new cars, used cars, and zero-emission motorcycles and e-bikes. The federal government is also considering expanded incentives: up to $12,500 per electric vehicle under the *Build Back Better* bill.

Several light-duty electric pickup trucks are entering the US market, creating a competitive market segment for a high-volume vehicle category that previously had no electric options. Battery prices are rapidly declining from $137/kWh in 2020 down to a projected $80/kWh in 2026 and $60/kWh in 2029. With these battery pack price decline, EVs are projected to track towards manufacturing cost parity with internal combustion engine (ICE) vehicles across most LDV use-cases between 2025 and 2028.[91] This general timeframe for cost-parity in the manufacturing costs of electric LDVs relative to their gasoline competition has been projected by a variety of sources.[92,93]

While EV range increases, model availability expansion, and price declines — bolstered by continued and expanding incentive programs in the near-term — are poised to ramp up EV share of the new car market, issues around charging infrastructure are not as clearly defined.[94] Range anxiety and access to reliable, time-efficient charging options remain commonly cited concerns that pose a barrier to the rate of vehicle electrification. We consider passenger vehicle public charging infrastructure needs in greater detail in the next section. While certain vehicles may rely solely on public-charging infrastructure, and a subset may get by with home charging from a pre-existing connection, the most typical use case is expected to involve Level 2 charging at home or the workplace and complemented by infrequent public charging. For EVs that rely on Level 2 charging capability at home, a typical range for new charging connections is $1,700 to $2,700 and may be shared across multiple cars in a single household.[95] This per-connection cost is much lower than projected cost for public charging stations.

How much of a barrier is presented by access to home charging is an active area of research. An October 2021 report from the National Renewable Energy Laboratory (NREL), projects that the share of EVs with home-charging access will decline as EVs reach greater market share (see Figure 10, taken directly from the NREL study).[96] According to NREL modeling, the biggest barrier to increased home-charging is better utilization of existing electrical access, which requires better consumer

Figure 10: Reproduced from October 2021 NREL Report, *There's No Place Like Home*[99]



information and education. Even at 25% of the vehicle stock, which no region in the US is currently close to attaining,[97] better consumer education increases the share of vehicles with at-home charging from around 35% to around 75% prior to enhancing electrical access.[98] While investing in enhanced electrical access does boost the percentage of EVs with home-charging access, this impact is much smaller. Better access is projected to have a similar influence as parking behavior modifications.

Overcoming the "education gap", "parking behavior gap", and "investment gap" could allow over 95% of LDV EVs home-charging access by the time one in four LDVs are electric. While this decreases to closer to 90% at half of the vehicle stock and 75% at full electrification of the light-duty segment, the NREL report clearly signals that the majority of the barrier to increased home-charging is informational and behavioral rather than more cost-intensive infrastructure. Even without enhanced electrical access, roughly 6 in 10 EVs would have home charging access by the time all LDVs are electric. As Washington considers how to close these charging gaps, it is clear that both greater education about charging options and additional investments to increase charging access are needed.

A TEST CASE

STUDY APPROACH

To estimate lifetime costs and avoided emissions benefits, we developed a companion modeling tool to our HDV calculator developed for the motor coach coach study. Both of these build upon a California Air Resources Board (CARB) calculator tool platform, with broad potential applications to inform vehicle purchase decisions and incentive program design. Through this model, the impact on vehicle TCO and the environmental benefits are calculated based on readily defined and easily adjustable use cases, vehicle characteristics, fuel costs, and emissions intensities. This information can feed into strategy development, programmatic design, and budget allocations that help address the most relevant barriers while limiting wasted resources.

KEY ASSUMPTIONS

For the vehicle examples described below, we assume a representative use case of 12,500 annual miles over the course of a 15-year lifetime (187,500 miles lifetime). We model emissions intensity of electricity for the EV that declines from a moderate start-point to zero by 2030. Fuel costs are influenced both by projected increases in the baseline cost of fuels and by the impact of programs such as the CFS, CCA, and CETA on gasoline and electricity prices.

The vehicles are assumed to satisfy 85% of charging needs with lower-cost home charging and generate maintenance cost savings of 1.3 cents per mile versus an internal combustion powered vehicle. We assume there is no battery replacement over the 15-year lifetime. We also assume that this vehicle requires $2,700 in infrastructure costs to install an at-home Level 2 station.[100] All vehicles evaluated are purchased with a 25% down payment and a 3-year, 2% financing agreement across all costs (vehicle and charging infrastructure).

2022 SUV/LIGHT-DUTY TRUCK

As one example, we consider a new 2022 light-duty truck with 33.2 MPG fuel efficiency based on California's vehicle projections and fuel economy standards.[101] For each metric ton of CO2e released, the model estimates that a 2022 light-duty truck would result in $11 of public health damages based on co-pollutant emissions. We assume an incremental cost of $13,000 based on a 250-mile range SUV cost premium projected by Figure 4 of the International Council on Clean Transportation's (ICCT) update on EV costs through 2030.[102] Vehicle price parity for a 250-mile range electric SUV is projected by the ICCT to occur by 2028. The estimated SUV vehicle price above $50,000 may place it above the threshold for certain incentives. Together with the home charging installation costs, the net incremental costs are $15,700 per vehicle.

2024 PASSENGER VEHICLE

As a second example, we consider an average new 2024 passenger car with 41 MPG fuel efficiency based on California's vehicle projections and fuel economy standards.[103] For each metric ton of CO_2e released, the model estimates that a 2024 model year passenger car would result in $13 of public health damages based on co-pollutant emissions. An incremental cost for a 2024 model of $3,500 for the vehicle purchase is assumed as generally representative of cost-parity being reached between 2025 and 2028. We also assume that this vehicle requires $2,700 in infrastructure costs to install an at-home Level 2 station.[104] Thus, the total net incremental costs are $6,200 versus the baseline, 41-mpg vehicle.

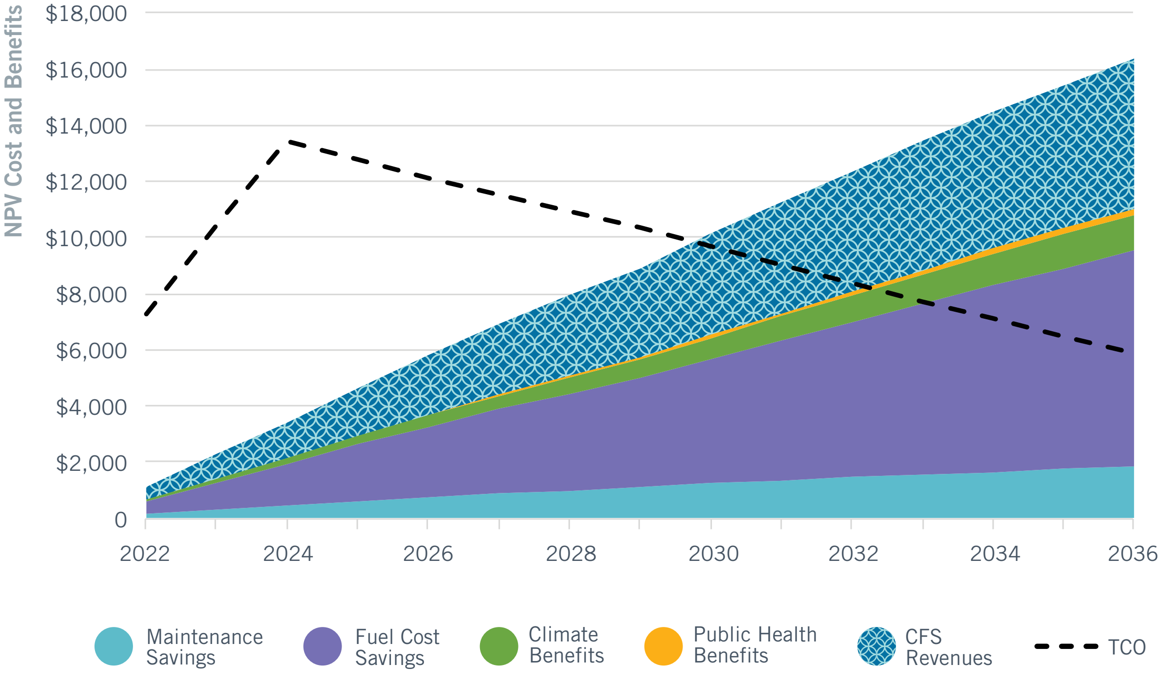
SUMMARY OF RESULTS

In the case of the 2022 SUV/light truck the abatement cost is $235/t$CO_2e$ by the end of 15 years. This abatement cost value indicates that, over the long-haul, reducing pollution incurs additional costs for vehicles purchased in the near-term. The incremental total costs of the EV peak in year 3 at $13,400 (Figure 11). Total benefits reach $1,500 over the vehicle lifetime, and there is also over $5,300 in potential Clean Fuel Standard (CFS) credits. The value of CFS credits, if realized, pushes the net costs to $500 by the end of the vehicle life.

Table 10: Summary of 2022 SUV/light truck and 2024 passenger vehicle test case results

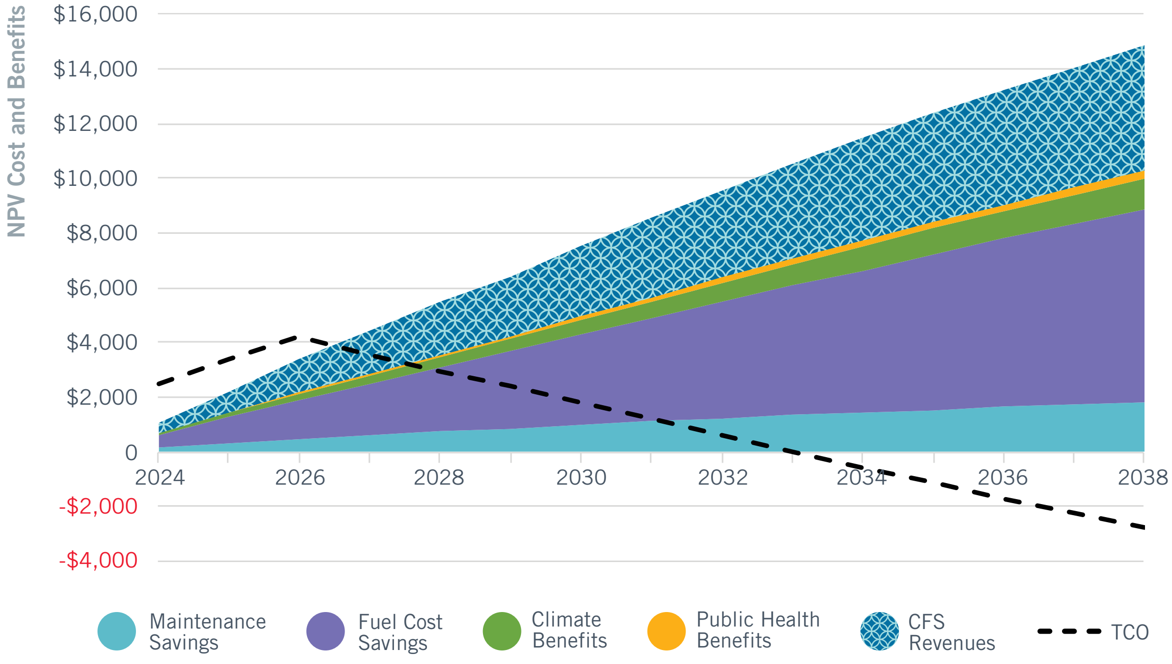
Vehicle / Time Frame considered	2022 SUV/Light Truck (2022-2036)	2024 Passenger Vehicle (2024-2038)
Public Health Benefits Multiplier ($/tCO$_2$e emitted)	$11	$13
Cumulative Avoided Emissions (tCO$_2$e)	35	30
NPV Public Health and Climate Benefits ($)	$1,500	$1,400
NPV costs ($)	$5,900	-$2,800
NPV Abatement Cost ($/tCO$_2$e)	$235	-$130
NPV CFS Credit potential ($)	$5,300	$4,600

Figure 11: Cumulative net present value of benefits associated with a 2022 electric SUV/light truck over time compared with TCO



In the case of the 2024 passenger vehicle, the abatement cost reaches *negative* $130/tCO$_2$e by the end of 15 years, despite replacing a vehicle that is much more fuel efficient (41 mpg) than the current vehicle fleet. The negative value indicates that, over the long-haul, reducing pollution saves money. Total benefits are $1,400 over the vehicle lifetime, and there is a potential of $4,600 in CFS credits. While the EV projects to save money and return net societal benefits over the extended lifetime, the EV TCO is more expensive (>$0 for the dashed black line in Figure 12) until year 11 and peaks at $4,200 in year 3. This initial capital outlay represents a significant barrier to ownership and increased electric LDV uptake. The value of CFS, if realized, pushes the peak TCO premium down to around $3,000 in year 3.

Figure 12: Cumulative net present value of benefits associated with a 2024 electric LDV passenger vehicle over time compared with TCO



DISCUSSION

EV TOTAL COSTS OF OWNERSHIP

Our selected cost premiums are not necessarily reflective of what purchase costs will be for a given customer at a given point in time and do not account for the use of any available incentives at the time of purchase. Many factors – manufacturing costs being a key one – determine the ultimate purchase price. That said, it is very likely that a new EV will reach these assumed price premiums prior to 2030 and price premiums will continue to decline to 2030 and beyond.

Because of barriers and access to capital, even a substantial negative abatement cost can hide the likely impact of incentives for accelerating EV uptake and increasing access to a greater share of the population. In Tables 11 and 12 below, we present the net TCO perspective of switching purchasing an EV rather than new gasoline vehicle over short-, medium-, and full-vehicle lifetime for a scenario with and without CFS credits.

Table 11: TCO premium for 2022 Light Truck/SUV Electric Vehicle

Timeframe	No CFS Credits	With CFS Credits
3-year net TCO	$13,400	$12,200
5-year net TCO	$12,100	$10,000
7-year net TCO	$11,000	$8,100
15-year (full life)	$5,900	$500

Table 12: TCO premium for 2024 Passenger Car Electric Vehicle

Timeframe	No CFS Credits	With CFS Credits
3-year net TCO	$4,200	$3,000
5-year net TCO	$3,000	$1,100
7-year net TCO	$1,800	-$800
15-year (full life)	-$2,800	-$7,400

Approaches to overcome these barriers could include financing arrangements that allow initial costs to be spread out and paid back as long-term fuel and maintenance savings accrue, or by upfront payments for long-term CFS potential and other benefits. Power utilities should also be engaged in the incentive process, as potential revenue over the passenger vehicle lifetime is substantial (around $6,000 in NPV at a 4% discounting rate) and may lead to additional utility revenue through CFS credits. The combined CFS credit and revenue impact for utilities over 15 years is estimated to be over $10,000 per passenger vehicle.

At the same time, the impact of EVs on power systems presents both challenges and opportunities for utilities. Smart charging and peak demand smoothing can help utilities get more efficient use of their resources and potentially lower overall costs. Conversely, uncontrolled charging and spikes in peak power demand can strain the grid and increase electricity costs.

The federal government is considering extending and expanding EV incentive programs significantly, up to $12,500 per vehicle.[105] To the extent that the combination of vehicle premium costs and existing incentives drives EVs towards or beyond cost-parity with conventional LDVs, the primary function of states should evolve. The federal EV tax credit incentive has helped motivate early-adoption of EVs, but it has not provided equitable opportunities for low-to-medium income individuals. To improve the equity of incentive programs, the state can consider additional incentives structured as rebates-like the Clean Vehicle Rebate programs in Oregon and California -- or income-linked rebates like the Charge-Ahead rebate in Oregon that specifically address cost-barriers for lower income residents, not just those with large enough tax liabilities like the federal program. Washington appears to be moving in this direction with state rebates proposed for new and used LDVs including an additional incentive for low-income customers.[106] Consumer-education and public outreach around EV options, benefits, and available incentives can be coupled to these programs in order to foster greater and more equitable impact.

Beyond broadening access to EVs, the state could also strengthen public support for charging infrastructure that considers multiple factors. Distributional pollution impacts of EV ownership based on location and access, enhancing charging infrastructure availability, and pushing towards synergies with the power sector and grid could become primary functions of state-led programs.

PASSENGER VEHICLE FOOTNOTES

[88] *State Energy Strategy Appendix B: Data Accompanying Deep Modeling Technical Report t.ly/MAMz*

[89] *Flatt, C. (2021, November 8). In new climate order, Inslee says Washington State vehicles to transition to electric. opb. t.ly/k6Kz*

[90] *Jay Inslee. December 2021. Policy Brief: Responding to the climate crisis and building Washington's clean energy future t.ly/ZvuD*

[91] *Colin McKerracher. June 2021. The EV Price Gap. BloombergNEF. t.ly/m8qx*

[92] *Nic Lutsey and Michael Nicholas, 2019. Update on electric vehicle costs in the United States through 2030. The International Council on Clean Transportation. t.ly/uP2E*
Figure 5 shows initial purchase price of 250-mile range EVs matching conventional car costs in 2026 (cars) or 2028 (crossover and SUVs), with shorter range vehicles crossing this threshold years earlier.

[93] *It has been reported that in 2020 UBS projected manufacturing cost parity of EV cars with conventional cars to be reached as soon as 2024. (Source: t.ly/Qlui)*

[94] *UBS, March 2021. The electric vehicle revolution is shifting into overdrive. t.ly/7I4J*

[95] *Carvana estimates unit and installation cost in the $1,700 to $2,700 range although if more extensive electrical upgrades are needed, these costs could be much higher. t.ly/cw1J*

[96] *Yanbo Ge, Christina Simeone, Andrew Duvall, and Eric Wood. October 2021. There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure. NREL. t.ly/NU0s*

[97] *As of Q2 2021, California paced the nation with 2.4% of vehicles in operation (VIO) being zero-emission vehicles (ZEVs), see page 7 of the October 2021 Get Connected Electric Vehicle Quarterly Report from the Alliance for Automotive Innovation: t.ly/Tq0f*

[98] *For reference, currently California leads the nation with 2.4% of all vehicles-in-operation being zero emission vehicles. The national average is 0.65% and Washington ranks 4th behind CA, HI, and DC with a 1.1% share. Alliance for Automotive Innovation. Get Connected Electric Vehicle Quarterly Report, Second Quarter 2021 t.ly/R4dJ*

[99] *Yanbo Ge, Christina Simeone, Andrew Duvall, and Eric Wood. October 2021. There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure. NREL. t.ly/NU0s*

[100] *Carvana estimates unit and installation cost in the $1,700 to $2,700 range although if electrical upgrades are needed, these costs could be much higher. t.ly/mmpB*

[101] *The vehicle selected in the calculator tool is LDT2: Light-Duty Trucks (GVWR<6000 lbs. and ETW 3751-5750 lbs.). There is no SUV model included in the CARB database for this model.*

[102] *Nic Lutsey and Michael Nicholas, 2019. Update on electric vehicle costs in the United States through 2030. The International Council on Clean Transportation. t.ly/uP2E*

[103] *Washington state follows the fuel economy standards of California: t.ly/B9eR*

[104] *For example, Carvana estimates unit and installation cost in the $1,700 to $2,700 range although if electrical upgrades are needed, these costs could be much higher. t.ly/T6Kd*

[105] *Edelstein, S. (2021, October 29). $12,500 EV tax credit, union-built bonus included in plan Biden claims can pass Congress. Green Car Reports. t.ly/fJJe*

[106] *Jay Inslee. December 2021. Policy Brief: Responding to the climate crisis and building Washington's clean energy future. t.ly/ZvuD*

CHARGING INFRASTRUCTURE

Preliminary Needs Assessment

PROJECT BACKGROUND

Some level of EV uptake will occur without expanded public charging infrastructure, but the overall pace and breadth of EV uptake will be limited without a reliable and distributed public charging network. Both Oregon and California have released EV Charging Infrastructure needs assessments.[107] These assessments, based on 1.1 million EVs for the Oregon assessment and 5 million EVs for the California assessment, anticipate different mixes of needed public charging infrastructure. In California, the projected public charging needs are for one fast-charging connection (50-350 kW) for every 200 vehicles and one Level 2 (around 10 kW) charger for every 7 vehicles. In Oregon, the emphasis on fast-charging is greater, at one projected for every 71 vehicles and one Level 2 charger for every 21 vehicles.[108]

LDV PUBLIC CHARGING INVESTMENT NEEDS BEYOND THOSE CAPTURED IN OUR PASSENGER VEHICLE CASE STUDY ARE ESTIMATED AT $1.1 BILLION TO $4.2 BILLION BY 2035.

The Washington Legislature has recently taken several steps around EV charging: in 2019, strong EV charging requirements for new buildings were established, which require that 10% of new building parking be wired for EV chargers (RCW 19.27.50);[109] in 2021, another requirement was established to model the state's infrastructure needs to facilitate EV uptake (2021 House Bill 1287, Ramel), and; starting in 2023, charging sessions throughout the state must be standardized based only on the electricity used (Senate Bill 5192, Das).[110] A newly released strategic climate agenda from the Governor's office calls for $22.9 million in general EV infrastructure and education funding as well as $4 million for 75 new charging stations on the I-5 corridor in Mount Vernon.[111] Despite recent actions regarding EV charging policies[112] and additional regulatory action following California's lead on Zero-Emissions Vehicle (ZEV) and Advanced Clean Truck regulations, charging infrastructure support and vehicle incentive programs lag behind those offered along the rest of the West Coast.

PROJECT DESCRIPTION

For the purpose of this preliminary needs assessment, we consider EV infrastructure needs centered around statewide growth to 1 million electric LDVs by 2030 and 2.3 million electric LDVs by 2035. We also consider infrastructure needs to cover 50% of current MHDV miles statewide. There is significant uncertainty around charging infrastructure costs. Estimated public charging installation costs range from $650 per kW of capacity (MJ Bradley technical feasibility report[113], for either Level 2 or fast-charging) with limited opportunities to decrease this cost ($533 per kW by 2050), to $2,000/kW total installation cost for fast-charging or $1,332/kW for Level 2 chargers (CEC Infrastructure Needs Report[114]).[115] Costs for charging infrastructure can vary substantially depending on needs for additional capacity delivery or expanded grid-access.

A PRELIMINARY ESTIMATE

LIGHT-DUTY VEHICLES

Washington's 2021 State Energy Strategy modeling for meeting the state's deep decarbonization strategies finds lower total costs to transition under an electrification strategy than through a low carbon fuels strategy.[116] Projections based on Oregon and California infrastructure needs assessments combined with charging infrastructure cost estimates from both the California Energy Commission and MJ Bradley & Associates translate to an estimated $500 to $1,800 in public charging infrastructure costs per passenger vehicle.[117] These upfront costs will be met by a combination of public and private sources.[118]

MEDIUM- AND HEAVY-DUTY VEHICLES

While infrastructure needs and the relative importance of establishing infrastructure to spur additional uptake are uncertain, there are some projections of both needs and costs. Examples of average charging infrastructure costs for MHDV range from around $20,000 to $100,000 per vehicle.[119,120,121] There is wide cost variability depending on the use-case, grid access, grid capacity, and other case-specific considerations.

According to MJ Bradley & Associates research, the current MHDV fleet in Washington includes over 45,000 Class 7-8 trucks, over 210,000 Class 3-8 buses and trucks, and over 280,000 Class 2b heavy-duty pickups and vans that travel over 8.5 billion annual miles and consume nearly 900 million gallons of fuel. Electrifying half of this fleet would total roughly 270,000 vehicles of varying classes with varying infrastructure needs.

RESULTS

For MHDV, the wide range of infrastructure cost estimates leads to a similarly wide range of combined investment needs for facilitating 50% electrification. With costs ranging from as little as $5,000 per vehicle (L2 charging for Class 2b trucks and vans) to $100,000 per vehicle (high-cost DCFC for Class 7-8 trucks), the combined investment needs span a wide-range of $1.8 billion to $9.2 billion.[122] These infrastructure needs, which are ultimately a combination of public and private home-based charging infrastructure, are already integrated into our drayage truck and motor coach case studies. However, they remain highly uncertain and dependent on use-case and existing grid access and capability as well as incentive and funding availability that may need to be pieced together from various sources.

For LDVs, the per vehicle public infrastructure costs are between $500 and $1,800 in public EV charging infrastructure investments per passenger EV. With a market size of 1 million electric LDVs by 2030 and 2.3 million by 2035, cumulative charging infrastructure investment reaches $500 million to $1.8 billion through 2030, and another $600 million to $2.4 billion from 2031 to 2035. Therefore, LDV public charging investment needs beyond those captured in our passenger vehicle case study are estimated at $1.1 billion to $4.2 billion by 2035.

DISCUSSION

Many different actors (electric power utilities, private companies, automakers, property owners, federal, state, and local governments) have roles to play and will benefit from the development of a robust charging infrastructure network. Therefore, what portion of this would be required from state-directed investments remains an active question. Presumably, this question will be informed by required infrastructure needs modeling (2021 House Bill 1287, Ramel).[123] While the relative share of investments between various actors is unclear, it is clear that significant public investment will be necessary, especially in the next 5-10 years. The reward for this investment is fuel cost savings and emissions reductions from the transportation sector. This allocation will be influenced by decisions around Federal infrastructure and reconciliation bills such as the recently approved Bipartisan Infrastructure Framework and the *Build Back Better* Act, which is currently under consideration.

Grants or low/no interest public funding can provide charging infrastructure in communities that may lack EV drivers initially. These lower EV-ownership communities are often located in BIPOC and low-income communities that are already exposed to higher levels of air pollution and spend a high share of income on fuel costs. In the case of electric utilities, incentives such as on-bill financing for EV charging infrastructure and investment for behind-the-meter infrastructure can provide key mechanisms to remove barriers to charging. Regulatory standards, such as building codes for more robust EV-readiness, a streamlined permitting process for charging infrastructure, and user-friendly payment methods will influence charging infrastructure buildout as well. Privately owned-and-operated charging infrastructure is another key component to sufficient and cost-effective infrastructure.

Thoughtfully designed standards can lay the groundwork for successful and smooth deployment of the charging infrastructure in all charging scenarios, from home to workplace to other public settings.[124] Standardizing the charging experience to address interoperability, connection types, payment options, and speed of refueling improves consumer confidence, and can be guided by the SB 5192 process noted above.

In California, the latest $1.4 billion, 3-year implementation plan for infrastructure deployment and in-state manufacturing calls largely upon general funding sources, front-loads spending, and emphasizes EV charging infrastructure with a particular prioritization for MHDV charging infrastructure.[125] The California Energy Commission (CEC), through its California electric vehicle infrastructure project (CALeVIP) has collected installation cost data for both Level 2 and DCFC charging connections.[126] To date, these rebates have covered about 45% of Level 2 installation costs for the projects that have received grants and about 66% of the DCFC installation costs for projects that have received grants. These rebates have covered a small portion of the existing statewide network of Level 2 chargers (681 connectors through CALeVIP versus over 66,000 existing chargers) and DCFCs (161 connectors out of 6,000 existing chargers).[127]

CHARGING INFRASTRUCTURE FOOTNOTES

[107] Oregon's Transportation Electrification Infrastructure Needs Assessment (t.ly/pizM) and California's Electric Vehicle Charging Infrastructure Assessment - AB 2127 (t.ly/OMOf)

[108] Bauer, G., Hsu, C., Nicholas, M., & Lutsey, N. (2021). Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure through 2030. The International Council on Clean Transportation. t.ly/xWP3

[109] Electric vehicle infrastructure requirements—Rules (RCW 19.27.540). (2021). Washington State Legislature. t.ly/Sako

[110] Mui, S., & Long, N. (2021, May 3). Setting the stage for an EV future in Washington State. NRDC. t.ly/hqCw

[111] Inslee, J. (2021). Policy Brief: Responding to the climate crisis and building Washington's clean energy future. Washington Office of the Governor. t.ly/ZvuD

[112] Mui, S., & Long, N. (2021, May 3). Setting the stage for an EV future in Washington State. NRDC. t.ly/hqCw

[113] Lowell, D., Saha, A., Freeman, M., MacNair, D., Seamonds, D., & Langlois, T. (2021). Clean Trucks Analysis: Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks. MJ Bradley and Associates. t.ly/fGfi

[114] Alexander, M., Crisostomo, N., Krell, W., Lu, J., & Ramesh, R. (2021). Electric vehicle charging infrastructure assessment - AB 2127. California Energy Commission. t.ly/MbOq

[115] Around $^{3}/_{4}$ of the cost is "additional cost" and $^{1}/_{4}$ of the cost are unit costs for DC stations (CALeVIP DC Fast Chargers Data: t.ly/zkZY). For Level 2 chargers, the additional costs are nearly $^{2}/_{3}$ of the total costs (CALeVIP Level 2 Chargers Data: t.ly/iFhJ). Cost projections from The ICCT appear to align more closely with the CEC estimates for DC Fast Charging ($18.5 billion for 180,000 chargers) and more closely to MJ Bradley estimate for Level 2 ($9.5 billion for roughly 2 million L2 public or workplace chargers): t.ly/LMz9

[116] 2021 State Energy Strategy. (2021, October 22). Washington State Department of Commerce. t.ly/1qaFL

[117] See Appendix for more detail.

[118] Bauer, G., Hsu, C., Nicholas, M., & Lutsey, N. (2021). Charging Up America: Assessing the Growing Need for U.S. Charging Infrastructure through 2030. The International Council on Clean Transportation. (t.ly/xWP3). These authors note that many different actors (electric power utilities, private companies, automakers, property owners, federal, state, and local governments) all have roles to play and benefits resulting from the development of a robust charging infrastructure network.

[119] Lowell, D., Saha, A., Freeman, M., MacNair, D., Seamonds, D., & Langlois, T. (2021). Clean Trucks Analysis: Costs & Benefits of State-Level Policies to Require No- and Low-Emission Trucks. MJ Bradley and Associates. t.ly/fGfi

[120] California electric vehicle infrastructure project (CALeVIP) cost data. (2021). California Energy Commission. t.ly/uuFj

[121] Table 18. Appendix H Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document. (2019). California Air Resources Board. t.ly/JDQW

[122] As described for the Motor Coach case study, this range is based generally off of Low: MJ Bradley projected charging needs (t.ly/fGfi) for a transit bus (50 kW home-depot charging, 20% at 500 kW public charging) with $650-$700/kW infrastructure costs; Mid: Advanced Clean Truck Drayage Truck Estimates as in the drayage truck case study (t.ly/oiHR); High: California Energy Commission DC-Fast Charging costs per station (t.ly/zkZY) with an assumed 0.87 chargers required per vehicle (more than one vehicle shares a single charger, on average).

[123] California's eVIP program, administered through the California Energy Commission (CEC) allocates an average of a $70,000 rebate per DCFC connector. For 1 million vehicles by 2030 in Washington, the California needs assessment is for 4,800 DCFC (the Oregon needs assessment is more heavily reliant on DCFC). At California rebate amounts, this works out to $330 million.

[124] Some additional policy recommendations can be found in the AchiEVe:Model Policies to Accelerate Electric Vehicle Adoption report (August 2020). t.ly/LSL8

[125] CEC approves $1.4 billion plan for zero-emission transportation infrastructure and manufacturing. (2021, November 15). California Energy Commission. t.ly/CTE3

[126] CALeVIP DC Fast Chargers Data (t.ly/zkZY) and CaleVIP Level 2 charger data (t.ly/iFhJ).

[127] Existing charger data taken from Table ES-1 of the November 2021 Lead Commissioner Report available as a pdf at t.ly/kKg0

CARGO-HANDLING EQUIPMENT

PROJECT BACKGROUND

The move to zero and near-zero cargo handling equipment (CHE) is a priority for the Northwest Seaport Alliance (NWSA) under the Northwest Ports Clean Air Strategy[128] and a critical step towards decarbonizing the Puget Sound ports. The CHE at the ports are off-road equipment that move cargo around terminals and to and from marine vessels, railcars, and on-road trucks, most of which use diesel fuel. The main CHE at NWSA's facilities include terminal tractors, top handlers, side handlers, reachstackers, rubber-tired gantry cranes (RTGs), straddle carriers, and forklifts. In total, there are over 700 CHE machines across the NWSA's facilities, including 68 pieces owned by the NWSA. Terminal tractors (347 total, 3 that are owned by NWSA and Port of Tacoma), forklifts (136 total, 34 owned by NWSA and Port of Tacoma), and top handlers (103 total, 0 NWSA or port-owned) are the most numerous pieces of CHE. A significant number of straddle carriers (29 out of 79) are owned by NWSA and/or Port of Tacoma. RTGs are the largest pieces of CHE, rated at up to 972 horsepower. As of 2019, 50% of the CHE within the NWSA's scope of operations met Tier 4 diesel emission standards or equivalent.

The ports and many bordering neighborhoods are identified as having the highest risk of environmental health disparities. Downtown, East Side, Hilltop, and Northeast Tacoma, as well as the City of Fife are all disproportionately impacted by air pollution, and all are located in close proximity to the harbors and the I-5 corridor. According to the Washington Department of Health's Health Disparities Map, the census tract that includes the Tacoma project location and surrounding census tracts all score either a 9/10 or 10/10 on the Washington Tracking Network's Diesel and Disproportionately Impacted Communities Index. In these census tracts, the percentage of persons below the poverty line is more than double the rate in Pierce County and the rest of the state, and the life expectancy (75 years) is lower than the state average (80 years). Many NWSA and Port of Tacoma properties lie within the boundaries of the Puyallup Indian Reservation, impacting indigenous communities as well. In Seattle, the project location scores 9/10 on the Washington Tracking Network's Diesel and Disproportionately Impacted Communities Index. Nearby census tracts to the east in Downtown Seattle and Beacon Hill score 10/10. King County is also on the 2018 National Air Toxics Priority List, so reducing pollution from the operations at the ports and harbors constitutes an opportunity to address environmental inequities, especially with regard to transportation pollution exposure. In addition to nearby communities, port workers themselves often bear a disproportionate burden of the health impacts associated with diesel exhaust working in or near diesel equipment.

Clean diesel requirements for new non-road engines implemented by the EPA have progressed from the 1990s to the implementation of stricter Tier 4 requirements in the mid 2010s with phase-in of these standards varying by engine size. These requirements include emission control technology for particulate matter, NO_x, and organic compounds. Tier 4 requirements were broadly applied to all new engines built after 2015. Zero-emissions CHE remains largely in the demonstration stage, particularly for larger and heavier-duty equipment. For example, battery electric terminal tractors, the most robustly demonstrated type of zero-emission CHE at California ports, cost about three times as much as a new diesel truck. As a result, the TCO would be about twice that of a diesel machine without incentives. Incentives of roughly 60% of the cost of the battery electric terminal tractor and charging infrastructure have been required to achieve cost parity with diesel. California has led on implementation of battery electric terminal tractors in recent years, using significant state grant funding, with projections of the technology being fully demonstrated by 2021.[129]

The first real-world demonstration of a battery electric top-handler began in 2019, meaning the technology is not yet broadly available and remains substantially more expensive than diesel equivalents. Similar equipment, such as straddle carriers, are likely to follow a similar timeline as top-handlers for availability and affordability.

Grid electric RTG cranes are fully commercially available and demonstrated—although this includes both grid-connected (via a bus bar system, such as 19 RTGs at Georgia Ports) and cable reel systems that require significant terminal redevelopment and reduce operational flexibility by confining RTG movement. These grid-connected RTGs need to fit terminal layout and operational strategy, while battery electric and fuel cell powered RTGs are still in the development stage. Because of their operational constraints and significant redevelopment requirements, grid connected RTGs are not being considered by the NWSA at this time. The market for hybrid engines has expanded in recent years, notably for RTG diesel-electric systems and retrofits that can reduce GHG emissions by more than 50% and reduce particulate matter by greater than 70% at relatively low cost.[130]

PROJECT DESCRIPTION

Tenants at the NWSA own the majority of the CHE of all equipment types: 654 out of 722 total pieces of equipment. Collaborations with NWSA's tenants are a central strategy to increasing use of zero and near-zero CHE, and will require funding to help offset upfront equipment and charging infrastructure costs, as well as balance the risk of adopting a new technology. The NWSA Demonstration Projects are planned to be split between Seattle and Tacoma. At the Seattle Harbor, the equipment would be owned by a private marine terminal operator and include 10 battery electric terminal tractors and charging infrastructure, 2 RTG retrofits, and 4 new hybrid RTGs. At the Tacoma Harbor, CHE upgrades would be focused on Port of Tacoma and NWSA owned and operated straddle carriers, which have not been broadly demonstrated, but present a unique and impactful opportunity for NWSA. In addition to 2 electric straddle carriers, the Tacoma project seeks to support 2 electric top handlers and 10 electric terminal tractors. The port would help fund and manage the infrastructure installation, and terminal operators would contribute towards the equipment purchases. External funding will be critical to making these demonstrations happen, offsetting incremental cost, and mitigating risk.

To model the emissions impacts, this case study relies in large part on emissions factors developed for California's *Clean Off-Road Equipment Voucher Incentive Project (CORE)* calculator tool.[131] We use the CORE model outputs of annual emissions and extend that into a lifetime model of impacts, with additional assumptions about fuel costs and capital costs.

KEY ASSUMPTIONS

This case study involves a wide range of equipment for which supporting information about costs and fuel consumption is very general. Based on supporting information provided by the NWSA, we assume new capital costs of $14.7 million for the Tacoma projects and $11.1 million for the Seattle projects.[132] These costs do not offset any immediate capital costs, as they replace existing equipment before the end of their useful life. However, these investments are assumed to save on later capital costs by displacing the need for future equipment replacement during the zero or near-zero emissions equipment's useful life. The avoided capital costs are assumed to occur at the mid-way point of the useful life of the new, lower emissions equipment, and are assumed to cost a fraction of the new piece of equipment.[133]

The lifetime of the equipment ranges from 12 years for a terminal tractor to 30 years for a new hybrid RTG. Other equipment is assumed to last for 15-20 years.[134] The CORE calculator tool requires inputs including baseline equipment year being replaced, annual fuel usage, hours of operation, and horsepower. Estimates were shared by the NWSA. For all equipment, 2,000 hours of annual operation was assumed. We used the following assumptions for each equipment type:

- **TERMINAL TRACTORS:** 2009 baseline year vehicles, 190 horsepower, 3,000 gallons diesel per year
- **RTGS:** 2005 baseline year equipment, 900 horsepower, 13,000 gallons diesel per year
- **TOP HANDLERS:** 2005 baseline year equipment, 360 horsepower, 9,000 gallons diesel per year
- **STRADDLE CARRIERS:** 2005 baseline year equipment, 370 horsepower, 9,000 gallons diesel per year

No maintenance savings were assumed for hybrid RTGs, while maintenance savings of $8.70 per hour were assumed for top handlers and straddle carriers, and $7.22 per hour were assumed for terminal tractors. In addition, the hybrid RTGs are assumed to reduce fuel consumption by 58%, while equipment that runs on electricity is assumed to have an emissions factor of near-zero based on the public-utility average fuel mix in Tacoma and Seattle.

With the exception of the terminal tractors, the calculation of public health damages as a function of the GHG emissions released was determined based on CORE model outputs. These public health damages are assumed to decline by 75% upon replacement of diesel equipment with newer diesel equipment, assuming the new diesel equipment tracks to improved engine tiers. For terminal tractors, the CORE model diverges sharply from the NWSA's own Marine Emissions Inventory (MEI). Therefore, we substitute the heavy-duty vehicle average of pollutants from the MEI (from Table 9.27). Starting public health damages are listed in Table 13.

Table 13: Public health damages from different types of equipment cargo-handling equipment

Equipment	Public Health Damages ($/t$CO_2$e emitted)
RTG	$127
Top Handler and Straddle Carriers	$249
Terminal Tractor	$244

SUMMARY OF RESULTS

Table 14: Summary of Tacoma CHE results

Time Frame	25 years
Average Public Health Benefits Multiplier (\$/tCO_2e emitted)	\$180
Cumulative Avoided Emissions (million metric tons CO_2e)	0.010
NPV Public Health and Climate Benefits (\$, M)	\$1.7
NPV costs (\$, M)	\$6.7
NPV Abatement Cost (\$/tCO_2e)	\$920
NPV CFS Credit potential (\$, M)	\$1.4

The Tacoma CHE project focuses on several pieces of demonstration equipment with a very high initial cost. While long-term fuel savings (\$2.8M), maintenance savings (\$2.15M), and future avoided capital cost savings (\$2.7M) are substantial, they are not enough to cancel out the high upfront costs of equipment and infrastructure. Lifetime NPV costs are around 50% of the upfront costs (40% if CFS credits are fully mobilized), and 78% of upfront costs are not recouped through the first 7 years of equipment lifetime (71% if CFS is fully mobilized).

The NPV public health benefits associated with reduced local air pollution are estimated at over \$1.3 million, reaching 80% of that (over \$1.1 million) in the first 10 years. Given the proximity of these pollutants to port workers and highly-impacted communities, the importance of near-term reductions in toxic air pollution should not be overlooked and may be underestimated using the state average figures for estimating damages, as done in this study.

Figure 13: Cumulative net present value of benefits associated with the Tacoma Cargo Handling Equipment project over time compared with TCO of the project

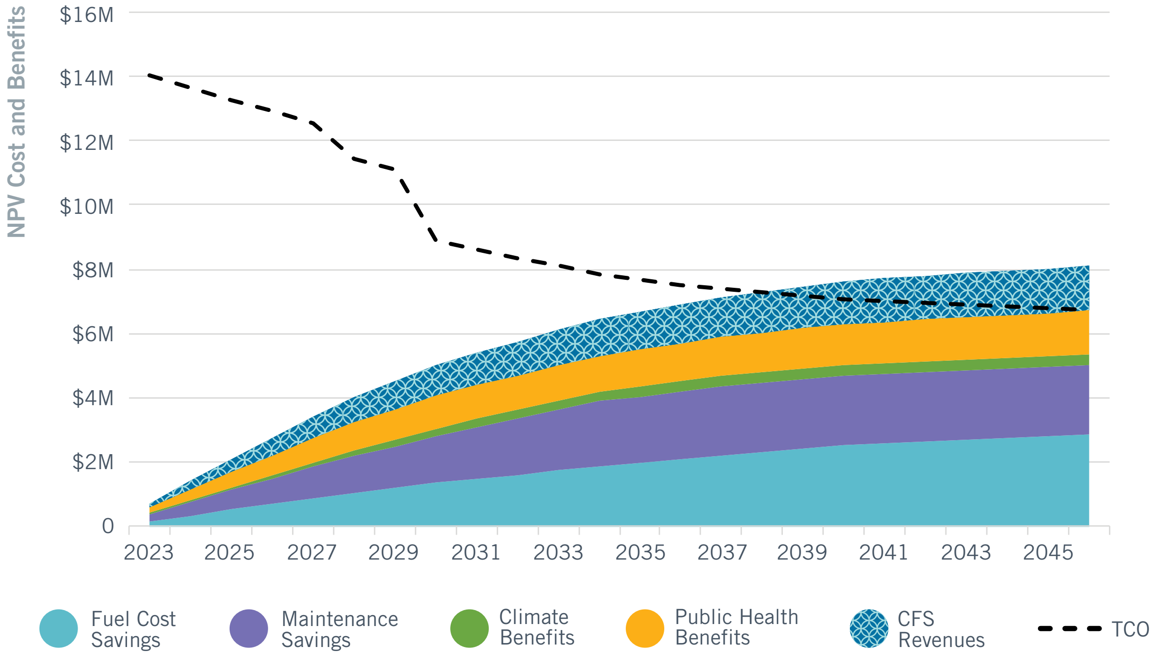


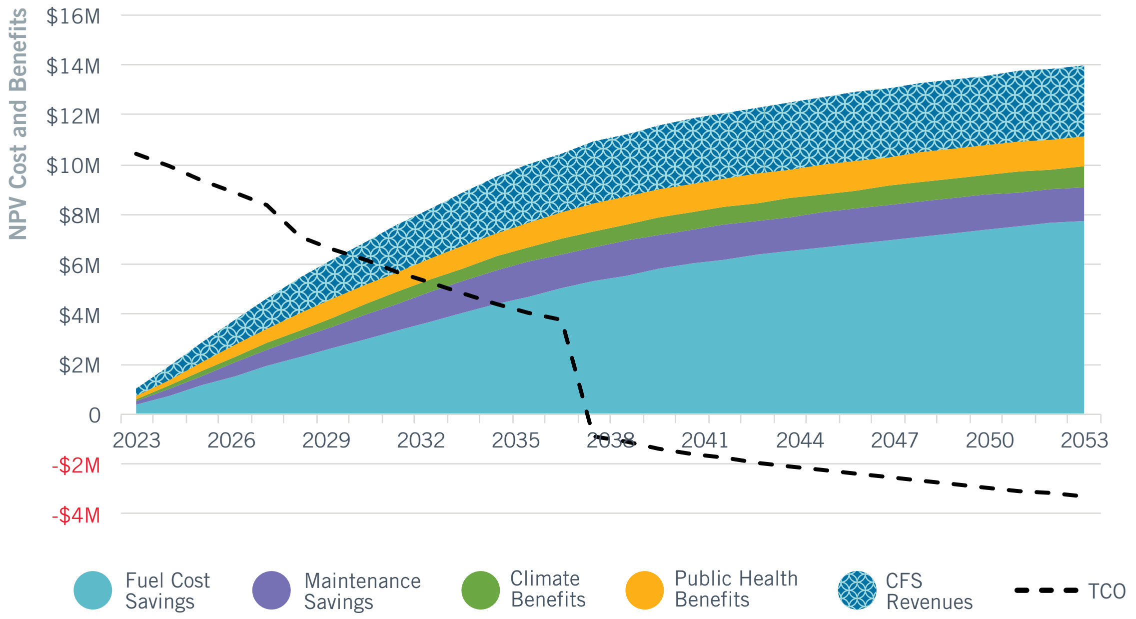
Table 15: Summary of Seattle CHE results

Time Frame	30 years
Average Public Health Benefits Multiplier ($/tCO$_2$e emitted)	$77
Cumulative Avoided Emissions (million metric tons CO$_2$e)	0.025
NPV Public Health and Climate Benefits ($, M)	$2.0
NPV costs ($, M)	-$3.3
NPV Abatement Cost ($/tCO$_2$e)	-$210
NPV CFS Credit potential ($, M)	$2.8

The Seattle CHE project features RTGs: the largest, most fuel-intensive pieces, which are also among the most mature technologies and have the longest useful lives. In this case, the long-term fuel cost ($7.7M) and maintenance cost ($1.4M) savings plus the future avoided capital cost ($5.1M) savings are large enough to more than pay back the upfront costs of equipment and infrastructure. Break-even NPV costs are achieved at the point in time that the original RTG equipment would have reached the end of its useful life (15 years from start-of-program under our modeling assumptions).[135] Despite these long-term savings, the net costs are still significant in the initial years. For example, the TCO after 7 years projects to $6.6M ($5.1M if CFS credits are fully mobilized), indicating a significant price barrier to deploying this technology.

Despite lower average public health benefits ($77 per tCO$_2$e released), the overall cumulative public health and climate benefits project to reach $2.0 million, with $1.4 million front-loaded to the first 10 years. As in the Tacoma program, the proximity of these pollutants to port workers and highly-impacted communities elevates the importance of near-term reductions in toxic air pollution.

Figure 14: Cumulative net present value of benefits associated with the Seattle Cargo Handling Equipment project over time compared with TCO of the project



DISCUSSION

These potential demonstration projects in Tacoma and Seattle are evaluated as two separate projects, each featuring a combination of CHE equipment. **Isolating the equipment by type would show that retrofit RTGs and new hybrid RTGs offer the largest and most cost-effective returns on investment, although they still take a decade or more to net a positive return on investment. RTGs are followed by terminal tractors, then top handlers, and then straddle carriers in terms of cost-effectiveness.** This is not a surprising result, given the annual fuel use and relative maturity of these technologies. However, the more expensive GHG mitigations from the non-RTG pieces of equipment also have some greater upside in terms of public health benefits. The economics of these projects will likely improve over time as the technologies mature and the upfront costs come down. The rate at which this cost reduction occurs is influenced by pilot and demonstration projects that occur, such as the one profiled here.

As equipment is naturally replaced and upgraded to a higher tier, lower emissions technology, the air quality and health benefits of converting to electric or hybrid systems decrease. This indicates that the greatest air quality opportunity is in the short-term, and depending on the relative prioritization of this outcome, a compelling case can be made for why these projects are worth prioritizing despite higher abatement cost for their GHG reduction potential. In addition, early demonstration projects can help drive future costs down by providing a market signal to manufacturers that zero emission technologies are desired, demonstrating the technologies through deployment, and providing critical lessons learned for future deployments. This could have multiplier effects that our model does not capture.

In this study, we have evaluated several categories of CHE: terminal tractors, RTGs, top handlers, and straddle carriers. While these two pilot projects combined are projected to reduce around 35,000 tCO_2e, the 347 terminal tractors, 79 straddle carriers, 103 top handlers, and 22 RTGs collectively have much greater potential, and transitioning them to zero emissions is a critical step towards decarbonizing the Puget Sound ports. Scaling our current model assumptions to that total inventory does not indicate cost-effectiveness at current costs ($800/$tCO_2e$, with capital costs of $641 million), but translates to at least an order of magnitude greater emissions reductions (510,000 tCO_2e) and public health benefits ($56 million), along with $65 million in potential CFS credits. The net capital costs across this theoretical, expanded inventory of CHE are $500 million after 7 years ($460 million with CFS credits) and $310 million after 15 years ($255 million with CFS credits).

CARGO HANDLING EQUIPMENT FOOTNOTES

[128] *Northwest Ports Clean Air Strategy Implementation Plan. (2021, June 30). Northwest Seaport Alliance. t.ly/hOZA*

[129] *Hydrogen fuel cell terminal tractors are being demonstrated but are farther from commercialization (San Pedro Bay Ports Clean Air Action Plan: 2018 Feasibility Assessment for Cargo-Handling Equipment t.ly/7OxZ)*

[130] *MJ EcoPower hybrid systems, Inc.—EcoCrane hybrid system. (2021, October 12). U.S. Environmental Protection Agency. t.ly/56KD (58% reduction in CO2, 84% in NOx, 74% in particulate matter).*

[131] *California quantification methodologies and calculator tools are accessible at: t.ly/sXTj*

[132] *Assumes a $0.45 million premium for vehicle and infrastructure of a new terminal truck, $0.5M to retrofit RTGs, $1.4M for new hybrid RTGs (or $1.3M for non-hybrid RTGs), $2.3M per top handler including infrastructure costs, and $2.8M per straddle carrier including infrastructure costs.*

[133] *The capital costs are around 30%d of an EV terminal truck for new terminal truck as a replacement ($100,000), 92% for a new non-hybrid RTG versus a hybrid, 30% for a new diesel straddle carrier compared to an electric straddle carrier, and 40% for a new diese top handler compared to an electric top handler.*

[134] *Baseline replacement equipment (diesel for diesel) is assumed to operate at 25% better efficiency.*

[135] *Even before those large, avoided capital costs, roughly half of the upfront costs are paid back by year 11 (two-thirds if CFS credits are fully mobilized).*

DISCUSSION AND FUTURE WORK

SUMMARY

With this report, we offer two primary contributions to the critical challenge of reducing carbon and toxic air pollution from the transportation system. First, we establish a methodological approach that provides an initial template for evaluating key metrics that span costs and benefits of potential projects. Second, we apply this template to seven available opportunities that span across multiple transportation sectors with an emphasis on electrification that takes advantage of Washington's steadily improving low-carbon electricity resources. While far from comprehensive in the strategies examined or the metrics evaluated, this report highlights substantial near-term opportunities to accelerate towards a cleaner transportation system and healthier air quality while prioritizing overburdened communities. This effort also offers an evaluation framework that can be applied to other important decarbonization efforts such as reduced vehicle-miles travelled and low-carbon liquid fuels. We stress that much more work is necessary to understand the full range of benefits from transportation decarbonization efforts, and that a greater emphasis on equity is needed. This includes a greater emphasis on equity of both access to improved transportation and distribution of environmental and economic impacts. It is our hope that this work can be a stepping stone to evaluating a wider range of transportation decarbonization opportunities that incorporate both more detailed equity-focused metrics and a more comprehensive set of benefits beyond simplified air quality health impacts.

Greater quantitative detail and context can be found in each case study chapter. It bears reiterating that this report is not designed as an aggregate portfolio or a decarbonization pathway. The primary focus is on the modeling approach and the individual merits described in each case study. However, it is informative to assess the relative scale and projected impact across these case studies with a focus on this *decisive decade* of the 2020s. In that vein, we offer two overarching perspectives: one that extends and aggregates the various technologies examined in the seven case studies (Table 16), and one that highlights the general characteristics of the technologies side-by-side (Table 17).

Table 16: Preliminary impact assessments of scaling case studies towards broader market potential[136]

	All Case Studies, scaled	All Case Studies, scaled minus EV infrastructure
Incremental Capital Costs ($, M)	$5,000	$4,200
NPV Costs ($, M)	$1,300	$510
Avoided emissions ($MtCO_2e$)	16	16
$/t$CO_2$e	$120	$40
Benefits/Cost	0.8	2.2
NPV CFS Credit Potential ($, M)	$1,900	1,900

Any impact assessment that relies on scaling-up these case studies is a very preliminary and general assessment, and should be regarded as useful only for broad discussion. This is the case with the totals presented in Table 16. Importantly, the influence on NPV costs, the benefit-to-cost ratio, and the overall abatement costs of shared EV charging infrastructure is substantial. Because the modeling approach for EV charging infrastructure is not designed to track potential payback or return on investment after installation, we show the scale of costs and other impacts both with and without the EV infrastructure for passenger vehicles included.[137]

With these caveats, the scale of additional capital costs of $4 to $5 billion are close to the total $5.2 billion allocated through 2038 for transportation decarbonization under the CERA investments of the Climate Commitment Act. These additional costs are likely to be shared across various parties including private, corporate, individual, federal, state, and local depending on the strategy in question. Therefore, the much smaller NPV costs may better represent the level of funding that would be mobilized under a single source, such as the CERA. In addition, our estimate of potential CFS credits represents additional savings against the NPV costs and has the potential to stimulate net savings, on average, across this suite of low carbon transportation strategies. Overall, the public health and climate benefits from reduced air pollution are likely to equal or exceed the net costs of the projects that generate them, even at a time of rapid transition towards much lower costs for transportation electrification strategies.

These are encouraging findings emerging from combining separate case studies in a manner that did not seek to optimize costs or benefits. This should highlight that a tremendous opportunity exists to accelerate emissions reductions throughout Washington's largest emissions sector, transportation, in a manner that does optimize various priorities, such as costs, benefits, and the distribution of benefits in an equitable manner. To target the best opportunities, it is important to understand the various characteristics of each investment opportunity. Table 17 offers this approach, summarizing general characteristics for each case study side-by-side.

Table 17: General comparison of case study characteristics

Intervention	Potential Investment Needs	Investment NPV	Benefits ROI	Equity Impact Potential
Ferry System Electrification	$$	Net savings	Substantial	Strong
OGV Shore Power	$	Net costs	Substantial	Strong
Electric Drayage Trucks	$$	Net costs, technology rapidly changing	Moderate, case-dependent	Moderate
Electric Motor Coaches & HDVs	$$$	Net costs, emerging technology	Small	Small to Moderate
Passenger Vehicles	$$$	Net costs, technology rapidly changing	Small	Design dependent
EV Charging Infrastructure	$$$	Not quantified, large upfront costs	Not quantified	Design dependent
Cargo Handling Equipment	$$	Net costs, emerging technologies	Moderate	Strong

DISCUSSION

THE FOCUS OF THIS ACCOUNT SHOULD CENTER ON ACHIEVING EQUITABLE EMISSIONS REDUCTIONS THAT ARE ADDITIONAL TO TYPICAL TRANSPORTATION PROGRAMS AND, THEREFORE, TRANSFORMATIVE IN REACHING STATEWIDE TARGETS IN 2030 AND BEYOND.

Previous reports that incorporated other transportation interventions in Massachusetts[138] and Washington[139] provide perspective on additional interventions, such as expanded public transit opportunities via either rail or buses, transit-oriented development, and active mobility. From an air pollution and cost-effectiveness perspective, low carbon buses have scored particularly well. These and other projects that do not score as well on cost-effectiveness or net benefits may offer a wide variety of additional benefits spanning economic development and job growth; avoided vehicle ownership costs;[140] travel-time savings; healthier outcomes through increased physical activity; and avoided traffic incidents. Many, if not all, of these interventions will be critical to increasing equity, liveability, and prosperity in the state.

However, general conclusions from earlier research combined with these new study findings add perspective on the question of how to invest with a specific focus on GHG emissions, air quality benefits, and equity-driven spending prioritization. In many cases, the emissions benefits are not primary -- or even secondary -- but the projects are still compelling on other grounds and worth pursuing. In those cases, the CERA may not be the best funding mechanism, as any funding decision comes with the opportunity cost of other programs that cannot be funded. Comparing all investment opportunities across a core set of metrics, including those featured throughout this report, is a critical step to matching available funding with priority outcomes.

Washington state has an opportunity to accelerate additional impact beyond the status quo and send clear signals to the broader market. While it may be convenient or expedient to repackage standard transportation budget items within new funding mechanisms such as CERA, doing so would be a missed opportunity. The focus of this account should center on achieving equitable emissions reductions that are additional to typical transportation programs and, therefore, transformative in reaching statewide targets in 2030 and beyond. Two examples from our case studies stand out as representative examples:

- **ELECTRIC FERRY ROUTES** evaluated by this study have marginal costs on the order of $300 million dollars out of a total system-wide investment of roughly $2 billion dollars. Most of this $2 billion dollars will be required whether or not the ferry system is electrified. It is this marginal investment that creates the additional positive impacts. Assigning around $300 million in funding under the CERA account for ferry electrification would be a cost-effective investment in ferry operations, carbon reduction and air quality improvements.

- **SHORE POWER SYSTEMS** at Puget Sound ports have a strong equity component given the pollution impacts and proximity with highly impacted communities identified by Environmental Health Disparities Mapping. Although the costs of the program are unlikely to be paid back directly, the public health benefits project to be substantial enough to balance out the net costs with improved air quality concentrated in highly impacted communities. This relative emphasis on local air pollution (and other equity dimensions) versus strict cost-effectiveness of reducing GHG emissions will be a key consideration for state-directed investments.

FUTURE WORK

ASSESSING AND INTEGRATING EQUITY

The choice and design of carbon emissions reduction programs is influential on the equity of outcomes. To help frame this topic for future work, we draw on Part II of the *Investing in a Better Massachusetts* report, in which the authors focused on conversations with frontline community leaders about what the priorities of climate investment packages should be.[141] Many of the themes from these conversations apply to transportation investments facilitated through Washington's Climate Commitment Act.

To ensure equity, frontline communities must be included in the design and implementation of the investment programs. Clear and actionable information about accessing investment benefits must reach these communities, address language needs, and include community organizations. The methods for distributing funds from these investments must be made as easy as possible and include mechanisms that: designate personnel to assist with applications, leverage community expertise and trust, and build on programs that are already effective in frontline communities.

> IT IS OUR HOPE THAT THIS WORK CAN BE A STEPPING STONE TO EVALUATING A WIDER RANGE OF TRANSPORTATION DECARBONIZATION OPPORTUNITIES THAT INCORPORATE BOTH MORE DETAILED EQUITY-FOCUSED METRICS AND A MORE COMPREHENSIVE SET OF BENEFITS BEYOND SIMPLIFIED AIR QUALITY HEALTH IMPACTS.

Equitable approaches to infrastructure development should incorporate the expansion of affordable public transportation to serve and connect frontline communities with places of work, expansion of EV infrastructure across the state so everyone has access to the technology, and implementation of EV rideshare programs in frontline communities. Additionally, funding sources should be leveraged to accelerate the development of new, deeply affordable housing near transportation access.

While the transition to deep decarbonization can promote strong job growth, in order to align with the priorities of frontline organizations:

- Job creation must prioritize hiring local and minority employees
- It must be easy for small businesses and contracting firms to bid on government contracts for these projects, which may be supported by parsing them into smaller projects that local businesses can fulfill
- Minority contractors must receive an equitable proportion of these contracts

EXAMINING ADDITIONAL DIMENSIONS AND CASE STUDIES

Completing impactful future work in this area will require expanding our group of collaborators, researchers, and reviewers, including from those with lived experiences in the most-impacted communities. This work will involve both building a better quantitative approach to understand project-based distributional outcomes, as well as engagement at the policy level to reinforce design elements that increase access to programs and drive actual, measurable environmental justice. Building out a more targeted and comprehensive set of dimensions and understanding the opportunities offered by each project and the nexus between program-design and equity outcomes is a crucial next step. In doing so, we can gain a better understanding of where future case studies should focus.

COMPARING ALL INVESTMENT OPPORTUNITIES ACROSS A CORE SET OF METRICS, INCLUDING THOSE FEATURED THROUGHOUT THIS REPORT, IS A CRITICAL STEP TO MATCHING AVAILABLE FUNDING WITH PRIORITY OUTCOMES.

There are many more sectors of the economy and potential interventions that are not captured by this sample of case studies. While in certain cases, such as with on-road vehicles and off-road equipment, this report offers a generally applicable framework and methodology, other opportunities are not captured in this specific report. This includes a deeper understanding of projects evaluated in the *Build Back Better* report but not extended to this analysis (low-carbon buses, commuter and high-speed rail, transit-oriented development), as well as market segments that our research has not yet examined (low carbon fuels for heavy-duty transportation needs in aviation, marine, and on-road). We look forward to opportunities to expand our portfolio while also enhancing the insights we can offer into equitable program design, investment priorities, and outcomes.

DISCUSSION AND FUTURE WORK FOOTNOTES

[136] *We make a rough estimate of what scaling these case studies to a broader market would look like through the 2020s. We consider the following scaling from the individual case studies: Drayage Trucks from 10 to 500, Motor Coaches or similar HDV from 60 to 1,000, Light-duty vehicles to 300,000 total, Cargo-Handling Equipment to one-third of the current equipment at the Seattle and Tacoma Ports, and Shore Power to a nearly doubling (90% increase) of impact by extension to three additional terminals (Terminal-30, PCT – Pierce County Terminal, and WCT – Washington United Terminals) based on relative emissions reduction potential reported in the Terminal 18 Shore Power Grant update (item 8D, second table on page 3) from September 2021 NWSA meeting materials. t.ly/YIRi Ferry system electrification has modest scaling potential on the timeframe considered, so only use the totals from the case study. For EV infrastructure, HDV charging infrastructure is considered within the respective case studies but for LDVs additional public charging infrastructure beyond the vehicle-specific case study is needed. Public EV infrastructure for LDVs alone totals over $800 million in NPV by 2030 assuming a growing stock of electric LDVs to reach 1 million electric LDVs.*

[137] *For our Heavy-Duty case studies, the estimated per vehicle infrastructure costs are embedded into the case study.*

[138] *Wincelle, R., Kurman-Faber, J., & Shimberg, N. (2021). Investing in a Better Massachusetts: An Analysis of Job Creation and Community Benefits from Green Investments. Climate XChange. t.ly/3x6H*

[139] *Kurman-Faber, J., Tempest, K., & Wincele, R. (2020). Building Back Better: Investing in a Resilient Recovery for Washington State. Low Carbon Prosperity Institute. t.ly/Wick1*

[140] *To the degree that these investments decrease the need for car ownership, there could be substantial net savings for at least a segment of the population. This impact is described in scenario analysis released by Climate Solutions: The Big Issue: Transforming our Transportation: t.ly/zuNo*

[141] *Gallo, A., Kurman-Faber, J., Ijadi, S., & Xu, S. (2021). Investing in a Better Massachusetts: Conversations with Frontline Organizations on Connecting Climate and Community Priorities. Climate XChange. t.ly/vIPg*