Summary and Evaluation of New Jersey Transit Bus Electrification Efforts

NJ TRANSIT'S ELECTRIFICATION EFFORTS AND THEIR EVALUATION - MASTER'S PRACTICUM

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A report on NJ Transit Bus Electrification Efforts

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Executive Summary

In recognition of the climate crisis, companies and governments worldwide are implementing strategies to reduce greenhouse gas (GHG) emissions. Electrification is a crucial strategy for decarbonizing the transportation sector. The transportation sector contributes 29% of the total US GHG emissions, and for New Jersey, this percentage is 42%. New Jersey has aggressive GHG reduction plans that include NJ Transit's fleet electrification. These plans outlay specific strategies for achieving carbon-neutral electricity generation, GHG emissions reduction, and an equally accessible community.

This report is based on the work done with NJ Transit in Summer 2021. The author of this report was assigned the following tasks:

1. Provide summaries of related GHG emissions reduction plans and laws and their evaluation to identify potential data gaps.
2. Highlight available charging infrastructure and their respective pros and cons.
3. Develop a tool to identify the best routes to deploy Battery Electric Buses (BEBs) during their pilot launch.

This report is also divided into three sections based on the tasks above. The first section offers summaries of these plans and their evaluation based on relevant knowledge and research data. What follows are the particular recommendations:

- Bus electrification is an effective strategy to curb GHG emissions arising from NJ's bus fleet running on diesel fuel.
- Battery-electric buses (BEBs) have reduced mileage and high cost than conventional diesel buses.
- NJT needs to consider alternate options to reduce GHG emissions until BEBs replace all the existing diesel buses by 2040.
- NJ Transit might want to invest in renewable energy infrastructure such as rooftop solar panels for garages and charging BEBs.
- NJ Transit may start transitioning towards BEBs by purchasing biodiesel buses or/and hybrid diesel buses as an interim strategy. Blending biodiesel up to a certain percentage (as high as 20%) in some cases is possible without requiring any engine modification. Appropriate arrangements for procuring biodiesel shall be required.
- Hybrid diesel buses also have higher mileage and lower GHG emissions than purely diesel buses, which can be a steppingstone toward BEBs. These buses do not require the installation of any unique infrastructure, like chargers for BEBs and biodiesel fuel pumps for biodiesel buses.

The report's second section briefs NJ Transit about the existing charging infrastructure for the battery-electric buses and various available options, such as on-route charging and depot charging. It briefly describes the overview, applications, and drawbacks of each kind of BEB refueling method. Fast pantograph chargers serve the best for very frequent routes that run on

small distances. Whereas, for longer routes with large layovers during their trips, level 2 depot charging serves the best purpose.

The last section of the report focuses on the excel tool developed for route analysis of the Newton bus garage. This tool provides duty cycles’ summary and sensitivity analysis of fuel economy for summer and winter weather. The tool also lists the specific routes which may or may not be able to complete their trip if replaced by BEB of a particular battery capacity. It also lists the routes that can repeat the same trip without charging in between.

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List of Abbreviations

AC: Alternating Current

ART: artillery

BEB: battery-electric bus

BPU: Board of Public Utilities

DC: Direct Current

DCFS: Direct Current Fast Charger

DEP: Department of Environmental Protection

EMP: Energy Master Plan

EPA: Environmental Protection Agency

EV: Electric Vehicle

EVSE: electric vehicle supply equipment

GHG: Greenhouse gas

GOV: government

GWRA: Global Warming Response Act

HEV: hybrid electric vehicle

HVAC: heating ventilation and air conditioning
IT: information technology

KPI: key performance indicator

LD: Light Duty

LLC: limited liability company

MMT: million metric ton

MO: Missouri

MW: Mega Watt

NJ: New Jersey

NJT: New Jersey Transit

NJT2030: New Jersey Transit 10-year strategic plan

NJTC: New Jersey Transit Corporation

NREL: national renewable energy lab

PA: Pennsylvania

PHEV: Plug-in Hybrid Electric Vehicle

SOC: state of charge

UK: United Kingdom

UN: United Nations

US: United States

ZEB: Zero-Emission Bus

Section 1

1.1. Introduction

There is little to no scientific doubt about climate change and the grave dangers and threats it poses to the planet earth and its inhabitants. Scientists across the globe have a near-unanimous consensus that it demands determined leadership and rapid actions to stop it and reverse it[1]. Today, 191 countries and the European Union have joined the Paris agreement on climate change, which calls for keeping the global temperature to 1.5°C above pre-industrial era levels [2,3]. This is why many countries make commitments to achieve carbon neutrality within the next few decades. Carbon neutrality means balancing emitting carbon and absorbing carbon from the atmosphere in Carbon Sinks [4]. This can be done locally at smaller scale processes or globally by deploying processes and techniques to capture the same amount of carbon emitted. This process of capturing or removing the carbon dioxide from the atmosphere and then storing it is known as carbon sequestration, a highly recommended technique to achieve net-zero emissions as simply curbing the GHG emissions might not help achieve the goal of carbon neutrality.

Achieving carbon neutrality by mid-century requires more than just setting the goals; it demands determining and demonstrating how any institution will accomplish that. Many countries, including the United States, have pledged to be carbon neutral by 2050, a few by 2060, including China, Kazakhstan, and Ukraine [5]. Few countries have passed their carbon-neutral targets like Denmark, France, Hungry, New Zealand, and the UK. A few US states, cities, and territories are also moving forward with legislation to help them achieve their carbon neutrality. Examples are New Mexico, Maryland, Washington, Puerto Rico, Los Angeles, Orlando, and Kansas City, MO. Many states are offering incentives for programs that will eventually lead them to be carbon neutral, like offering grants and rebates for installing solar and having hybrid or electric vehicles.

New Jersey has also been working on its goals to help them achieve carbon neutrality. Governor Phil Murphy set a carbon-free goal for the power sector in 2018 and directed the board of public utilities (BPU) to develop an Energy Master Plan, which was released in 2020. A further achievement in setting the goals was achieved by passing legislation: an Electric Vehicle Law, which was adopted on January 9, 2020. This EV law aimed to help NJ meet the targets of the Global Warming Response Act (GWRA) and its energy master plan. EV law is one of the few plans and goals to help NJ achieve carbon neutrality.

EV Law promotes the incentives and accessibility of charging for plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) and requires the state’s transportation authority, NJ Transit Corporation, to electrify its fleet. As per EPA 2019 report, the transportation sector accounted for more than a quarter of the US GHG emissions, followed by the electricity sector, as shown in Figure 1 below [6].

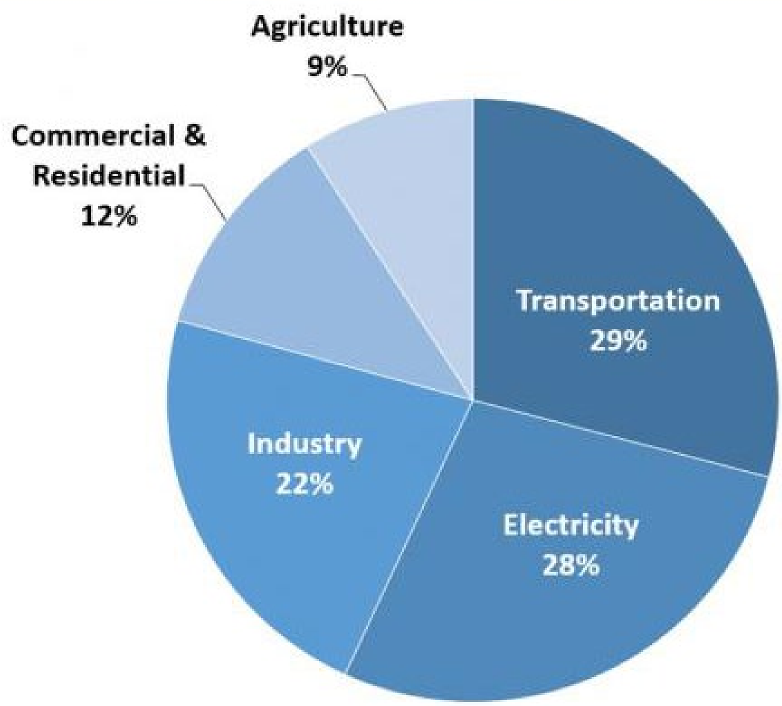

Figure 1: U.S. Greenhouse Gas Emissions distributions among various sectors with the transportation sector emitting 29% of the total GHG emissions

Following the requirements set by EV law, NJ Transit has also developed a few of its plans on carbon neutrality and sustainability. NJ Transit operates the country's most geographically expansive public transportation system, covering over 5,000 square miles in New Jersey and the surrounding New York and Philadelphia metropolitan areas [7]. Being such a massive system requires significant consideration of the organization dynamics when setting the targets and goals of the organization, particularly those related to carbon neutrality and sustainability. The most heavily used mode of the NJT system is their bus system, which primarily runs on fossil fuels. With all these considerations, the future of NJ Transit was laid out in their 10-year strategic plan known as NJT2030 with their strategic goals of ensuring the reliability of the transit system, delivering a high-quality experience, powering a fairer New Jersey for all, and promoting a more sustainable future by also building an accountable and inclusive organization.

The first section of the following report offers summaries of NJ and NJ Transit's published plans pertaining to fleet electrification, and GHG emissions reduction followed by the evaluation of each of these plans based on the relevant published knowledge in the context of state's broader GHG emissions reduction goals. Lastly, the author lists a few of his recommendations and alternative pathways that can help NJ and NJ Transit to achieve carbon neutrality, swiftly. The second and third sections of the report focus on NJ Transit's fleet electrification plans; the second section is the summary section for various available charging techniques for their upcoming electric buses deployment, and the third section describes the tool that was developed by me for NJT to streamline the process of electric buses deployment in their bus garages.

1.2. GHG reduction plans' summaries

1.2.1. Energy Master Plan

New Jersey's Energy Master Plan (EMP) sets forth a strategic vision for the production, distribution, consumption, and conservation of energy in the State of New Jersey. It outlines the rigorous plan to achieve 100% carbon-neutral for electricity generation. The plan also includes emission reduction from the transportation sector by 80% from 2006 levels by 2050. In NJ, the transportation sector alone accounts for 42% of the state's net GHG emissions [8]. This will be achieved through electrification and will help meet, or exceed, the Global Warming Response Act (GWRA) set emissions reduction standards. That is to reduce Carbon Dioxide equivalent (CO_2e) to 80% below their 2006 levels by 2050. The master plan is built upon seven following key strategies:

1. Reducing Energy Consumption and Emissions from the Transportation Sector,
2. Accelerating Deployment of Renewable Energy and Distributed Energy Resources,
3. Maximizing Energy Efficiency and Conservation, and Reducing Peak Demand,
4. Reducing Energy Consumption and Emissions from the Building Sector,
5. Decarbonizing and Modernizing New Jersey's Energy System,
6. Supporting Community Energy Planning and Action in Underserved Communities, and
7. Expand the Clean Energy Innovation Economy.

Executive order No. 100 was produced that directs the Department of Environmental Protection (DEP) to adopt regulatory reforms to reduce emissions and adapt to climate change within two years.

1.2.2. Global Warming Response Act 80x50 Report

The Global Warming Response Act (GWRA) 80x50 Report was written in response to the Global Warming Response Act mandate (reduce 80% of CO_2e emissions by 2050). It analyzes New Jersey's emissions reductions to date, evaluates plans presently in place for further emission reductions, and presents a set of strategies across seven emission sectors for policymakers to consider in formulating legislation, regulations, policy, and programs to ensure that New Jersey achieves the 80x50 goal that is defined below.

The GWRA established GHG goals by setting the targets of emissions reductions to the level of 1990 by the year 2020 and by 80% less than the 2006 level by 2050 (known as the "80x50" goal). It establishes the GHG reduction program for energy production inside and outside the NJ state. It also spreads public awareness by mandating the disclosure of environmental traits of energy on consumer utility bills and asking utilities to create their renewable energy portfolio standards and reduce their dependency on natural gas. It also motivates consumers to self-generate wind and solar power by providing credits. According to the report, the transportation sector represents the largest source of GHG emissions in New Jersey, followed by the combined residential and commercial sectors, as shown in figure 2 below [9]. This percentage is significantly higher than the US average. Trucks and buses, running on diesel fuel, are responsible for a disproportionate share of this pollution [10].

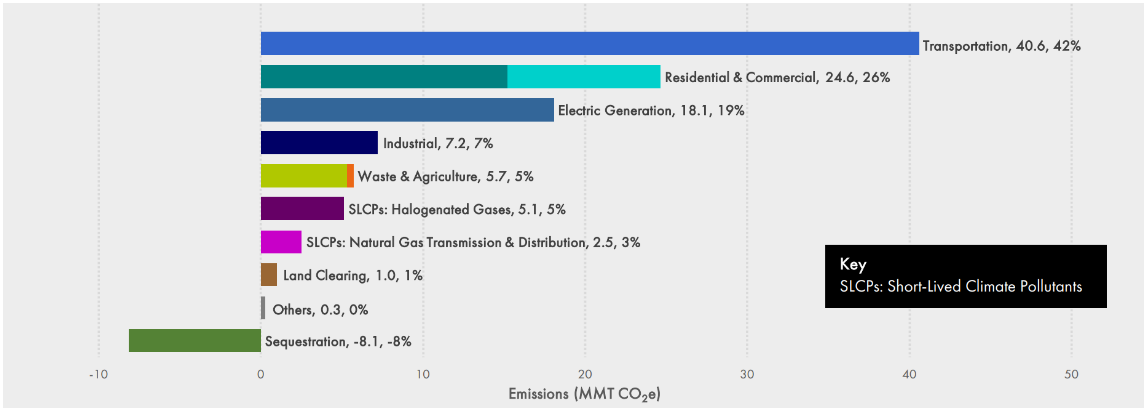

Figure 2: New Jersey GHG Emissions Inventory for 2018 (MMT CO_2e and percentage)

1.2.3. EV Law

The law, meant to meet the targets of GWRA and EMP, promotes electric vehicle supply equipment (EVSE) deployment across the state of New Jersey. It sets targets for achieving at least 330,000 light-duty PHEV by 2025, 2 million by 2035, and 85% of all new LD vehicles sold to be PHEV by 2040. Travel corridors are public roads in the state that are heavily used; a few examples are the Garden State Parkway, the New Jersey Turnpike, the Atlantic City Expressway, federal interstate highways and a subset of federal or state roads that support the majority of daily travel by local drivers and majority of long-distance travel through the state. By setting the objective of at least 400 Direct Current Fast Chargers (DCFCs) installation across the travel corridor and 1000 Level 2 chargers by 2025, EV Law also opens opportunities for the public to start considering transitioning towards either PHEVs or EVs since having plenty of charging stations boosts the confidence against the range anxiety. The EV Law requires at least 75 charging locations on travel corridors, equipped with at least two DCFCs per location, each capable of providing at least 150 kW of power, and no more than 25 miles between charging locations [11]. EV law increases publicly accessible charging infrastructure by requiring 15% of multi-family residential properties to be equipped with EVSE by 2025. It also requires 20% of franchised overnight lodging establishments to be fitted with EVSE by the same year, i.e., 2025.

To meet the targets, EV Law also sets forth a requirement for electrification of fleets. At least 25% of state-owned non-emergency light-duty vehicles shall be plug-in EVs by 2025 and 100% by 2035. It requires NJ Transit to purchase 10% of the new bus purchases to be battery-electric buses by 2024, 50% by 2026, and 100% by 2032.

According to this, the board of public utilities shall establish incentive/rebate programs for low duty PHEVs with $30 Million a year over the next decade and “Cash on the hood” Rebates of up to $5,000 (based on total mileage & price) [12]. This is in addition to Federal Tax Credit and State Sales Tax Exemption.

1.2.4. 5-year Capital plan:

This capital plan identifies the needed projects, budget considerations, and an aggressive schedule for improving the speed, reliability, safety, reach, and quality of NJ TRANSIT service [13]. This plan focuses on introducing improvements in transit structure and the modernization of bus garages and buses to provide efficient service and accommodation to a more significant number of riders with rising expectations. This plan also proposes purchasing zero-emission buses and building new garages to reduce the burden on the existing ones, some of which run over design capacity. With new garages and electric buses, NJ Transit hopes to promote a more sustainable future and help improve air quality.

The capital plan outlays the estimated future expenses related to garage modernization and fleet electrification over the next five years in a very holistic approach. NJ Transit hopes to achieve reduced lifecycle costs, improved health conditions, and improved customer satisfaction and fulfill the NJT2030 vision through these measures. This is dependent on infrastructure and equipment maintained to a state of good repair, which the plan hopes to achieve through capital investments.

1.2.5. 10-year strategic plan:

New Jersey Transit's 10-year strategic plan, also known as NJT2030, was released in June 2020. NJ Transit's 10-year strategic plan is built around five goals of ensuring the reliability and safety of the system, delivering high-quality customer experience, expanding equitable NJ to all communities, promoting a more sustainable future, and building an accountable and inclusive organization. The plan then lists various strategies to achieve each goal with some measurable success, such as achieving 95% on-time performance for bus, rail, and access link service and 98% for Light Rail by 2023 as a part of their goal one, which ensures the reliability and continued safety for their transit system. Goal 2 of delivering a high-quality experience for all customers has a measuring success of having one of the lowest crime rates of any extensive public transportation system and maintaining or improving the current national ranking of #2.

To make their services available to a broader population and power a more robust and fairer New Jersey for all communities, this plan shall increase the percentage of the NJ population that has access to high-frequency service from 27% to 40% by 2030. This will also require improving the accessibility so that 80% of riders use stations with accessible platforms by 2030, which will be more than the current 70%. Goal four, which is about a sustainable future, aims to increase system-wide ridership by 15% by 2030, purchase only zero-emission vehicles by 2032, and convert all buses to zero-emission buses by 2040 as per EMP.

1.2.6. Bus Garage Modernization:

This detailed document spans the five garages and their renovation/modernization to accommodate BEBs in the future. The most immediate is the Newton Bus Garage, with a limited deployment to be completed by Fall 2021. The limited deployment will accommodate 8 BEBs for the first phase. Similarly, the program plans to prepare the Hilton garage to accommodate 8 BEBs. The modernization program is divided into three stages: 1) design of 8 charging stations at Hilton and 10% design of the bus capacity at other garages along with their systemwide survey. 2) Concept design, preliminary engineering, and Recommended Garage Modernization IT

Improvements for Facility Operations, Management & Maintenance. 3) Final design and construction. This document is in the persuasion of NJ Transit's 5-year capital and 10-year strategic plan and fulfills the purchase requirements.

1.2.7. NJ Transit ZEB system design and investment planning study:

The investment planning study lays out various tasks required to be prepared for the deployment of BEBs. These tasks are focused on reviewing the current garage infrastructure and bus operations to assess the existing dynamics, followed by understanding the needs of the new infrastructure to accommodate a 500 BEB deployment. The last few tasks establish Implementation Phasing Options, Timeline, Benefit-Cost Analysis, and Cost Estimates.

This planning study is designed around 500 ZEB deployment that does not start until 2025, which, if possible, could be moved up ahead in the timeline.

1.3. NJ State's GHG emissions reduction plans assessment

1.3.1. GHG reduction through Electrification:

New Jersey's EMP targets are in line with GWRA and EV Law. EMP enlists the strategies to achieve those goals promptly, no matter how rigorous they might seem. Electrification is the linchpin in transportation emissions reduction goals, whether in transit buses or other vehicles. It must be noted that even though 42% of the State's emissions are coming from the transportation sector, emissions are also arising from the residential, commercial, and industrial sectors.

The building sector accounts for 62% of end-use energy consumption. Out of that, 36.8% is coming from Natural Gas-Fired power plants. Even though the master plan states the strategy of accelerated deployment of renewable energy, fleet electrification of NJ Transit could potentially put an increased burden on the electricity generation and existing renewable energy generation (currently at 4.8%) will not be sufficient to meet the GHG reduction goals in a timely fashion. As per the report [14], US will demand nearly 90% more power than it did in 2018, in a scenario in which all new passenger vehicles sold by 2030 are electric. Currently, the state plans to install 7500 MW of offshore wind energy. This translates to 29% of the current electricity generation capacity. However, as per the IEA report [15] the global electricity demand is projected to increase 4-5%. Similarly, the total projected electricity generation in the US is to be increased by 4% by 2023 from 2020 [16]. This will require further investment in renewable energy ventures beyond 7500 MW. Hence, a plan to continuously meet the need and continue growing the renewable energy blend in total electricity generation is required.

1.3.2. Promoting PHEV and EVs:

With the EV Act promoting and requiring a specific number and percentage of HEV and PHEV, this must be noted that this would increase the burden on the grid to charge the increasing number of PHEVs and EVs apart from the NJ Transit's electric fleet. To cope with this challenge, the state needs to meet the anticipated increased energy demand, and the individuals need to be encouraged to play their role, such as installing rooftop solar panels. Increased electricity demand might affect the continued supply, at least from clean energy sources.

1.3.3. Investing in clean energy:

With the plan of investing and deploying certain MW of solar and wind power [17, NJT Energy Master Plan], it must be noted that these resources are not available 24/7 and rely heavily on their energy source, sunlight, and wind, respectively. With the possibility of EV owners benefitting from decreased off-peak rates to charge their vehicles overnight, the increased demand must be met through sustainable clean energy sources, even when the sun is down, and the wind turbines aren't operating.

1.4. Assessment of NJ Transit fleet electrification

1.4.1. BEBs Procurement Plan:

EV law mandates NJ Transit that 10% of new purchases be BEB by 2024, 50% by 2026, and 100% by 2032. With BEBs costing twice as much as diesel buses [18], a financial plan outlaying the number of buses to be procured each year is necessary and is nonexistent, at least as of right now. Since the total number of buses purchased each year can vary, this will affect the number of BEBs to be bought. Hence, instead of requiring a percentage of total buses be BEBs, as the law stipulates, mandating the number of BEBs to be purchased each year can help in the efficient financial preparation as well as that of charging infrastructure development. Moreover, as learnt during the work with NJ Transit, it must be noted that BEBs are not as readily available as diesel buses. Knowing the number of buses to be purchased each year would streamline the procurement process (opening, filling, and finalizing contracts) and give the manufacturer their needed time to meet the demands.

1.4.2. Assessment Study:

A consultant prepared a Preliminary Engineering and Planning Assessment Study (PEPAS) for NJ Transit did an in-depth and thoughtful study of the prospective garage modernization and procurement of a 100% electric fleet at four garages. The study offers a detailed report of the future scenarios and cost comparisons of different charging infrastructure approaches. However, improvements or alternative methods might help NJ Transit achieve the targets faster.

1.4.2.1. Using reduced mileage as an advantage:

The study considers three scenarios of 20%, 50%, and 100% BEB deployment at the four garages studied. It also discusses the various charging options. However, while deciding the deployment and procurement approach at the four garages, it must be pointed out that NJ Transit's target is to achieve carbon-neutrality, and it should be prioritized. There can be a tradeoff between battery capacity and affordability. If purchasing a higher battery capacity is expensive, the option of reduced battery capacity should be considered if it helps reach the target of GHG reduction faster and cost-effectively since buses with smaller batteries have lower purchase costs than those with higher batteries. However, routes also require a minimum capacity to be completed which must be considered. The tool developed by the author and that is mentioned in the last section of this report can help in determinizing the suitable routes for a given battery capacity. Funding expensive BEBs, with bigger batteries can be a factor in the slow transition to ZEBs. Buses with smaller batteries have the drawback of offering low mileage but if these are fast charge buses, such as those using Lithium Titanate batteries [19], this can be turned into a positive factor as these fast charge buses also provide the advantage of quick charging through fast and ultra-fast chargers (5-10 minutes of charge can offer an hour of operation) [20]. Installing fast pantograph chargers across the route can provide the advantage of fast charging to these lower range buses and be used by long-range buses as Proterra offers addition of 24 to 33 miles for 10 minutes of charge via 500 kW EVSE. This will introduce an added challenge of route planning and sequencing to the garages and dispatchers; however, this problem can be addressed with adequate knowledge and training.

1.4.2.2. Inductive Charging:

The report also did not include the possibility of installing inductive chargers. This option might sound daunting as it requires underground connections and is relatively expensive than conventional conductive chargers [21]. However, the case of technological advances and increased adoption might make it beneficial [22], particularly for the scenarios where increased utilization over the day can distribute the cost and be utilized for charging buses with lower mileage.

1.4.2.3. Retirement and Replacement of BEBs

The PEPAS report either does not consider or mention the cost of replacing the BEBs purchased. Li-Ion batteries are limited by the charge cycle and need replacement once their batteries' capacity is reduced to 80% or less [23]. Typically, vehicle batteries are designed for a 10year/150,000-mile vehicle service life and be expected to have 80% of its nameplate amp-hour capacity at retirement [24]. However, based on experimental research data, battery life for buses in service for 8 hours per day is about 4 years [25]. NJ Transit must consider the plan of either to replace the batteries and associated labor cost or to replace the buses; both options would incur additional charges and potentially increased GHG emissions since the disposal of the bus would necessitate the production of a new one instead of just the batteries if only the batteries are being replaced. Continued usage of buses and only replacing the batteries can avoid those unnecessary emissions associated with the manufacturing of the bus housing. Although the PEPAS shows the option of 10% growth capacity, NJT needs to be prepared if the ridership increases or the demand for certain routes cause NJT to purchase more buses.

1.5. Beyond BEB/Low-Hanging Fruits:

BEBs have attracted increased interest in recent years when it comes to deploying 100% zero-emission buses (ZEB) and including NJ Transit many transit operators around the world are transitioning towards 100% BEBs; however, until that stage, where all buses are ZEB, arrives (somewhere around 2040), there are a few alternate scenarios that could potentially help NJT in reducing GHG emissions faster. The best effective, reliable, and readily available option from manufacturers like New Flyer and Gillig LLC is biofuel or hybrid diesel buses. Buses using Cummins engine can already accommodate B5 (5% biodiesel blended with diesel), and some can even accommodate as high a biodiesel blend as 20% without requiring any engine modification, [26,27]. Although 100% biofuel buses can cost slightly higher than the baseline diesel buses, these are much cheaper than BEBs. They are comparable in mileage and offer a tremendous immediate advantage of reduced emissions. Numerous studies [2,4,5] have shown a proportional decrease in GHG emissions with an increasing blending percentage of biodiesel. B20, a 20% biodiesel blend with diesel, does not typically require any engine or transmission modification [28], yet it still offers around a 12-15% reduction in lifecycle GHG emissions. With increasing blending percentage, the emissions can further be decreased. NOx can be a concern as biodiesel tends to cause an increase in NOx emissions [29]. However, this challenge can be answered with improved after-treatment systems/catalytic converters.

Unlike BEBs, these emission reductions are absolute as charging BEBs still emit GHG emissions from the grid electricity. Moreover, the primary aim of this strategy is to help the transition to lower GHG emissions as the immediate deployment of 100% BEB, to eliminate diesel emissions is not currently possible. Deploying biodiesel buses would help achieve GHG emissions reduction immediately rather than waiting for a few years to buy BEBs. Also, biodiesel buses cost cheaper than BEBs, at least around 30% cheaper[30].

A detailed study for the practicality of this option is needed to answer the questions such as below and more:

- Is the existing bus fleet able to accommodate biodiesel blends, and if so, what percentage of biodiesel blend can the engines run safely without requiring any modification? Moreover, if the modification is necessary, is it worth achieving a significant GHG reduction?
- Are the new buses being ordered able to accept biodiesel blends? If not, is it feasible to order ones that can take biodiesel blends?
- Should NJ Transit order 100% biodiesel buses, and should it require a certain percentage of new buses being purchased, to be biodiesel buses?
- How easily available is biodiesel? Who and where are the suppliers of it? Do we have to build new infrastructure, like pumps, to handle biodiesel, or can we somehow utilize the existing one?
- How much lifecycle GHG emissions reduction can the new biodiesel buses achieve, and what is the cost to benefit (GHG emissions reduction) ratio?

Those above are a few questions that need to be studied before procuring biodiesel blends or biodiesel buses,, [31,32,33]. Hydrogen-fueled buses are also another course of action. However, the existing infrastructure might not offer the feasibility of this venture.

Hybrid-diesel or hybrid-biodiesel buses are also a great option. These offer the immediate benefit of increased range? and reduced GHG emissions, although they do not offer 100% GHG emissions reduction yet perform better than conventional diesel buses in terms of fuel economy and emissions reduction. When used with B20, this can provide the maximum GHG emissions reduction possible without bearing the expenses of BEBs, for the time being.

Lastly, concurrent to the deployment of 100% BEBs, low-hanging fruit to benefit from and reduce the carbon footprint of NJ Transit, is to opt for renewable energy, the easiest of which is solar panels installation. Generating renewable energy to charge BEBs and power the garages is another faster and easier way to reduce carbon footprint. NJT may also consider investing in offsite wind farms to help NJT and the state achieve their renewable electricity goals faster.

1.5.1. Further Recommendations:

- Key Performance Indicators (KPIs) must be listed before the pilot study begins to ensure the effectiveness and success of the program.

- The training of drivers and dispatchers needs to be planned to get the best possible outcome of the program, particularly on best practices to drive and re-charge. Batteries perform better when charged at 40% to 70% instead of depleting them to 20% and charging them to 100% [35]
- Instead of fixing the number of chargers with the number of BEBs being deployed, installing more on-route and depot chargers can help speed up BEB deployment. It might incur more cost; however, having the confidence of fast charging availability can boost deploying more BEBs.
- The route assignment should be prioritized based on the areas at risk of pollutant exposure. This would help attain one of NJ Transit's 5-year capital plan goals.
- NJT’s 5-year capital plan anticipates that all goals will be achieved in a timely fashion. However, having a backup plan in case of difficulties and complications is strongly advised.
- NJ Transit’s 10-year strategic plan sets the goal of 100% clean energy by 2050 but does not provide a roadmap that achieves this goal. NJ Transit should study the least-cost clean energy pathways and identify initiatives to achieve this goal.

Section 2

2.1. Charging Infrastructure

2.1.1. Introduction

With numerous manufacturers of battery-electric vehicles and technology options, there exist various kinds of charging infrastructures categorized on different bases such as power source, either AC or DC, charging cables, either Mode 2 or mode 3, and charging plugs, such as Type 1, Type 2, or CHAdeMO. While purchasing BEBs and preparing the charging infrastructure, either at bus garages or on the route, these facts must be considered carefully since each method has advantages and disadvantages. For example, on-route charging can benefit from fast or ultra-fast chargers where buses have only a few minutes to stop. In contrast, in depots, they can be parked for a few hours until their next assignment and can be charged for a few hours benefitting from off-peak hours reduced pricing, if applicable. Below are the various categorizations of currently available charging systems.

2.1.2. Charging Speeds:

As per Society of Automotive Engineers (SAE) categorization, there exist three kinds of charging stations based on their input voltage and their charging speed known as altermatic current (AC) Level 1, AC Level 2, and direct current fast charging (DCFC) level 3 [36]. Level 1 chargers are the slowest of all, running on 120V AC and delivering the power of 1.4-2.0 kW. These chargers are generally installed at home to charge battery-electric or plug-in hybrid electric vehicles. Since they are running on single-phase 120V, they offer 3-5 miles per hour of charging. The next-generation AC chargers are Level 2 chargers which provide significantly higher power than Level 1, typically 7kW. These are also running on AC but at a higher voltage of 208-240V and offer 10-20 miles per hour of charge. Lastly, the most advanced type of charging station in the market these days are Direct Current Fast Chargers, also known as DCFC. The new revision of SAE standards further classifies DCFC into DC Level 1 and DC Level 2 [37]. These chargers are typically rated at 50kW and can charge up to 80% of the battery. The aforementioned charging times are for battery-electric cars. For buses, which tend to have bigger batteries than electric cars, DCFCs of higher power rating are required to truly benefit from fast and ultra-fast charging with minimum time available. Commercial DCFC for large scale electric fleet available with the power rating of as high as 1.5MW [38]

Charging speed, along with maximum voltage, and depth of discharge affects the rate of battery capacity loss [39]. Particularly for Li-ion batteries, higher charging and discharging current rates can accelerate cell degradation due to an uneven distribution of current, temperature, and material stress [40]. These unevenly distributed conditions can lead to uneven ageing, including deposition of metallic lithium, and SEI growth at certain parts of the electrodes [41]. Careful practices must be observed when charging since overcharging, one of the most serios problems, lead to the fast decay of battery life and can result in thermal runaway because external energy is being directly added into the battery [42].

2.1.3. Depot Charging

Depot charging refers to the charging infrastructure located within or near the facility where BEBs are stationed, for example, bus garages. Typically, BEBs are charged with plug-in connectors, just like most electric cars are charged at home. The overhead or underground charging infrastructure can also be installed depending on various factors such as capital cost, operational cost, utilization, and maintenance cost. The charging process can take anywhere between 1 to 8 hours, depending on the charging speed and battery capacity of BEBs. Overnight charging might be preferred for the reasons of low charging cost due to off-peak hours and potentially low ridership. However, to achieve a full day of running and charging only at night, buses should be equipped with large batteries to sustain running all day. Depot charging is currently the most popular option in the world [43]. Since charging speed is the priority, only DCFCs are used for depot charging.

2.1.4. On-Route Charging:

Although battery-electric buses being sold in the market can travel much longer than they used to a few years ago, they are still limited by the longer charging durations (1-5 hours) compared to filling a diesel bus with fossil fuel (typically 5 minutes). Diesel buses can run all day and night without any range limitation, provided these have 5-minutes of intervals to refuel; however, battery-electric buses can only travel a maximum of 300-350 miles (with current bus technologies available in the US market). This challenge can be met with the solution of on-route charging, sometimes referred to as “opportunity charging” [44] through high-powered fast chargers. On-Route charging can be classified into three types: 1) Conductive Charging, 2) Inductive Charging, and 3) Battery Swapping.

On-route conductive charging is carried out by installing a pantograph on the vehicle’s roof or mounted on an overhead charging station, generally known as an inverted pantograph. Buses equipped with this technology typically have sensors that communicate with the charging station for automatic docking. Charge time can vary as it is directly proportional to the charging power; however, 5-10 minutes of charging should be plenty to recuperate part of the energy for the remainder of the trip. The potential drawback for this type of charging station can be high installation and operational costs as the charging would be happening during peak hours and at high power.

Inductive charging, also known as wireless charging, has the benefit of occurring wirelessly without making any physical connection with the battery-electric bus. In this charging method, inductive charging coils are buried beneath the road at the bus stop. Like conductive charging, as the bus approaches the bus stop, it wirelessly communicates with the charging station to initiate the charging process. The benefit of inductive charger is that it provides electrical safety under all-weather conditions[45]. It can also eliminate a major stumbling block that is the range limitation. It can also encourage in acquiring BEBs with downsized batteries. The tradeoff, however, is the requirement of large-scale charging infrastructure deployment that incurs significantly higher capital costs, since the technology is newer and is not as common in the United States as conductive charging [46]. Based on the route characteristics, this study by Bi [47] shows that the battery downsizing for wireless charging bus can offer reduced Bus battery weight by as much as 73% and rate of energy consumption by 6.8%. The life cycle GHG emissions were not shown to be significantly different. However, these buses pose an increased peak load demand during the day requiring extra grid supply.

Lastly, the battery swapping method is as simple as it sounds. However, this is the least common among the three. This employs the physical removal of batteries with a low charge state and is replaced with already charged batteries. Generally, there are two types of operation modes for battery swapping system: central charging and local charging [48]. In the central charging mode, EVs swap their batteries in swapping station, and the empty batteries are sent to the central charging station. After empty batteries are fully charged, they are delivered back to the swapping station. The other mode utilizes a local charging system which charges depleted batteries in local battery swapping stations [49].

One working model for battery swapping exists in Qingdao, China. With the help of robots, the drained batteries are automatically swapped with the charged ones in seven minutes [50]. In Pohang, Korea, BEBs were equipped with a roof-mounted battery exchanging mechanism that could swap a battery in less than 1 minute. However, relatively smaller battery packs of 48.62 kWh are being used with one serving as the main battery pack and an optional second pack serving as backup or range extension [51]. Drawbacks for this method include the cost of additional batteries and the risk factors associated with the battery replacement process.

Section 3

3.1. BEB Deployment analysis

This last section of the project report focuses on the analysis of BEB deployment at NJ Transit's bus garages, mainly the Newton bus garage in Camden. NJ Transit is operating more than 2300 buses from 17 bus garages. Buses are assigned to each garage with specific duty cycles serving multiple bus garages. Only the Newton bus garage serves 109 duty cycles and has approximately 94 buses, as per information reported in May 2021. Inspecting each duty cycle, analyzing the route characteristics that it runs on, and then making the decision based on the calculation about battery-electric bus characteristics can be as cumbersome as it sounds, not to mention the possibility of errors that it can account for. To avoid all these hassles, save the workforce time, and set a standard to analyze a particular bus garage's duty cycle and route characteristics based on the provided BEB characteristics, an organized system or tool is required.

For the very same purpose, an excel based tool was developed to analyze the duty cycles being considered for deployment (of BEB) from the Newton bus garage with the added capability of analyzing duty cycles originating from other 16 bus garages as well as long as the duty cycle characteristics including, origin, start-stop, deadheads, route time, route length, and others are provided.

Based on the characteristics of the route that a particular duty cycle takes, the tool assesses if the bus can complete the trip with the desired minimum state of charge after the trip ends. The tool considers the total battery capacity, the HVAC load being put on the battery, and the minimum state of charge that the buses must have by the end of their respective trip. The tool also analyses two sensitivity analyses simultaneously: for winter and summer weather. For winters, the assumption is that heating is being provided through a separate accessory, a heat pump, running on diesel or biodiesel. For summers, however, the HVAC system is powered by the buses' batteries, taking a toll on the energy. For anonymity, the duty cycle numbers have been replaced.

3.1.1. Test Conditions

Even though the tool can take any desired test condition, however, for this project report, three cases are being presented: 1) ALTOONA test, 2) ALTOONA test with extreme mileage values, 3) ALTOONA test with highest energy consumption with HVAC.

The "Larson Transportation Institute's bus research and testing center," located in Altoona, PA, tests buses for maintainability, reliability, safety, performance, structural integrity and durability, fuel/energy economy, noise, and emissions [52]. A few BEBs were tested at this facility. Among those was a Proterra bus which gave an average energy consumption of 1.75 kWh/mile. BEBs were tested for three simulated courses being Central Business District (CBD), Arterial (ART), and Commuter (COM) phase. The first two cycles, CBD and ART, are 1.91 miles each with 7 and 2 stops per mile, respectively. The commuter phase is approximately 3.82 miles with a single stop. This bus's lowest energy consumption was 1.41 kWh/mile for the commuter phase, and the highest was 2.10 kWh/mile for the Arterial phase.

3.1.2. Assumptions

Following are the assumptions and test conditions:

1. This must be noted that the ALTOONA base test does not operate the bus with HVAC; however, it does consider the distributed passenger load.
2. Battery degradation has not been considered.
3. The impact of temperature on the battery capacity is not modeled
4. HVAC is running on battery and has a load of 15kW
5. Heating is provided through a heat pump powered by diesel or biodiesel
6. Desired minimum SOC is 30%

3.1.3. Base Case Scenario

Approximately 109 duty cycles are being operated from the Newton bus garage. With the base case scenario, the average fuel economy of 1.75 kWh/mile was used, taken from the ALTOONA test. As shown in figure 3 below, the tool shows that 100% of the buses can complete their first trip when running during winters, when the heating is provided through a heat pump and not through the batteries.

Can Complelte the Trip	Can repeat the same Trip?	No. of trips that can be repeated
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
No	No	0.00
No	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
Yes	No	0.00
No	No	0.00
Yes	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
Yes	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
No	No	0.00
Yes	No	0.00
Yes	No	0.00
No	No	0.00
No	No	0.00

Enter Desired Operating Conditions		
Bus Battert Capacity	487	kWh
Enter Mileage	1.75	kWh/mile
Enter HVAC load	15	kW
Desired Min. SOC	30	%

No HVAC	ALTOONA T	1.75	kWh/mile
30% HVAC	Foothill tra	2.2	kWh/mile
15% HVAC	Foothill cor	1.5	kWh/mile
	Proterra cla	1.43-2.33	kWh/mile
	DuoPower	1.28-2.08	kWh/mile

Bus Garage Summary			%
Total Number of Routes		109	
HVAC OFF	No. of routes able to complete the same trip	103.00	94.50
	No. of Routes that are able to make more than 1 trip	47.00	43.12
	No. of Routes unable to make one complete trip	6.00	5.50
HVAC ON	No. of routes able to complete the same trip	67	61.47
	No. of Routes that are able to make more than 1 trip	3	2.75
	No. of Routes unable to make one complete trip	42	38.53

Routes with peak characteristics					
Min. Dist.	40.859	miles	Min. Time	133	minutes
Corresp. Time	133	minutes	Corresp. Dist.	40.859	miles
Route	97		Route	97	
Row No.	100		Row No.	100	
Max. Dist.	195.36	miles	Max. Time	541	minutes
Corr. Time	437	minutes	Corr. Dist.	151.506	miles
Route	1		Route	13	
Row No.	4		Row No.	16	

Trip Distance (miles)				Trip Duration (min)			
From	To	# of busse	%	From	To	# of busses	%
0	50	0	0.00	0	25	0	0.00
50	100	0	0.00	25	50	1	0.92
100	150	1	0.92	50	75	7	6.42
150	200	2	1.83	75	100	27	24.77
200	250	2	1.83	100	125	21	19.27
250	300	4	3.67	125	150	23	21.10
300	350	8	7.34	150	175	19	17.43
350	400	26	23.85	175	200	11	10.09
400	450	29	26.61	200	225	0	0.00
450	500	18	16.51	225	250	0	0.00

HVAC OFF		HVAC ON	
Routes that can't camplete	Routes that can complete	Routes that can't camplete	Routes that can complete
1	7	1	68
2	8	2	93
3	9	3	97
4	10	4	
5	11	5	
6	12	6	
	13	7	
	14	12	
	15	13	
	16	23	
	17	25	
	18	26	
	19	27	
	20	28	
	21	29	
	22	30	
	23	31	
	24	33	
	25	34	
	26	35	
	27	36	
	28	37	
	29	38	
	30	41	
	31	42	
	32	43	
	33	44	
	34	45	
	35	46	
	36	48	
	37	56	
	38	71	
	39	73	

Figure 3: A partial sample of the excel-based tool showing the summary of duty cycles for the Newton bus garage.

The first block with highlighted row "Enter Desired Operating Conditions" asks the user to enter the bus-related information such as total battery capacity, energy consumption rate, HVAC load, if any, and the desired minimum SOC.

In the second block section of "Bus Garage Summary," the case scenario for summers, i.e., when HVAC is running on batteries, shows that up to 96% of the duty cycles can complete their first trip. While around 4% of buses cannot complete their first trip, there are at least 11 duty cycles that can complete the same trip again, at least one more time.

3.1.4. Sensitivity analysis:

As mentioned earlier, the arterial phase showed the worst mileage with 2.1 kWh/mile consumption. However, all the duty cycles emerging from Newton bus garage could complete their first trip with HVAC turned off. With HVAC turned on, however, 18 duty cycles could not complete their initial deployment, as shown in Fig. 2 below.

Enter Desired Operating Conditions		
Bus Battert Capacity	660	kWh
Enter Mileage	2.1	kWh/mile
Enter HVAC load	15	kW
Desired Min. SOC	30	%

Bus Garage Summary			%
Total Number of Routes		109	
HVAC OFF	**No. of routes able to complete the same trip**	109.00	100.00
	No. of Routes that are able to make more than 1 trip	56.00	51.38
	No. of Routes unable to make one complete trip	0.00	0.00
HVAC ON	**No. of routes able to complete the same trip**	91	83.49
	No. of Routes that are able to make more than 1 trip	9	8.26
	No. of Routes unable to make one complete trip	18	16.51

Figure 4: Summary of the Newton bus garage-based duty cycles for the worst-case scenario as outlaid by ALTOONA test

With the commuter phase showing the highest fuel economy, all duty cycles were able to complete their trip, be it the winter season or the summer season when HVAC is running on battery. Not only this but also the number of duty cycles which can repeat the same trip, at least one time, is 31 for the summer season. For the winter season, this increases to 102, making the composition of the number of buses able to repeat the same trip more than 93%. It must be noted that among these 102 buses, some would make the same journey more than twice.

Enter Desired Operating Conditions		
Bus Battert Capacity	660	kWh
Enter Mileage	1.41	kWh/mile
Enter HVAC load	15	kW
Desired Min. SOC	30	%

Bus Garage Summary			%
Total Number of Routes		109	
HVAC OFF	No. of routes able to complete the same trip	109.00	100.00
	No. of Routes that are able to make more than 1 trip	102.00	93.58
	No. of Routes unable to make one complete trip	0.00	0.00
HVAC ON	No. of routes able to complete the same trip	109	100.00
	No. of Routes that are able to make more than 1 trip	31	28.44
	No. of Routes unable to make one complete trip	0	0.00

Figure 5: Summary of the Newton bus garage-based duty cycles for the best-case scenario as outlaid by ALTOONA test

3.1.5. Listing eligible duty cycles:

Lastly, the tool also has the functionality of listing the duty cycles with specific characteristics such as duty cycles that cannot complete their first trip and duty cycles that can complete the same trip more than once. This option is available for both peak seasons, summer and winter. Figure 6 is an example of what the list might look like for specific operating parameters.

HVAC OFF		HVAC ON	
Routes that can't camplete	Routes that can complete	Routes that can't camplete	Routes that can complete
1	7	1	68
2	8	2	93
3	9	3	97
4	10	4	
5	11	5	
6	12	6	
	13	7	
	14	12	
	15	13	
	16	23	
	17	25	
	18	26	
	19	27	
	20	28	
	21	29	
	22	30	
	23	31	
	24	33	
	25	34	
	26	35	
	27	36	
	28	37	
	29	38	

Figure 6: Sample of the list showing duty cycles that cannot complete their trips and those that can complete the same journey more than once

4. Conclusion:

NJ Transit has several plans and ongoing efforts to support their fleet electrification in order to achieve their 100% BEB goal by 2040 and reduce GHG emissions. Four bus garages are under consideration for their initial deployment out which the Newton bus garage will have its first BEB by summer 2022. A preliminary assessment study was carried out by a consultant which has been reviewed and assessed in this document along with several other efforts. A few of the recommendations that could potentially help NJ Transit in rapid GHG emissions reductions and streamline their fleet electrification for the longer term are as follows:

- Deploy hybrid diesel buses for immediate GHG emissions reduction by reducing fuel consumption
- Consider purchasing biodiesel buses which can reduce CO_2 emissions up to 20%
- Consider investing in renewable energy efforts to reduce Scope 1 emissions
- Invest in ultra-fast over-the-head pantograph chargers for rapid charging buses at the bus stops serving most of the BEBs

An excel-based duty cycle assessment tool was also developed that analyzes the duty cycles originating from Newton bus garage and provides summaries for the routes. It runs the feasibility assessment of the duty cycles, which can be considered for initial BEB deployment by analyzing their distance and run time. It must be noted that the run time also includes the time of layovers, if any. The tool provides the summary for both season scenarios, summer and winter. Lastly, the tool also lists the specific duty cycles that are unable to complete their first trip for the desired operating parameters and the routes that can repeat the same trip at the same conditions, at least once, for both kinds of weather; summer and winter. The summer and winter weather can be identified based on the HVAC status. HVAC status represents summer weather when air conditioning is running. In contrast, HVAC off means winter weather when heating is provided through a heat pump not powered by the bus’s battery.

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