THESIS

AN ANALYSIS OF THE COSTS AND PERFORMANCE OF VEHICLES FUELED BY ALTERNATIVE ENERGY CARRIERS

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In partial fulfillment of the requirements

For the Degree of Master of Science

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Spring 2024

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ABSTRACT

AN ANALYSIS OF THE COSTS AND PERFORMANCE OF VEHICLES FUELED BY ALTERNATIVE ENERGY CARRIERS

The transportation sector stands at the crossroads of new challenges and opportunities, driven by the pressing need to mitigate environmental impacts, enhance energy efficiency, and ensure sustainable mobility solutions. This transition will occur across diverse transportation modes, each with distinct characteristics and challenges. From light duty vehicles embracing electrification to maritime transport adopting alternative fuel engines, the push for low-carbon technology is reshaping the landscape of transportation.

In this context, it is necessary to conduct a review and assessment of technologies, environmental benefits, and costs of alternative fuels and powertrains across a broad set of applications in the transportation sector. This study seeks to perform this assessment by combining bottom-up cost analysis, environmental assessments, and reviews of the literature to examine the techno-economic aspects of various fuel and powertrain options in the transportation sector. This approach involves detailed evaluations of individual components and systems to model the cost structures and efficiency profiles of vehicles. The results illustrated in this thesis will be embedded into adoption models to enable governments, utilities, private fleets, and other shareholders to make informed transportation planning decisions.

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INTRODUCTION

The transportation sector stands at the crossroads of new challenges and opportunities, driven by the pressing need to mitigate environmental impacts, enhance energy efficiency, and ensure sustainable mobility solutions.

Currently, transportation is largely dependent on the burning of fossil fuels. Gasoline and diesel are the main fuel types used by internal combustion engine (ICE) on-road vehicles. Aviation has historically relied upon kerosene in aircraft engines and turbines. International maritime shipping utilizes heavy fuel oil, which contains a much higher sulfur content than most fossil fuels and releases dirty particulate emissions. Freight rail and agriculture utilize diesel fuel in locomotives and tractors.

In 2021, the transportation sector accounted for the largest portion of total U.S. greenhouse gas emissions at 29% [1]. Globally, transport accounts for one-fifth of total CO2 emissions [2]. These emissions can be broken down by category in the figures below.

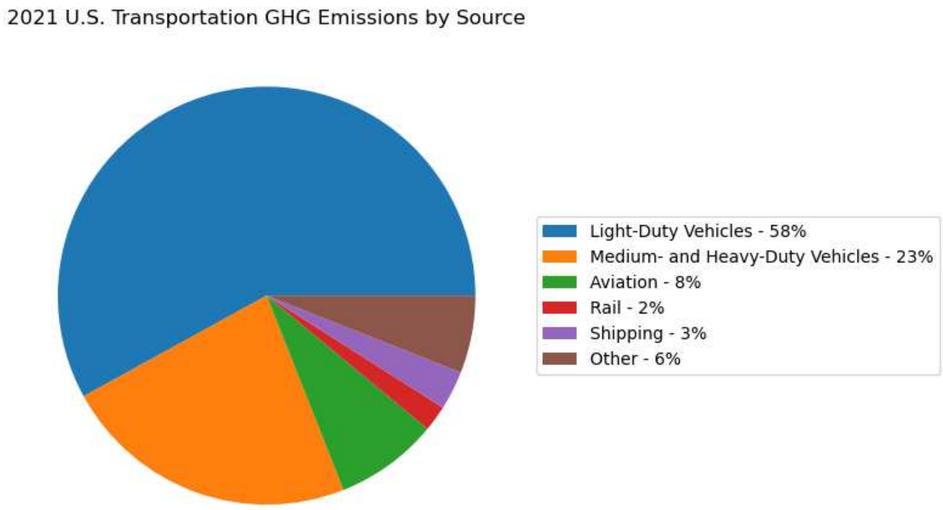

Figure 1: 2021 U.S. Transportation Greenhouse Gas Emissions by Source [1]

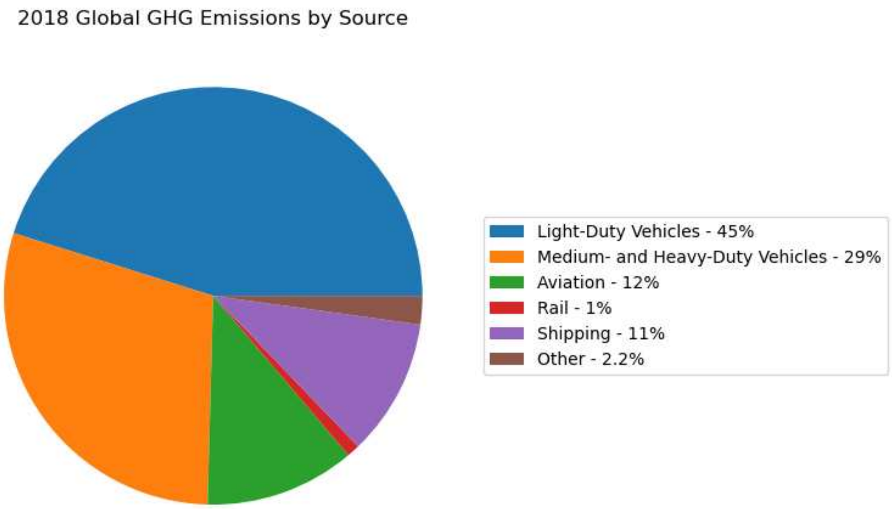

Figure 2: 2018 Global Greenhouse Gas Emissions by Source [2]

In total, the transportation sector contributed 8 Gt of CO2 in 2022, a 3% rise from 2021. To meet the goals of the Net Zero Emissions Scenario detailed by the International Energy Agency, transport emissions must drop by 25% by 2030 [3]. Achieving this decrease will require rapid decarbonization across a diverse range of transportation modes, each with distinct characteristics and challenges that require customized solutions.

In this context, it is necessary to conduct a review and assessment of alternative fuel powertrain technologies and their application in various transportation sectors. While there are many papers that compare the technoeconomic benefits of different energy carriers among a specific vehicle type, there exists a gap in literature in which a paper analyzes all energy carriers across all transportation modes.

This thesis presents novel work, as the performance and cost of alternative fuel powertrains are studied across eight different vehicle groups, outlined in Table 1. Data from many sources including literature, industry representatives, and government research are used in conjunction with consistent assumptions and equations across all vehicle groups. This provides benefit to the academic community as comparisons can be made among multiple fuels across multiple vehicle types across multiple transportation sectors. Data that covers performance and costs of different powertrain vehicles are collected and presented such that these alternative fuels and vehicle types and be compared for their best applications. The output of this assessment will assist government and industry representatives in transportation planning and decision making.

LITERATURE REVIEW

A literature review was performed in preparation for performing this research on costs and environmental performance of alternative fueled vehicles. This section summarizes the findings of this review.

Light and Medium Duty Vehicles

The existing body of literature on alternative fuel powertrains primarily focuses on their use in light and medium duty vehicles. Light and medium duty vehicles account for more than half of the transportation GHG emissions in the U.S. Several studies exist that quantify the manufacturing cost and energy usage of a variety of fuels and vehicle sizes in this class [4], [5], [6], [7], [8], [9], [10], [11]. Early studies of the costs and environmental performance of alternative fueled vehicles focused on hybrid electric and plug-in hybrid electric powertrains as the main alternative to conventional gasoline and diesel powered vehicles [4]. The study of full battery electric and hydrogen fuel cell vehicles is relatively recent in the context of cost and performance analysis, with some studies projecting future scenarios based on optimistic technological advancements [6]. A key reference for this work is a set of studies by The Argonne National Laboratory, which produced a report considering low, medium, and high success cases through 2045 [10]. These studies are all limited to light and medium duty vehicles, with some references to use in heavy duty vehicles.

Class-8 Tractor-trailers

The literature on alternative fuels used in heavy-duty vehicles is more limited than the literature on light duty vehicles, but there is a collection of recent, detailed papers that conduct component-level bottom-up analysis of the costs and performance of class-8 tractor-trailers. These papers reveal a shared emphasis on the importance of powertrain sizing when conducting this analysis. The 2021 study by Argonne National Laboratory (ANL) stands out as the most inclusive, examining LDVs, MDVs, tractor trailers, and buses, while considering internal combustion engine (ICE), hybrid electric (HEV), plug-in hybrid electric (PHEV), fuel cell electric (FCEV), and battery electric (BEV) powertrains [6]. The ANL work does not consider off-road vehicles. Other studies also consider a range of size classes and powertrains for heavy-duty vehicles by employing component-based models to quantify the impacts on vehicle-level fuel consumption and manufacturing costs associated with different technologies [12], [13], [14]. Collectively, these studies contribute to an understanding of the interplay between vehicle size, powertrain technologies, environmental impacts, and overall costs.

Buses

Similar to other on-road vehicles, early research on alternative fuels to be used in buses focused on hybrid electric powertrains, as well as natural gas combustion engines [15]. While these powertrains are still important in buses, recent literature has turned to studying the viability of battery electric (BEB) and fuel cell electric (FCEB) buses [16], [17], [18]. Through direct in-service comparison, researchers have found that BEBs are approximately 3 times as energy efficient as diesel buses, and that cold climates have a significant impact on energy economy [16], [17]. Published data from eight transit agencies showed that for temperature drops from 50-60° to 22-32° Fahrenheit, battery electric buses lost around 32.1% efficiency, while fuel cell electric buses dropped 28.6% [19]. Overall, these studies found that battery electric and fuel cell buses showed performance improvements over their diesel counterparts, yet the capital cost of these buses remains a significant barrier. In general, published studies are limited to city transport buses, and do not include shorter range, lower power school buses, or higher ranger, higher power charter buses.

Regional Aviation

The analysis of costs and performance of alternative fuels in aviation applications is primarily published at the component and simulation level. There are very few public sources of test and evaluation data for alterative fueled aviation applications. The electric and hydrogen aircraft that exist today are either small, like the Pipistrel Velis Electro, or are still in testing and development, such as the Universal Hydrogen Dash-8 [20], [21]. The commercial implementation of aircraft that use battery or hydrogen storage requires continued advancement of energy storage technology [22]. Because of this, much of the published research is centered on the state of technology and improvement forecasts. For battery electric aircraft, focus is placed on the specific power and efficiency of electric machines, power converters, and electrical cables, and the specific energy of battery storage [23], [24], [25], [26]. Hydrogen fuel cell aircraft development is dependent on specific power and efficiency of fuel cells and the volumetric density of hydrogen storage in cryo-compressed or liquid forms [27], [28]. Cost projections for these technologies rarely appear in the literature, as the technology readiness levels are still very low, and manufacturing is performed at small scale. On the other end of the spectrum, sustainable aviation fuels are the subject of considerable literature studies for its use in long-range commercial aviation [29], [30], [31]. While it is currently ready to be used in flights, SAF has much higher costs than conventional kerosene fuels [32].

Maritime Transport

The study of alternative fuels in the maritime transport sector is significantly different than for aviation and on-road applications. Due to the weight and cost of battery energy storage, the shipping industry has looked to study alternative liquid fuels to use in large combustion engines, including fuels such as LNG, methanol, and ammonia [33], [34], [35]. Cost considerations of these fuels and powertrains focus more on fuel infrastructure and fuel prices, as the engines used for these fuels are similar in manufacturing cost to conventionally fueled engines, and the operational costs associated with maritime shipping dominate lifecycle costs [33], [35]. Significant differences in fuel storage and support systems are cited as having an impact on construction cost and cargo volume [33], [36]. In summary, many papers exist that study emerging marine propulsion technologies, but few encompass multiple technologies across a range of ship sizes and applications.

Rail

Freight rail has long relied on diesel-electric locomotives to deliver goods across large distances, but research on alternative fuels and powertrains is somewhat recent. On the other hand, heavy gauge passenger rail has a large fraction of electrified applications in urban and suburban regions of the US. In 2001, the U.S. DOE convened a workshop to set critical research and development (R&D) goals for rail, which included 50% improved fuel efficiency [37]. Work was focused on diesel-electric locomotive advancements, but also included the potential benefits of fuel cells, LNG, and electrification. In a 2019 key reference, ANL analyzed the total cost of ownership of fuel cell and hybrid powertrains versus conventional diesel-electric locomotives [38]. More recent work has been done to access the feasibility of these technologies from a cost and energy storage perspective [39], [40]. Implementation of these technologies in the rail industry will largely depend on fuel prices and development of fueling infrastructure [38].

Agricultural Equipment

Similar to the on-road sector, electrified agricultural equipment such as tractors and skid-steers offer benefits over conventional fuels such as higher efficiency, higher torque, less maintenance, and no tailpipe emissions, yet have drawbacks in the form of high capital cost, increased weight, and limited energy capacity [41], [42]. For applications such as battery electric tractors, the cost and weight of the battery pack is significant, and these increase significantly with the large vehicle power demands of agricultural applications [42]. Determining the required energy needs of farming operations is important for the correct battery sizing for tractors [43], [44], [45]. The literature focusing on ammonia and hydrogen as fuels in tractors is limited, yet work is being done to modify engines to accept these fuels [46], [47], [48], [49]. Fuel cell tractors that utilize the same technology as on-road vehicles are also in development [50]. Many studies agree that the cost of electricity and fuel is a driving factor in the economic viability of these alternative powertrain vehicles [41], [42], [46], [50], [51].

Forklifts

Electric powertrains are commonly used in lift truck (forklift) classes 1 through 3, and technological advancements such as higher voltage and AC-drive systems, and high- frequency charging have increased industry use [52]. Class 4 and 5 forklifts are still dominated by internal combustion fueled by propane or diesel [52]. Hydrogen fuel cell powertrains are being studied and now implemented to replace ICE and electric forklifts as they are clean, efficient, and easily refuellable [53]. When compared to electric forklifts with fast charging capability, fuel cell forklifts are characterized as having a high capital cost and a high price of hydrogen fuel [54], [55], [56]. There are still significant unknowns in the economic models that are associated with alternative fueled forklifts, and the relative cost forecast of batteries, electricity, fuel cells, and hydrogen will play a significant role in the economic viability and adoption of these technologies.

METHODS

This study seeks to perform an assessment of alternatively fueled vehicles by combining bottom-up cost analysis, environmental assessments, and reviews of the literature to examine the technoeconomic aspects of various fuel and powertrain options in the transportation sector. This approach involves detailed evaluations of individual components and systems to model the cost structures and efficiency profiles of vehicles. The transportation applications of interest to this study are categorized into the following groups:

Table 1: Vehicles and Fuels Studied

Vehicle Group	**Vehicles Studied**	**Fuels Studies**
Light & Medium Duty	Crossover, Pickup Truck, Delivery Van, Box Truck	Gasoline, E85 (a mixture of 85% ethanol and 15% gasoline by volume), Diesel, Biodiesel, Battery Electric, Plug-in hybrid, Hybrid, H_2 (hydrogen) Fuel Cell
Class-8 Tractor-trailers	Long-haul Sleeper Tractor Trailers	Diesel, Biodiesel, Renewable Natural Gas (RNG), Battery Electric, Plug-in Hybrid, Hybrid, H_2 Fuel Cell, Hydrogen Internal Combustion Engine (HICE)
Buses	School, Transit, and Intercity Charter	Diesel, Biodiesel, RNG, Battery Electric, Plug-in Hybrid, Hybrid, H_2 Fuel Cell, HICE
Regional Aviation	Medium size turboprop	Kerosene, Sustainable Aviation Fuel (SAF), Battery Electric, H_2 Fuel Cell, H_2 Turboprop
Maritime Vessels	Bulk Carrier, Container Ship, Roll-on/Roll-off (RoRo) Ferry, Passenger Roll-on/Roll-off (RoPax) Ferry, Fishing Vessel, Recreational Vessel*	Heavy Fuel Oil (HFO), Renewable Liquid Natural Gas (RLNG), Ammonia, Methanol, Biofuels, Ammonia/Diesel Blend, Diesel*, Electric*, H_2 Fuel Cell*
Freight Locomotives	Line-haul, Line-switcher	Diesel, Biodiesel, RLNG, Electric Catenary, Battery Electric, H_2 Fuel Cell
Agricultural Machines	Farm tractor, mini excavator, skid-steer	Diesel, Biodiesel, RNG, Ammonia, Battery Electric, H_2 Fuel Cell

Forklifts	Lift capacities of 8000, 20,000, and 40,000 lbs.	Diesel, Propane, Lead-acid battery, Lithium-Ion Battery, H_2 Fuel Cell

To determine costs and performance of alternatively fueled vehicles, bottom-up models were developed by dividing each vehicle into two main systems, then breaking it down into modular components. The first system is the glider, which is the collection of components of the vehicle that are not specific to generating propulsion. This will remain constant for every fuel used for one vehicle type. The other main system is the powertrain, or the system that enables propulsion. This system was changed according to the specific fuel type of interest, and this is where the meat of the design process went. Powertrain components were then spec'd to meet vehicle constraints such as power and energy requirements and mass and volume constraints. Figure 3 shows an example of a block diagram for a battery electric class-8 tractor-trailer, and the design decisions involved in its powertrain components.

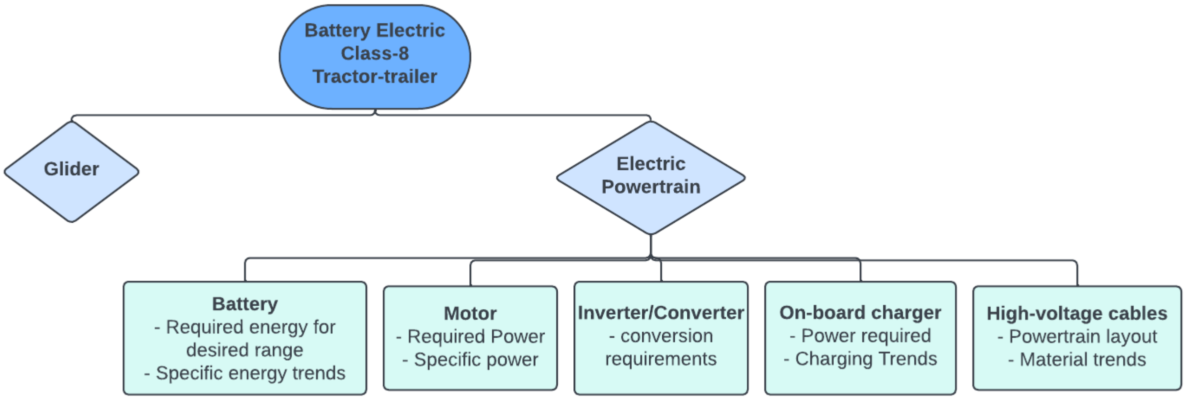

Figure 3: Component block diagram for a battery electric class-8 tractor-trailer

The component model was also used to guide vehicle performance simulation and modeling. Metrics considered were vehicle energy consumption, range, energy storage capability, payload capacity, and refueling rates. In this process, mass and efficiency summations, as well as vehicle simulations were performed. Energy consumption is measured from fuel/battery to output and does not consider the fuel/energy production pathways. Figure 4 shows how the component model was used to calculate performance specifications for a battery electric class-8 tractor-trailer.

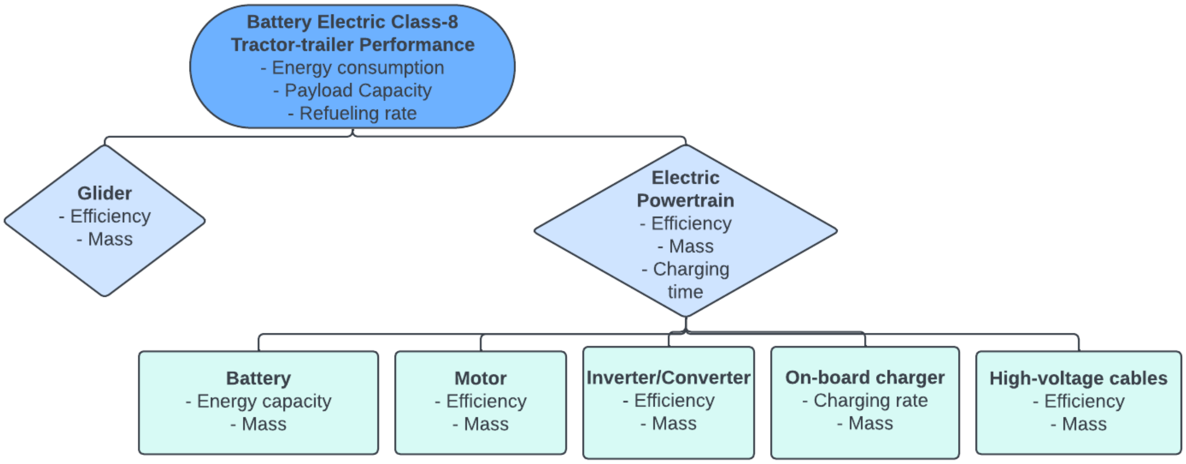

Figure 4: Performance calculation block diagram for a battery electric class-8 tractor-trailer

Each component was then analyzed individually to determine the resources required and the associated costs of manufacturing. These individual cost estimates are then aggregated to calculate the total vehicle cost. Glider costs were sometimes found by deleting costs of conventional components. As seen in Figure 5, component costs were scaled by vehicle requirements to determine the cost of a powertrain. This is shown for a battery electric class-8 tractor-trailer but was repeated for every vehicle combination in Table 1. For this process, the cost forecasts of each component were determined out to 2050.

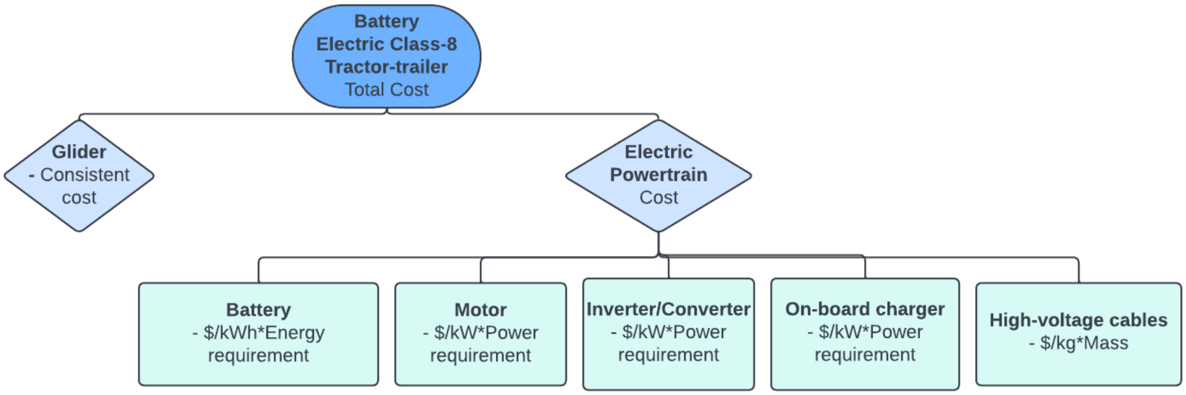

Figure 5: Cost block diagram for a battery electric class-8 tractor-trailer

Data for each vehicle group was compiled in a series of spreadsheets attached as appendices. The relevant information needed to create the cost model was largely gathered through literature review, expert interviews, and modeling of future scenarios. Because the state of costs and technologies is rapidly changing within the alternatively fueled vehicle landscape, this review both synthesizes existing literature and incorporates industry projections. The degree of information present within each of the above applications varies considerably. There is a large pool of literature that assesses the costs and performance of on-road vehicles, while the literature coverage of off-road vehicles is sparser and more dated. In many cases, the data was supplemented by industry consultations and independent calculations to ensure coverage of both economic and technical considerations.

Previous research and publications from EPRI and LCRI served as a foundational element in this study, providing references for on-road vehicles' costs and performance [1]. Additionally, for each vehicle class, there are key papers that guide many of the assumptions and regressions, and these are referenced in the relevant sections. Further resources and references are cited in the individual cost models provided in the appendix.

The methods employed in this study encompass a combination of detailed bottom-up analysis, a comprehensive literature review, energy consumption calculations, and reference to previous EPRI LCRI work. Findings are presented as vehicle manufacturing cost and performance trends out to the year 2050. Manufacturing cost includes the direct costs of material and labor, and indirect overhead costs. Some vehicle groups have costs presented as purchase price. All costs are in 2023 US dollars. These can be seen in the graphs in the results sections and viewed in the model spreadsheets.

Overarching Assumptions

For this study, it is assumed that gasoline/E85, diesel/biodiesel, kerosene/Sustainable Aviation Fuel (SAF), and Heavy Fuel Oil (HFO)/ biofuels utilize the same powertrain and share comparable efficiencies. This assumption presumes biodiesel, SAF, and maritime biofuels can be used as drop in fuels in conventional engines. While biofuels do offer operational differences, this thesis assumes that under conditions where biofuels might be able to be a mass-market fuel, the cost differences and operational differences become negligible.

Battery Trends

The cost of lithium-ion batteries is a main driver of battery electric vehicle (BEV) prices. Battery cost trends will largely influence the price of electric vehicles out to 2050. This study adopts forecasts done by Bradley [11]. High energy batteries are used for all-electric and plug-in hybrid electric vehicles (PHEVs), as they are designed to store and deliver a large amount of energy over a long period of time. High power batteries are used in hybrid electric vehicles (HEVs), as they are designed to deliver large amounts of power quickly. It was assumed high power batteries are 1.3 times more expensive than batteries designed for high energy capacity [57]. Total battery cost for each vehicle is determined by multiplying battery cost per kilowatt hour by total required energy storage.

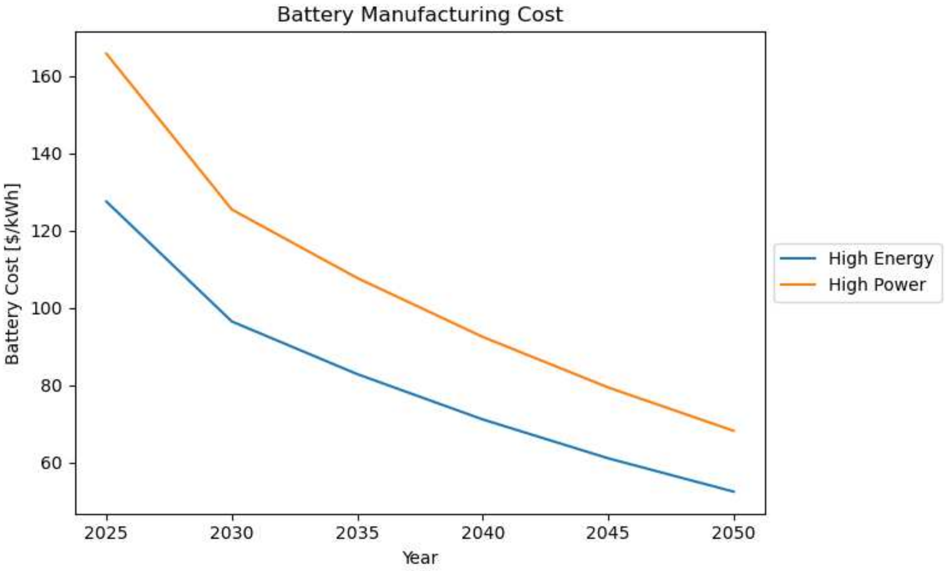

Figure 6: Battery manufacturing cost trends out to 2050

Fuel Cell Trends

Much like batteries in BEVs, fuel cell stack costs are a driving factor in the cost trends of hydrogen fuel cell vehicles (FCEVs). In this study, it was assumed that fuel cell stack costs would align with projections made by a fuel cell manufacturer, Ballard, for the near term [58]. These projections were blended with the Department of Energy (DoE) projections for the longer term [59]. Conversations with industry experts indicated DoE projections are optimistic for near term estimates. Total fuel cell cost for each vehicle is determined by multiplying fuel cell cost per kilowatt power by the required power of the vehicle.

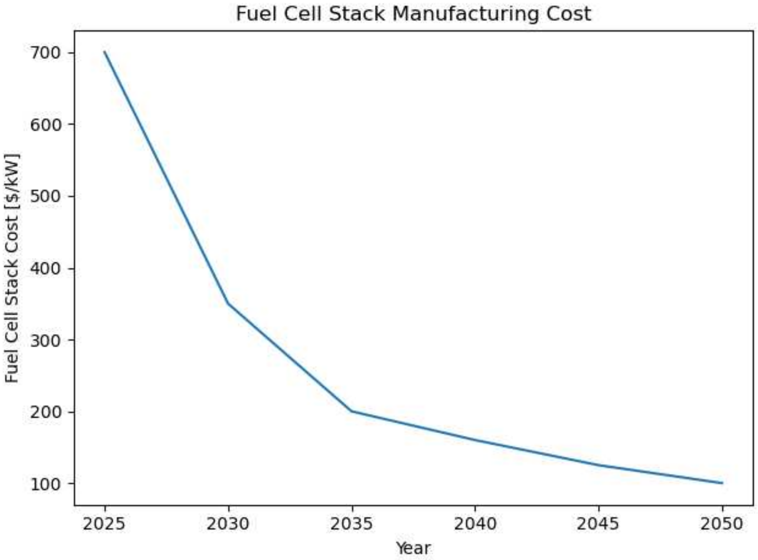

Figure 7: Fuel cell stack manufacturing cost trends out to 2050

LIGHT AND MEDIUM DUTY VEHCILES

Background and State-of-Field

Gasoline and diesel-powered cars and light trucks have enabled efficient transportation for generations of drivers. While the use of conventional vehicles is affordable and convenient, they present significant challenges in their emissions of greenhouse gases. In recent years, policy makers and car manufactures have emphasized the development of low and zero-emission alternatives. These vehicles encompass a wide range of options including Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), as well as Fuel Cell Electric Vehicles (FCEVs). One of the central challenges facing the widespread adoption of BEVs and PHEVs, together referred to as electric vehicles (EVs), has been high initial cost due to the cost of lithium-ion battery energy storage. Recent years have witnessed a reduction in battery costs, driven by advancements in manufacturing, increased economies of scale, and improvements in battery chemistry. As a result, the price parity between EVs and Conventional Vehicles (CVs) has gradually narrowed. EVs are characterized by high performance and high efficiency. Lowered costs and improved packaging means that BEVs can be purchased with driving ranges of over 200 miles on a single charge.

Study Overview

This section aims to analyze alternative fuel powertrains for light and medium duty on-road vehicles. The specific vehicle types analyzed are a crossover, a light pickup truck, a delivery van, and a box truck. The powertrains analyzed are conventional gasoline and diesel, BEVs, PHEVs, HEVs, and FCEVs. For BEVs and FCEVs, both short-range and long-range versions were included in the analysis to investigate their cost competitiveness in different use cases. These vehicles and powertrains are analyzed for their capital cost and fuel consumption trends out to 2050.

Methods and Assumptions

A bottom-up cost model was performed by summing the manufacturing costs of individual powertrain components and the glider. The glider cost and weight remain consistent across various fuel types. The glider includes the vehicle body structure, chassis, drivetrain, thermal management and HVAC, brakes, and steering. Powertrain components for each fuel type are as follows:

- Gasoline/Diesel: Engine, fuel system, transmission, exhaust aftertreatment
- BEV: Battery, motors, inverter, converter, transmission, on-board charger, high voltage (HV) cables
- HEV: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, HV cables
- PHEV: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, on-board charger, HV cables
- FCEV: Fuel cell, hydrogen fuel system, battery, motors, inverter, converter, transmission, on-board charger, HV cables

The main resources used to drive assumptions for this model were [6], [11], [60]. BEV consumption was modeled after the Tesla Model Y Environmental Protection Agency (EPA) performance metrics [61]. This was directly used for crossover performance, and scaled with power for the pickup truck, delivery van, and box truck. For plug-in PHEVs with a 50-mile all-electric range, a utility factor of 0.68 was adopted from the Society of Automotive Engineers information report J2841 [62]. This implies that on average, 68% of the vehicle's energy usage is derived from electricity in typical driving conditions. HEVs are assumed to have an efficiency 1.28 times that of conventional internal combustion engine vehicles [63]. In the case of pickup trucks featuring hybrid technology, a full-sized engine is included due to high power requirements for towing. It was assumed that increased battery weight in higher range vehicles has a negligible effect on vehicle energy consumption. All costs presented are manufacturing costs before dealer/retail markup, which tends to be around 20%.

Results

The following section presents the results of the light and medium duty model in the form of cost and performance trends out to 2050. Results are separated by vehicle type, and the costs and performance of different powertrain types are directly compared. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Light Duty Vehicle (LDV) & Medium Duty Vehicle (MDV) Cost Model in the appendix.

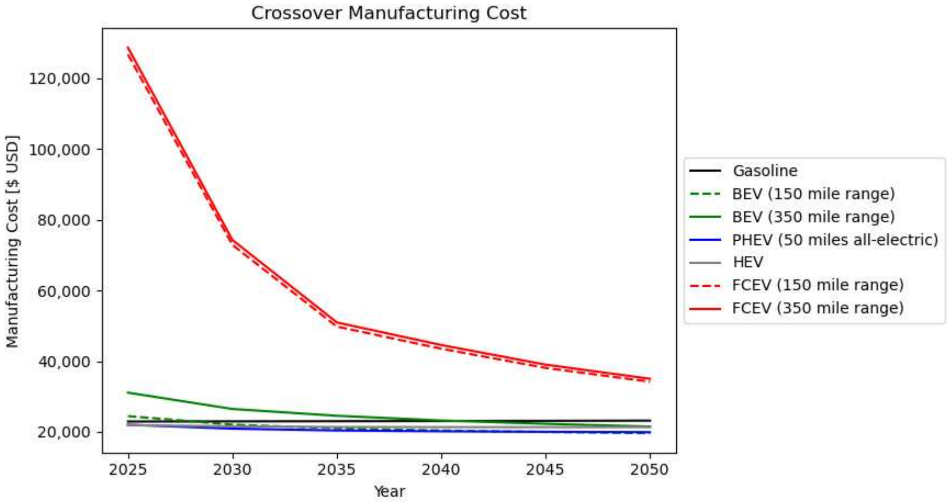

Figure 8: Crossover manufacturing cost trends out to 2050 for various powertrain types

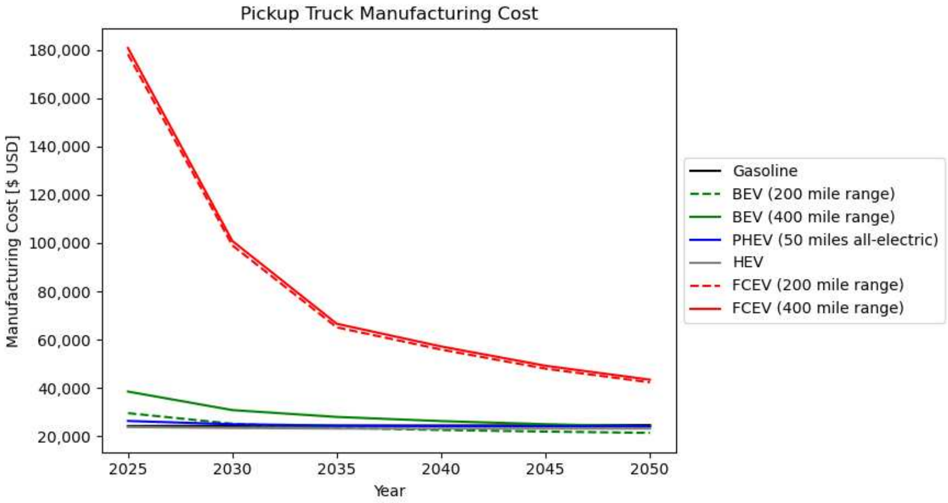

Figure 9: Pickup truck manufacturing cost trends out to 2050 for various powertrain types

Crossovers and light pickup trucks share similar cost trends over the next 25 years. FCEVs have very high costs in the near term due to the high cost of fuel cell stacks. Although this drops significantly, FCEVs will not become competitive by 2050 in these vehicle segments. In the near term, long range BEVs have a manufacturing price that is 1.5 times that of a conventional gasoline vehicle. This price drops as battery costs go down, and crossover BEVs become competitive by 2035, especially for short ranges. The Infrastructure Reduction Act will significantly reduce the purchase costs of BEVs in the near term, and other state regulations will have significant effects on relative BEV and FCEV retail prices [45].

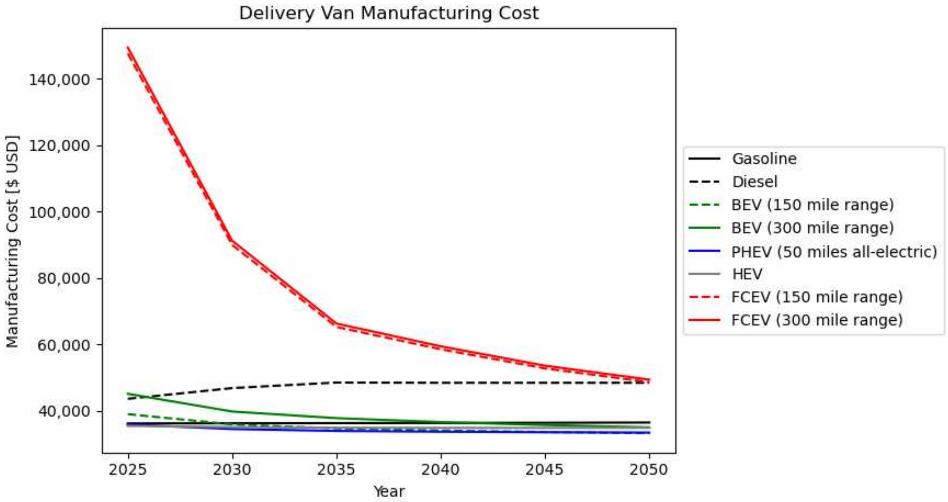

Figure 10: Delivery van manufacturing cost trends out to 2050 for various powertrain types

Delivery vans are unique because current conventional vehicles come in both gasoline and diesel options. While diesel engines have many advantages, they cost much more than a gasoline engine, making the manufacturing cost of diesel vehicles much higher. Additionally, increased emissions regulations over the next 10 years will raise the price of exhaust aftertreatment for diesels. BEVs with a 300-mile range become less expensive than diesel vans by 2030. This price equilibrium does not happen until 2045 for 300-mile BEVs and gasoline delivery vans. FCEVs are very expensive in the near term and only become competitive with diesel vans by 2050.

The cost trends for box trucks show that BEVs become less feasible as vehicle energy requirements increase. Due to high battery costs, 300-mile BEVs will be more expensive and less competitive with conventional diesel box trucks in the near term. BEVs reach price parity with diesel box trucks by 2040. FCEVs only become competitive with diesel box trucks by 2050.

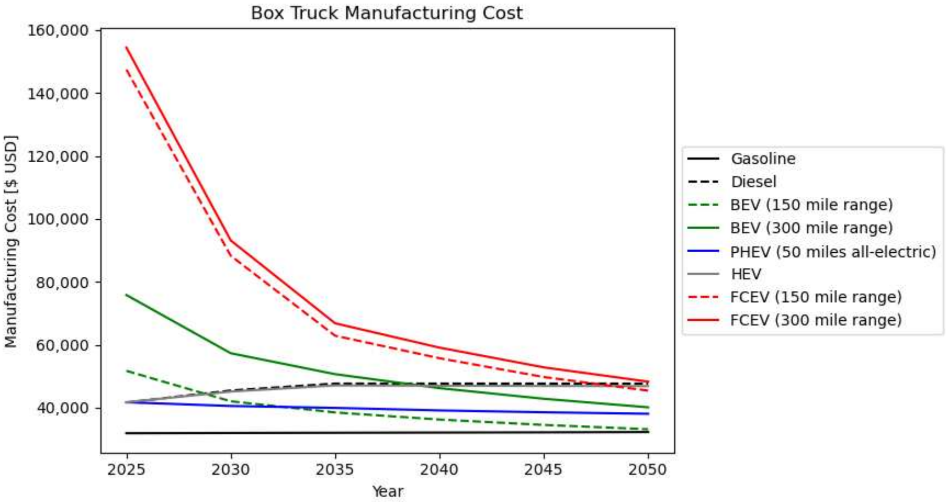

Figure 11: Box truck manufacturing cost trends out to 2050 for various powertrain types

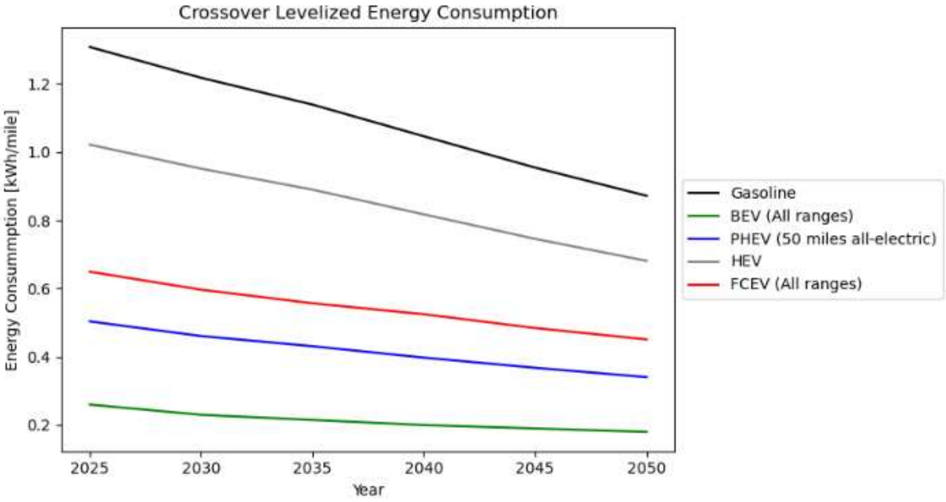

Figure 12: Levelized energy consumption trends for crossovers out to 2050

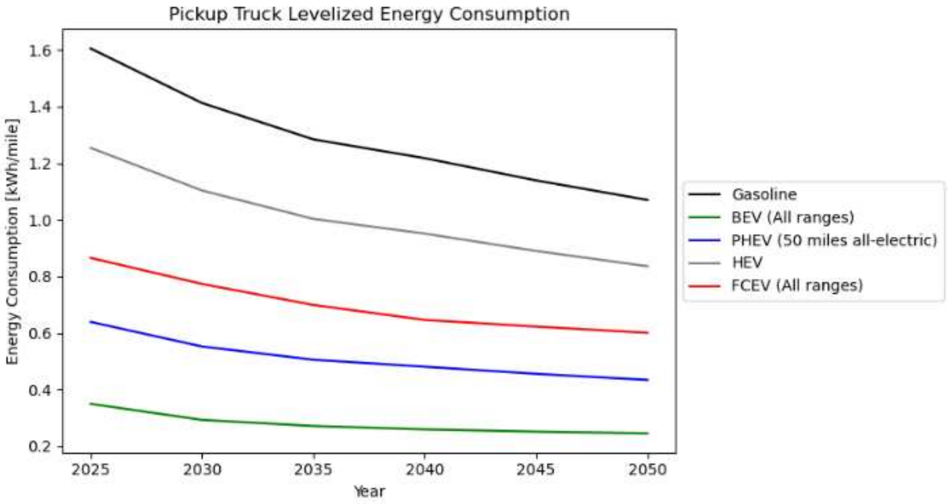

Figure 13: Levelized energy consumption trends for pickup trucks out to 2050

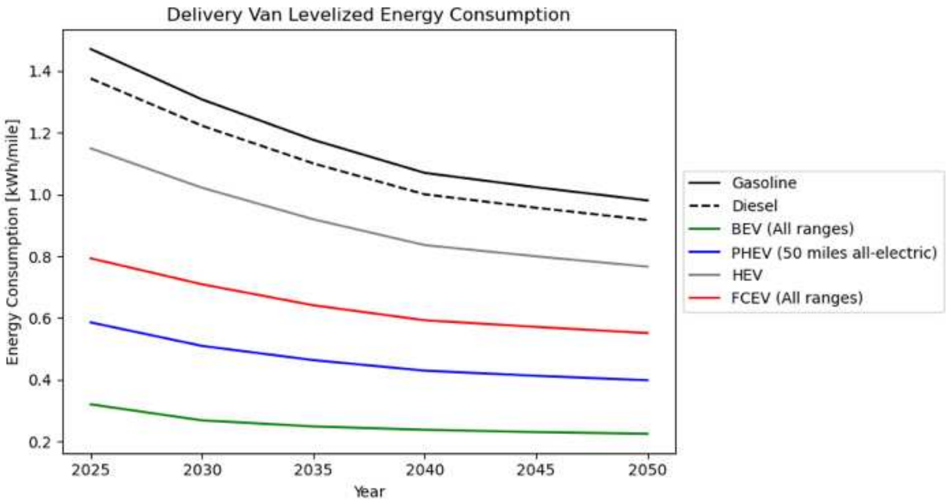

Figure 14: Levelized energy consumption trends for delivery vans out to 2050

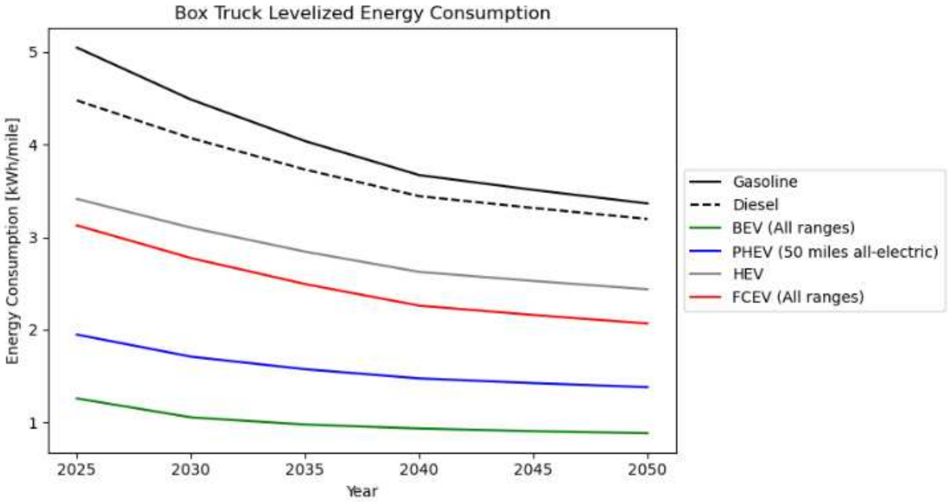

Figure 15: Levelized energy consumption trends for box trucks out to 2050

Summary

The model suggests that the up-front cost of BEVs becomes competitive with CVs by 2035 for nearly all vehicle types. A major trend seen in the data is the overwhelmingly high cost of FCEVs in the near term. This is largely due to the high cost of fuel cells. As fuel cell manufacturing costs decline by 2050, these vehicles become competitive for vehicles with higher energy requirements. The energy consumption trends for each of the four vehicles are relatively straightforward, with BEVs having the lowest energy consumption, followed by PHEVs, yet this may change with varying daily operating distances. FCEVs show improvements over HEVs and CVs. All fuel types will experience efficiency increases as vehicle gliders improve.

CLASS-8 TRACTOR-TRAILERS

Background & State of Field

The conventional diesel powertrain has been the mainstay of class-8 tractor-trailers for many years. Compressed Natural Gas (CNG) has also been used in spark-ignited engines in a small percentage of trucks on the road [64]. These tractor-trailers are responsible for roughly half of fuel consumption and greenhouse gas (GHG) emissions from the heavy-duty vehicle sector in the United States and the European Union [65]. To reduce these emissions, interest in alternative fuels for heavy-duty trucks has accelerated globally. While battery electric options are limited by the high weight and low range of battery energy storage, and fuel-cell powered trucks are held back by hydrogen production and storage costs, they each provide zero-emission alternatives to conventional fossil fuel powered trucks. Yet, capital cost and performance trajectories of these vehicles remain uncertain.

Study Overview

This section aims to analyze alternative fuel powertrains for Class-8 long-haul (700-mile range and 500-mile range) and short-haul (300-mile range) tractor-trailers. Figure 16 shows the daily usage of these vehicles, indicating that about one quarter of vehicles require above 300 miles of daily range while almost half of vehicle miles are due to shorter-distance driving. The powertrains analyzed are conventional diesel, renewable natural gas (RNG), battery electric (BET), plug-in hybrid electric (PHET), hybrid electric (HET), hydrogen fuel cell (FCET), and hydrogen internal combustion engine (HICE). BETs and FCETs are studied at 300, 500 and 700-mile ranges. All powertrains are analyzed for their capital cost, energy consumption, refueling time, and payload capacity out to 2050.

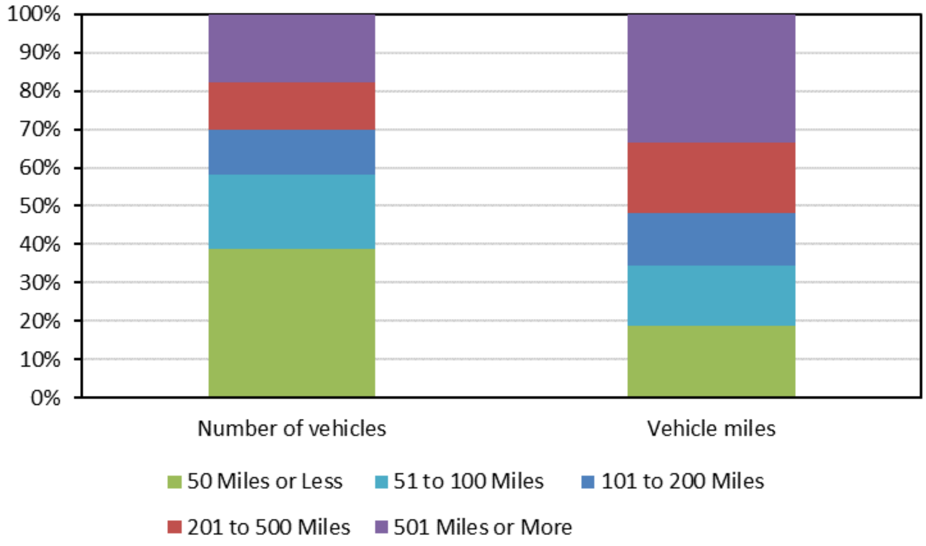

Figure 16: Distribution of daily Class 8 truck use [47]

Methods and Assumptions

A bottom-up cost model was performed by summing the manufacturing costs of individual powertrain components and the glider. The glider cost and weight remain the same for all powertrain types. The glider includes the truck body structure, chassis, drivetrain, thermal management and HVAC, air brakes, and steering pump. Cost-driving powertrain components for each fuel type are as follows:

- Diesel/Biodiesel/RNG: Engine, fuel system, transmission, exhaust aftertreatment
- BET: battery, motors, inverter, converter, transmission, on-board charger, HV cables
- HET: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, HV cables
- PHET: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, on-board charger, HV cables
- FCET: Fuel cell, hydrogen storage, battery, motors, inverter, converter, transmission, on-board charger, HV cables
- HICE: Engine, hydrogen storage, transmission, exhaust aftertreatment

The conventional diesel class-8 trucks in this study are based on the maximum loaded gross vehicle weight rating (GVWR) of 80,000 lbs., which encompasses the truck weight plus its payload. However, the Fixing America's Surface Transportation Act signed in 2015 allows CNG & RNG powertrains to have a GVWR up to 82,000 lbs. [66] and California's Assembly Bill No. 2061 extends that to zero-emissions vehicles [67].

It was assumed that an engine/motor power of 310 kW would fulfill short- and long-haul trucking requirements. The manufacturing costs for the motor, inverter, transmission, converter, and HV cables are assumed to be the same as light duty vehicles on a $/kW basis. The main resources used to drive assumptions for this model were [12], [13], [14], [68].

A highway driving cycle was used to produce fuel consumption data out to 2050. This data is pulled from Argonne National Lab [69]. It was assumed that diesel-powered trucks will see a 50% decrease in fuel consumption by 2050 due to glider improvements. Alternative powertrains will share these improvements, while also boasting an increase in system efficiency.

Results & Discussion

The following section presents the results of the class-8 tractor-trailer model in the form of cost and performance trends out to 2050. The manufacturing costs, energy consumption, payload capacity, and refueling time of different powertrain types are directly compared. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Class-8 Cost Model in the appendix.

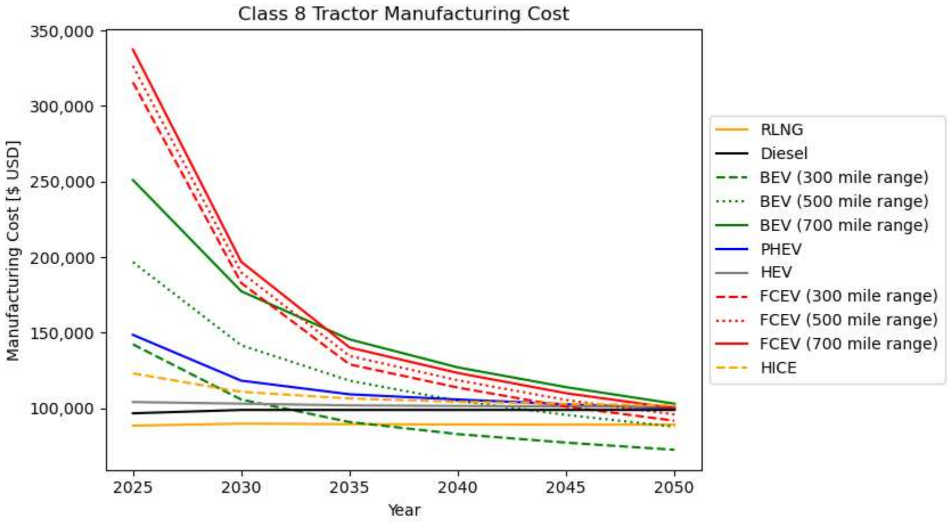

Figure 17: Class-8 tractor-trailer manufacturing cost trends out to 2050 for various powertrain types

Figure 17 displays the manufacturing cost trends for all vehicles in the Class-8 model. The costs vary greatly in 2025 yet converge over time, and zero emission vehicles are significantly more expensive in the near term. The cost of BETs is highly dependent on the capacity of the battery. For every 200-mile increase in range, the cost of BETs increases by $50,000. As fuel cell costs decrease, FCETs reach manufacturing cost parity with BETs at 700 miles of range by 2035, and with diesel trucks by 2050. 300-mile and 500-mile BETs reach manufacturing cost parity with diesel trucks by 2040.

BETs offer the lowest energy consumption out of all powertrain types. FCETs and PHETs offer rates under 4 kWh/mile. Also shown is the energy consumption of the Tesla Semi quoted by the manufacturer.

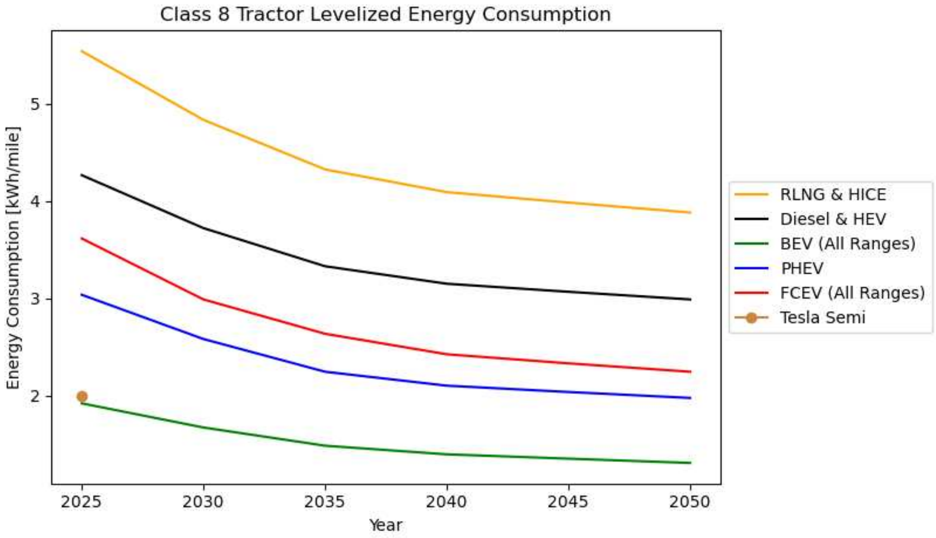

Figure 18: Levelized energy consumption trends of class-8 tractor-trailers out to 2050

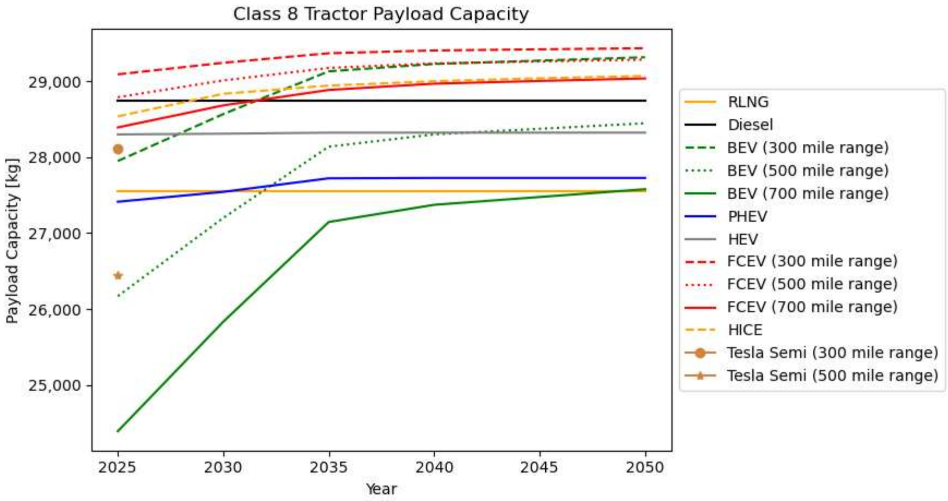

Figure 19: Payload capacity trends of class-8 tractor-trailers out to 2050 (the maximum weight of a Class-8 vehicle is 36,300 kg for conventional tractors and 37,200 kg for zero-emission tractors)

Payload capacity is an important factor in the business model of the trucking industry. The heavier a powertrain is, the less cargo it can haul, representing a potential loss to the owner/operator/carrier. Current diesel trucks have payload capacities of 28,740 kg. BETs suffer from high battery mass, and larger battery capacities equate to heavier powertrains and a lower payload capacity. This is more pronounced for the longer-range BETs, as they require larger battery packs due to higher energy requirements. 300-mile BETs suffer an 800 kg reduction in payload capacity, while 700-mile range BETs suffer a 4400 kg penalty. FCETs offer payload capacities that are comparable to current conventional diesel trucks.

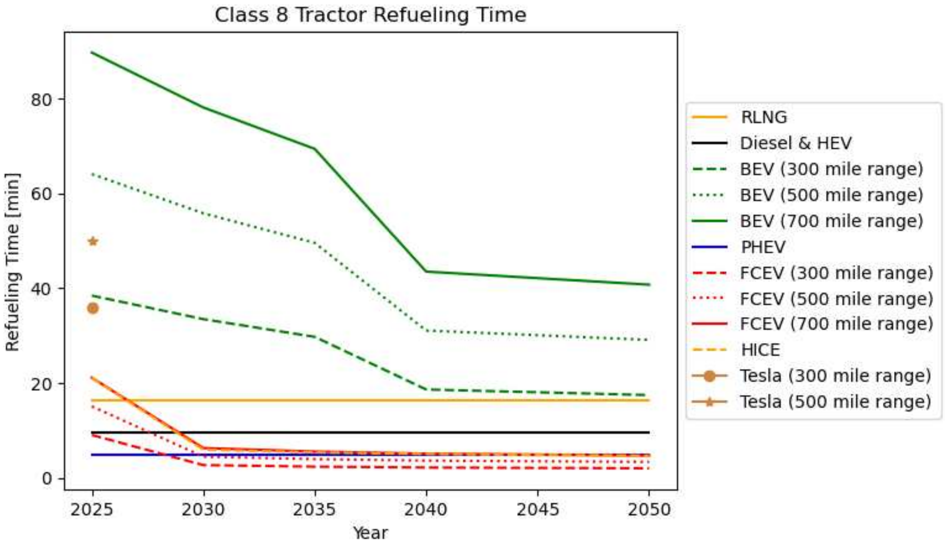

Figure 20: Refueling time trends of class-8 tractor-trailers out to 2050

The refueling time of BETs is largely dependent on the capacity of the battery and the power of the charger. BET charging time decreases over the next 25 years as chargers are introduced with powers of 1 MW and above. At these levels, thirty minutes of charging during driver breaks would provide sufficient range without impairing normal operations, as short-haul and long-haul trucks travel 150 miles and 190 miles between driver breaks, respectively [70]. The refueling time of FCETs will decrease over the next 5 years to become very competitive with conventional diesel tractors.

Summary

Due to the high energy usage and long-range requirements of class 8 tractor-trailers, it is expensive and technically difficult to replace a conventional diesel powertrain with a zero-emission alternative. Most of the cost of battery electric trucks and fuel cell electric trucks comes from the batteries and fuel cells, respectively. Major decreases in vehicle manufacturing costs are seen as the cost of these components drops over time. A major question within the trucking industry is whether fuel cell electric trucks provide a good alternative to heavy and expensive battery electric trucks. In this thesis, it was found that FCETs have lower manufacturing costs than BETs for higher range trucks. BETs have the lowest manufacturing cost among zero emission options for short-haul operations.

BUSES

Background and State of the Field

The landscape of bus transportation is undergoing a transformative shift, marked by a diverse array of propulsion technologies aimed at improving sustainability and efficiency. Conventional buses, powered primarily by diesel and natural gas, have long been the norm, but they come with environmental challenges due to emissions and fossil fuel dependency. The rise of alternative propulsion methods, particularly battery electric buses (BEBs) and hydrogen fuel cell electric buses (FCEBs), is reshaping the industry. BEBs are gaining significant traction, driven by advancements in battery technology that enable longer ranges, improved charging infrastructure, and reduced operating costs. FCEBs offer zero-emission solutions with faster refueling times compared to batteries, although challenges persist in terms of hydrogen infrastructure. The decision-making process for bus operators, encompassing city transit authorities, school districts, and charter services, weighs the capital cost and performance of the vehicles as critical factors.

Study Overview

This section focuses on alternative fuel powertrains for school, city transit, and intercity charter buses. The powertrains analyzed are conventional diesel, RNG, battery electric (BEB), plug-in hybrid electric (PHEB), hybrid electric (HEB), hydrogen fuel cell (FCEB), and hydrogen internal combustion engine (HICE). These powertrains are analyzed for their capital cost, energy consumption, passenger capacity, and required vehicle range out to 2050. The effects of climate on energy consumption were included due to heating and cooling loads for passenger comfort.

Methods and Assumptions

A bottom-up cost model was performed by summing the manufacturing costs of individual powertrain components and the glider. Some of the data for conventional diesel and RNG buses was derived by reverse-engineering from the purchase prices, utilizing a price markup factor of 1.2 for purchase prices over manufacturing prices. The glider cost and weight remain the same for all powertrain types. The glider includes the bus body structure, chassis, drivetrain, thermal management and HVAC, air brakes, and steering pump. Powertrain components for each fuel type are as follows:

- Diesel/Gasoline/RNG: Engine, fuel system, transmission, exhaust aftertreatment
- BEV: Battery, motors, inverter, converter, transmission, on-board charger, HV cables
- HEV: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, HV cables
- PHEV: Engine, fuel system, exhaust aftertreatment, battery, motors, inverter, converter, transmission, on-board charger, HV cables
- FCEV: Fuel cell, hydrogen storage, battery, motors, inverter, converter, transmission, on-board charger, HV cables
- HICE: Engine, hydrogen storage, transmission, exhaust aftertreatment

The latest alternative vehicle offerings from manufacturers like New Flyer boast equivalent seating capacities as conventional buses, contributing to the assumption that passenger capacity will be unchanged across all powertrain types [71]. It's important to note that all the costs mentioned are modeled manufacturing costs.

Bus operating range was determined for each bus type by analyzing daily operating distances and route length statistics from several studies, namely the NREL's Fleet DNA and ANL's AFLEET projects [72], [73]. Figure 21 shows the distribution of daily operating distances for conventional diesel school and city transit buses.

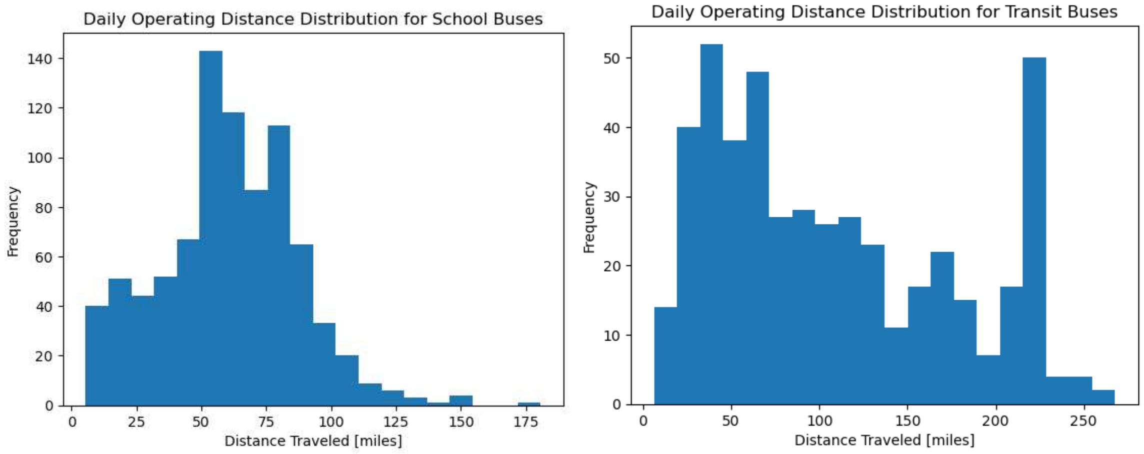

Figure 21: Daily operating distance distribution for school and city transit buses [72]

The required range for transit buses will be largely affected by route planning and charging logistics. Although improbable, a transit bus with a short range is possible when paired with distributed fast charging. A low-end and high-end range was chosen for each bus class: 50 miles and 150 miles for school and transit buses, and 100 miles and 500 miles for intercity charter buses. The utility factors for PHEBs were determined as follows: 0.72 for school buses, 0.42 for city transit buses, and 0.33 for intercity charter buses [62]. For HEBs, regenerative braking provides improvement in fuel economy for school and transit buses due to frequent stops in their driving cycle, while it was assumed that there would be minimal to no improvement for intercity charter buses. The effects of hot and cold weather on BEB and FCEB energy consumption were determined by reviewing studies in the literature [16], [19].

Results

The following section presents the results of the buses model in the form of cost and performance trends out to 2050. The manufacturing costs and energy consumption of different powertrain types are directly compared. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Buses Cost Model in the appendix.

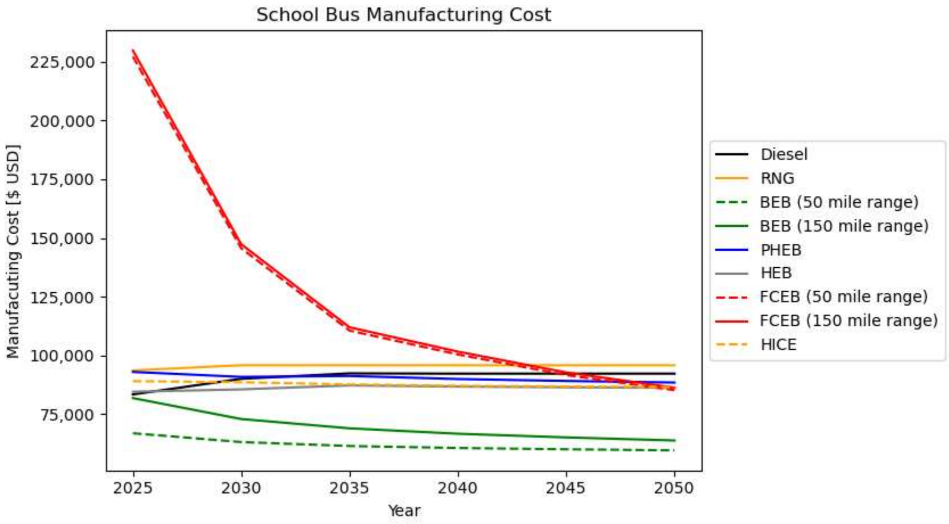

Figure 22: School bus manufacturing cost trends out to 2050

Due to the high degree of variability in daily operating distance data, low and high ranges of 50 miles and 150 miles were used for the school buses. The relatively low range contributes to the low cost of BEBs. As seen in Figure 22, BEBs are the least expensive option at both these ranges. FCEBs become competitive by 2045 at both ranges.

The trends of school buses and transit buses are similar, despite the higher cost of transit buses. A slight difference is the cost of long range BEBs starts higher than diesel buses yet becomes cheaper by 2030.

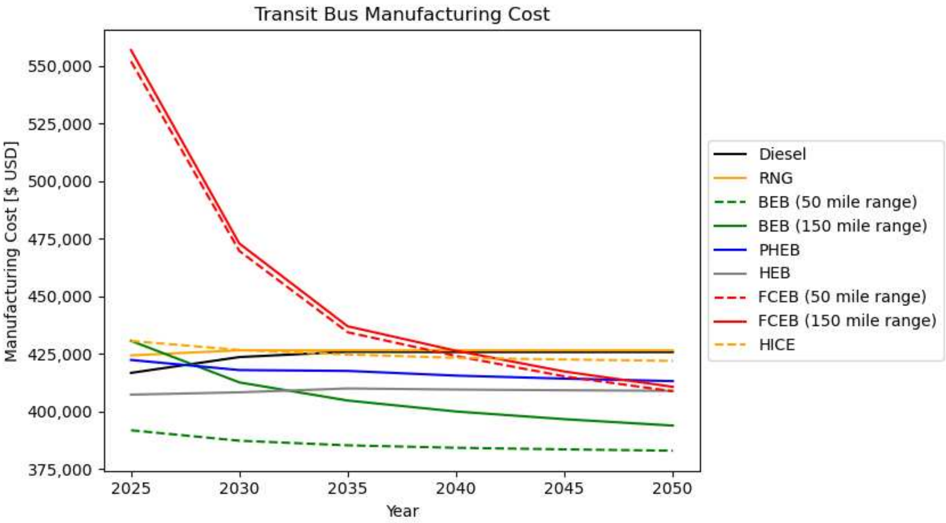

Figure 23: Transit bus manufacturing cost trends out to 2050

When looking at intercity charter buses, one must consider the difference between the 100 mile and 500-mile ranges. 100-mile BEBs are competitive with diesel buses yet can only be used for regional transportation. 500-mile BEBs are extremely expensive and are only competitive with diesel buses by 2045. Similarly, FCEBs can provide 500 miles of range at an equivalent price by 2045.

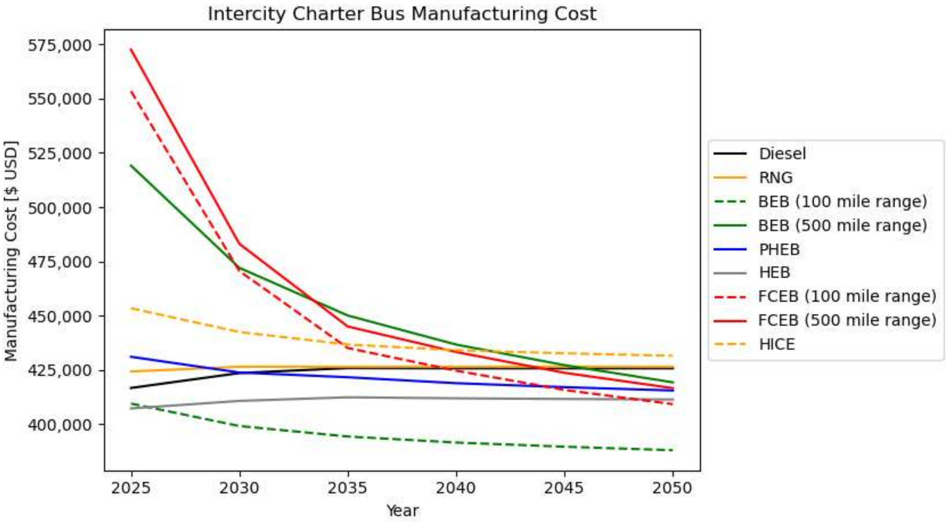

Figure 24: Intercity charter bus manufacturing cost trends out to 2050

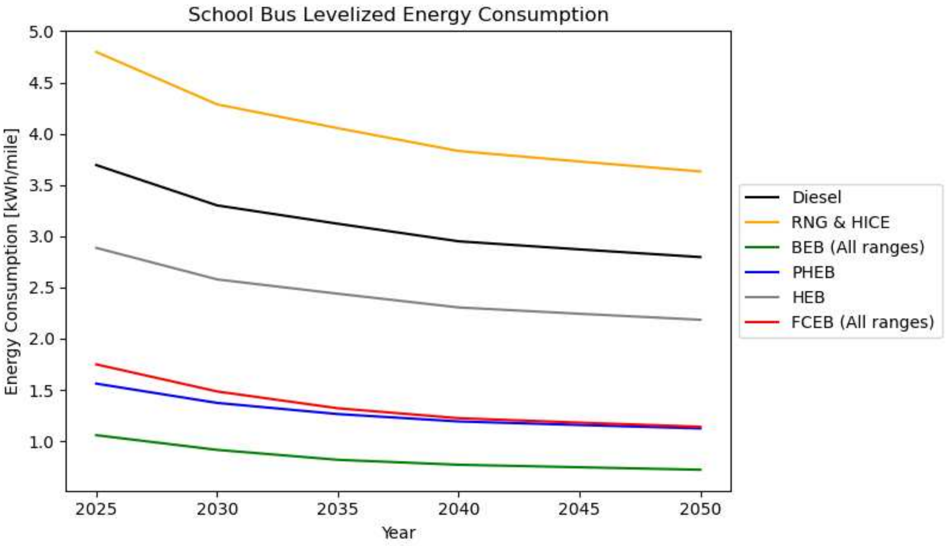

Figure 25: School bus energy consumption trends out to 2050

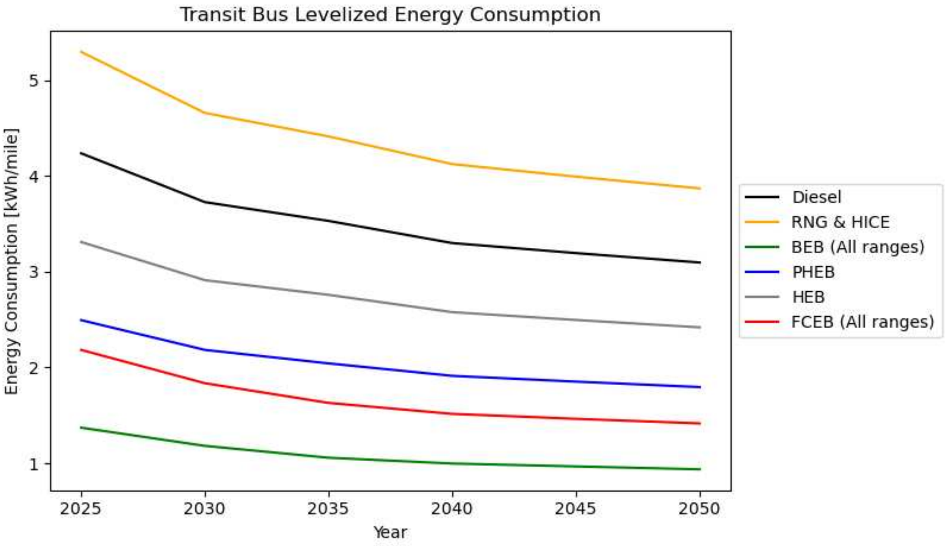

Figure 26: Transit bus energy consumption trends out to 2050

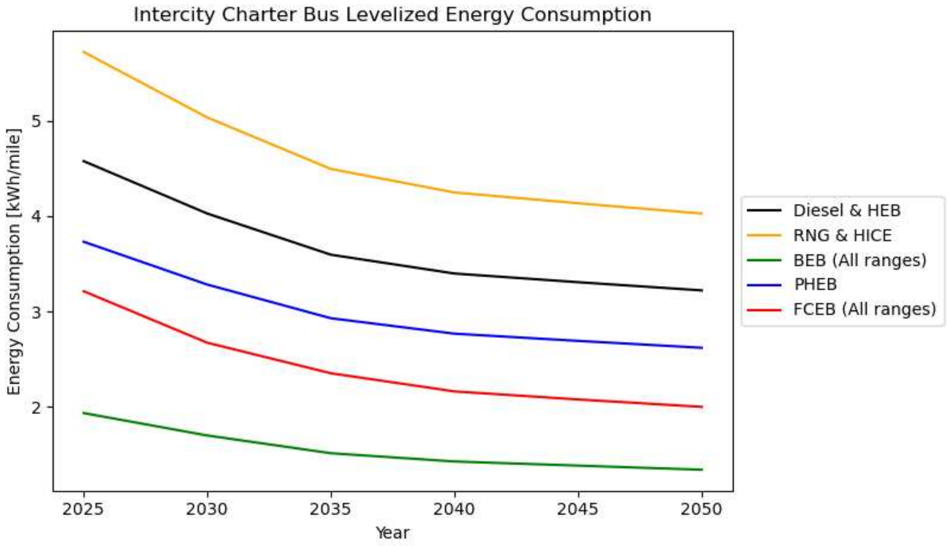

Figure 27: Intercity Charter bus energy consumption trends out to 2050

Figure 25, Figure 26, and Figure 27 show the energy consumption for various powertrains in school, transit, and intercity buses. School buses have the lowest energy consumption due to their lower weight, followed by intercity charter because of its continuous driving cycle, and lastly city transit due to its dynamic driving cycle. The PHEB utility factors are reflected by the differing PHEB energy consumption in the graphs. Hybrid buses provide energy consumption improvements for the stop/start buses, yet no benefit for intercity charter travel.

As seen in Figure 28, outdoor temperatures have a significant impact on bus energy consumption due to passenger compartment heating and cooling requirements. BEBs experience as much as a 32.1% increase in energy consumption while FCEBs experience a 28.6% increase in energy consumption in cold weather [19].

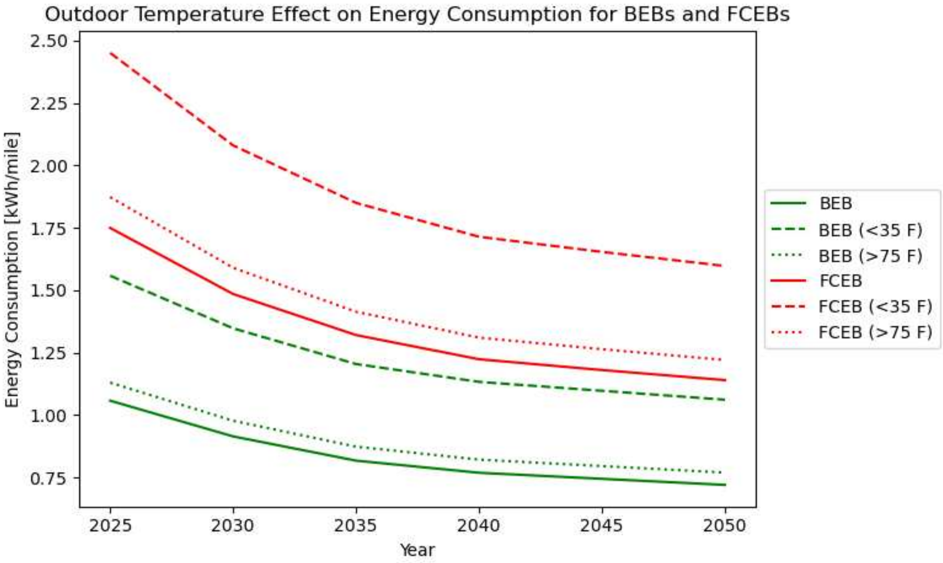

Figure 28: Effect of outdoor temperature on energy consumption of battery electric school buses and fuel cell electric school buses

Summary

Range and daily operating distances play a large role in the costs of a zero-emission bus. Low ranges equate to BEB manufacturing costs that are competitive with conventional diesels in the near-term and cheaper in the far-term. FCEBs become the cheaper zero-emission option when longer ranges are needed, such as inter-state transit. Increased loads due to heating and cooling of the passenger compartment contribute to higher energy consumption during hot and cold weather for BEBs and FCEBs.

REGIONAL AVIATION

Background and State of the Field

The progression of aviation history has been closely linked with the rise of conventional airplanes, primarily driven by turbine engines fueled by kerosene. These aircraft have significantly improved global connectivity by enabling swift travel across long distances. Their efficiency and reliability have solidified their prominence in the aerospace sector. The growing emphasis on reducing carbon emissions and embracing sustainability has compelled the aviation industry to explore the potential of next-generation aircraft. This shift is particularly relevant in the context of regional aviation, where innovations are steering the development of lower-carbon air travel options. These range from emerging battery electric technologies to the exploration of hydrogen-powered solutions.

Study Overview

This section analyses the cost and performance of alternative powertrains for regional aircraft. Regional size aircraft was chosen as an intermediate between aircraft that has already been electrified – small, 2 to 5-seater aircraft - and 100-200 passenger aircraft that is used for most commercial flights. The target fuels studied were kerosene and sustainable aviation fuel (SAF) which share the same engine technology, battery electric (BEA), fuel cell electric (FCEA), and hydrogen gas turbine (HGT). These powertrains are analyzed for their capital cost, efficiency, and range out to 2050.

Methods and Assumptions

A bottom-up cost model was performed by summing the purchase costs of individual powertrain components and the glider. Purchase costs were used for this section as more data is available. The glider purchase price was found by subtracting the costs of a conventional powertrain from the price of a new aircraft. The baseline aircraft chosen was the De Havilland Dash-8. It has a passenger capacity of 30-50, a maximum power of 3500 kW, a payload of 4647 kg, and a maximum range of about 1100 miles [74]. However, 50% of the Dash-8 flights are under 250 miles, and 90% are under 500 miles [75]. It was assumed that the aircraft structure would remain as a tube and wing, keeping the glider cost and weight the same across the board. It is likely that next generation aircraft will come with changes in aircraft structure, but it is unknown what that will look like at this time. A 25% markup on the manufacturing price of alternative fuel technologies was used to estimate purchase price. Powertrain components for each fuel type are as follows:

- Kerosene/SAF: Turboprop engines, APU engine, fuel system
- BEA: Electric motor, power inverter, electric bus, battery
- FCEA: Electric motor, power inverter, electric bus, fuel cell, liquid hydrogen (LH_2) storage
- HGT: Turboprop engines, APU engine, LH_2 storage

Battery costs trends are similar to the on-road model, yet with an aerospace premium. The cost is estimated to be \$500/kWh in 2025 and drop to \$300/kWh by 2050. The increase over on-road batteries is due to the different packaging and factors of safety needed for aircraft applications. Similar aerospace premiums are expected on prices for electric motors, power inverters, electric buses, and hydrogen storage. Resources that drove the assumptions made in this model are [22], [23], [24], [25], [26] and correspondence with a principle technical fellow at Collins Aerospace.

Results

The results of the aviation model are presented in the form of purchase price and aircraft range trends out to 2050. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Aviation Cost Model in the appendix.

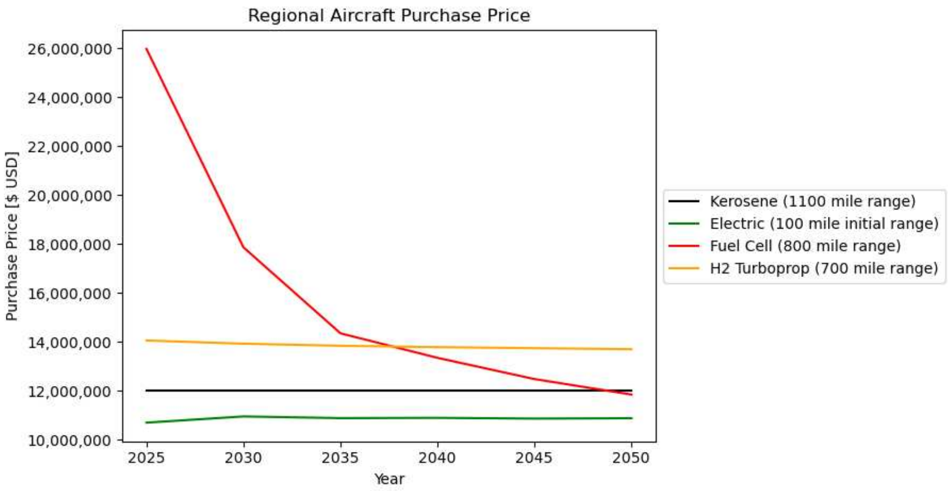

Figure 29: Aircraft purchase price trends out to 2050

Shown in Figure 29 are the purchase prices for regional aircraft with various powertrains. Electric aircraft are less expensive than conventional aircraft. This is because weight constraints limit the capacity of aircraft batteries, subsequently resulting in a reduced cost, as well as a restricted range, as illustrated in Figure 30. The HGT comes in at a slightly higher price than conventional aircraft due to the increased cost of the hydrogen fueled turbines and hydrogen storage. Once again, the fuel cell stack cost is a driving factor in the price of the FCEA. Reductions in stack costs allow the FCEA to become competitive in the long term.

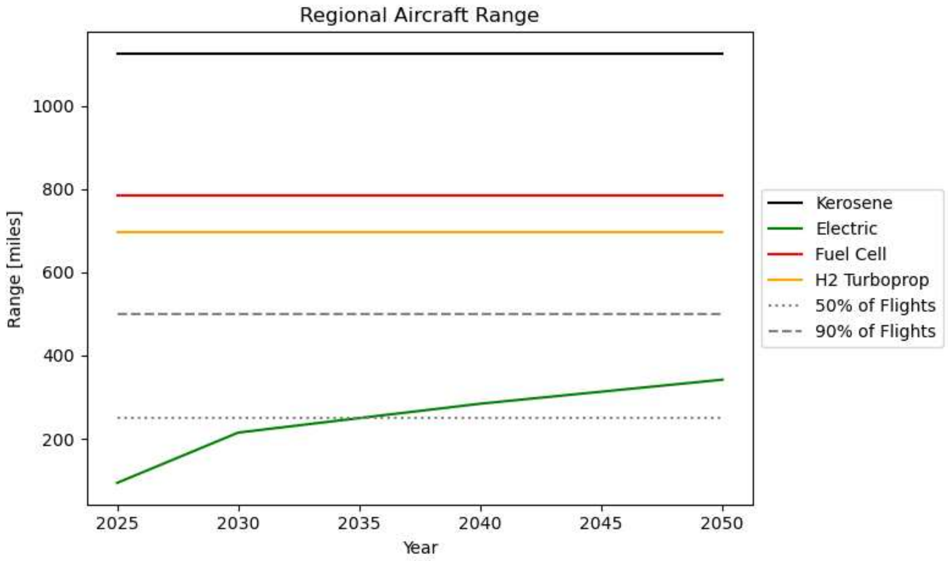

Figure 30: Aircraft range trends out to 2050, presented in miles; alternative fuel aircrafts were optimized for range while retaining ~50% original payload capacity

Shown in Figure 30 are the ranges of regional aircraft with different powertrains. The baseline, kerosene, has a range of 1100 miles. The two dashed lines represent the distances that are traveled by regional turboprop aircraft 50% and 90% of the time. For both hydrogen fuel cell and hydrogen gas turbine aircraft, a fuel tank size was chosen that optimizes passenger capacity and range. These ranges are constant in this model, yet may increase with changes to aircraft fuselage design. While FCEAs and HGTs do not meet the same range as conventional aircraft, they meet 90% of regional turboprop flights. Electric aircraft, on the other hand, are just barely feasible for 50% of dash-8 flights by 2050. Due to the weight of batteries, the onboard capacity is limited. This reduces overall range.

Summary

When purchase prices of various powertrains are compared, the range of the aircraft needs to be taken into account. The electric aircraft that was modeled in this study has a purchase price that is roughly $2 million less than a conventional aircraft, yet its range is significantly reduced to the point where a large portion of typical regional flights are not feasible. New developments need to be made in battery technology for electric aircraft to be feasible for regional flights. FCEA and HGT aircraft are more expensive than conventional aircraft yet provide ranges that are feasible for the majority of regional flight distances. As fuel cell costs decrease, FCEAs with optimized tank volumes become competitive with conventional regional aircraft by 2050. While these aircraft offer reduced maximum ranges, they are adequate for more than 90% of regional turboprop flights.

MARITIME TRANSPORT

Background and State of the Field

Vessels in the maritime shipping industry predominantly rely on conventional engines powered by heavy fuel oil (HFO), and less commonly liquified natural gas (LNG). These engines, commonly large two-stroke diesel engines, efficiently generate propulsion for a wide range of vessels. However, these conventional fuels pose challenges due to emissions of greenhouse gases and other pollutants. To address these concerns, a transition towards alternative fuels has gained momentum. Notably, ammonia, methanol, and biofuels are emerging as potential substitutes for HFO. The inherent properties of these alternatives make them attractive options for maritime applications, as they offer the potential for reduced GHG and criteria pollutant emissions. As the maritime sector seeks more sustainable solutions, the development of engines capable of utilizing these alternative fuels could improve the industry's ecological footprint and uphold performance requirements.

Study Overview

This section seeks to study the use of alternative fuels in a range of maritime applications. The vessels studied are bulk carriers, container ships, Roll-on/roll-off (RoRo) ferries (designed to carry wheeled cargo), Passenger Roll-on/roll-off (RoPax) ferries (designed to accommodate passengers in addition to wheeled cargo), and fishing vessels. The combustion fuels studied are conventional heavy fuel oil (HFO), renewable liquified natural gas (RLNG), ammonia, methanol, and a 50/50 ammonia/diesel blend. Recreational vessels are also studied, although the fuels focused on are diesel, gasoline, methanol, battery electric, and hydrogen fuel cell. This section focuses on the vehicle powertrains alone, excluding costs of the vessel glider. Vessel powertrains are analyzed for capital cost and energy use.

Methods and Assumptions

The cost of each powertrain was found by summing the costs of individual components, following a bottom-up cost model structure. The main components of each powertrain were the engine, the fuel storage system, and the exhaust aftertreatment system. The costs of the engine and fuel system were directly related to engine power and vessel size. Vessel size can vary depending on operational logistics, thus making it difficult to designate one powertrain to represent all vessels within a specific category. Table 2 shows the baseline vessel sizes that were chosen for this study.

Table 2: Baseline ship properties for different vessel groups

Ship Type	Total Power [kW]	Cruising Speed [knots]	Voyage Length [nm]
Bulk Carrier	20,000	21	7,000
Container	20,000	21	7,000
RoPax Ferry	5,400	23	400
RoRo Ferry	20,000	21	1,000
Fishing Vessel	1,500	8	3,000
Recreational Vessel	300	14	300

It is anticipated that any reductions in prices will be marginal, as economies of scale do not significantly impact the maritime industry, with fewer than 500 ships being constructed annually [76]. By 2050, all engines will have a similar manufacturing cost. All engines are assumed to share the same efficiency of 40%. Voyage energy use was found by multiplying ship cruising power by engine hours and dividing by engine efficiency. The required stored energy on board was found by multiplying voyage energy use by a fuel margin factor of 1.2. Vessel powertrain costs are largely adapted from [33].

Results

The results of the maritime model are presented in the form of engine cost trends and tabulated data on powertrain manufacturing cost, tank size, and vessel energy use. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Maritime Cost Model in the appendix.

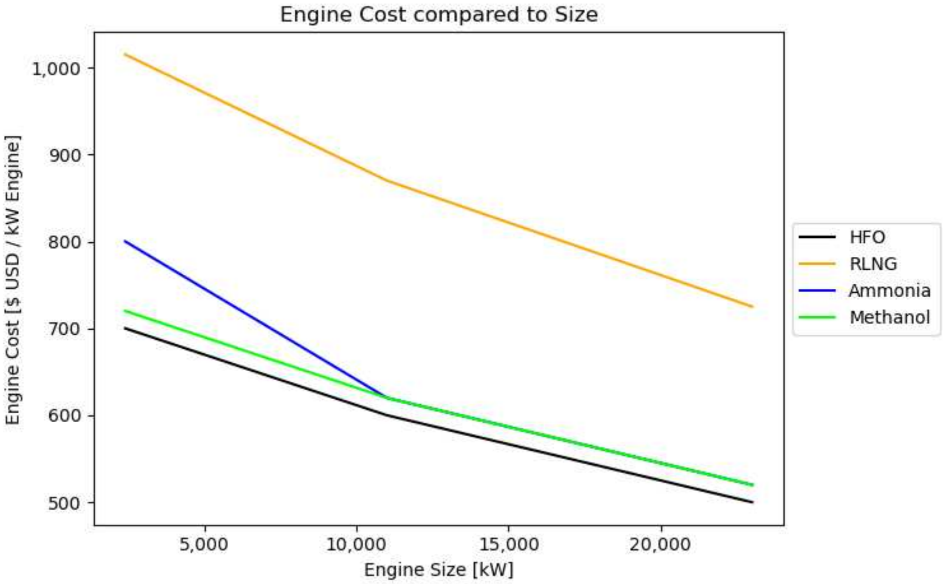

Figure 31: Engine cost vs engine size in maritime vessels

Engine and storage costs scale down with increased ship size. Shown in Figure 31, engine cost per kW decreases as the size of the engine gets larger for conventional HFO, RLNG, methanol, and ammonia engines. RLNG engines have the highest cost per kW, while ammonia has a marginal cost increase over conventional due to necessary dual fuel injection technology [34], [77]. The cost of a methanol engine is assumed to be the same as a traditional HFO engine [78].

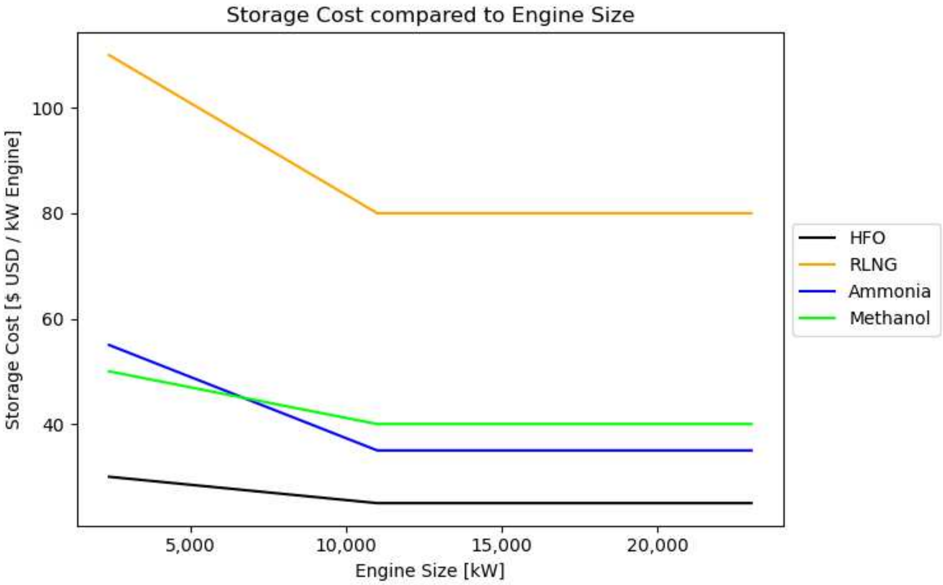

Figure 32: Fuel storage costs vs engine size in maritime vessels

The cost of fuel storage also decreases with engine power, due to larger engines most often requiring larger fuel tanks and thus less material per MWh of fuel. RLNG fuel systems must handle the cryogenic properties of RLNG. Specialized materials, insulation, and increased safety measures contribute to the increased cost of RLNG storage. The increased storage costs of ammonia and methanol come from the need for double walled fuel tanks and increased safety measures, due to the human health risks that they pose.

Table 3: Powertrain manufacturing cost for various ship types and fuels

Ship Type	Fuel	Powertrain Manufacturing Cost [2023 $ USD]
Bulk Carrier (20,000 kW)	HFO	14,617,000
	RLNG	18,984,000
	Ammonia	13,505,000
	Methanol	13,804,000
	Ammonia/Diesel Blend	13,370,000
	Biofuels	13,703,000
Container Ship (20,000 kW)	HFO	14,617,000
	RLNG	18,984,000
	Ammonia	13,505,000
	Methanol	13,804,000
	Ammonia/Diesel Blend	13,370,000
	Biofuels	13,703,000
RoPax Ferry (5,400 kW)	HFO	4,443,000
	RLNG	5,793,000
	Ammonia	4,090,000
	Methanol	4,198,000
	Ammonia/Diesel Blend	4,089,000
	Biofuels	4,196,000
RoRo Ferry (20,000 kW)	HFO	12,465,000
	RLNG	15,679,000
	Ammonia	13,171,000
	Methanol	13,561,000
	Ammonia/Diesel Blend	13,158,000
	Biofuels	13,551,000
Fishing Vessel (1,500 kW)	HFO	1,246,000
	RLNG	1,644,000

	Ammonia	1,157,000
	Methanol	1,185,000
	Ammonia/Diesel Blend	1,149,000
	Biofuels	1,177,000
Recreational Vessel (300 kW)	Diesel	26,000
	Gasoline	17,000
	Methanol	26,000
	Electric	1,519,000
	Hydrogen	22,000
	Biofuels	26,000

While offering reduced emissions, RLNG engines come at a premium cost due to the complexity of the engine and fuel system. Ammonia and methanol fuels emerge as competitive choices with powertrain costs often on par with HFO. Their ability to provide cleaner emissions and reduced environmental impact positions it as an attractive alternative, especially for vessel owners seeking to align with stringent emission regulations. These engines need slight manufacturing changes that add a small incremental cost.

Table 4: Comparison of storage tank volume for different fuels used in a container ship; columns 3, 4 and 5 present lost cargo due to changes in fuel storage volume

Fuel	Tank Volume [m^3]	Cargo Volume Lost relative to HFO [m^3]	Cargo Lost [TEUs]	Percent Cargo lost
HFO	2503.7	-	-	-
RLNG	3471.4	967.7	25.4	0.8%
Ammonia	5038.5	2534.8	66.5	2.2%
Methanol	4866.9	2363.2	62	2.1%
Biofuels	2503.7	-	-	-
Ammonia/Diesel Blend	3345.1	841.4	22	0.7%

Comparing alternative fuels to HFO involves examining their impact on the requirement volume of fuel storage tanks and resulting cargo capacity impacts. RLNG exhibits a tank volume 1.4 times that of HFO, while ammonia's tank volume is 2.0 times larger. Methanol's tank volume is 1.9 times that of HFO, and the ammonia/diesel blend features a total tank volume 1.3 times greater than HFO. Biofuels are assumed to share the same tank volume as HFO. The effect of tank volume on cargo capacity can be seen in Table 4.

Table 5: Energy use for various ship types

Ship Type	Voyage Energy Use [MWh]	Fuel Margin Factor	Stored Energy [MWh] (HFO)	Voyage Fuel Cost (HFO) [$]
Bulk Carrier	20238	1.2	24286	$1,240,000
Container	20238	1.2	24286	$1,240,000
RoPax	200	1.2	239	$14,700
RoRo	2024	1.2	2429	$149,000
Fishing Vessel	1195	1.2	1434	$88,000
Recreation	13	1.2	5	$1,000

Summary

A main finding of this work is that engine and storage costs scale down with increased ship size. Overall, when one considers that large maritime vessels can cost upward of $100 million, these cost differences for the engine and storage are negligible [33]. Additionally, throughout the course of the research, it was observed the relatively small impact of capital costs associated with these ships, particularly in contrast to the operational expenses. While beyond the scope of this thesis, it is important to emphasize the considerable role played by fuel costs, which exert a substantial influence on the overall economic viability.

RAIL

Background and State of the Field

The field of freight locomotives has evolved significantly over the years, driven by the need for efficient and sustainable freight transportation. Line-haul locomotives, designed for long-distance travel, and line-switcher locomotives, used for yard operations, constitute the primary segments of the freight locomotive landscape. The prevailing locomotive technology is diesel-electric, in which a diesel engine generates electricity that powers alternating current (AC) traction motors driving the wheels. This hybrid system provides high torque at low speeds and better fuel efficiency compared to traditional diesel powertrains. Amid the imperative to reduce emissions and enhance sustainability, the freight rail industry is exploring various new technologies. RLNG locomotives utilize natural gas for power, offering lower emissions compared to diesel. Electric catenary systems provide continuous power through overhead wires but require extensive infrastructure modifications. Battery-electric locomotives store energy in onboard batteries yet come with energy storage limitations for long-haul operations. Hydrogen fuel cell locomotives (FCELs) offer another option yet require hydrogen storage and fueling infrastructure.

Study Overview

This section analyzes the cost and performance of these baseline and alternative fuel powertrains in freight locomotives. The locomotives studied are line-haul, used for long distances, and line-switcher, used to assemble trains in rail yards. The fuels studied are the baseline diesel-electric, RLNG, electric catenary, battery electric (BEL), fuel cell electric (FCEL) and hybrid electric (HEL). For FCEL options, both liquified hydrogen (LH_2) and cryo-compressed hydrogen (CcH_2) storage options were studied. The various powertrains are studied for their manufacturing cost and efficiency out to 2050.

Methods and Assumptions

A bottom-up cost model was performed by summing the manufacturing costs of individual powertrain components and the locomotive glider. The glider cost and weight remain the same for all powertrain types. Powertrain components for each fuel type are as follows:

- Diesel Electric: Engine, alternator, rectifier, AC traction motor, fuel system
- RLNG: Engine, alternator, rectifier, AC traction motor, fuel system
- Electric Catenary: Pantograph/transformer, inverter, AC traction motor
- BEL: Battery, inverter, AC traction motor
- FCEL: fuel cell, battery, inverter, AC traction motor, fuel system
- HEL: Engine, battery, alternator, inverter, AC traction motor, fuel system

Assumptions were guided by [38], [79]. For this study, it was initially assumed the operational range of the alternative powertrain locomotives is the same as conventional diesel electric. This creates high costs and low feasibility for battery electric powertrains. Much like heavy-duty vehicles, the operational logistics and range requirements can change with different fuel types. Powertrain efficiency was adopted from work done by [80].

It was assumed hybrid locomotives would follow the "mother-slug" design, in which two locomotives are used in tandem, one being traditional diesel electric, and one being battery electric. This configuration is currently used in yard operations by Union Pacific [81].

Results

The results of the locomotive model are presented in the form of manufacturing cost trends and tabular data of locomotive efficiency. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Rail Cost Model in the appendix.

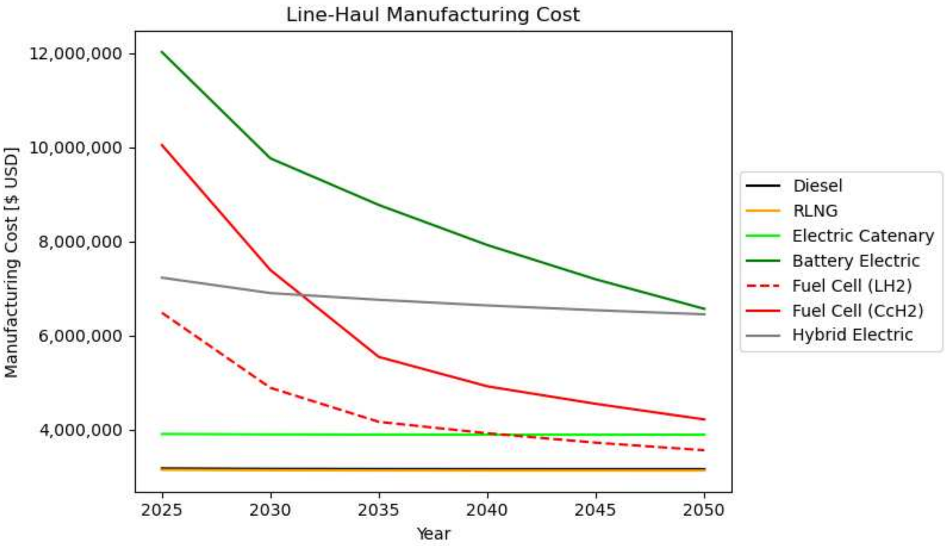

Figure 33: Manufacturing cost trends for line-haul locomotives

For Line-Haul operations, diesel-electric locomotives remain the cheapest option for years to come. RLNG options are competitive from a capital cost standpoint and provide emissions improvements over conventional diesel electric locomotives but have disadvantages in the way of fueling infrastructure. The cost of BELs proves to be very high for long range applications. Rail is directly electrified through electric catenary infrastructure throughout the world, but there is limited use of direct electrification in the U.S. [46]. The high cost of installing electric catenary infrastructure and current low availability may negate the capital cost competitiveness of electric catenary locomotives.

The most promising alternative fuel for decarbonization of long-haul freight operations appears to be hydrogen fuel cell technology. While still in development, liquid hydrogen storage allows for the needed energy to be stored in tender cars at a fraction of the price of cryo-compressed hydrogen. The addition of the tender car allows FCELs to reach ranges equal to that of a conventional diesel-electric locomotive. Again, the development of fuel production and fueling infrastructure will be necessary for FCELs to operate effectively.

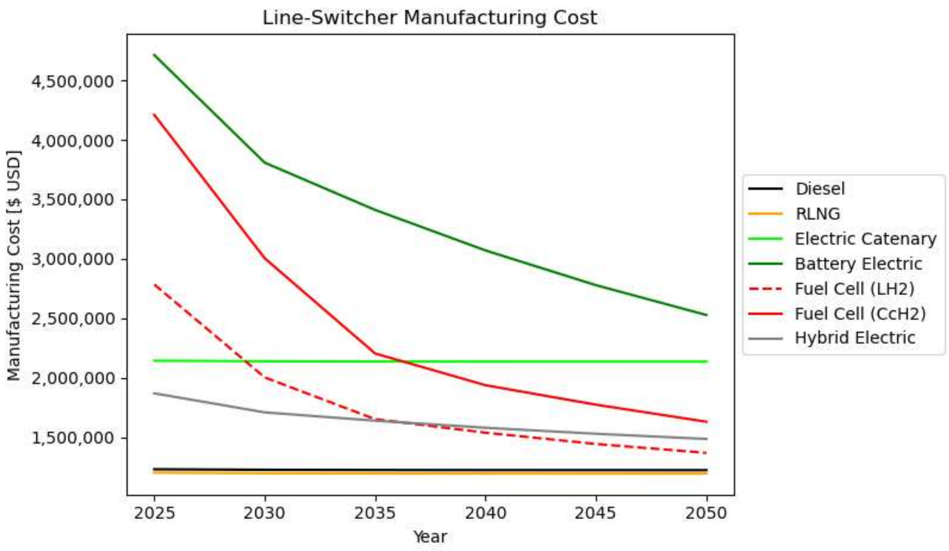

Figure 34: Manufacturing cost trends for line-haul locomotives

For Line-Switcher operations, BELs become more feasible due to the smaller battery energy capacity needed. Still, changes in operations are required, as a BEL would need an energy capacity of 28 MWh to operate for the same amount of time as a diesel-electric line-switcher. For reference, current production BELs have capacities around 4 MWh [82]. In yard applications, RLNG and LH_2 tanks could fit on the locomotive, eliminating the need for a tender car. By 2050, the capital cost of FCELs for line-switcher operations will be very competitive with diesel-electric locomotives, and operational costs will ultimately decide which locomotives are best. BELs will also be within the range of 2x the cost of diesel-electric, which when paired with cheap electricity for charging could prove to be a competitive option for yard applications.

Table 6: Locomotive efficiency by component and powertrain

	Diesel	RLNG	Electric Catenary	Battery Electric	H_2 Fuel Cell
Component Efficiency	Engine: 40%	Engine: 40%	Pantograph: 95%	Battery: 95%	Fuel Cell: 49%
	Alternator: 92%	Alternator: 92%	Transformer: 95%		
	Inverter: 97.5%	Inverter: 97.5%	Inverter: 97.5%	Inverter: 97.5%	Inverter: 97.5%
	Electric Motor: 92%	Electric Motor: 92%	Electric Motor: 95%	Electric Motor: 95%	Electric Motor: 95%

	Transmission: 95%	Transmission: 95%	Transmission: 95%	Transmission: 95%	Transmission: 95%
	Auxiliaries: 95%	Auxiliaries: 95%	Auxiliaries: 95%	Auxiliaries: 95%	Auxiliaries: 95%
Vehicle Efficiency	30%	30%	76%	79%	42%

Table 6 above highlights the efficiency factors for distinct vehicle powertrain components across different propulsion technologies. Notably, electric catenary and battery electric powertrains demonstrate higher efficiencies, reaching 76% and 79% overall vehicle efficiency, respectively. Diesel and RLNG exhibit 30% vehicle efficiency. Hydrogen fuel cell technology records an overall vehicle efficiency of 42%.

Summary

For long-distance Line-Haul operations, diesel-electric locomotives retain cost competitiveness due to the relatively low costs of their powertrain and infrastructure, with RLNG options facing fueling infrastructure challenges. Battery electric locomotives (BELs) are cost-prohibitive for extended ranges that diesel-electric locomotives cover. Electric catenary locomotives also lose capital cost competitiveness due to extensive infrastructure expenses. Hydrogen fuel cell technology emerges as a promising alternative for long-haul freight, leveraging liquid hydrogen storage in tender cars for cost-effective energy storage, potentially matching diesel-electric locomotive ranges. For Line-Switcher operations, BELs emerge as the most cost-competitive low-carbon option, though operational changes are needed. By 2050, FCELs could be competitive with diesel-electric counterparts for yard applications.

AGRICULTURAL EQUIPMENT

Background and State of the Field

Conventional internal combustion engines, predominantly fueled by diesel, have long been the driving force behind agricultural machinery. Yet, this technology will slowly move towards advanced powertrains as they are developed for other transportation applications. Battery electric and fuel cell propulsion systems offer clean, efficient, and quiet propulsion. The exploration of ammonia as a potential power source could offer convenience for farmers. These innovative powertrains not only hold the potential to elevate operational efficiency but also contribute significantly to minimizing the environmental impact of farming practices. Capital cost and fuel efficiency will be important drivers in the adoption of alternative technologies.

Study Overview

This section aims to look at the same alternative powertrains reviewed over the course of this study and how they will fit into agricultural applications. The vehicles studied are a utility tractor, a skid steer loader, and a mini excavator. The fuels studied for these vehicles are diesel, RNG, battery electric, hydrogen fuel cell, and ammonia. The various powertrains are studied for their cost and vehicle energy use out to 2050.

Methods and Assumptions

A bottom-up cost model was developed to estimate the cost of alternative fueled agricultural vehicles out to 2050. The glider costs of each vehicle type were determined by subtracting the conventional powertrain components from the purchase price of a new piece of machinery. A John Deere 7 Series 290 hp (216 kW) was chosen as the baseline for the utility tractor. The Bobcat S62 (50kW) was used as the baseline skid steer, and the Bobcat E42 R2 (25 kW) was chosen for the baseline mini excavator. Once again, glider cost and weight remain the same for all powertrain types. The powertrain components for each fuel type are as follows:

- Diesel: Engine, fuel system, transmission

- RNG: Engine, fuel system, transmission
- Ammonia: Engine, fuel tank, transmission
- Battery electric: Battery, inverter, electric motor
- Hydrogen fuel cell: Fuel cell, battery, inverter, electric motor, fuel system

The vehicle energy use for the conventional diesel tractor is adapted from the Nebraska Tractor Test Laboratory [83]. Using this as the baseline, the energy consumption of the other powertrain types is determined using their comparative powertrain efficiencies.

For the skid steer and mini excavator, vehicle energy use is presented in energy use per hour of operation. To determine this, the average power required by the equipment was multiplied by the efficiency of the powertrain.

Results

The results of the agriculture model are presented in the form of manufacturing cost trends and tabular vehicle energy use data. More detailed information on component costs and performance calculations can be found in the spreadsheet titled Agriculture Cost Model in the appendix.

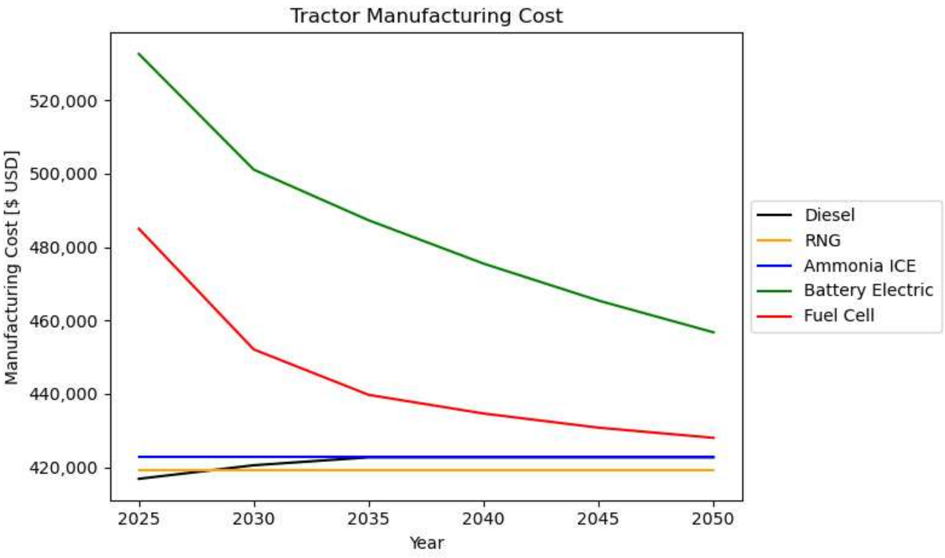

Figure 35: Tractor manufacturing cost trends out to 2050 for various powertrain types

Figure 35 shows the manufacturing cost trends for a 216 kW utility tractor. At this power, battery electric tractors are very expensive due to the high battery capacity required to offer a similar range as a diesel tractor. Fuel cell vehicles offer a slightly cheaper zero-emission alternative. RNG and ammonia engines have manufacturing costs similar to that of diesel engines.

For skid steers, lower energy requirements allow the battery electric option to become cheaper than its diesel alternative by 2035. Fuel cell and HICE skid steers have a high manufacturing price due to fuel cell stack and hydrogen storage costs.

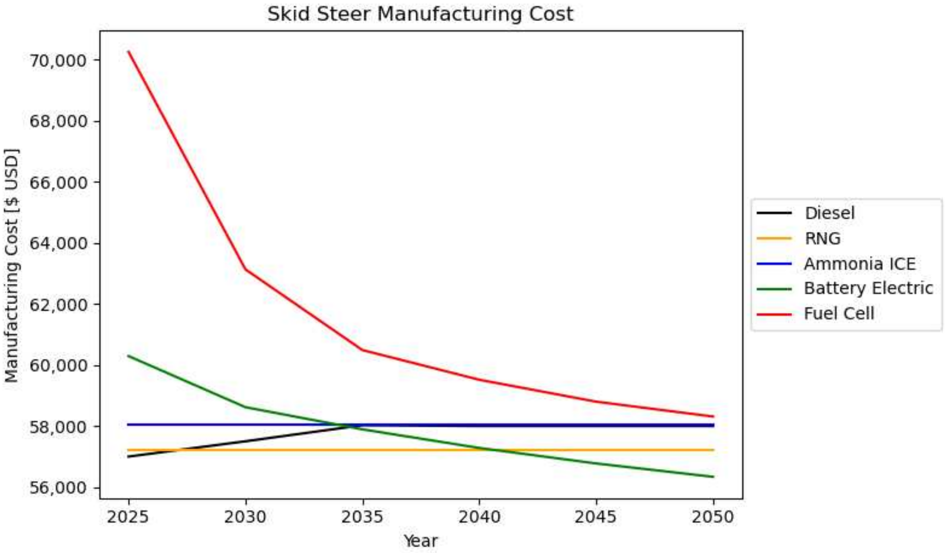

Figure 36: Skid steer manufacturing cost trends out to 2050 for various powertrain types

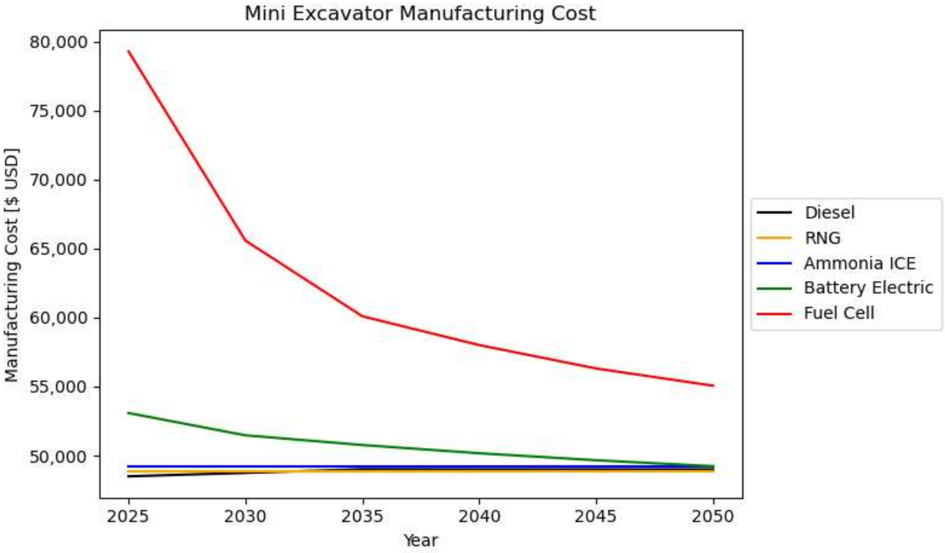

Figure 37: Mini excavator manufacturing cost trends out to 2050 for various powertrain types

For mini excavators, fuel cell costs are very high, while battery electric machines only become competitive by around 2050.

Table 7: Utility tractor energy use

Fuel Type	Powertrain Efficiency	Required Power [kW]	Power consumed [kW]	Gal/hr	kg/hr
Diesel	30%	204.3	543.8	14.33	--
RNG	30%	204.3	543.8	--	40
Ammonia	30%	204.3	543.8	--	105.4
Battery Electric	90%	204.3	181.27	--	--
H_2 Fuel Cell	49%	204.3	271.9	--	10

Table 8: Skid steer energy use

Fuel Type	Powertrain Efficiency	Required Power [kW]	Power consumed [kW]	Gal/hr	kg/hr
Diesel	30%	50	166.6	4.39	--
RNG	30%	50	166.6	--	12.3
Ammonia	30%	50	166.6	--	32.3
Battery Electric	90%	50	55.55	--	--
H_2 Fuel Cell	49%	50	83.3	--	3

Table 9: Mini excavator energy use

Fuel Type	Powertrain Efficiency	Required Power [kW]	Power consumed [kW]	Gal/hr	kg/hr
Diesel	30%	25	83.3	2.19	--
RNG	30%	25	83.3	--	6.12
Ammonia	30%	25	83.3	--	16.15
Battery Electric	90%	25	27.78	--	--
H_2 Fuel Cell	49%	25	41.67	--	1.5

For Table 7, Table 8, and Table 9, Diesel, RNG, and ammonia exhibit equivalent power requirements and consumption rates. The battery electric powertrain stands out with 90% efficiency. Hydrogen fuel cell technology boasts 49% efficiency.

Summary

In the agricultural sector, battery electric and fuel cell vehicles often come with higher costs compared to conventional diesel alternatives. Battery electric tractors are pricier due to increased battery capacity requirements while RNG and ammonia powertrains exhibit costs similar to diesel. Skid steers see battery electric becoming competitive with diesel by 2040, while fuel cell and hydrogen ICE options have high costs. Mini excavators show high relative costs of fuel cell technologies, with battery electric competitiveness expected by 2050. Efficiency patterns remain consistent across diesel, RNG, and ammonia powertrains, with battery electric demonstrating 90% efficiency, and hydrogen fuel cell technology maintaining 60% efficiency.

FORKLIFTS

Background and State of the Field

Forklifts are an integral tool of industrial operations, facilitating material handling and logistics across diverse sectors. The present landscape of conventional forklifts encompasses diesel, propane and lead-acid battery electric models, with a relatively small but growing share of hydrogen fuel cell options. Diesel forklifts offer robust performance with quick refueling but raise emissions concerns and can only be used outdoors. Lead-acid battery electric variants provide a cleaner alternative, albeit with limited runtime and long recharging times. However, the field is in transition, as next-generation forklifts propelled by advanced power sources are emerging. Lithium-ion battery electric models stand as a promising progression, offering extended uptime and quicker recharging, while hydrogen fuel cell forklifts demonstrate a potential for zero-emission operation and rapid refueling.

Study Overview

This section looks at the cost and performance of alternative powertrains used in industrial forklifts. This is a sector in which these powertrains are already being implemented. The forklift models studied have lift capacities of 8000 lbs., 20000 lbs., and 40,000 lbs., respectively. The fuels studied were diesel, propane, lead-acid battery electric, lithium-ion battery electric, and hydrogen fuel cell. The various powertrains are studied for their cost, and vehicle energy use out to 2050.

Methods and Assumptions

A bottom-up cost model was developed to estimate the manufacturing cost of alternative fueled forklifts out to 2050. The main resources that drove the assumptions in this model are presented in [84] and [85]. The glider costs of each vehicle type were determined by subtracting the conventional powertrain components from the total cost as presented in the EPRI forklift cost calculator [84]. Once again, glider cost and weight remain the same for all powertrain types. The powertrain components for each fuel type are as follows:

- Diesel: Engine, fuel system

- Propane: Engine, fuel system
- Lead-acid battery electric: lead-acid battery, inverter, electric motor
- Battery electric: lithium-ion battery, inverter, electric motor
- Hydrogen Fuel Cell: Fuel cell, battery, inverter, electric motor, fuel system

Energy use was calculated as energy used per shift. A shift consists of 6 hours of continuous use at an average power that is assumed to be 10% of the maximum power of the forklift.

Results

Shown below are the results of the forklift cost and performance model. Results are presented as cost trends out to 2050, and energy consumption at different lift capacities. More detailed results can be accessed in the spreadsheet titled Forklift Cost Model in the appendix.

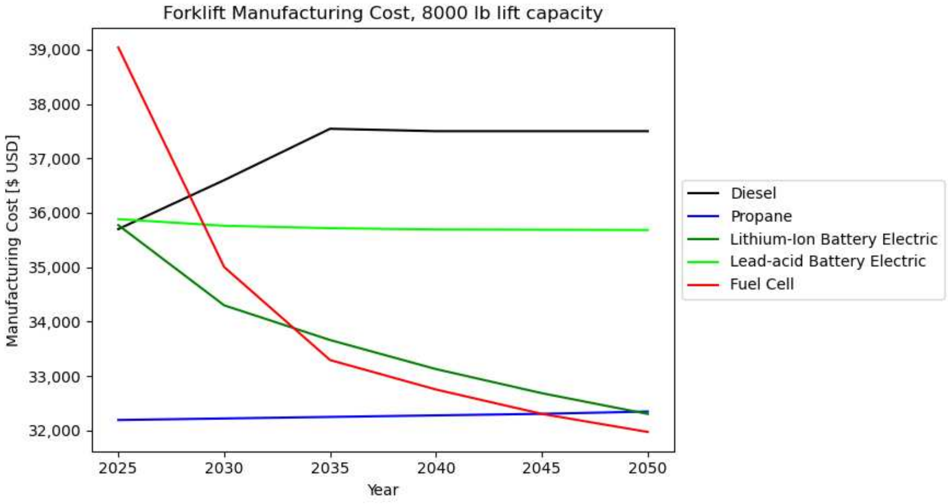

Figure 38: Manufacturing cost trends of forklifts with an 8,000 lb. lift capacity

As seen in Figure 38, Figure 39, and Figure 40, forklifts of different lift capacities share similar cost trends. Lithium-ion battery electric forklifts are competitive in 2025 and fuel cell forklifts become cost competitive with both diesel and lead-acid battery electric forklifts around 2030. Propane forklifts have a low capital cost due to their inexpensive engine and fuel tanks.

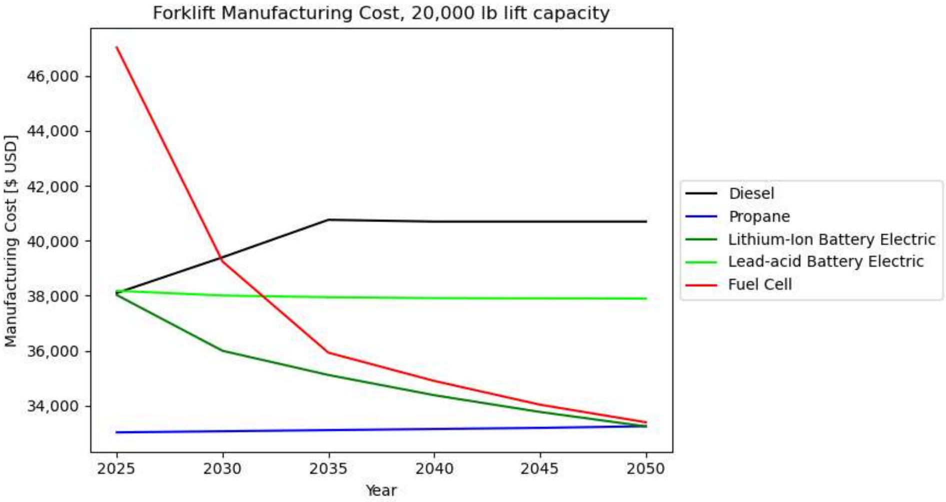

Figure 39: Manufacturing cost trends of forklifts with a 20,000 lb. lift capacity

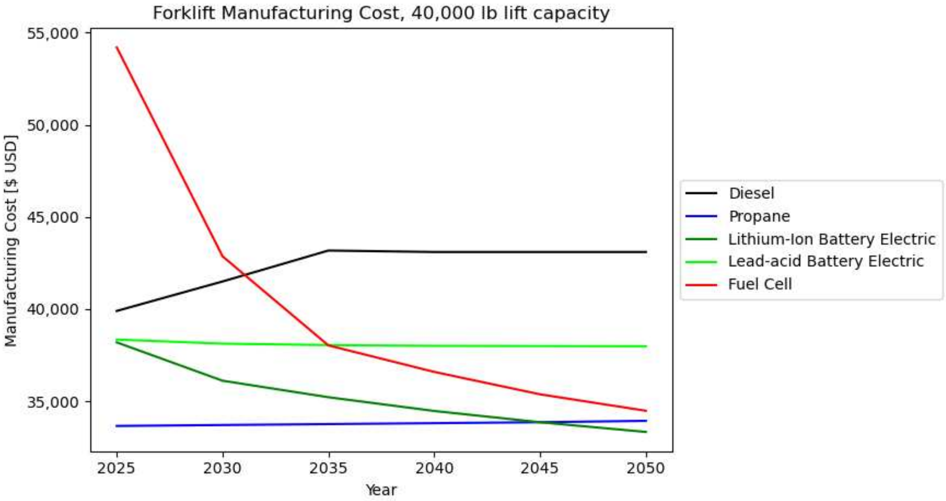

Figure 40: Manufacturing cost trends of forklifts with a 40,000 lb. lift capacity

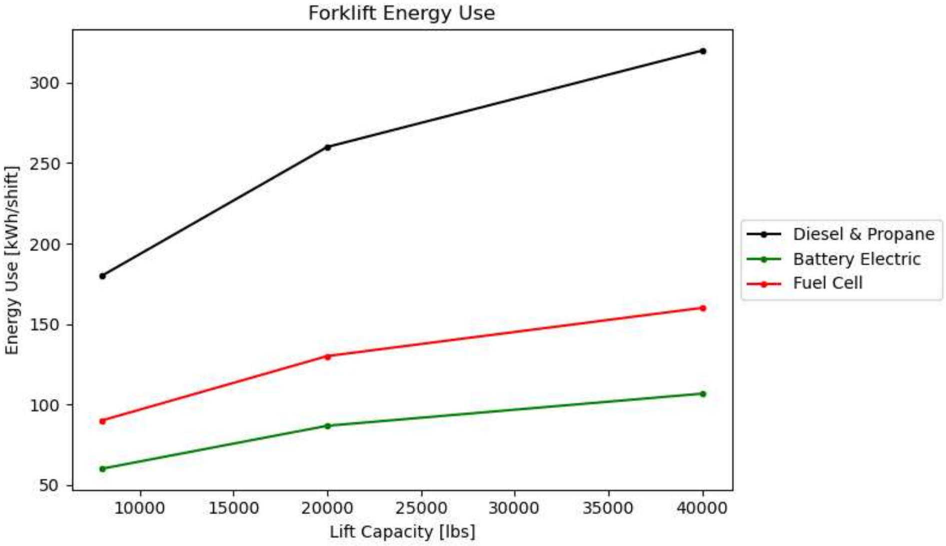

Figure 41: Forklift energy use vs lift capacity

Figure 41 shows the forklift energy use of different powertrain types at different lift capacities. Lithium-ion and lead-acid battery electric offer the most efficient systems, while fuel cell forklifts still offer significant improvements over diesel and propane.

Summary

Lead-acid battery electric forklifts are currently the least expensive zero-emission powertrain option. Lead-acid batteries have a low manufacturing cost, and the high weight is an advantage for forklifts. While more expensive in the near term, lithium-ion batteries will become cheaper than lead-acid batteries as the technology continues to scale. This will translate into cheaper lithium-ion forklifts. Similarly, fuel cell forklifts will drop in price as fuel cell stack costs drop. Fuel cell forklifts tend to be good for high-workload environments where advantages like shorter refueling times and no need for a dedicated battery charging room justify the high capital-cost [86]. While battery electric forklifts offer the greatest efficiency and competitive price, fuel cell forklifts may fit certain applications while still being an improvement over diesel and propane.

DISCUSSION

This study provides insights about the capital costs and performance of alternative fueled propulsion technologies through 2050 across a range of vehicle types. The results, presented as cost and performance forecasts, will be embedded into adoption models to enable governments, utilities, private fleets, and other entities to better prepare for the future of transportation. This work has subsequently been deployed in the EPRI energy-economy REGEN model, contributing to analysis that considers consumer choices and end-use energy demand, and its corresponding effect on the electric grid.

Baseline and Revision of Assumptions

Due to the uncertainty in the rate and types of technological advancements over the next 25 years, discussion of the uncertainty in model assumptions can help to understand the source of possible error in modeling results. For example, in this study, it was assumed that the glider cost and weight would remain largely the same across different propulsion technologies as a function of time, yet into the future there could be changes in the glider construction that could influence manufacturing costs [87]. This has increased importance among tractor trailers, in which the absence of high torques reduces the required strength of the structure [88], [89], [90], which perhaps makes for an opportunity for exteme lightweighting; and in electric and hydrogen aircraft where the fuselage will be designed to be structurally optimized for energy storage [21], [91], [92], [93]. Vehicle gliders will change in the next 25 years and as these technologies become more defined, this work must be updated to reflect that.

Battery and Fuel Cell Price Sensitivity

Additionally, this study incorporates an assumption that battery, fuel cell, and hydrogen storage technology used across various vehicle groups will be very similar, effectively harnessing economies of scale and driving down the cost of these technologies. The reliance on forecasts for battery and fuel cell cost trends introduces an element of uncertainty, as future developments in these technologies and market dynamics may deviate from the optimistic and automotive-centric trends projected in this study [94], [95].

The cost of battery and fuel cells are the main drivers of the cost of battery electric and fuel cell electric vehicles.

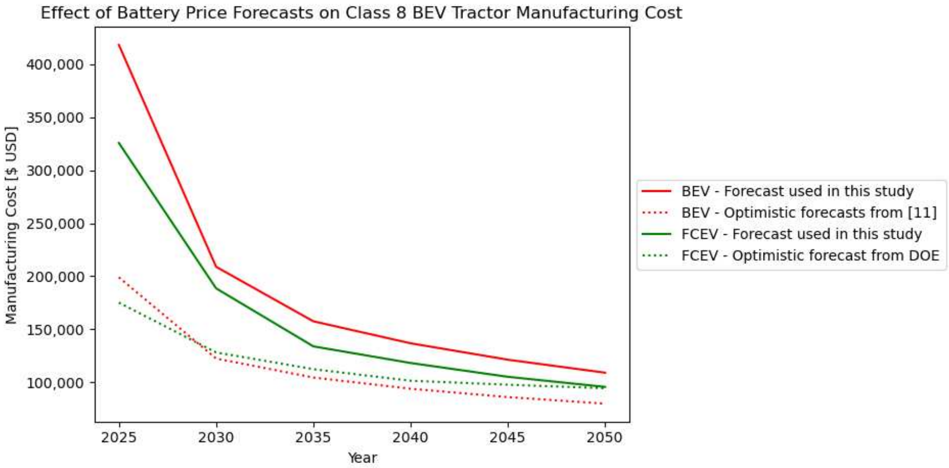

Figure 42: Effect of battery price forecasts on class-8 BEV tractor manufacturing costs

As simulated and illustrated in Figure 42 for class-8 tractor-trailers, slight fluctuations in battery and fuel cell costs will impact overall cost of battery and fuel cell vehicles. Battery prices will be even more important when considering battery lifetimes. Due to chemical degradation, batteries have limited operational lifetimes, and need to be replaced after a certain number of cycles [96], [97], [98]. The cost of battery replacement will be a major factor in fleet management [99], [100], [101]. As battery lifetimes change with changes in technology and control, the opportunity to revisit these results will realize changes to technology costs and benefits.

Operational Cost Sensitivity

Operational costs were not studied in this research, but they do have a major effect on the adoption of alternative fuel vehicles. While batteries have high capital cost, the costs of electricity for charging and maintenance for battery electric vehicles are low, providing incentive for their adoption [6]. The same is not yet true for alternative fuels such as biodiesel, hydrogen, ammonia, or methanol [33], [101], [102]. These fuels currently come at a cost premium due to the small scale of their production and distribution network [103], [104], [105]. Tables 10-12 highlight capital costs found in this study and corresponding operational costs that will affect their adoption.

Table 10: Operational costs of class-8 tractor-trailers over 10-year lifetime [6]

Powertrain Type	2025 Purchase Price	Fuel & Maintenance Cost	Lifetime Fuel & Maintenance (62751miles/year [106])
Diesel ICE	$96,744	$0.62/mile	$389,000
Battery Electric 300	$275,235	$0.45/mile	$282,000
Fuel Cell Electric	$315,250	$1.01/mile	$633785

Table 11: Operational costs of regional aircraft over 20-year lifetime

Powertrain Type	2025 Aircraft Purchase Price	2024 Fuel Cost	2024 Flight Cost (375 miles)	Lifetime Fuel Costs (4 flights/day)
Kerosene	$12 million	$91/MWh	$928	$27 billion
SAF	$12 million	$203/MWh [32]	$2071	$60 billion
Hydrogen Fuel Cell Electric	$25.6 million	$363/MWh [107]	$3703	$108 billion

Table 12: Operational costs of a bulk carrier over 20-year lifetime

Powertrain Type	2025 Powertrain Purchase Price	2025 Vessel Purchase price	2024 Fuel Cost ($/MWh) [108]	Voyage Cost	20 Year Lifetime Fuel Cost
HFO	$14.6 million	$127 million	$51/MWh	$1.24 million	$430 million
RNG	$18.9 million	$131.3 million	$42/MWh	$1.03 million	$357 million
Ammonia	$13.5 million	$126 million	$150/MWh	$3.65 million	$1.27 billion

In on-road vehicles such as the class-8 tractor-trailer, electric vehicles have a lower operational cost than conventional fuels while fuel cell vehicles have a higher operational cost due to the high cost of hydrogen fuel [6], [12]. In aviation applications SAF was assumed to be equivalent with standard kerosene jet fuel due to its drop-in capability, yet when considering operational costs SAF comes at a cost premium that decreases its economic viability [32]. The case is similar for hydrogen fuel, as only slight propulsion technology changes need to be made for HGT aircraft, but the cost of fuel is high [107]. The cost of battery replacements will be an important factor to consider in battery electric aircraft, due to the high charge and discharge rates and repeated cycles in daily operation that decrease a battery's overall operational lifetime. In the maritime sector, operational costs are the driving economic factor in propulsion technology decisions. The cost premiums of emerging alternative fuel engine technology are negligible compared to the difference in fuel price between HFO, RLNG, and ammonia. As seen in Table 12, the current cost of ammonia fuel is three times the cost of HFO [109]. The use of hydrogen fuel in rail and agricultural applications faces similarly high operational costs due to fuel prices [110]. Tables 10-12 present evidence that indicate the importance of operational costs such as fuel and maintenance in adoption scenarios. The costs of various fuels will change over the next 25 years and will need to be forecasted and included in an overall adoption analysis.

Vehicle Range Sensitivity

Another operational characteristic that must be considered is the required range of various vehicle types. Through decades of the use of fossil fueled powered vehicles, transportation logistics have been planned around the extended ranges of ICE powertrains [111]. This thesis used these conventional ranges as a baseline to compare alternative powertrains with those currently in use, yet changes in operational ranges and schedules could improve the cost and performance competitiveness of various alternative powertrains [112], [113]. This thesis found cost deviations across multiple operational use cases for light and medium duty vehicles, buses, class-8 tractor-trailers, maritime shipping, and freight rail. A few of these are highlighted in Table 13.

Table 13: Impact of required range on vehicle capital cost

Vehicle	Range	Capital Cost
BEV Transit Bus	50 miles	$495,000
	250 miles	$643,000
BEV Class 8 Tractor	300 miles	$275,000
	500 miles	$418,000
	700 miles	$561,000
BEV Freight Rail Locomotive	2000 miles (Line-Haul)	$19 million
	800 miles (Line-Switcher)	$7.5 million

The integration of operational costs and logistics and a broader range of battery and fuel cell cost forecasts will play a major role in this work's continued development. Work done to date incorporates a set of specific cost forecasts for alternative technologies and a limited set of vehicle ranges. It would be of use to perform a broad sensitivity analysis for each vehicle group that considers the spectrum of alternative technology cost forecasts and the various operational logistic options that affect performance requirements. The work completed to date alongside further developed operational studies would contribute to a full total cost of ownership analysis across a broad set of transportation modes.

CONCLUSION

The bottom-up cost analysis performed in this study produced trends that highlight the converging costs of alternative powertrains with conventionally fueled powertrains. The cost differences are initially very great, yet rapidly decline as technology such as batteries, fuel cells, hydrogen storage, and alternative engines improves, and manufacturing costs decline. The performance of alternative fuels varies across vehicle groups. Battery electric vehicles boast higher efficiencies, yet often prove to be too mass intensive to meet range requirements. Hydrogen fuel cell and storage technology shows promise to fill in the gaps left by downfalls of batteries yet is still very high in cost. Across all vehicle groups, different trends emerge that indicate future transportation scenarios.

The study underscores the emergence of competitive BEVs by 2035 in the light and medium duty on-road vehicle segment, while FCEVs grapple with initial cost challenges. Energy consumption analyses highlight BEVs' efficiency advantages, and trends point towards efficiency enhancements as vehicle gliders evolve.

Examining class-8 tractor-trailers, the research highlights the complexity of replacing diesel powertrains with zero-emission alternatives due to high energy and extensive range demands. The optimization of powertrain size for different applications will be important. BETs and FCETs face significant costs tied to battery and fuel cell components. Still, BETs provide a viable alternative for shorter range requirements, and when paired with fast charging during driver breaks, can be implemented for long-haul trucking.

Range and daily operating distances are critical in shaping zero-emission bus costs. Short-range BEBs emerge as cost-competitive with conventional diesels, while longer-range FCEBs offer economic advantages for intercity charter travel. Outdoor temperatures have a significant impact on energy consumption for buses due to passenger cabin heating and cooling requirements, most pronounced for BEBs and FCEBs.

Considering regional aircraft, the interplay between powertrain costs and range emerges as a pivotal consideration. Electric aircraft present lower purchase costs, yet reduced ranges due to battery storage technology challenge their feasibility. FCEAs and HGT aircraft stand out for offering feasible ranges, albeit at higher costs. Much of the analysis remains at the component and simulation level.

Within maritime transport, the study underscores that despite minor variations in engine and storage costs for large vessels, the impact of powertrain capital cost is marginal in comparison to total vessel cost and operational expenses. The significant influence of fuel costs on overall economic viability is highlighted.

Transitioning to freight rail, the study reveals that for long-distance line-haul operations, diesel-electric locomotives remain the most cost-competitive, while BELs prove expensive for extended ranges. Hydrogen fuel cell technology, leveraging liquid hydrogen storage, shows promise for long-haul freight. For line-switcher operations, BELs offer potential, with FCELs possibly competing with diesel-electric counterparts by 2050.

In agriculture, battery electric and fuel cell electric machinery often carry higher costs than conventional diesel options. Battery electric tractors face elevated expenses due to battery capacity, while the cost competitiveness of skid steers and mini excavators shifts with evolving battery and fuel cell technologies.

Forklifts highlight diverse powertrain choices, with lead-acid battery electric options currently reigning as the least expensive and widely adopted choice. Trends foresee a shift towards cost-competitive lithium-ion battery electric forklifts and diminishing expenses for fuel cell forklifts.

In summation, battery electric and fuel cell powered electric vehicles are the low-carbon powertrains with the most momentum/traction, yet their cost competitiveness heavily relies on the drop in price of batteries and fuel cells over the next 25 years. Improvements in battery technology and hydrogen storage will also expand the application possibilities of these powertrains.

Future Work

The future work outlined in the discussion section involves the integration of operational costs, a broader range of battery and fuel cell costs, and alternative vehicle ranges into a comprehensive sensitivity analysis. For this work to match much of the literature studies reviewed, full vehicle lifecycles must be considered. A large factor in this is operational cost, including but not limited to battery replacement costs. In electric aircraft, work will be done to study the relationship between battery capacity, operational battery life, and operational costs due to energy consumption and battery replacement. Battery and fuel cell costs are main cost drivers of alternative vehicles, and an analysis of a vehicle’s sensitivity to various cost projections would prove useful. Lastly, required vehicle range may vary as adopters plan new logistics that optimize the use of alternative vehicles, and predicting these variations would contribute to vehicle adoption. Studies like these will help contribute to a better understanding of alternative vehicle adoption scenarios, allowing for better, more informed decision making.

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APPENDIX

LDV & MDV Cost Model

Class 8 Tractor Cost Model

Buses Cost Model

Aviation Cost Model

Maritime Cost Model

Rail Cost Model

Agriculture Cost Model

Fork Lift Cost Model

LIST OF ABBREVIATIONS

AC – Alternating Current

ANL – Argonne National Laboratory

BEA – Battery Electric Aircraft

BEB – Battery Electric Bus

BEL – Battery Electric Locomotive

BET – Battery Electric Truck

BEV – Battery Electric Vehicle

CcH2 - Cryo-compressed Hydrogen

CNG – Compressed Natural Gas

CV – Conventional Vehicle

DoE – Department of Energy

E85 – High-level ethanol-gasoline blend

EPA – Environmental Protection Agency

EPRI – Electric Power Research Institute

EV – Electric Vehicle

FCEA – Hydrogen Fuel Cell Electric Aircraft

FCEB – Hydrogen Fuel Cell Electric Bus

FCEL – Fuel Cell Electric Locomotive

FCET – Hydrogen Fuel Cell Electric Truck

FCEV – Hydrogen Fuel Cell Electric Vehicle

GHG – Greenhouse Gas

GVWR – Gross Vehicle Weight Rating

HEB – Hybrid Electric Bus

HEL – Hybrid Electric Locomotive

HET – Hybrid Electric Truck

HEV – Hybrid Electric Vehicle

HFO – Heavy Fuel Oil

HGT – Hydrogen Gas Turbine

HICE – Hydrogen Internal Combustion Engine

HV – High Voltage

HVAC – Heating, Ventilation, and Air Conditioning

ICE – Internal Combustion Engine

LCRI – Low-Carbon Resources Initiative

LH2 - Liquified Hydrogen

LNG – Liquified Natural Gas

NREL – National Renewable Energy Laboratory

PHEB – Plug-in Hybrid Electric Bus

PHET – Plug-in Hybrid Electric Truck

PHEV – Plug-in Hybrid Electric Vehicle

RLNG – Renewable Liquified Natural Gas

RNG – Renewable Compressed Natural Gas

RoPax – Passenger Roll-on/Roll-off Ferry

RoRo – Roll-on/Roll-off Ferry

SAF – Sustainable Aviation Fuel