White Paper

The Electrification of School Buses

Assessing Technology, Market, and Manufacturing Readiness

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List of Acronyms

Acronym	Definition
BIL	Bipartisan Infrastructure Law
BABAA	Build America, Buy America Act
CARB	California Air Resources Board
CHIPS Act	Creating Helpful Incentives to Produce Semiconductors Act of 2022
EPA	Environmental Protection Agency
ESB	Electric School Bus
EV	Electric Vehicle
FTA	Federal Transit Administration
GHG	Greenhouse Gas
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program
IRA	Inflation Reduction Act
LCFS	Low Carbon Fuel Standard
MHD	Medium- and Heavy-Duty
MRI	Market Readiness Index
MRL	Manufacturing Readiness Level
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer

PM	Particulate Matter
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
V2G	Vehicle-to-Grid Integration

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Executive Summary

The United States government has invested heavily in deploying electric school buses (ESBs) to meet its climate, air quality, and public health objectives. As of 2022, there are 3,053 ESBs that have been funded, ordered, or deployed. This represents a small percentage of the 500,000 school buses in the United States. The Bipartisan Infrastructure Law provided $5 billion of funding to deploy ESBs through the Clean School Bus Program. The Clean School Bus Program is expected to greatly accelerate the pace at which ESBs will be deployed. In the Clean School Bus Program's first round, about 2,000 ESBs were funded.

The market's interest in ESBs is an encouraging sign for market transformation. However, to facilitate this transformation, the market will need to rapidly adapt to meet demand and prepare the market for mass adoption. As a result, an examination of the ESB market is warranted. CALSTART supported this effort by investigating multiple aspects of the ESB market including technology readiness, market readiness, and manufacturing readiness.

CALSTART evaluated the technology readiness of ESBs. Technology readiness was evaluated using a metric called technology readiness level (TRL). TRL is evaluated on a scale between one and nine, with one defined as a technology platform with scientific evidence for potential innovation and nine defined as a fully commercialized product that is in the early stages of market entry. TRLs can change over time with technological development, and they provide a way to compare a technology's progress over time. In 2021, ESBs were considered to have a TRL of 7.7 indicating that most ESB deployments were pilot projects. As of 2022, ESBs have advanced to a TRL of 8.5. This advance occurred because early ESB deployments allowed manufacturers to identify and address any performance problems that emerged in real-world operations. There were also several fleets that made large orders for ESBs through the Clean School Bus Program. This interest indicates that ESBs are moving away from pilot projects and toward at-scale deployments.

While ESB technology is rapidly developing, it is important to note that technological maturity is not the same as market readiness. There are several economic factors and non-technological barriers that can impede the development of the market. These factors include charging infrastructure availability, the development of a repair and maintenance service network for ESBs, manufacturing production capacity, total cost of ownership compared to traditional school buses, and the ability of ESBs to meet typical school bus duty cycles. ESBs need to overcome all these barriers to be considered "market ready." ESBs are considered market ready for the duty cycle factor and are making progress toward market readiness for the infrastructure, manufacturing production capacity, and total cost of ownership factors. However, the maintenance and repair service network for ESBs is still underdeveloped.

Manufacturing was also identified as a potential barrier to the growth of the ESB market. CALSTART identified several factors that pose barriers to manufacturing. These include supply chain disruptions for major components like high-voltage power electronics and chassis and increases in the price of raw materials. These barriers have led to significant delivery delays and increases in manufacturer backlogs. Despite these challenges, manufacturers have made significant investments in ESB manufacturing facilities. CALSTART assesses that manufacturers have enough industry-wide production capacity to meet ESB demand in the absence of supply chain problems. Furthermore, manufacturing capacity can also be scaled up to meet future increases in demand. CALSTART also analyzed manufacturing readiness levels (MRLs) to understand the maturity of the production process. There are major disparities in manufacturing readiness. Several manufacturers have developed small-scale production lines and are ready to experiment with serial production lines. However, other manufacturers are still in the pilot phases for their production line.

This study identified several barriers to the ESB market. These barriers will need to be addressed. To overcome these barriers, CALSTART recommends the following:

- **Establish Workforce Development Initiatives for ESB Maintenance Technicians:** School districts need to have maintenance technicians to keep their ESB fleets in good repair. As a result, school districts are very concerned about the shortage of maintenance technicians. This labor shortage needs to be addressed to facilitate widespread adoption of ESBs. The Federal Transit Authority has addressed this problem for the electric transit bus sector by funding workforce development initiatives. The Federal Transit Authority has also allowed transit agencies to use grant funding to pay for workforce development when they purchase electric buses. To date, there are currently no equivalent funding mechanisms in place to fund workforce development efforts for school districts. To address this problem, the EPA can allow school districts to use some of their awarded funding from the Clean School Bus Program to pay for workforce development.
- **Establish an American EV Component Supply Chain:** OEMs reported supply chain problems as a barrier to manufacturing. These supply chain disruptions were caused

by a variety of factors including COVID-19 lockdowns, disruptions at American ports, and the Ukraine-Russia War. Onshoring production is a potential solution for these problems as it makes the industry less vulnerable to foreign supply chain disruptions and geopolitical shocks. Legislation such as the Bipartisan Infrastructure Law, the Creating Helpful Incentives to Produce Semiconductors Act, and the Inflation Reduction Act have provisions that encourage onshoring of vital electric vehicle components. This legislation encourages the onshoring of vital components like batteries, inverters, and semiconductors by providing a production tax credit. However, it does not provide support for other vital components like DC-to-DC converters and high-voltage power electronics. These production tax credits should be extended to DC-to-DC converters and high voltage power electronics so they can receive comparable supports as other major ESB components.

- **Consider Funding for the Manufacturing of Repowered ESBs:** OEMs reported major shortages of medium-duty chassis. This problem has been made worse because other electric vehicle sectors, like medium-duty trucks and cutaway buses, also require chassis. As a result, this problem is likely to get worse as demand for all electric vehicle segments increases. Repowered ESBs can make use of an existing chassis on a traditional school bus and convert it to an ESB by installing an electric drivetrain. This allows OEMs to produce an ESB without needing to procure increasingly scarce chassis. There are currently few mechanisms for funding repowered ESBs through federal funding programs and only a few states have incentive programs that will fund repowered ESBs. The EPA Clean School Bus Program has restrictive eligibility criteria that only allows newer traditional buses to be repowered. The Clean School Bus Program should consider changing the eligibility requirements to allow some of the older school buses to be repowered. Further research should be conducted to determine rules for funding repowered ESBs and appropriate funding levels.
- **School Bus Standardization:** School buses are not a standardized product because OEMs must build buses to the specifications of their customer. Since each state and school district has different requirements for school buses, there are thousands of different specifications for school buses. This lack of standardization makes it difficult for OEMs to mass produce traditional school buses and ESBs because the production process is not entirely repeatable. The price of ESBs would decrease if there was greater standardization of ESBs. While it is not possible to standardize the entire ESB across jurisdictions, there are some smaller steps toward standardization that are more feasible. Industry can begin by standardizing certain parts of the ESB, such as

the location of the charging port. ESB funding programs can be designed to incentivize this standardization.

It is important to note that the ESB market is experiencing similar challenges as other zero-emission vehicle segments. The wider electric vehicle industry is also experiencing supply chain challenges and labor shortages for maintenance technicians. As a result, taking action to address these problems will benefit the entire zero-emission vehicles industry.

I. Introduction

The U.S. government has invested considerably in the zero-emission transportation sector to reduce greenhouse gas (GHG) emissions and to improve air quality. The government has particularly focused on medium- and heavy-duty (MHD) vehicles because while they are less numerous than their light-duty counterparts, they are responsible for 26% of transportation-related GHG emissions (EPA 2022b). MHD vehicles also produce criteria pollutants like particulate matter (PM) and nitrogen oxide (NOx) emissions.

Transit buses are the first MHD segment that transitioned to zero-emission technology at scale. The government supported the zero-emission transit bus sector with funding for technology development and demonstration projects. These efforts have greatly advanced the ZEB industry.

The U.S. government has also begun to focus on deploying electric school buses (ESBs). The Biden Administration has focused on ESBs because, like zero-emission transit buses, they produce fewer GHG emissions and eliminate criteria pollutants like PM and NOx, thereby improving air quality. This is especially important because school buses often operate in disadvantaged communities which already have elevated levels of pollution. Children, who are more vulnerable to air pollution, are also disproportionately exposed to the pollution that school buses emit.

The ESB market is currently in the earlier stages of market transformation. There are approximately 500,000 school buses transporting 26 million students every day in the United States; over 95% of those school buses run on diesel, which account for over five million tons of yearly greenhouse gas emissions (De La Garza, 2021). Less than 1% of the nation's school bus fleet is electric (Burgoyne-Allen and O'Keefe, 2019). As of September 2022, there are 3,053 ESBs that have been funded, ordered, or deployed in the United States. 846 of these ESBs have been delivered or are in operation (Freehafer and Lazer, 2023). To date, all but a few ESBs deployed have been new vehicles. However, some manufacturers are able to "repower" buses. This occurs by replacing an existing school bus's internal combustion engine with an electric drivetrain, thereby converting existing traditional school buses to ESBs. Repowered school buses could play a role in the transition to ESBs (Ly and Werthmann, 2023).

The Bipartisan Infrastructure Law (BIL) is expected to accelerate the deployment of ESBs. BIL provided $5 billion in funding between FY22-26 to fund the replacement of existing school buses with clean school buses, including low emission and zero-emission school buses. This funding is being distributed by the Environmental Protection Agency (EPA) through the Clean School Bus Program. At the time of writing, $1 billion in funding has been allocated through the Clean School Bus Program. This funding was awarded to nearly 400 school districts to purchase about 2,000 ESBs. This program is expected to play a transformative role in ESB deployments and commercialization.

While the ESB market lags that of zero-emission transit buses, the U.S. government aims to rapidly deploy ESBs. To keep matching the subsequent demand for these buses that will follow, ESB technology must mature to full commercialization quickly. As a result, an examination of the ESB market is warranted. This study will focus on examining the state of ESB technology and the factors that influence commercialization. Specifically, this study will focus on ESB technology readiness, which measures the progression of a technology from a mere concept to a product that is ready for early market adoption. It is important to note that technological development is not the same as market readiness, which refers to other non-technological factors that affect market acceptance of ESB technology. Lastly, this study will focus on the state of ESB manufacturing and industry's ability to meet demand for the vehicles.

Table 1. ESB Metrics

Metric	Definition
Technology Readiness Level	TRL is a method of estimating the maturity of a technology at a specific point in time. TRL is measured on a scale of 1-9
Market Readiness Index	Market readiness describes the viability of a platform to succeed when addressing production factors, economic factors, and non-technological barriers that could impede the development or adoption of a platform. For each indicator, MRI is measured on a scale of 0% to 100%, in 25% increments.
Manufacturing Readiness Level	MRL is a method of estimating the maturity of an entity's ability to manufacture a product at a certain point in time. MRL is measured on a scale of 1-10

It is important to note that these metrics interact with each other. TRL is a major factor for both MRI and MRL. MRI is not relevant until a vehicle segment reaches a certain level of technological maturity. Typically, this occurs when a TRL of 8 is achieved. Before this point, the lack of technological maturity prevents market adoption. Generally, when a TRL of 8 is achieved, the vehicle segment has undergone enough technological development to where other economic and non-technological factors prevent market adoption. TRL also constrains MRL. This occurs because vehicle segments with a lower TRL are less stable and are subject to major technological and design changes. Developing a mature manufacturing process for an unstable technology is not possible because changing the technology would require changes to the manufacturing process.

II. Technology Readiness

Technology platforms develop over time. Technology platforms start as a theoretical and unproven idea and then can advance to eventually becoming a fully mature product. Technology development can be measured through a metric called technology readiness level (TRL). TRL is a method of estimating the maturity of a technology at a specific point in time. This approach was originally developed by NASA and was later adopted by the Department of Defense. Other institutions like the European Space Agency have also adopted this approach (Héder, 2017). TRL is valuable because it can show how a particular technology has developed over time. It also provides a scale by which the technological status of different products can be compared.

TRLs are measured on a scale from one to nine, with one defined as a technology platform with scientific evidence for potential innovation and nine defined as a fully commercialized product that is in the early stages of market entry. TRLs take into account factors related to technological development. The primary method of measuring technological development is by analyzing the environment (i.e. lab environment, controlled conditions, real-world conditions) under which the technology platform can successfully operate. The definitions and general technology level of each TRL score are detailed below:

Table 2. TRL Criteria

TRL Level	General Technology Level	TRL Definition	Example Technology
9	Early Market	Full commercial application. Technology in general availability for users. Manufacturing phase. Successfully operated in uncontrolled commercial environment.	Battery-Electric Bus; Fuel Cell Electric Forklift; Methane Engine 8.9 Liters
8	Large Scale Pilot	Pre-production. First of its kind commercial system. Technology ready to support commercial activity. In limited release assessment numbers. Vehicle succeeds in uncontrolled environment.	Battery-Electric Harbor Craft Vessels; Battery-Electric Mobile Power Unit
7	Early Pilot/Late Demonstration	Demonstration system. Operating in intended environment at pre-commercial scale. Unit succeeds in a relevant environment.	Fuel Cell Electric Drayage; Fuel Cell Electric Harbor Craft Vessels
6	Early Demonstration (Advanced Prototype System)	Tested in intended environment at close to expected performance. Limited vehicle builds. Vehicle succeeds in first real world scenarios.	0.02 NOx Diesel Engine; Fuel Cell Electric Automated Guided Vehicle
5	Prototype	Large scale prototypes. Tested in intended environment; tested well enough to validate in real world scenarios.	John Deere GridCON Autonomous Tractor
4	Technology Development	Small scale (ugly) prototypes. First prototypes built and tested to perform under specific conditions.	Fully Autonomous Long-Haul Trucks
3	Research	Benefits and viability of technology confirmed in lab (Pre-Prototype).	-
2	Research	Early invention stage. Concept and application have been finalized.	-
1	Research	Scientific evidence for potential innovation.	-

CALSTART has adopted TRL analysis for zero-emission vehicles and has an established process for evaluating TRL. Determining a TRL score begins with the internal CALSTART team. CALSTART also consults with the California Air Resources Board (CARB), which has expertise in the state of technology for zero-emission vehicles. Members of the internal CALSTART and CARB team develop a list of vehicle segments (i.e. ESB, electric bus) and OEMs that produce vehicles in each segment. This scoring rubric is provided to industry experts to provide input on technology readiness. The methodology is detailed in Appendix A.

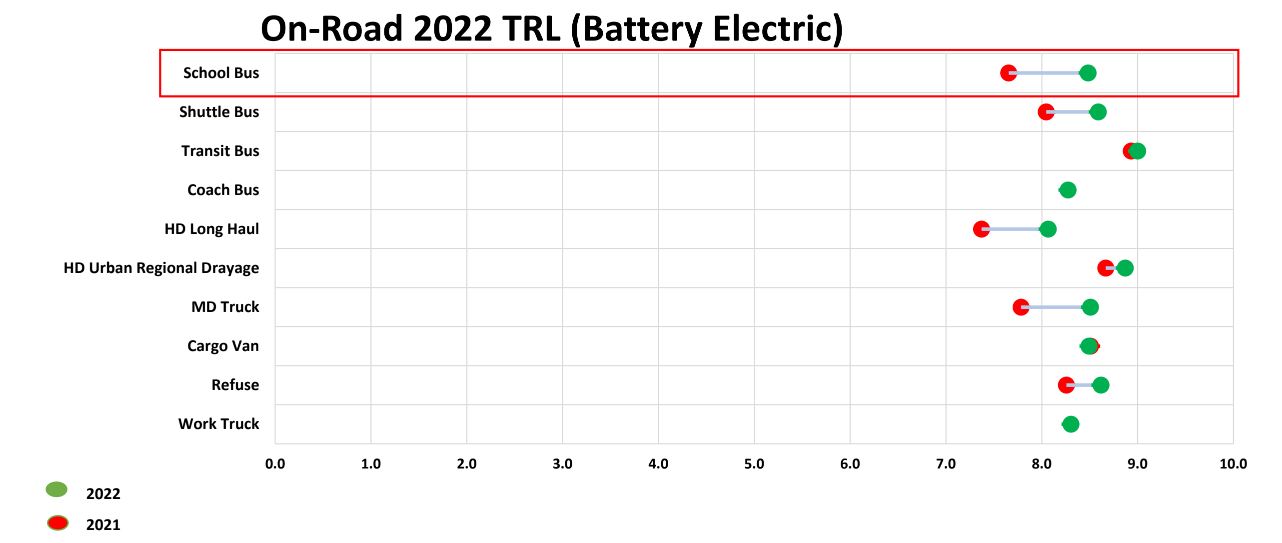
Once the list of vehicle segments and OEMs are finalized, internal industry experts score the technologies according to the scoring rubric. Each industry expert scores all OEMs within each vehicle segment based on their individual assessment of the vehicle's TRL.

A discussion is then held to calibrate results and rectify any large discrepancies in the scoring. Once each score has been vetted by industry experts, the results are aggregated. During the aggregation process, each vehicle evaluated is weighted based on a manufacturer multiplier, which gives a higher weighting to vehicles from companies that have larger market penetration and demonstrated ability to ramp up production. TRLs are expressed as the general weighted score for each vehicle segment.

Assessing Electric School Bus Technology Readiness

TRLs are useful because they provide a basis for comparing technological development. These comparisons can occur between different vehicle segments. Comparisons can also be made within the same vehicle segment at different points in time. CALSTART found that ESBs had a TRL of 7.7 in 2021. ESBs were assigned this score in 2021 because physical deployments of ESBs were low. Although there were many vehicles ordered, most had not been delivered. The number of school districts that had received ESBs was limited and each school district typically deployed only a few ESBs. As a result, the ESB deployments were effectively pilot projects. ESB TRL advanced to 8.5 in 2022. This was a substantial increase in TRL over the course of a year. This large advancement occurred for several reasons. First, the ESBs that had already been deployed had been in service. This real-world experience with ESBs allowed OEMs to uncover and address any problems or design flaws in their vehicles. 2022 also saw larger orders for ESBs. The EPA's Clean School Bus Program provided funding to school districts for ESBs. Many school districts used this program to fund ESB orders, which increased the number of school districts that will be employing ESB technology. Many of the orders placed for ESBs were large, with some school districts ordering 25 ESBs, which is maximum number of ESBs that can be funded through this round of the Clean School Bus Program. These developments demonstrated a move towards at-scale deployments, rather than pilot deployments.

Figure 1. Zero-Emission On-Road Vehicles TRL



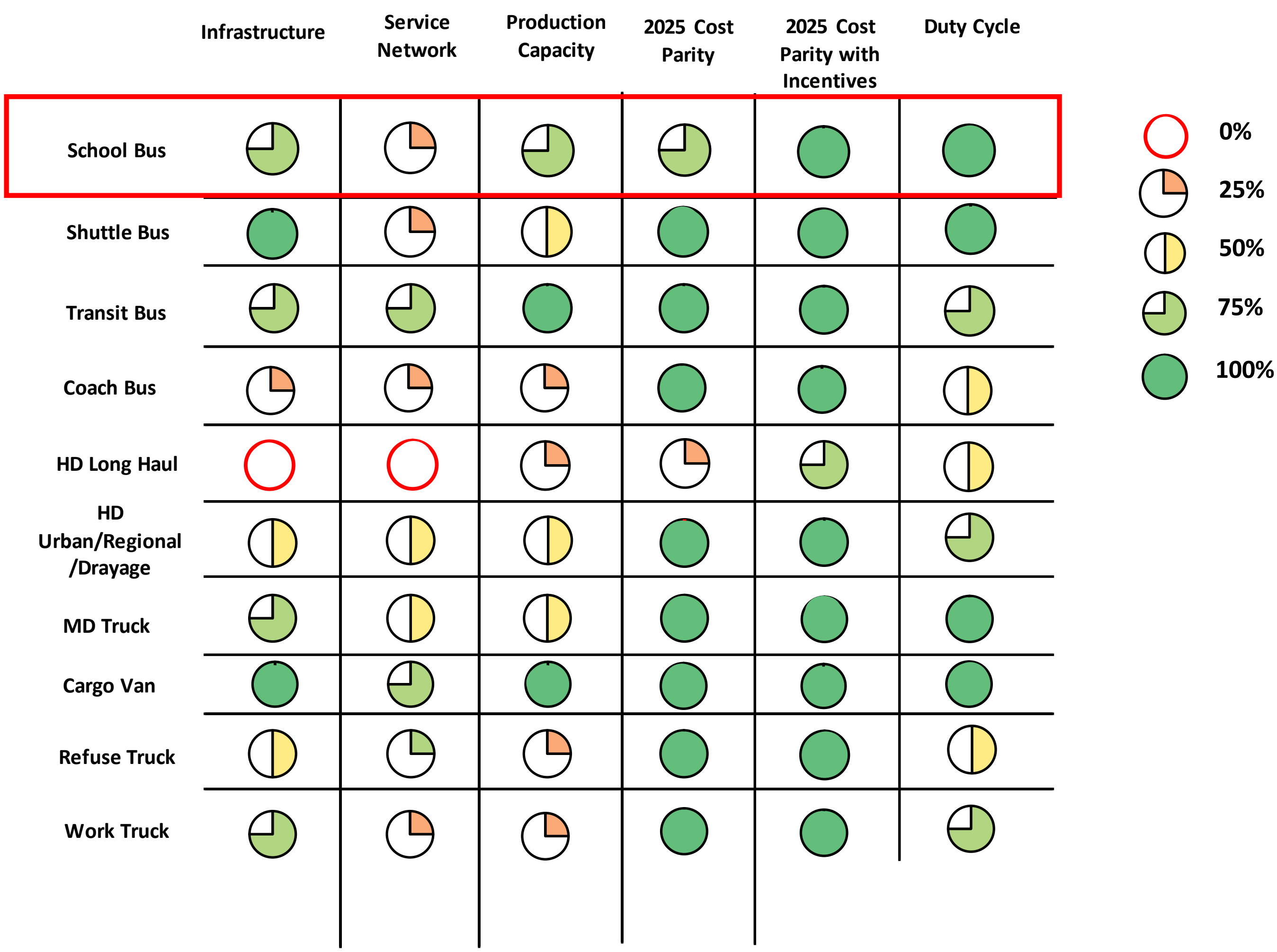
III. Market Readiness

A technology is considered to be commercialized when it reaches a TRL of 9. At this point, the market for the technology has transitioned from pilot projects to being an early market product. ESBs are rapidly advancing towards commercialization and technological maturity. However, technological maturity is not the same as market readiness. Market readiness describes the viability of a platform to succeed when addressing production factors, economic factors, and non-technological barriers that could impede the development or adoption of a platform. As a result, vehicles that are technologically mature can still face serious barriers to adoption.

CALSTART aims to quantify market readiness through the Market Readiness Index. MRI takes into account many non-technological barriers to deployment. These factors include infrastructure, service network, production capacity, total cost of ownership (TCO) cost parity (with and without incentives), and duty cycle capability. Similar to TRL, CALSTART evaluated each of these factors by determining a quantitative score for each of these factors. When a platform achieves a high score across all of these factors, it is likely that it will be commercially viable. However, if it does not have a high score across all of these factors, the platform will likely need market support, such as financial incentives or other actions to help fleets overcome barriers to deployment. The methodology for scoring the factors in the MRI is detailed in Appendix B.

Based on this analysis, the MRI analysis is displayed below.

Figure 2. National MRI Analysis for On-Road Vehicles



Assessing Electric School Bus Market Readiness

Infrastructure

ESBs scored highly for the Infrastructure criteria. Most ESBs are not in operation for a significant portion of the day. ESBs are most likely to be used in the morning to take students to school and in the afternoon to take them home. As a result, most ESBs are idle during the middle of the day and at night. Given the lengthy dwell times, most ESBs can be charged with Level 2 chargers. ESBs with a more rigorous duty cycle, such as longer routes and shorter dwell times, can use DC Fast Chargers.

ESBs, however, do face some challenges with deploying infrastructure. Deploying charging infrastructure can be a lengthy process, involving extensive design and engineering work and coordination with the utility company. Infrastructure deployment is usually lengthy if utility upgrades are required to support the infrastructure. Space constraints at the school district's depot can also complicate the installation of infrastructure. School districts oftentimes adapt to these problems by double parking buses in the depot or by having bus operators "park-out" at home. These parking arrangements can complicate infrastructure deployment and charging schedules. School districts will also need to navigate issues like charger interoperability and charger reliability and downtime. These challenges are common to other types of electric vehicles.

One unique challenge encountered by ESBs is the economics of deploying buses with a high upfront cost and low driving miles. If purchased without grant funding, there are cases where it can be difficult for school districts to realize a return on investment. Employing vehicle-to-grid integration (V2G) is a way to address this issue. V2G is a technology that allows the ESB to send power from the battery to the grid when signaled to do so by the electric utility (such as during times of high demand). Under this model, utilities pay school districts for the electricity sent to the grid. While V2G can provide school districts with a revenue stream, V2G-capable chargers are more expensive and more complicated than regular chargers. In addition, the utility interconnection process is more difficult than for traditional chargers. This barrier will need to be overcome.

Service Network

ESBs were given a score of 25% for the Service Network criteria. Traditional internal combustion engine school buses are maintained by either the school district or a contractor. Maintenance is typically carried out by diesel mechanics, who have expertise in repairing and maintaining diesel engines and other mechanical bus systems like brakes and suspension. This is an established occupation and there are multiple institutions, like community colleges and trade schools, that provide job training for this field. ESBs must be maintained by technicians who have expertise in mechanical bus systems, as well as electric motors and batteries. ESB maintenance technicians also need training in high-voltage electrical safety and specialized training on electric drivetrains and bus systems.

The skillset required to maintain electric buses is less widespread. Transit bus OEMs provide field service representatives to transit agencies to help them maintain and repair buses. Some transit agencies have begun to become more self-sufficient and are developing in-house expertise to maintain and repair ZEBs. However, ESBs are in an earlier stage of market transformation. As a result, school districts generally have not yet made this transition to self-sufficiency and are currently reliant on OEMs to send a field service representative to provide maintenance for ESBs. Under this model, it might take several days or even weeks for an ESB to be repaired. To address this problem, industry will need to expand training programs to address the shortage of maintenance technicians. This will likely require programs to both upskill existing maintenance staff and train new maintenance technicians.

It is important to note that the maintenance technician skillset is transferrable between different vehicle segments. For example, a maintenance technician that works on ESBs can also easily learn how to maintain other vehicles like electric trucks, electric transit buses, and even electric cars. As a result, increasing training programs for maintenance technicians will help to address the maintenance technician shortage for all vehicle types. However, this also creates unique labor market challenges for school districts. School districts typically offer lower wages than private sector fleets. As a result, there is a risk that school districts will have to compete with commercial fleets to hire and retain maintenance technicians. A similar dynamic has already occurred in the labor market for school bus operators (Towey, 2021). As a result, labor market competition represents a long-term barrier to the development of the service network for ESBs.

Production Capacity

ESBs scored highly for the Production Capacity category. ESBs are still in earlier stages of commercialization and, as a result, production capacity is relatively low. A major indicator for the maturity of manufacturing is the manufacturing process that OEMs employ. In earlier stages of commercialization, when production volumes are low, OEMs typically manufacture vehicles one at a time in a workshop. However, as the market matures, OEMs receive larger orders and begin to engage in serial production on an assembly line. The ESB market is currently in transition. Most OEMs produce vehicles in lower volumes in a workshop. However, there are some OEMs that are transitioning toward an assembly line production method. This topic is discussed further in the ESB Manufacturing section.

Cost Parity

Cost parity is an important factor for commercialization. Cost parity is measured as the difference between the TCO of a traditional school bus and an ESB. Cost parity is a major constraint for school districts and ESBs need to have a comparable TCO for school districts to adopt them.

Cost parity was measured based on Type C ESBs. The following assumptions were used for this analysis:

Table 3. ESB TCO Assumptions

Parameter	ESB	Diesel School Bus
Miles per Day	38	38
Lifetime (years)	12	12
Projected 2025 Vehicle Price	$340,000	$215,000
Sales Tax	20%	20%
Fuel Economy	1.5 kWh per mile	5 miles per gallon
Fuel Price	$0.22 per kWh	$4.21 per gallon
Maintenance Cost (per mile)	$0.705 per mile	$0.94 per mile
Midlife Costs	$0	$0
Registration Fees	$23,359	$29,398
Charging Power	19 kW	N/A
Charging Cost	$5,000	N/A
Infrastructure Upgrade Cost	$25,000	N/A
Residual Value (% of purchase price)	24%	24%
LCFS Credit Value	$100 per credit	N/A

CALSTART measured cost parity in two different ways. The first way is cost parity, which compares the TCO of traditional school buses directly to ESBs. This analysis is representative of ESB TCO for the majority of states, which do not have incentive programs for ESBs. CALSTART's analysis found that the TCO for ESBs is 5% greater than that of a diesel school bus. Based on this figure, ESBs scored highly on the TCO metric.

The second method for measuring TCO is "Cost Parity with Incentives." This method analyzes whether incentive funding can achieve parity between the TCO of traditional school buses and ESBs. This analysis is based on incentive funding from the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Program (HVIP) and Low Carbon Fuel Standard (LCFS) credits. HVIP provides incentive funding to entities purchasing zero-emission vehicles to offset the incremental cost of the vehicles. LCFS credits are awarded to entities that displace gasoline or diesel fuels with clean fuels. This analysis is representative of the TCO for ESBs in California, which offers both HVIP funding and a LCFS credits program. CALSTART's analysis found that the TCO for ESBs with incentives is 16% lower than that of a diesel school bus. Based on this figure, ESBs were considered to be commercially viable for the Cost Parity with Incentives Category.

It is important to note that these cost parity calculations reflect the TCO over the entire life of the bus. The upfront capital costs for ESBs are currently higher than traditional school buses. This will still pose a barrier for school districts. In addition, these calculations do not take into account funding from the Clean School Bus Program. The funding offered through the Clean School Bus Program is higher than that provided through HVIP. As a result, ESBs funded through the Clean School Bus Program will have an even more favorable TCO. In addition, this analysis only considers new vehicles. Repowered buses are cheaper than new vehicles (Ly and Werthmann, 2023) and would have a more favorable cost parity calculation than for new vehicles.

Duty Cycle

ESBs are considered to be commercially viable for the Duty Cycle criteria. ESBs were scored highly because school buses typically have low daily mileage with a gap in service during the day. As a result, ESBs have enough range to meet 90% of school bus routes (Huntington et al., 2022). It is important to note that school buses are also occasionally used for additional functions beyond transporting students to and from school. School buses are also used to transport students for athletic events, like football games. When school buses are used for these functions, they have increased daily mileage and a more rigorous duty cycle. ESBs might struggle to meet this duty cycle if their schedule does not allow for midday charging. A potential avenue for meeting this duty cycle would be to charge at public charging stations or at the school district that is hosting the athletic event. For this charging strategy to be viable, a more robust public charging network needs to be deployed and additional school districts need to deploy chargers that are compatible with ESBs. ESBs are also able to meet the required payload capacity as they can carry the same number of students as a traditional school bus. They can also deliver an equivalent amount of power and torque as a traditional school bus.

IV. Manufacturing Readiness

ESBs are in the early stages of commercialization. As of September 2022, there were only 3,053 ESBs in the United States that were funded, ordered, or deployed. However, interest in ESBs has grown sharply and there are now commitments to order approximately 13,053 ESBs (Freehafer and Lazer, 2023). The pace of ESB adoption is expected to increase as the U.S. government has committed more resources to facilitate deployments. The EPA is investing heavily in deploying ESBs. The Clean School Bus program is providing $5 billion in funding for cleaner school buses over five years. This program is intended to deploy cleaner buses to replace the current fleet of school buses. This program provides funding for cleaner internal combustion engine buses, powered by natural gas and propane, as well as zero-emission school buses. The BIL allocates half of the $5 billion to ESBs and half to cleaner internal combustion engine buses. However, in the funding allocated in FY22, approximately 90% of the funding was awarded to ESBs.

To date, ESBs comprise a small percentage of the school bus market. The 3,053 ESBs funded, ordered, or deployed represent a small percentage of the 253,159 school buses that were sold during the same period (School Bus Fleet, 2023). Since ESB deployments are expected to scale up rapidly, manufacturing capacity will also need to increase to meet demand. If manufacturing capacity cannot keep up with demand, manufacturing can pose a barrier to ESB adoption. As a result, industry's ability to manufacture ESBs is a salient topic. CALSTART conducted research to better understand the state of ESB manufacturing. This analysis was conducted by analyzing the ESB industry's Manufacturing Readiness Level (MRL), which quantifies the state of manufacturing and the maturity of the manufacturing process. However, MRL, by itself, does not measure the industry's ability to meet customer demand or any barriers that manufacturers are facing. To understand these other factors, CALSTART conducted research on manufacturing metrics and barriers and challenges to production.

Manufacturing Readiness Levels

The state of manufacturing can be quantified using a metric called Manufacturing Readiness Level (MRL). MRL is a method of estimating the maturity of an entity's manufacturing process at a certain point in time. This method was modified to estimate the ability of an OEM to manufacture ESBs. This approach was developed by the U.S. Department of Defense (Department of Defense, 2011).

MRLs are measured on a scale from one to ten. One represents the earliest stages of manufacturing, where basic research is being conducted on manufacturing needs. Ten represents the most mature stage where a full manufacturing system is established, and the manufacturing process is being optimized. MRL is connected to TRL because the manufacturing process cannot fully mature until the technology has matured. As a result, TRL typically places limits on how far MRL can advance. The definition of each MRL stage is listed below (Department of Defense, 2011):

Table 4. MRL Scoring Criteria

Scale	Definition	Minimum TRL
1	Basic Manufacturing Implications Identified	-
2	Manufacturing Concepts Identified	-
3	Manufacturing Proof of Concept Developed	-
4	Capability to produce the technology in a laboratory environment	4
5	Capability to produce prototype components in a production relevant environment	5
6	Capability to produce a prototype system or subsystem in a production relevant environment	6
7	Capability to produce systems, subsystems, or components in a production representative environment	7
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	7
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	9
10	Full Rate Production demonstrated and lean production practices in place	9

The data used to complete this analysis was gathered from interviews with OEMs. CALSTART interviewed nine OEMs between October and December 2022.

ESB Manufacturing Operations

CALSTART conducted qualitative analysis on ESB manufacturing to better understand the maturity of the manufacturing process. This analysis was conducted by interviewing OEMs to understand their manufacturing operations. Additional information was also gathered by analyzing regulatory filings that are made available by the U.S. Securities and Exchange Commission and the Canadian Securities Administrators (these documents are only available for OEMs that operate as publicly traded corporations). This information was used to analyze the manufacturing process that OEMs employ to build ESBs and to understand industry-wide manufacturing capacity. More information about the interview methodology can be found in Appendix E.

ESB Manufacturing Process

OEMs reported using different processes to manufacture ESBs. The manufacturing process that an OEM uses is largely dependent on manufacturing volume. Certain processes only become viable at high manufacturing volumes. CALSTART identified three general categories for ESB manufacturing processes.

Workshop

A workshop is used for low volume production. In a workshop process, the manufacturing facility contains several "bays" where vehicles are manufactured. These bays contain a lift or a pit so workers can have access to the bottom of the vehicle. These bays also have tools for manufacturing vehicles. The workshop production method can be implemented in two ways. One method is where the vehicle stays at the same bay throughout the entire production process, as components are added to the vehicle. As a result, each individual bay can only produce one vehicle at a time. Alternatively, each bay can be used for a specific part of the production process and vehicles are moved to different bays as they progress through the manufacturing process. This would be akin to an assembly line but on a much smaller scale. The workshop process is typical for OEMs that are producing low number of vehicles or are repowering traditional school buses that have an internal combustion engine.

Traditional Assembly Line

An assembly line process is employed by OEMs capable of serial production. Under this process, the vehicle is produced on an assembly line, which consists of multiple workstations in series. Each workstation is assigned a certain task in the manufacturing process. Certain components and systems are added to the vehicle at each workstation. Once the component or system has been added, the vehicle is moved to the next workstation so additional components or systems can be added to the vehicle. Once the vehicle has been moved from the first workstation, the first workstation is now available to add components or systems to another vehicle. This process is highly standardized and allows an OEM to have multiple vehicles in production on the same assembly line. Many OEMs have multiple assembly lines at their facility. This process is used by larger OEMs that are producing vehicles in high volumes.

OEMs reported that traditional assembly lines have limited automated procedures. This occurs because OEMs must build school buses to the specifications provided by their customer. Since each state and school district has different requirements for school buses, school buses are highly customized and there are thousands of variations of school buses. Due to this variation, the use of an assembly line with a high level of automation is not likely to occur in the near future.

Parallel Assembly Line

A parallel assembly line is a variation of the traditional assembly line. This process is used by legacy OEMs that have historically built internal combustion engine school buses but have recently entered the ESB market. The main premise behind a parallel assembly line process is that there are a lot of similarities between the manufacturing processes for internal combustion engine school buses and ESBs. These vehicles have many components in common, such as the chassis, and the main difference is that ESBs have a different drivetrain and other zero-emission components. As a result, the two vehicle types can use the same assembly line until the drivetrain, batteries, and other components need to be installed. At this point, the ESB is removed from the main assembly line and sent to a parallel assembly line, where the drivetrain and zero-emission components are installed. This production method is beneficial because it allows a legacy OEM to produce ESBs with minimal changes to the manufacturing facility and without disrupting the production of traditional school buses. As ESBs comprise an increasing share of sales, the parallel assembly line would transition to a traditional assembly line that produces ESBs.

Quality Control

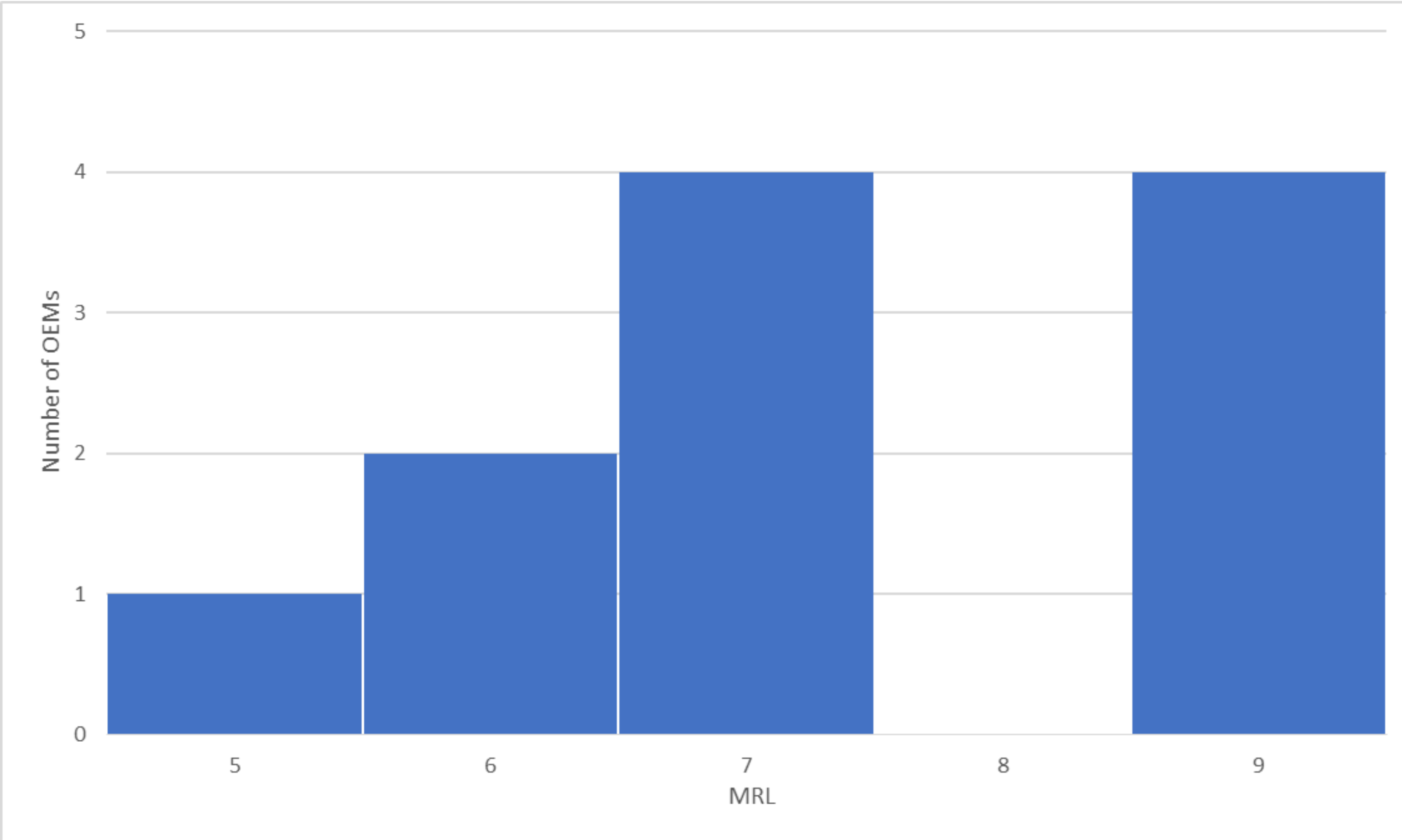
All OEMs employ quality control measures to ensure their production process builds reliable vehicles. OEMs reported a variety of quality control procedures. OEMs have quality control checks during the production process to ensure that individual components operate properly and are installed correctly on the bus. OEMs also typically test buses after they are fully manufactured. OEMs reported driving the buses through a few charging cycles to test the bus and ensure that the battery operates properly.

ESB Manufacturing Readiness Level Analysis

CALSTART used this data to conduct analysis on MRL for both individual OEMs and for the industry as a whole. The CALSTART internal team assessed the MRL for each individual OEM based on secondary research and information gathered from interviews with OEMs. MRL was assigned specifically based on an OEM's ESB manufacturing process, regardless of its ability to manufacture other vehicle segments. It is important to note that MRL is based on an OEM's capacity to produce ESBs, rather than the number of ESBs they have deployed. As a result, it is possible for an OEM with lower total sales to have the same MRL as a larger OEM. CALSTART also conducted analysis on industry wide MRL. CALSTART calculated an industry wide MRL by aggregating the MRL assigned to each individual OEM. The industry wide MRL was calculated using a weighted average. Each OEM's MRL was weighted based on the percentage of existing and announced manufacturing capacity that the OEM controls.

The MRL for each individual OEM was assessed. The distribution of MRLs for each OEM is displayed below. It is important to note that there are major disparities in manufacturing readiness across the ESB industry. Several OEMs were assigned an MRL of 9. This occurred because these OEMs have developed proven small-scale production lines. In addition, they are ready to experiment with serial production lines and are prepared to scale up production. There are also several OEMs that are in the earlier stages of manufacturing readiness. These OEMs are mostly new entrants to the ESB market who are still piloting their production process.

Figure 3. Distribution of Assigned MRLs



CALSTART also calculated the industrywide MRL as 7.9. While there are some OEMs that have a mature small-scale production line, other OEMs still need to further develop their production line. Industry-wide MRL is expected to increase as new market entrants gain more experience with ESB manufacturing and their manufacturing process becomes more mature.

ESB Manufacturing Metrics

CALSTART conducted analysis of ESB manufacturing by analyzing manufacturing metrics. Manufacturing metrics can provide insights into the current state of ESB manufacturing. They can also provide insights into industry-level trends. As a part of this study, CALSTART analyzed three major metrics to evaluate ESB manufacturing:

- Lead time: Lead time is the length of time between when a bus is ordered and when it is accepted by the customer. The lead time consists of two periods. The first period is "Time to Delivery." This consists of the time between when the order is placed and when the vehicle is physically delivered to the customer. The second period is the "Acceptance Period." This consists of the time between when the vehicle is physically delivered and when the customer accepts the vehicle, usually after a period of in-service testing. Lead time is an important metric because it measures the OEM's ability to deliver the vehicle in a timeline manner. A lengthy lead time can indicate that the OEM is facing delays or problems in their manufacturing process and that they will struggle to meet demand for vehicles. Long lead times harm the industry because they inhibit ESB deployments. This metric is particularly important in the context of the EPA's Clean School Bus Program because buses that receive funding must be delivered within two years of being awarded (EPA, 2022).
- Backlog: Backlog is the number of buses that an OEM has on order but has not finished producing at a specific point in time. Backlog is an important metric because it can reveal problems with manufacturing. An increasing backlog indicates that an OEM does not have sufficient manufacturing capacity to meet customer demand. It can also indicate that there are problems or delays in the manufacturing process.
- Manufacturing Capacity: Manufacturing capacity is the number of buses that the entire ESB industry can produce in a year. This metric is important because it acts as a constraint on how quickly ESBs can be deployed. If demand exceeds manufacturing capacity, orders will go unfilled. This will cause both lead time and backlog to increase.

Lead Time

CALSTART analyzed lead time using data from HVIP, which is the state of California's main incentive funding program for zero-emission vehicles. This analysis found the average lead time for ESBs is 707 days (approximately 23 months). Physical delivery takes an average of 577 days (approximately 19 months) and the average acceptance period is 130 days (approximately 4 months). It is important to note that there is a lot of variation in lead times.

This variation occurs between OEMs. In addition, there is significant variation in lead times within OEMs. CALSTART also analyzed how lead time has changed over time. The table below displays the lead time for ESBs that were funded in each year.

Table 5. ESB Lead Time

Year HVIP Funding Awarded	Number ESBs Ordered	Average Time to Delivery	Average Acceptance Period	Average Total Lead Time
2017	27	578	155	733
2018	30	288	52	340
2019	194	652	135	730
2020[1]	-	-	-	-
2021	294	560	136	696
Total	545	577	130	707

It is important to note that there are some limitations to this data. The data from HVIP only includes ESBs sold in California. However, since the vast majority of ESBs have been deployed in California, HVIP data was considered to be representative of nationwide ESB deployments. In addition, there were 302 vehicles ordered through HVIP in 2019 and 2021 that have still not been delivered as of February 25, 2023. 65 of these vehicles were ordered in 2019 and the remaining 237 were ordered in 2021. HVIP rules normally require OEMs to deliver vehicles within 18 months. However, extensions had to be granted due to supply chain problems.

Given the length of time that has elapsed since these ESBs were awarded funding, these vehicles increased the average lead time. CALSTART used February 25, 2023 as the delivery date for these vehicles in this analysis to capture this. However, since these vehicles were not actually delivered as of February 25, 2023, the actual lead time for these vehicles will be higher. As a result, the delivery time figures for 2019 and 2021, underestimate the actual lead times.

[1] No ESBs were funded by HVIP in 2020

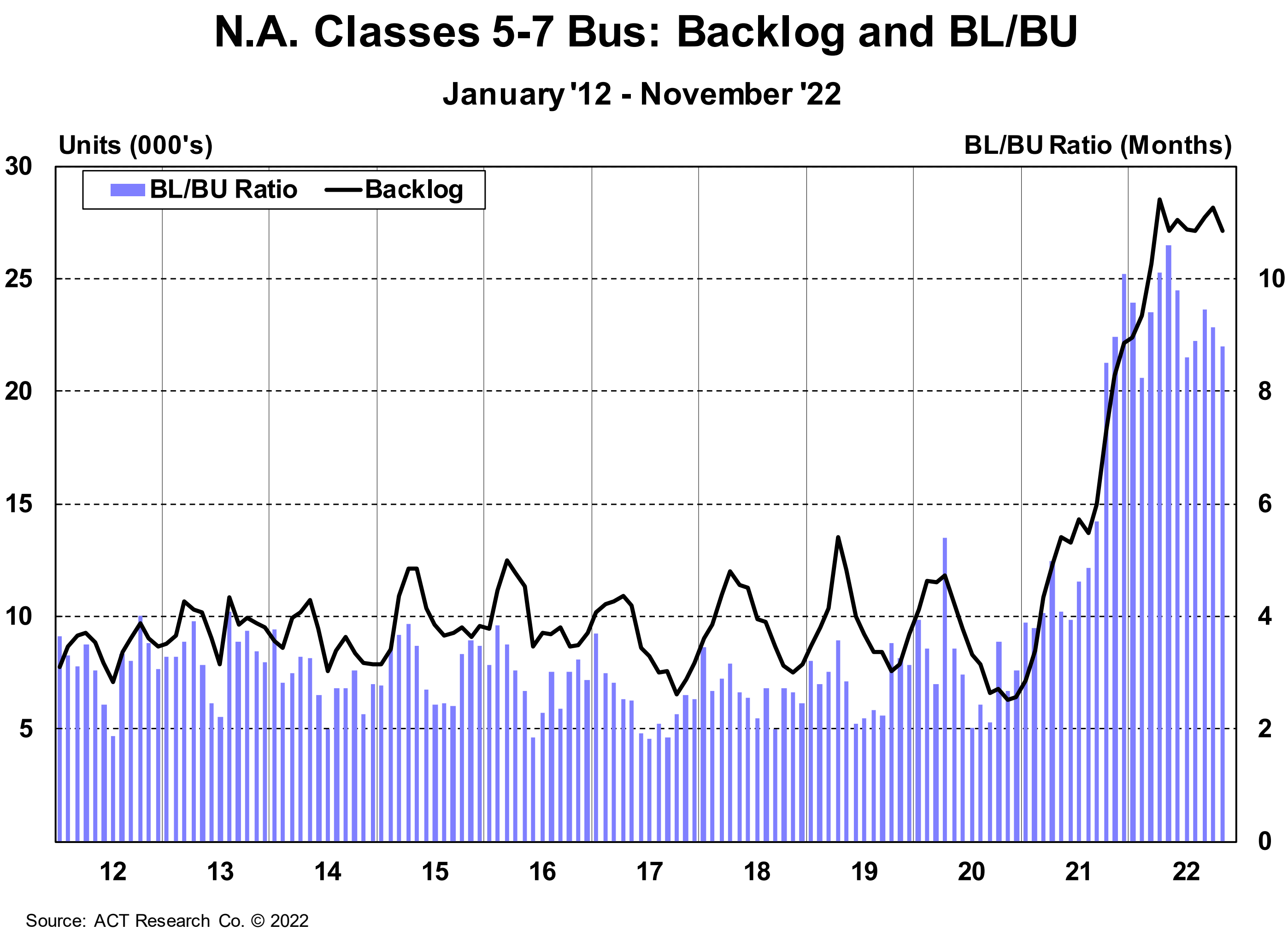
This data shows that the average lead time has remained high over time. In 2017, lead times were high because ESBs were a new technology and OEMs were establishing their production process for the first time. Lead times started to decrease as OEMs became more proficient at manufacturing. However, lead times increased for vouchers awarded in 2019 and after. OEMs cited COVID-19 pandemic-related disruptions and supply chain issues as the primary reason for this increase. This topic is explored further in the Barriers to ESB Manufacturing section.

Backlog

Many reports indicate there has been an increasing backlog for vehicles in the bus and transit sector. The American Society of Civil Engineer's 2021 Report Card for America's Infrastructure indicates that about $176 billion of transit vehicles and transit infrastructure in backlog (American Society of Civil Engineers, 2021). Data from ACT Research confirms this. As of 2022, there were more than 25,000 Class 5-7 buses (both traditional buses and ESBs) in backlog in the North American market.[2]

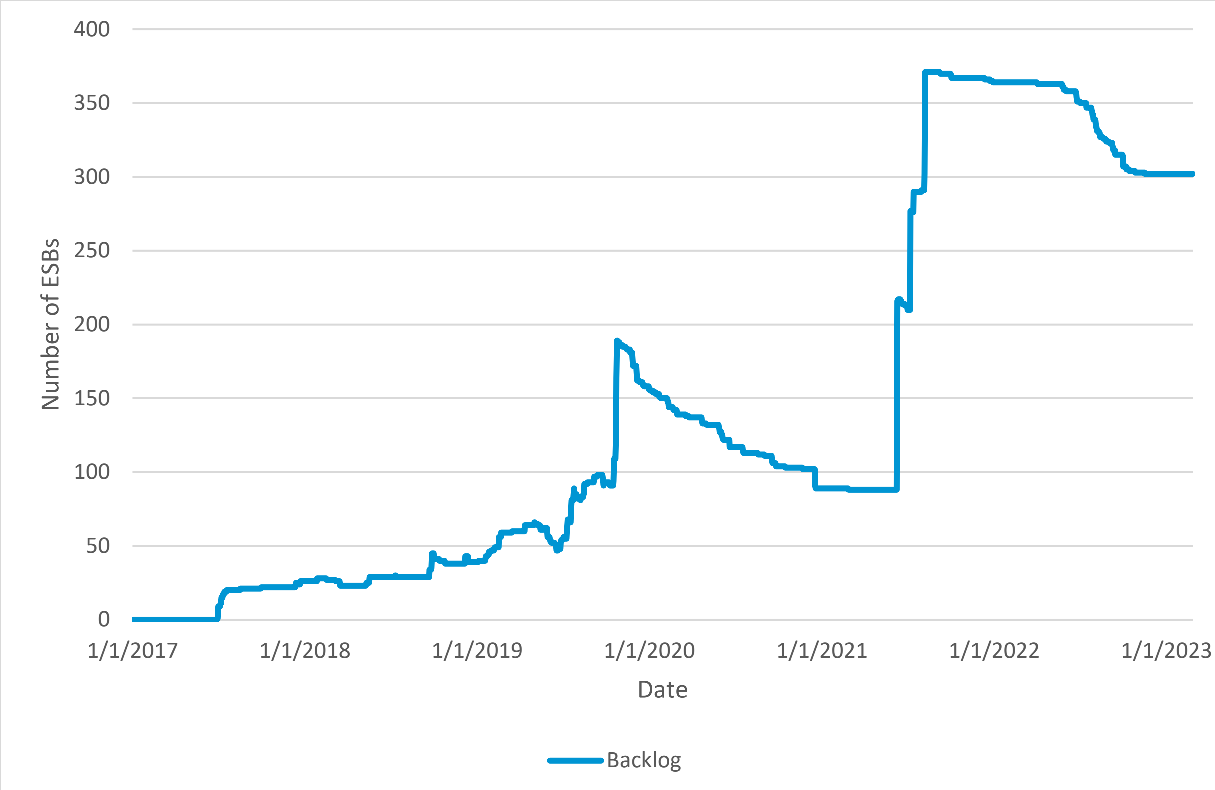
[2] Since this data only includes Class 5 – 7 buses, Class A buses are not included in these backlog figures.

Figure 4. North American Class 5 – 7 Bus Backlog Data (ACT Research Co., 2022)



This data indicates that the entire bus industry is experiencing increasing backlogs. Furthermore, there have been media reports about this problem occurring in the zero-emission transit bus industry (Zukowski, 2022). Given the prevalence of backlogs in the bus industry, CALSTART collected data on backlogs for ESBs. Based on HVIP data, CALSTART found that the ESB market segment is also experiencing increasing backlogs. The backlog increases rapidly during every HVIP funding window before decreasing as ESBs are either delivered. However, historically, deliveries have not kept pace with news orders, which has led to increasing backlogs. The ESB market's backlog is also exhibiting similar patterns as the rest of the North American bus market. Like the North American bus market, ESBs have experienced a major increase in backlogs. In addition, the backlog for ESBs started in 2021, mirroring that of the North American bus market.

Figure 5. ESB Backlog for HVIP-Funded ESBs

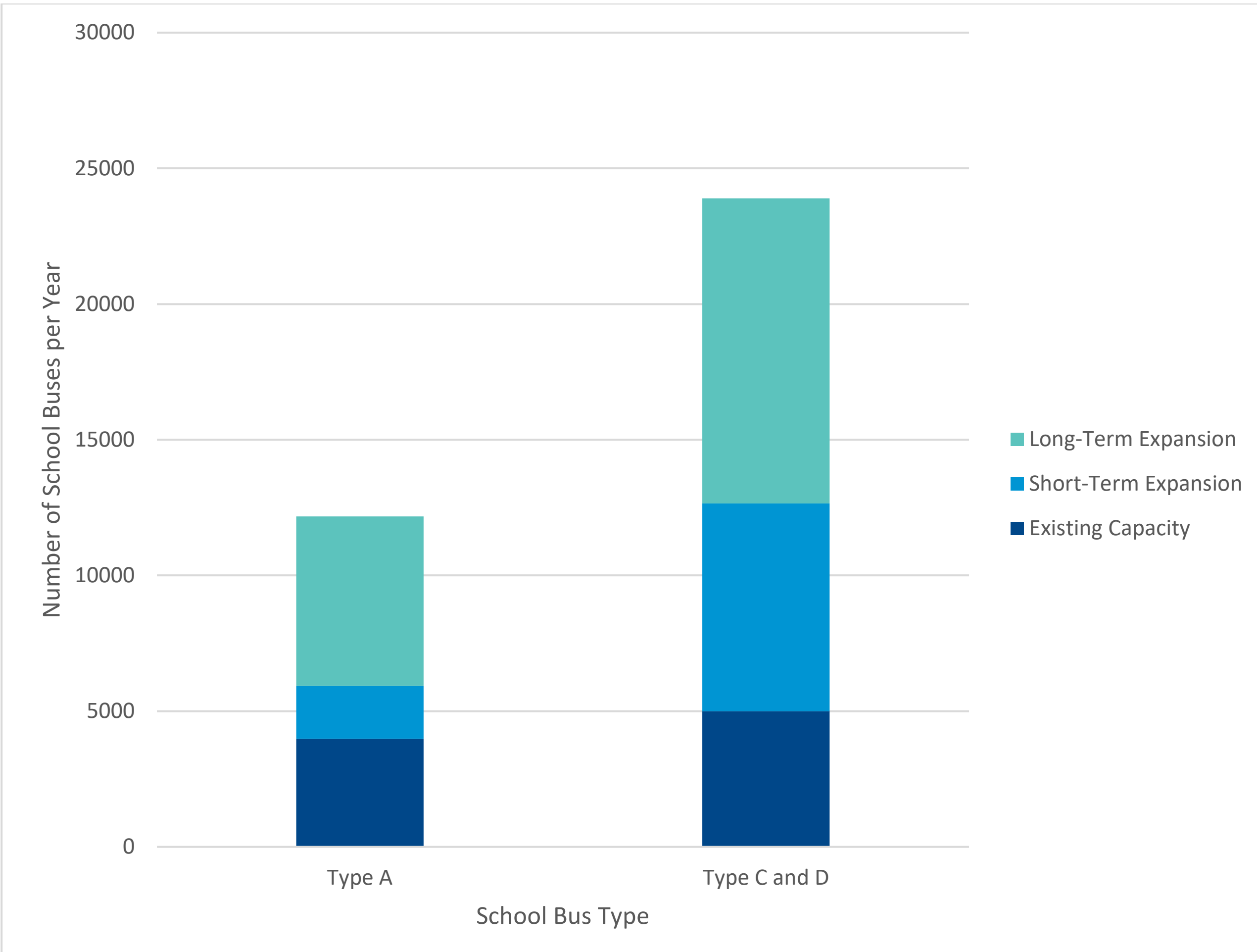


It is important to note that this backlog data is based on HVIP data. HVIP data only encompasses ESB sales in California. As a result, this backlog data does not include any ESBs purchased outside of California or that have been funded by the EPA's Cleaner School Bus Program. Due to these limitations, this data should be used to gauge trends in ESB backlog, rather than as a comprehensive count of the ESB backlog. More information about the methodology can be found in Appendix D.

Manufacturing Capacity

Since the ESB market is expected to grow rapidly, manufacturing capacity can emerge as a potential barrier to ESB deployments. CALSTART calculated estimates for the industry-wide manufacturing capacity for ESBs. CALSTART gathered data by interviewing individual OEMs to understand how many vehicles can be produced each year. This data was broken down into three categories: existing capacity, short-term expansion, and long-term expansion. Existing capacity is manufacturing capacity that exists today. Short-term expansion is manufacturing capacity that is expected to come online by the end of 2024. Long-term expansion is announced manufacturing capacity that is expected to come online after the end of 2024. This data was then aggregated to determine the industry-wide manufacturing capacity. This data was also broken down by school bus type. The results are displayed below in Figure 6. It is important to note that this data is subject to change if OEMs announce further investments in manufacturing capacity or if any announced plans are cancelled. The methodology used to conduct this analysis can be found in Appendix D.

Figure 6. Annual Industry-Wide ESB Manufacturing Capacity



Existing capacity represents manufacturing capacity that exists today. Short-term expansion represents manufacturing capacity that is expected to come online by the end of 2024. Long-term expansion represents announced manufacturing capacity that is expected to come online after the end of 2024.

It is important to note that some OEMs reported that ESBs require more labor hours to produce than a traditional school bus because the installation of high-voltage circuits is more labor intensive. This difference in labor hours will decrease over time as workers gain more experience installing high-voltage circuits. However, the number of labor hours between the two vehicle types is not expected to reach parity. This manufacturing capacity analysis does not account for this difference in required labor hours.

Furthermore, manufacturing capacity is not static and can change over time. Manufacturing capacity can change if an OEM modifies its manufacturing process or invests in additional or expanded manufacturing facilities in the future. The results from this analysis are based on data collected through interviews and are subject to change if OEMs decide to invest in further manufacturing facilities or cancel plans to build announced facilities. However, OEMs, in interviews, indicated that they also have the ability to increase manufacturing capacity without expanding their existing facilities or investing in new facilities. Most manufacturing facilities are only operating on one shift per day. Most OEMs indicated that they could increase production capacity by introducing additional shifts per day. The main constraint on this strategy would be hiring additional labor. Many of the OEMs interviewed also stated that they have more room at their existing manufacturing facilities to expand production. These OEMs stated that they can also expand production by building additional factory space. Increasing production in this manner would require capital investment for production equipment and additional labor to build buses. These figures do not include the ability to scale up production by adding additional shifts.

The EPA Clean School Bus Program awards that were announced in October 2022 provided funding for about 2,000 ESBs. This figure includes Type A and Type C & D ESBs. On the assumption that the same number of ESBs are funded every year, CALSTART predicts that there is enough manufacturing capacity to produce the buses funded under the Clean School Bus Program.

Barriers to ESB Manufacturing

CALSTART's analysis uncovered several barriers to manufacturing including supply chain for zero-emission components like batteries and electric motors is a major vulnerability for OEMs (Huntington et al., 2022; Zukowski, 2022). In corporate regulatory filings, some OEMs also cited price increases for raw materials due to the Ukraine-Russia war, labor shortages, and labor wage increases as a barrier to manufacturing. CALSTART interviewed OEMs to see whether they faced these problems and how these problems affected their specific manufacturing operations. CALSTART also sought to uncover whether OEMs were facing supply chain and labor barriers to ESB manufacturing. The results from these interviews are detailed in this section.

Supply Chain

One of the barriers to ESB manufacturing that was universally reported by OEMs was supply chain problems. OEMs reported supply chain problems made it difficult to obtain the parts required to manufacture ESBs and other electric vehicle types in a timely manner. HVIP also cited supply chain problems as a cause for delayed deliveries.

CALSTART identified multiple factors that drove supply chain problems. COVID-19 pandemic disruptions were a major cause of these disruptions. This was especially true for OEMs that source components from overseas. COVID-19 lockdowns in China caused major disruptions to component manufacturing. In addition, backlogs at major American ports also led to delays in the delivery of imported components. Geopolitical factors also drove supply chain problems. The Ukraine-Russia war disrupted the supply chain of raw materials. Some OEMs reported that the Ukraine-Russia war caused the price of raw materials to increase. OEMs also identified supply chain issues in semiconductors, both legacy and modern, as a direct driver of supply chain problems for ESB components. Furthermore, since semiconductors are used in ESB production equipment, supply chain problems for semiconductors indirectly affected manufacturing as procuring manufacturing equipment became more difficult.

These factors drove supply chain problems for a variety of components. Although some OEMs reported having supply chain problems with major zero-emission components like batteries and electric motors, many OEMs stated that other zero-emission components were more problematic. OEMs cited high voltage electronic accessories and electronics, such as inverters and DC-to-DC converters, as having supply chain problems. OEMs also reported chassis shortages as a major to manufacturing. Several OEMs stated that they were having difficulty sourcing a medium-duty chassis. This is problematic because OEMs need a platform to build an ESB on. Lastly, OEMs also reported supply chain issues with non-zero-emission components like bus seats and HVAC systems. It is important to note that many of these supply chain issues were common to the wider electric vehicle (EV) industry.

OEMs reported using a variety of strategies to mitigate these problems. A prominent strategy was to stockpile extra components to protect against delays in the supply chain. OEMs also used or considered using multiple component suppliers to mitigate the risk of any single supplier facing supply chain problems. However, this strategy is costly because OEMs must do due diligence and quality control when working with new suppliers. In addition, OEMs must also reengineer their systems to accommodate components from a different supplier. Some OEMs also mitigated their supply chain problems through vertical integration. The OEMs pursuing this strategy purchased or merged with component or chassis companies to secure their supply chain.

Some OEMs can produce vehicles by repowering existing vehicles. During the repowering process, the OEM removes the internal combustion engine and other supporting equipment from an existing vehicle and replaces them with zero-emission components. Some OEMs have proposed repowers as a way to address the chassis shortage. Since there are vehicles with functioning a chassis, repowering existing school buses can be a way to deploy ESBs despite the shortage in new chasses.

Buy America

The Federal Transit Administration (FTA) has historically enforced the Buy America Requirements outlined in 49 C.F.R. Part 661. The Buy America Requirements were enacted to support American metallurgy and manufacturing industries. The Buy America Requirements mandate that all iron, steel, and manufactured products in projects funded by the FTA are produced in the United States. Rolling stock procurements, including buses, were exempted from this requirement if they meet domestic content requirements. Specifically, the domestic content requirements mandate that the cost of the components produced in the United States exceeded 60% of the cost of all components and that the final assembly of the vehicles occurs in the United States. These domestic content requirements have become more stringent over time due to the Fixing America's Surface Transportation Act, which was signed into law in 2015. Under this legislation, the domestic content requirement was gradually increased over time. The terminal domestic content requirement is 70% for all rolling stock funded in FY2020 and beyond (FTA, 2023).

The BIL was signed into law in November 2021. The Build America, Buy America Act (BABAA) is a provision enacted under the BIL. BABAA also requires domestic content for federally funded infrastructure projects. Like the Buy America Requirements, BABAA requires that iron, steel, and construction materials used in federal infrastructure projects (EPA, n.d.) be manufactured in the United States. Manufactured products must also be manufactured in the United States and 55% of the total cost of all components must be manufactured in the United States, unless another domestic content standard has been established (Office of Management and Budget, 2022).

The BIL provided funding for zero-emission transit buses and ESBs. The FTA has determined that the Buy America Requirements take precedence over BABAA and have continued to enforce Buy America Requirements for zero-emission transit buses funded through their Low and No Emissions Grant program and the Bus and Bus Facilities Grant program. The EPA, however, has determined that vehicles funded through the Clean School Bus program are not subject to BABAA. The EPA also granted a waiver to BABAA for electric vehicle charging infrastructure funded through the Clean School Bus program. This waiver was granted because there are few electric vehicle chargers that can meet BABAA requirements and there were concerns that the quantity of BABAA-compliant chargers would not be sufficient to meet demand (EPA, 2022a).

Opinion on BABAA is mixed. Some OEMs have expressed concerns about BABAA. While the EPA is currently exempting ESBs funded through the Clean School Bus program from BABAA, there are concerns BABAA might be enforced in the future or for future ESB funding or incentive programs. Some OEMs are opposed to BABAA. OEMs opposed to BABAA are concerned they will be required to primarily source components from the United States, which would disrupt their established supply chains. These OEMs stated that the American supply chain for ESB components is not as developed as foreign supply chains. As a result, components obtained from suppliers in the United States are more expensive than equivalent components from their current suppliers.

OEMs opposed to BABAA stated that it would cause the cost of their vehicles to increase by about one third. OEMs also raised concerns about having to work with new suppliers because they would have to incur quality assurance and engineering costs to integrate new components into their vehicles. OEMs also stated that the documentation process for complying with BABAA is onerous and imposes an administrative burden on them.

Other OEMs, however, do not oppose BABAA. These OEMs stated that BABAA can be difficult to comply with because the American market for electrified components is underdeveloped compared to other countries. However, these OEMs expressed support for BABAA because they are optimistic this policy will encourage onshoring of component manufacturing, which can make supply chains more resilient over the long term.

Manufacturing Labor

CALSTART investigated whether labor shortages pose a barrier to ESB manufacturing. Labor shortages were cited as a barrier to ESB manufacturing in OEM corporate regulatory filings. Furthermore, during industry ESB working groups hosted by CALSTART in December 2022, representatives from community colleges noted that most workforce development activities in the ESB sector focused on training vehicle maintenance technicians, rather than manufacturing labor.

During interviews, OEMs had varying opinions about labor shortages. Some OEMs reported they did not have any labor shortages. However, others reported they were experiencing labor shortages. OEMs reported a shortage of general manufacturing labor. These workers need to have skills in high-voltage circuits and safety, welding, pneumatics, and operating hand tools. OEMs also reported a shortage of workers with skills in high-voltage circuits and safety. One of the causes of this problem is that many automotive trade schools and community college programs provide training in low-voltage circuits, which are typically found on traditional vehicles, but do not provide sufficient training for high-voltage circuits.

Many OEMs are working with educational institutions like trade schools, community colleges, and four-year universities to source labor. These OEMs have formal partnerships or apprenticeship programs that they use to recruit workers. OEMs have also reported engaging with other community organizations like local Chambers of Commerce. The OEMs that are not currently engaging with educational institutions or community organizations have expressed interest in doing so in the future. OEMs also reported that they are actively recruiting veterans, formerly incarcerated, and homeless persons.

During interviews, some OEMs stated that ESBs require more labor hours to produce than a traditional school bus. The difference in labor hours is due to the fact that high-voltage wiring takes longer to install onto the bus. In addition, commissioning for high-voltage circuits takes longer than for the low-voltage circuits that are installed on traditional vehicles.

The labor hours required to produce an ESB will decrease as workers gain more experience installing high-voltage circuits and the process becomes more standardized. However, the number of labor hours for ESBs and traditional school buses is not expected to ever reach parity.

V. Recommendations

ESB technology has rapidly advanced. School districts have shown substantial interest in this technology and orders for ESBs have quickly increased. However, technological development does not necessarily equate to commercial readiness. CALSTART analyzed market readiness according to several metrics including infrastructure, service network, production capacity, cost parity with internal combustion engine buses, and duty cycle capability. CALSTART's analysis found ESBs are commercially viable according to the cost parity and duty cycle metrics. However, they are not commercially viable according to the infrastructure, service network, and production capacity network. Industry action will need to be taken to address these issues and advance the commercialization of ESBs.

Manufacturing is also a major factor for ESB commercialization. Although there is considerable interest in ESBs, manufacturing is a potential chokepoint for ESB deployments. As a result, CALSTART has placed special emphasis on this factor. CALSTART found that industry-wide, there is enough physical manufacturing capacity to meet ESB demand. However, OEMs face barriers that result in increasing lead times and backlogs. This is problematic because the current Clean School Bus program rules require that ESBs be delivered within two years of being awarded. Historical data indicates that OEMs will struggle to meet this requirement and there is little reason to believe that the situation has improved.

To address these challenges, CALSTART recommends the following actions:

Establish Workforce Development Initiatives for ESB Maintenance Technicians

OEMs had mixed experiences with obtaining labor that can manufacture ESBs. However, OEMs largely expressed concerns about obtaining ESB maintenance technicians. EV maintenance technicians have a unique skillset. Since the EV industry is new, the industry as a whole is experiencing a shortage of maintenance technicians. This is especially true for the MHD vehicle sector.

The transit bus sector's experience with workforce development can be informative for ESBs. Transit agencies are responsible for maintaining and repairing transit buses. This is typically done through one of two methods. Transit agencies can have diesel mechanics on staff to maintain and repair their buses or they contract out maintenance to a transportation services company. As transit agencies have transitioned to ZEBs, they have become reliant on their OEMs to provide field service representatives to maintain and repair the buses. However, some transit agencies and transportation service companies have invested in upskilling their diesel mechanics so that they can become EV maintenance technicians and operate on ZEBs.

Transit agencies have made use of resources from the FTA to provide their staff with training. The Low or No Emission Program allows transit agencies to use grant funding for workforce development. The FTA has set up workforce development programs such as the West Coast Center of Excellence. Workforce development consortia such as the California Transit Training Consortium also provides instruction on ZEB maintenance and repair to transit agencies. These resources have helped transit agencies develop their own maintenance staff. However, despite this advancement, transit agencies fear that they risk having their maintenance technicians poached by private fleets, who can offer higher monetary compensation.

School districts face similar challenges as transit agencies. School districts either repair their buses with their own staff or contract maintenance to a transportation services company. Due to these operational similarities, school districts can follow similar strategies as transit agencies. At this point in time, however, school districts have not been afforded the same workforce development resources that transit agencies have. Thus far, there has been no federal funding allocated for school districts to develop ESB maintenance technicians. Furthermore, some regional training organizations such as the California Transit Training Consortium do not currently have the resources to offer training to school districts. As a result, school districts at present have fewer options for obtaining workforce development training.

Federal resources should be made available to school districts to support workforce development activities. One option for achieving this would be for the EPA to allow school districts to use some of their awarded funding from the Clean School Bus program on workforce development. This would allow school districts to develop in-house maintenance and repair expertise. Increasing the number of maintenance technicians could also benefit the entire industry as it would reduce competition for this skillset and would reduce the need for fleets to poach technicians from other fleets.

Establish an American EV Component Supply Chain

OEMs have cited supply chain disruptions as a major barrier to manufacturing. OEMs have experienced disruptions caused by COVID-19 lockdowns, disruptions at American ports, and from the Ukraine-Russia war. This has led to increasing lead times and backlogs. Some OEMs have also expressed concerns about needing to find suppliers if ESBs are ever subjected to Buy America requirements as well as the cost of components produced in America.

Onshoring production is a potential solution to these problems. One of the main barriers to onshoring is that the American market for components is less developed than in foreign markets. Countries like China have more EVs deployed than the U.S., which has allowed their component markets to become more developed. The component market in the United States is less developed due to lower volume. Developing the component market in the United States will allow American component manufacturers to benefit from economies of scale. This will give OEMs more options for sourcing components which will increase the resiliency of supply chains and provide more protection against international supply shocks. This is beneficial to OEMs regardless of whether ESBs are required to comply with Buy America.

The Biden Administration has taken some initial steps toward onshoring component manufacturing. Semiconductors are a component that OEMs have experienced major supply chain problems. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act enacted several provisions to address these supply chain problems. The CHIPS Act aims to achieve this by encouraging the onshoring of the semiconductor supply chain. The CHIPS Act provides $50 billion to fund semiconductor manufacturing and research and development activities. Of this $50 billion, $39 billion is devoted to funding the deployment of additional semiconductor manufacturing capacity (either new facilities or upgrades to existing facilities). $2 billion is devoted to increasing production of legacy semiconductors. The CHIPS Act also aims to mobilize private financing by providing a 25% tax credit for investments in semiconductor manufacturing facilities.

The Inflation Reduction Act (IRA) also contains provisions that encourage onshoring of EV manufacturing. Section 50142 provides an additional $3 billion in funding for the Advanced Technology Vehicle Manufacturing program. The Advanced Technology Vehicle Manufacturing program operates under the Department of Energy Loan Program Office. This program provides loans and financing support to entities that are deploying, expanding, or reequipping facilities to manufacture low or no emission vehicles or components. OEMs and component manufacturers are eligible to use this program. The BIL expanded this program to include MHD vehicles (Department of Energy, n.d.). Section 50143 of the IRA provides an additional $2 billion in funding for the Domestic Manufacturing Conversion Grant program. The Domestic Manufacturing Conversion Grant program operates under the Department of Energy. This program provides loans to entities that are converting facilities to manufacturing EVs, hybrid vehicles, and hydrogen fuel cell vehicles. Section 45X of the IRA enacts the Advanced Manufacturing Production Credit. This production credit is offered to entities that produce raw materials such as aluminum, chromium, cobalt, lithium, manganese, and other critical minerals. This section also provides a production tax credit for batteries and inverters.

The BIL, CHIPS Act, and IRA mark major changes in industrial policy that will encourage onshoring of the ESB supply chain. Despite this support, there are additional actions that can be taken to support onshoring. These acts provide major support for manufacturing. They also aim to resolve supply chain problems for semiconductors and batteries. However, these are not the only components that OEMs have faced supply chain challenges with. OEMs also reported supply chain challenges with lesser-known components, including high-voltage electronics like DC-to-DC converters. These components are vital to ESBs and the vehicle cannot be built without these components. To address these supply chain challenges, the Advanced Manufacturing Production Credit should be extended to these components so they can receive comparable incentives as other major ESB components.

Consider Funding for the Manufacturing of Repowered ESBs

OEMs have experienced supply chain problems with many components. However, some OEMs stated that shortages of chassis have been a pervasive issue. This has been particularly problematic for OEMs that purchase chassis from third-party suppliers. The chassis shortage has been exacerbated by the fact that other types of EVs also need chassis and are also competing to procure scarce supplies. For example, Type A buses might use the same chassis as medium-duty electric trucks and cutaway electric buses. This problem could get worse as demand for all types of EVs increases.

Repowers are a potential avenue for addressing the chassis shortages. Repowers can make use of an existing chassis on an internal combustion engine bus and convert it to an ESB. This allows OEMs to produce an ESB without needing to procure increasingly scarce chassis. Repowers can also potentially accelerate the transition to zero-emission as school districts can do a mid-life conversion of their existing buses instead of waiting until the end of the useful life of the bus to purchase a new ESB.

At the time of writing, the funding options that a school district can use to repower their buses is limited. Most school districts do not have excess budget to pay for ESBs. In addition, the EPA Clean School Bus program, which is the main funding program for ESBs, will only fund repowered vehicles under certain conditions (Ly and Werthmann, 2023). To date, no repowered ESBs have been funded through the Clean School Bus Program. California and New York are the only states with voucher programs that will fund repowered ESBs. Colorado and New Jersey also have grant programs that allow funding for repowered ESBs. However, there are no funding options for ESBs in the rest of the states.

The EPA Clean School Bus Program should consider expanding the types of buses that are eligible for funding as a repowered ESB. Under the current program rules, only newer internal combustion engine buses can be repowered with Clean School Bus Program funding. The Clean School Bus Program should consider changing the eligibility criteria so that some of the older school buses can be repowered as well. Expanding the eligibility criteria to allow more buses to qualify for funding could help to accelerate the pace of repowered ESB deployments. By doing so, this would allow OEMs to avoid the chassis shortage problem and potentially deploy ESBs faster. Implementation of this, however, will require funding agencies to make program design decisions. Funding agencies will need to decide how much funding will be allocated for each vehicle. OEMs that expressed an interest in manufacturing repowered ESBs were split on how much funding repowers should be allocated per vehicle. Some OEMs wanted repowers to receive the same amount of funding as new ESBs. However, other OEMs stated that repowered ESBs can be financially viable if they receive less funding than new ESBs.

School Bus Standardization

OEMs reported that school buses are not a standardized product. This occurs because OEMs must build school buses to the specifications provided by their customer. Each state and school district has different requirements for school buses. As a result, OEMs produce vehicles with a wide range of specifications. For example, an OEM might produce Type A buses with different lengths and configurations based on the exact specifications that the customer provides.

OEMs have stated that the lack of standardization makes it difficult to mass produce ESBs. The high degree of customization required means that the production process is not entirely repeatable. As a result, this increases the amount of engineering labor that is required to build ESBs. OEMs stated that the price of ESBs would decrease if school buses were more standardized. OEMs recognize that standardizing ESBs is difficult because each school district and state is a different jurisdiction. However, OEMs stated that steps toward standardization can be taken in the short term by standardizing certain parts of ESBs. For example, the industry can start by standardizing items, such as the location of the charging port. OEMs also proposed that ESB funding programs be designed to incentivize standardization of ESBs.

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Appendix A: TRL Methodology

Determining a TRL score begins with the internal CALSTART and CARB team, which consists of subject matter experts with expertise in at least one vehicle or equipment segment. This team develops a list of vehicle segments (i.e. ESB, transit bus, Class 8 truck, etc.) for which TRL will be evaluated. The team then develops a comprehensive list of vehicles and OEMs for consideration that fall within each vehicle segment being evaluated. Members of the internal CALSTART and CARB team assess and record each individual vehicle or OEM's capabilities and development progress. Factors such as economic or market challenges are not weighted in TRL scoring, as these characteristics contribute instead to market readiness.

Once the individual vehicle and OEM assessments are compiled, internal industry experts score the technologies according to the scoring rubric. Each industry expert scores all technologies based on their individual assessment of the vehicle's development progress. A discussion is then held to calibrate results and rectify any large discrepancies in the scoring.

Figure A-1. TRL Scoring Rubric

TRL Level	General Technology Level	TRL Definition	Example Technology
9	Early Market	Full commercial application. Technology in general availability for users. Manufacturing phase. Successfully operated in uncontrolled commercial environment.	Battery-Electric Bus; Fuel Cell Electric Forklift; Methane Engine 8.9 Liters
8	Large Scale Pilot	Pre-production. First of its kind commercial system. Technology ready to support commercial activity. In limited release assessment numbers. Vehicle succeeds in uncontrolled environment.	Battery-Electric Harbor Craft Vessels; Battery-Electric Mobile Power Unit
7	Early Pilot/Late Demonstration	Demonstration system. Operating in intended environment at pre-commercial scale. Unit succeeds in a relevant environment.	Fuel Cell Electric Drayage; Fuel Cell Electric Harbor Craft Vessels
6	Early Demonstration (Advanced Prototype System)	Tested in intended environment at close to expected performance. Limited vehicle builds. Vehicle succeeds in first real world scenarios.	0.02 NOx Diesel Engine; Fuel Cell Electric Automated Guided Vehicle
5	Prototype	Large scale prototypes. Tested in intended environment; tested well enough to validate in real world scenarios.	John Deere GridCON Autonomous Tractor
4	Technology Development	Small scale (ugly) prototypes. First prototypes built and tested to perform under specific conditions.	Fully Autonomous Long-Haul Trucks
3	Research	Benefits and viability of technology confirmed in lab (Pre-Prototype).	-
2	Research	Early invention stage. Concept and application have been finalized.	-
1	Research	Scientific evidence for potential innovation.	-

Once each score has been vetted by industry experts, the impact each vehicle and/or OEM has on the entire TRL for that vehicle segment is weighted based on a manufacturer multiplier, which gives a higher weighting to vehicles from companies that have larger market penetration and demonstrated ability to ramp up production. These weighted factors are preferable to a simple average: early-stage vehicles and equipment do not define the entire status of a vehicle segment. Further, vehicles and equipment that have not made as much commercialization progress still impact the overall status of a vehicle platform. For instance, a model from a vertically integrated global OEM receives more weight than a model from a start-up manufacturer. This approach enables a more realistic assessment of a vehicle segment's overall technical and commercial readiness. TRLs are therefore displayed as the weighted scores of the entire vehicle segment. In doing so, this approach may result in a vehicle segment receiving a score of seven or eight (i.e., entering the pilot stage) while some models from certain manufacturers in the platform may already be in commercial production.

Figure A-2. OEM Weighting System

Manufacturer Type	Rank
Conventional OEM	5
Born ZE with Market Share	4
Born ZE Manufacturer	3
Retrofit Manufacturer	2
Start-Up	1

Once the TRL score was determined, the results were visualized. It is important to note that this methodology is used to determine the TRL for ESBs in California. Since the majority of ESB deployments in the United States have occurred in California, it was assumed that TRL for California and for the entire nation will be the same.

Appendix B: MRI Methodology

Similar to the TRL methodology, determining a market readiness score begins with the internal CALSTART team, which consists of subject matter experts with expertise in at least one vehicle or equipment segment. This team identifies vehicle and equipment platforms that have scored an eight or above with respect to technology readiness to be assessed for market readiness. Members of the internal CALSTART team assess and record each vehicle or equipment segment's market readiness on a scale of 0% to 100%, in 25% increments, for each of the six indicators described in detail below. Scores are assessed according to the scoring rubric, which is found below.

Market Readiness Scoring Rubric

Infrastructure

This category measures the extent to which charging or refueling infrastructure is available and easy to install for a given on- or off-road vehicle platform. A score of 0% represents the case where the appropriate charging or refueling infrastructure is completely unavailable commercially or in pilot/demonstration projects. A score of 100%, on the other hand, represents the case where charging or refueling equipment is completely available.

Service Network

Service network measures the existence and accessibility of a workforce for maintenance and repair of the ZE vehicles and equipment. A score of 0% corresponds to the case where no service network is available through the OEM, dealer, or independently in California. A score of 100% corresponds to the case where a developed service network exists that is geographically distributed to serve demand; there are no wait times significant enough to inhibit uptime of the vehicles and equipment.

Production Capacity

This category estimates the current manufacturing capacity of an on- or off-road technology segment, where 0% represents production limited to pilot/demonstration vehicles, while 100% represents the case where multiple OEMs have begun serial production at relatively high volumes and are positioned to meet the entirety of current diesel market demand in the next one to five years.

TCO Cost Parity (With and Without Incentives)

Cost parity is a measure of the difference between ZE TCO and diesel or gasoline TCO. CALSTART conducted TCO analysis on ESBs. The assumptions used in the ESB TCO calculations are displayed below:

Figure B-1. ESB TCO Assumptions

Parameter	ESB	Diesel School Bus
Miles per Day	38	38
Lifetime (years)	12	12
Projected 2025 Vehicle Price	$340,000	$215,000
Sales Tax	20%	20%
Fuel Economy	1.5 kWh per mile	5 miles per gallon
Fuel Price	$0.22 per kWh	$4.21 per gallon
Maintenance Cost (per mile)	$0.705 per mile	$0.94 per mile
Midlife Costs	$0	$0
Registration Fees	$23,359	$29,398
Charging Power	19 kW	N/A
Charging Cost	$5,000	N/A
Infrastructure Upgrade Cost	$25,000	N/A
Residual Value (% of purchase price)	24%	24%
LCFS Credit Value	$100 per credit	N/A

Two ESB TCO cases are presented. The first case is "Cost Parity," which compares the TCO of ESBs directly to traditional buses. The second case is "Cost Parity with Incentives," under which the TCO calculations for ESBs take into account LCFS credits that are awarded and incentive funding from HVIP. All TCOs are based on projected ESB capital costs in 2025. For both TCO categories, a score of 0% corresponds to the case where the ZE TCO is greater than 30% higher than diesel TCO. A score of 100% corresponds to the case where the ZE TCO is at or below cost parity with diesel.

Duty Cycle Applicability

Duty cycle applicability measures how well a given technology platform can meet the range of duty cycles required of it. For on-road vehicles, a score of 0% represents the case where range, payload capacity, and power of ZE models are not sufficient to meet the majority of duty cycle requirements, while a score of 100% means that ZE models can meet all known requirements. For off-road technologies, a 100% score corresponds to the case where power, lift capacity, and operating time of ZE models are sufficient to meet duty cycle requirements.

MRI Rubric

The rubric used to determine scores for MRI is included below.

Figure B-2: MRI Rubric

MRI Score	Production Capacity	Service Network	TCO Cost Parity[10]
0%	Production capacity is limited to prototypes or pilot/demonstration vehicles.	No service network[11] is available through the OEM, dealer, or independently in California.	2025 ZE TCO is greater than 30% higher than diesel TCO.
25%	Production capacity is limited to small volumes of vehicles currently, although vehicles may be entering serial production soon.	Some service network is trained and available in California, but not widely enough to provide ZE customers certainty that their vehicles will be repaired in a timely fashion. Customers regularly experience significant delays that prevent the full utilization of ZE vehicles and deter them from adopting future ZE vehicles.	2025 ZEV TCO is between 20-30% higher than diesel TCO.
50%	At least one OEM has begun serial production at relatively high production volumes (above specialized/retrofit manufacturing).[12]	Some workforce is trained and available in California, but not widely enough to provide ZE customers certainty that their vehicles will be repaired in a timely fashion. Some customers experience significant delays that prevent the full utilization of ZE vehicles and deter them from adopting future ZE vehicles.	2025 ZE TCO is between 10-20% higher than diesel TCO.

MRI Score	Production Capacity	Service Network	TCO Cost Parity[10]
75%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current diesel market demand in the next 5-10 years if demand were to increase.	A well-trained workforce exists and is available but is unevenly distributed geographically within California.	2025 ZE TCO is between 5-10% higher than diesel TCO.
100%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current diesel market demand in the next one to five years if demand were to increase.	A well-trained workforce exists and is available to all customers who need it regardless of geographic location.	2025 ZE TCO is at or below cost parity with diesel.

MRI Score	Duty Cycle Capability	Infrastructure
0%	Range, payload capacity, and power of ZE models are not sufficient to meet the majority of duty cycle requirements.	Appropriate charging/refueling equipment is completely unavailable commercially and in pilot/demonstration projects.
25%	Only one of range, payload capacity, or power requirements is sufficient.	Appropriate charging/refueling equipment is available in small quantities commercially or in pilot/demonstration projects.
50%	Two of range, payload capacity, or power requirements is sufficient.	Appropriate charging/refueling equipment is available commercially but has one or more significant barriers[13] which may prevent the installation of charging infrastructure or the adoption of ZE vehicles.
75%	Range, payload capacity, and power are sufficient to meet the majority of duty cycle requirements.	Appropriate charging/refueling equipment is available commercially, but has one or more significant barriers that are on track to be overcome and do not necessarily prevent installation of charging infrastructure or adoption of ZE vehicles.
100%	Range, payload capacity, and power are sufficient to meet all known duty cycle requirements.	Charging/refueling equipment is completely available to all customers who want it with no significant barriers.

Appendix C: MRL Methodology

MRLs are measured on a scale from one to ten. One represents the earliest stages of manufacturing, where basic research is being conducted on manufacturing needs. Ten represents the most mature stage where a full manufacturing system is established, and the manufacturing process is being optimized. MRL is connected to TRL because the manufacturing process cannot fully mature until the technology has matured. As a result, TRL typically places limits on how far MRL can advance. The definition of each MRL stage is listed below (Department of Defense, 2011):

Table C-1. MRL Scoring Criteria

Scale	Definition	Minimum TRL
1	Basic Manufacturing Implications Identified	-
2	Manufacturing Concepts Identified	-
3	Manufacturing Proof of Concept Developed	-
4	Capability to produce the technology in a laboratory environment	4
5	Capability to produce prototype components in a production relevant environment	5
6	Capability to produce a prototype system or subsystem in a production relevant environment	6
7	Capability to produce systems, subsystems, or components in a production representative environment	7
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	7
9	Low Rate Production demonstrated; Capability in place to begin Full Rate Production	9
10	Full Rate Production demonstrated and lean production practices in place	9

CALSTART analyzed MRL to understand the state of manufacturing for ESBs. CALSTART conducted this analysis for both individual OEMs and for the industry as a whole. The CALSTART internal team assessed the MRL for each individual OEM based on secondary research and information gathered from interviews with OEMs.

CALSTART also conducted analysis on industry-wide MRL. CALSTART calculated an industry-wide MRL by aggregating the MRL assigned to each individual OEM. The industry-wide MRL was calculated using a weighted average. Each OEM's MRL was weighted based on the percentage of existing and announced manufacturing capacity that the OEM controls. The formula used to make this calculation is included below:

$$Industry\ MRL = \sum (OEM\ Share\ of\ Industry\ Manufacturing\ Capacity) * (OEM\ MRL)$$

Appendix D: Manufacturing Metrics Methodology

CALSTART gathered data from a variety of sources to conduct analysis on manufacturing metrics. CALSTART conducted analysis on the current state of manufacturing. To conduct this analysis, CALSTART gathered quantitative data for manufacturing metrics. This data came from HVIP. HVIP is a voucher incentive program that provides incentive funding for a variety of zero-emission medium- and heavy-duty vehicles. HVIP only provides funding for vehicles in California. As a result, the data from HVIP only includes ESBs sold in California. However, since the vast majority of ESBs have been deployed in California, HVIP data was considered to be representative of nationwide ESB deployments. This data is current as of February 25, 2023.

CALSTART also gathered data on manufacturing capacity. CALSTART held interviews with OEMs to understand their manufacturing operations and gather this data. More information about the interviews can be found in Appendix E.

Lead Time

CALSTART used data from HVIP to analyze lead time to understand the industry's ability to manufacture ESBs in a timely manner. HVIP data breaks down lead time into two segments. The first segment is the time until physical delivery. This represents the time between when the ESB is ordered until when it is physically delivered to the customer. The second segment consists of the acceptance period. During the acceptance period, the customer operates the bus to ensure that it meets contracted quality standards. This segment lasts from the date of physical delivery until the vehicle is accepted by the customer. The HVIP data includes information on when the HVIP voucher was requested, the delivery date for the ESB, and the date when the voucher was paid. The time between when the HVIP voucher was requested and the delivery date was considered to be the time until physical delivery. The time between the delivery date and the date when the voucher was paid was considered to be the acceptance period.

It is important to note that there were many vehicles that had been ordered but not delivered as of February 25, 2023. There are 302 of these ESBs. 65 of these ESBs were awarded funding in 2019 and the remaining 237 were awarded in 2021. Given the length of time that has elapsed since these ESBs were awarded funding, these vehicles increased the average lead time. CALSTART used February 25, 2023 as the delivery date for these vehicles in this analysis. However, since these vehicles were not actually delivered as of

February 25, 2023, the actual lead time for these vehicles will be higher. As a result, the delivery time figures for 2019 and 2021 underestimate the actual lead times. Since these vehicles have not been delivered, they do not have an acceptance period. To avoid skewing the average acceptance period, these vehicles were excluded from acceptance period analysis.

Backlog

CALSTART used data from HVIP to analyze backlog. The dataset contains data on all ESBs ordered through HVIP through February 25, 2023. The dataset includes the date when the HVIP voucher was requested and when the vehicle was physically delivered to the customer. Backlog measures the number of vehicles that OEMs have on order but have not yet produced. CALSTART considered a vehicle to have entered the backlog when the HVIP voucher was requested, and to have exited the backlog when the bus was physically delivered to the customer. CALSTART calculated the period when each individual bus entered the backlog and then exited the backlog. CALSTART then calculated how many buses were in the backlog for each individual day between January 1, 2017 and February 25, 2023.

The data shows that there are several periods where backlog spikes and increases rapidly. This occurs because HVIP vouchers can only be submitted during certain periods of time. These windows are typically very short, and OEMs typically submit their voucher requests early in these windows to ensure that their requests are submitted before funding for that window is exhausted. This phenomenon explains why backlogs increase sharply over time, rather than gradually.

It is important to note that this backlog data does not encompass the entire ESB industry. HVIP data only encompasses ESB sales in California. As a result, this backlog data does not include any ESBs purchased outside of California or that have been funded by the EPA's Cleaner School Bus Program.

Manufacturing Capacity

CALSTART gathered data on manufacturing capacity from each OEM that was interviewed. OEMs provided a numerical value representing the number of ESBs that they can produce per year. This analysis was complicated by the fact that many OEMs use the same manufacturing facility to produce multiple types of vehicles, including transit buses, school buses, and trucks. Some OEMs provided manufacturing capacity for all vehicle types that they produce. OEMs reported that the manufacturing process for each vehicle type is similar. Most OEMs reported that they used the same chassis and drivetrain for the different types of vehicles they produce and that the main difference between the vehicle types is the cab/body that is added to the vehicle. As a result, they reported that they can easily switch production between vehicle types. Consequently, CALSTART assumed that production capacity for different vehicle types is completely fungible. For example, if an OEM reported that they have manufacturing capacity for 1,000 electric trucks, CALSTART assumed that this capacity can easily be converted to manufacturing capacity for 1,000 ESBs.

Some OEMs also produce both internal combustion engine school buses and ESBs. Based on conversations with the OEMs, CALSTART assumed that manufacturing capacity between internal combustion engine school buses and ESBs is not fully fungible. For these OEMs, ESB manufacturing capacity was adjusted based on delivery volume. Some OEMs were also in the process of expanding their existing manufacturing facilities when interviews were held, meaning that their manufacturing capacity will increase in the future. CALSTART included this additional manufacturing capacity in this analysis. However, this was split into short-term expansion and long-term expansion. Short-term expansion is defined as manufacturing capacity that is expected to come online by the end of 2024. Long-term expansion is defined as manufacturing capacity that is expected to come online after the end of 2024.

This data was then aggregated to determine the industry-wide manufacturing capacity. This capacity was expressed as the number of vehicles that can be produced by the ESB industry per year. This data was also broken down by school bus type. Since no manufacturers are currently producing Type B ESBs, this vehicle type was excluded. Type C and D buses are of similar size and were aggregated into the same category. As a result, the data was broken down into manufacturing capacity for Type A buses and Type C and D buses. Many OEMs produce either Type A or Type C and D buses. If an OEM produces one type of bus, their entire production capacity was allocated to that bus type. It is important to note that some OEMs only produce one type of ESB but have expressed an interest in expanding their production into other types of ESBs. For example, an OEM might produce a Type A ESB but has expressed an interest in producing Type C and D buses in the future. In this case, 75% of the OEM's short-term expansion and long-term expansion manufacturing capacity was allocated to the type of ESB they currently produce and the remaining 25% to the type of ESB they have expressed interest in producing. Some OEMs produce more than one type of ESB. If an OEM produces both Type A and Type C and D buses, their manufacturing capacity was split evenly between the two categories.

Appendix E: OEM Interviews

CALSTART conducted interviews with ESB OEMs to learn more about their manufacturing operations. CALSTART conducted interviews with the following OEMs:

- Blue Bird
- BYD
- GreenPower Motor Company
- Lightning e-Motors
- Motiv Power Systems
- Navistar/IC Bus
- Pegasus Specialty Vehicles
- Phoenix Motorcars
- SEA Electric

Interviews were semi-structured interviews. Interviews were held between October 2022 and December 2022. The following questions were asked during interviews:

1. How many vehicles per year are you currently able to produce (segmented by vehicle type)?
    a. How is production prioritized between ESBs and other types of vehicles?
    b. How far out (years/weeks) is forecasting needed to change the production line?
    c. If applicable, how is production prioritized between different types of ESBs (i.e. Type A vs. Type C and D)?
    d. Are you able to quickly shift from producing other types of vehicles to ESBs? Are there any challenges to do this?
2. What type of production line do you have?
    a. Do ESBs share the same production process as other vehicles and other electric vehicles in your product line?
3. Do you have plans to scale up production for ESBs? What do you need to do to achieve this?

4. What quality control processes do you use?
5. How many vehicles do you currently have in your backlog?
    a. How long will it take to clear this backlog?
    b. What are the main challenges resulting in the backlog?
6. How long after a purchase order is placed does it take to manufacture and deliver a vehicle?
    a. What are the intermediate steps between an order being placed and the bus being delivered to the school district?
    b. Are there any barriers that are causing the lead time to be extended?
7. What bottlenecks are you experiencing in the production and delivery of vehicles?
8. Are you facing any shortages in your supply chain?
9. Do you have redundant suppliers in the event of supply chain problems?
10. What are the most limiting parts of the supply chain right now?
11. Are you facing any labor shortages?
    a. If so, which types of workers or skillsets are you experiencing shortages for?
12. Do you engage with any high schools, community colleges, trade schools, 4-year universities, employment centers, job training programs, etc. to source manufacturing workers?
13. Are there any other manufacturing-related topics that you would like to discuss?