Project 2546 | August 2026

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Advancing Clean Mobility: Hydrogen Fuel Cell Electric Bus Workforce Development for Transit Agencies

Manideep Tummalapudi, PhD
Shantanu Kumar, PhD
Jaskaran Singh

CSUTC California State University Transportation Consortium

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Report 26-24

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A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

Technical Report Documentation Page

1. Report No. 26-24	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Advancing Clean Mobility: Hydrogen Fuel Cell Electric Bus Workforce Development for Transit Agencies		**5. Report Date** August 2026
		6. Performing Organization Code
7. Authors Manideep Tummalapudi, PhD Shantanu Kumar, PhD Jaskaran Singh		**8. Performing Organization Report** CA-MTI-2546
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.**
		11. Contract or Grant No. SB1-SJAUX_2023-26
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		**13. Type of Report and Period Covered**
		14. Sponsoring Agency Code
15. Supplemental Notes 10.31979/mti.2026.2546		

16. Abstract

Hydrogen fuel cell electric buses (FCEBs) are rapidly transforming public transportation in the United States. However, while transit agencies are investing heavily in new zero-emission vehicles and fueling infrastructure, far less attention has been paid to the workforce needed to operate and maintain them. As agencies accelerate toward ambitious climate and fleet transition goals, they are also confronting a critical challenge: preparing workers for an entirely new set of technologies, safety requirements, and operational demands. This study addresses that gap by systematically identifying the knowledge, skills, and abilities (KSAs) required for FCEB vehicle operators and maintenance technicians, assessing current training programs, and investigating effective workforce recruitment and retention strategies. The research team conducted semi-structured qualitative interviews with 20 stakeholders across transit agencies, original equipment manufacturers (OEMs), training organizations, and industry associations in California, Ohio, Illinois, and Washington. Data were analyzed using thematic analysis following Braun and Clarke's (2006) six-phase framework. Findings reveal that FCEB workforce readiness is not simply a training issue but a system-level challenge requiring transit agencies to develop new tri-disciplinary competencies spanning mechanical, electrical, and hydrogen chemical safety—a combination no single predecessor technology fully provides. Electrical fundamentals emerged as a universal prerequisite. Findings also identified structural training gaps, including the absence of a standardized national curriculum for FCEB and the misalignment between OEM training delivery and practical application. The study proposes curriculum frameworks for FCEB technician and operator training, alongside identifying workforce strategies centered on "grow-your-own" development (developing talent internally), apprenticeship models, and regional training consortia. The findings underscore that the success of the zero-emission transit transition depends not only on vehicles and infrastructure, but on people. The research concludes that coordinated policy interventions, including a national certification pathway, investment in regional training infrastructure, and stronger community college partnerships are essential to building a skilled, adaptable workforce capable of supporting the FCEB transit transition.

17. Key Words Fuel cell vehicles, Workforce development, Transit personnel, Training programs, Zero emission vehicles	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 78	**22. Price**

Form DOT F 1700.7 (8-72)

DOI: 10.31979/mti.2026.2546

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2546

Acknowledgments

The research team sincerely thanks the study participants representing transit agencies, OEMs, training organizations, and industry associations for sharing their expertise and operational insights.

The research team also extends its appreciation to Rashidi Barnes of Tri Delta Transit for his support of this research and contributions to advancing innovation in public transportation.

The research team also gratefully acknowledges the Mineta Transportation Institute (MTI) at San José State University for funding this research and thanks Lisa Rose and Editing Press for editorial services, as well as MTI staff Project Assistant, Rajeshwari Rajesh and Graphic Design Assistant, Katerina Earnest.

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Background and Purpose

The transition of U.S. public transit fleets to hydrogen fuel cell electric buses (FCEBs) is accelerating under the combined pressure of state and federal zero-emission mandates, including California's Innovative Clean Transit (ICT) regulation requiring 100% zero-emission bus purchases by 2029. FCEBs offer distinct operational advantages over battery-electric buses including longer range, faster refueling, and grid independence, making them well-suited for high-frequency, long-route, and mixed-climate transit service. However, this technological shift demands a parallel and equally significant transformation in the workforce that operates, maintains, and manages these vehicles.

Despite growing FCEB deployment, the workforce dimension of this transition remains critically underexamined. Transit agencies face a compounding challenge: a sector-wide shortage of mechanics and operators, intensifying competition from renewable energy and private sector employers, and the absence of a standardized training framework for FCEB-specific competencies. This study directly addresses these gaps by identifying the knowledge, skills, and abilities (KSAs) required for FCEB vehicle operators and maintenance technicians, assessing current training programs and their structural limitations, and documenting effective strategies for FCEB workforce recruitment, retention, and development.

Research Approach

The research team conducted semi-structured qualitative interviews with 20 stakeholders actively involved in FCEB deployment across the United States. Participants included maintenance directors, operations leaders, safety directors, and fleet managers from transit agencies of varying sizes and FCEB adoption stages; training directors and technical representatives from original equipment manufacturers (OEMs); curriculum developers from transit training organizations; and workforce development professionals from industry associations. Agencies represented California, Ohio, Illinois, and Washington, spanning early planning through advanced fleet operations with up to ten years of FCEB experience.

Interview data were analyzed using Braun and Clarke's (2006) six-phase thematic analysis framework, supported by NVivo qualitative data analysis software. Two researchers independently coded all 20 transcripts and resolved discrepancies through collaborative intercoder reconciliation. Findings were triangulated with a comprehensive literature review covering FCEB technology, workforce development, training programs, and recruitment and retention strategies.

Key Findings

FCEB Workforce Readiness Is a System-Level Challenge

The central finding of this study is that FCEB workforce readiness is not simply a training problem but a system-level challenge. Effective FCEB operations require transit agencies to simultaneously develop new tri-disciplinary technical competencies spanning mechanical systems, high-voltage electrical systems, and hydrogen chemical safety while redesigning recruitment, training, and organizational strategies to support them. No single predecessor transit technology—diesel (ICE), compressed natural gas (CNG), or battery-electric buses (BEBs)—fully prepares workers for this combination.

Operator KSAs: Targeted Behavioral Adaptation

FCEB vehicle operators require meaningful but manageable retraining concentrated in three areas: hydrogen safety awareness, energy management behavior, and procedural discipline during fueling and emergency events. The most operationally consequential operator gap is energy management: Operators transitioning from diesel or CNG buses carry ingrained acceleration habits that measurably reduce FCEB range. Emergency response readiness, including hydrogen-specific positioning, invisible flame recognition, and Emergency Responder Guide delivery, are identified as non-negotiable KSAs required by FCEB Operators.

Maintenance Technician KSAs: Tri-Disciplinary Competency Integration

Maintenance technicians face the most complex and consequential workforce challenge in FCEB deployment. The study identified KSA competency domains required for FCEB maintenance. Electrical fundamentals emerged as the single most critical prerequisite. PEM fuel cell electrochemistry and degradation mode recognition, dual de-energization (simultaneous high-voltage and hydrogen system isolation), and root cause troubleshooting from electronic data are the required KSAs for FCEB maintenance technicians.

KSA Transferability: CNG and BEB Backgrounds are Complementary

CNG and BEB prior technology backgrounds are not interchangeable; they are complementary. CNG technicians contribute high-pressure storage knowledge, PRD familiarity, and gas system safety; BEB technicians contribute high-voltage safety, electrical fundamentals, and OEM diagnostic software experience. Their combination provides the strongest single preparation for FCEB work. Three competency domains—PEM fuel cell electrochemistry, fuel cell degradation modes, and integrated tri-disciplinary safety practices—transfer from no prior background and represent irreducible new-learning requirements for every FCEB maintenance technician regardless of experience.

Training Gaps

The study identified the training gaps below for FCEB training:

- Absence of a comprehensive, standardized national FCEB training framework and certification pathway
- OEM training that is product-specific, one-time at delivery, and structurally insufficient at scale
- OEM training timing misalignment: training delivered during warranty when technicians cannot practice independently, producing knowledge decay by the time self-sufficiency is required
- No structured framework for transitioning from OEM-led to in-house maintenance capability
- Limited FCEB content in community college and vocational programs, constraining the entry-level pipeline
- A two-tier capacity gap: Large agencies have built training infrastructure whereas smaller agencies remain entirely dependent on OEM support

Workforce Strategies: Grow-Your-Own is the Only Viable Model

Nine workforce strategies were identified across recruitment, retention, and organizational readiness dimensions. The foundational and fully saturated finding confirmed by all 20 participants is that transit agencies cannot recruit FCEB-ready technicians from an external labor market because that market does not exist. The only viable model is grow-your-own: Recruit for mechanical aptitude, electrical awareness, and diagnostic mindset, then develop FCEB competency internally over a structured multi-year pathway. The most reliable predictor of FCEB technician success is not prior technology background but a diagnostic disposition—the curiosity and persistence to pursue a fault systematically until the root cause is found.

Additional strategies include pay differentials tied to demonstrated FCEB competency rather than seniority alone; a three-level pipeline connecting high school CTE programs, community college technical preparation, and transit agency apprenticeships; structured mentorship with progressive authorization before independent FCEB work; transparent career ladders that frame FCEB specialization as upward advancement; regional training consortia that pool resources across agencies to address the two-tier capacity gap; and change management directed at supervisors and mid-level managers as a precondition for training effectiveness.

Policy Recommendations

The findings point to the coordinated policy interventions required to support effective FCEB workforce development at scale:

- Establish a standardized national or regional FCEB training framework and certification pathway to ensure consistent competency levels and safety preparedness across all agencies regardless of size or geography.
- Direct public investment toward regional training centers and shared training infrastructure to close the two-tier capacity gap between large and small agencies for FCEB training.
- Develop and expand FCEB training programs beyond technicians to explicitly include operators and facility staff, with structured behavioral compliance verification mechanisms alongside instruction.
- Support FCEB-specific apprenticeship program development, mentorship models, and skill-based career progression structures through federal and state grant mechanisms, including dedicated workforce funding tied to FCEB procurement.
- Strengthen partnerships between transit agencies, community colleges, and technical education programs through curriculum co-development funding and regulatory flexibility that allows FCEB training delivered at transit facilities to qualify for academic credit.

Conclusion

The transition to hydrogen fuel cell electric buses presents transit agencies with one of the most complex workforce challenges in the history of public transportation. The technical demands of FCEB operations are real, specific, and substantially different from any prior transit technology. But the data from this study are ultimately optimistic: Agencies that have invested in structured workforce development, such as building internal training infrastructure, engaging labor partners, developing regional consortia, and starting before buses arrive, have achieved measurable fleet reliability improvements. Achieving this at scale, however, requires moving beyond agency-by-agency innovation toward coordinated policy investment and shared infrastructure that places effective FCEB workforce development within reach of every transit agency, not just the largest and most resourced.

1. Introduction

The transportation sector stands as the foremost contributor to greenhouse gas (GHG) emissions in the United States. According to the U.S. Environmental Protection Agency, transportation accounted for, 28% of total U.S. greenhouse gas (GHG) emissions in 2022, the largest portion (U.S. EPA, 2024a). Between 1990 and 2022, GHG emissions from the transportation sector grew more in absolute terms than any other sector of the economy, driven in large part by increasing demand for travel (U.S. EPA, 2024b). Public transit buses, while representing only a fraction of total vehicle miles traveled, have a disproportionately negative impact, and their emissions directly affect the health and air quality of communities (U.S. EPA, 2024a).

The state of California faces an even more acute challenge: Transportation is the leading source of GHG emissions, accounting for approximately 40% of the state's total emissions (Center for Biological Diversity, n.d.). This reality has placed California at the forefront of policy and technology innovation aimed at decarbonizing the public transportation sector, making the state a national model for transitioning transit fleets away from fossil fuel propulsion systems.

The technological transition to cleaner bus fleets demands a parallel transformation in the workforce that operates, maintains, and manages these vehicles. Understanding how transit agencies can build and sustain the workforce needed to support this shift is therefore a challenge of national significance.

1.1 The Evolution of Transit Bus Propulsion: From ICE to CNG to Zero-Emission

The urgency of decarbonizing public transit must be understood within the context of a long technological evolution in bus propulsion systems. Public transit buses in the United States have historically relied on internal combustion engine (ICE) technology powered by diesel fuel, a propulsion system well-understood but associated with significant GHG emissions and particulate matter. In response to growing environmental and public health concerns, many transit agencies began transitioning to compressed natural gas (CNG) during the 1990s as a lower-emission alternative (Alternative Fuels Data Center, 2019). While CNG buses offered measurable reductions in particulate matter and certain regulated pollutants compared to diesel, they continued to produce GHG emissions and fell short of the zero-emission standard increasingly demanded by regulators.

This limitation catalyzed interest in zero-emission bus (ZEB) technologies, primarily battery-electric buses (BEBs) and hydrogen fuel cell electric buses (FCEBs), which produce no direct emissions during operation. The California Air Resources Board (CARB) adopted the Innovative Clean Transit (ICT) regulation in December 2018, requiring that beginning in 2029, 100% of new bus purchases by transit agencies must be ZEBs, with the full fleet transition goal set for 2040 (CARB, 2018). This landmark mandate is the first of its kind in the United States that has set the stage for a fundamental transformation of the transit bus operations and workforce landscape.

1.2 Workforce Challenges in Public Transit

The technological transformation of transit fleets is unfolding against the backdrop of a profound and worsening workforce crisis in the public transit industry. Public transit providers across North America face a persistent shortage of operators and mechanics, a crisis that has strained agency budgets and forced widespread service reductions (American Public Transportation Association, 2022). The transit workforce shortage stems from multiple interrelated causes: An ageing industry population has led to increased retirements, while agencies have failed to maintain a robust pipeline of new workers (APTA, 2022). In a 2022 APTA survey of 117 transit agencies of all sizes, 71% reported service reductions or service delays because of worker shortfalls (MTI, 2024). These systemic challenges in the broader transit workforce form the foundation upon which the more specific demands of FCEB deployment are layered.

1.3 Workforce Challenges Specific to Fuel Cell Electric Buses

If the general transit workforce shortage presents a significant operational challenge, the transition to hydrogen fuel cell buses (FCEBs) introduces an additional and more specialized dimension. Workforce-related challenges represent a primary barrier to the widespread adoption of FCEBs, as agencies are confronted with persistent workforce limitations (Jakovich & Reeb, 2022; Noland et al., 2021). FCEBs represent a fundamental departure from the mechanical and operational principles of diesel and CNG buses, requiring personnel with specialized knowledge of hydrogen safety protocols, high-pressure systems, high-voltage electrical systems, and fuel cell system diagnostics, competencies largely absent from conventional transit technician training programs (Jakovich & Reeb, 2022). Moreover, the technological complexity of fuel cell buses limits the direct transferability of skills from workers accustomed to diesel or natural gas systems, further exacerbating workforce preparedness gaps (Jakovich & Reeb, 2022).

These technical challenges are often compounded by significant recruitment and retention pressures. Skilled trades across the transit sector, including vehicle operators, mechanics, and technicians, are experiencing workforce shortages driven by retirements, competition from other industries, and a declining interest in technical careers among younger generations (Noland et al., 2021). FCEB recruitment challenges are further intensified by competition from adjacent sectors, including renewable energy, industrial hydrogen production, and automotive manufacturing, which often offer higher compensation than public transit agencies (Ghorbani et al., 2025).

Despite the urgency of these challenges, limited attention has been paid to workforce development in fuel cell bus research. While considerable scholarly effort has focused on fuel cell stack performance, hydrogen production technology, and refueling infrastructure, the workforce dimensions of successful FCEB deployment have received far less systematic examination (Ahuchogu et al., 2024; Wijayasekera et al., 2024). This imbalance poses a significant risk for transit agencies seeking to move beyond pilot programs to large-scale FCEB adoption.

1.4 Research Need and Purpose of the Study

Existing workforce development literature in the transit sector tends to focus on conventional internal combustion engine (ICE) technologies or, more recently, battery-electric vehicles. The limited research that touches on FCEB-related workforce needs often does so in a general context without delineating the specialized knowledge, skills, and abilities (KSAs) required for hydrogen systems. While original equipment manufacturers (OEMs) and training providers have begun to offer hydrogen-related technical courses, no comprehensive, standardized framework exists that aligns training content with the actual operational requirements of transit agencies. Further, most studies tend to focus on training programs or certification pathways without addressing the broader institutional challenges associated with a full fleet transition to hydrogen technology (Jakovich & Reeb, 2022). These challenges include the necessity of restructuring organizational hierarchies, revising standard operating procedures (SOPs), incorporating hydrogen safety measures into regular operational processes, and harmonizing staff training programs with infrastructure deployment plans. Other institutional challenges include a reliance on OEM knowledge during the initial implementation stages, limited internal capabilities for providing training, and inadequate systems of governance for developing curricula and accreditation standards (Jakovich & Reeb, 2022). Notably absent from the literature is a systematic examination of how workforce gaps emerge across distinct occupational categories, including vehicle operators, maintenance technicians, and facility staff, and how responsibility transitions from OEM-led maintenance to in-house agency services over time.

The purpose of this study is to address these gaps by systematically identifying the KSAs required for hydrogen FCEB operations and maintenance across key occupational categories, assessing the adequacy of current training programs and curricula, and developing evidence-based strategies for workforce recruitment, retention, and upskilling to support transit agencies transitioning to a hydrogen fuel cell fleet. Drawing on a comprehensive literature review and qualitative data collected from transit agency personnel, maintenance technicians, operations leads, and OEMs, this study integrates documented knowledge with current operational realities to produce findings grounded in practice. The findings are intended to serve as a practical roadmap for transit agencies at various stages of FCEB adoption as they work to build and sustain a qualified hydrogen fuel cell workforce.

1.5 Research Objectives

This study pursues two interrelated objectives that together address the scope of FCEB workforce readiness.

Objective 1: To identify the core competencies, encompassing knowledge, skills, and abilities (KSAs) required for transit agency personnel engaged in the operations and maintenance of hydrogen fuel cell electric vehicles.

Objective 2: To assess current training programs, curricula, and educational offerings for FCEB workforce development and to identify gaps between existing training capacity and the evolving needs of transit agencies deploying FCEBs.

1.6 Research Questions

In pursuit of the above objectives, this study is guided by three research questions:

- RQ1: What knowledge, skills, and abilities (KSAs) are essential for vehicle operators and maintenance technicians responsible for hydrogen FCEBs?
- RQ2: What gaps exist between current training programs and curricula available to transit agency personnel for effective FCEB operations and maintenance?
- RQ3: What recruitment and retention strategies exist for FCEB workforce?

By answering these questions, this study aims to provide strategic, actionable guidance for transit agencies transitioning to hydrogen FCEB technologies, ensuring that workforce readiness keeps pace with technological innovation.

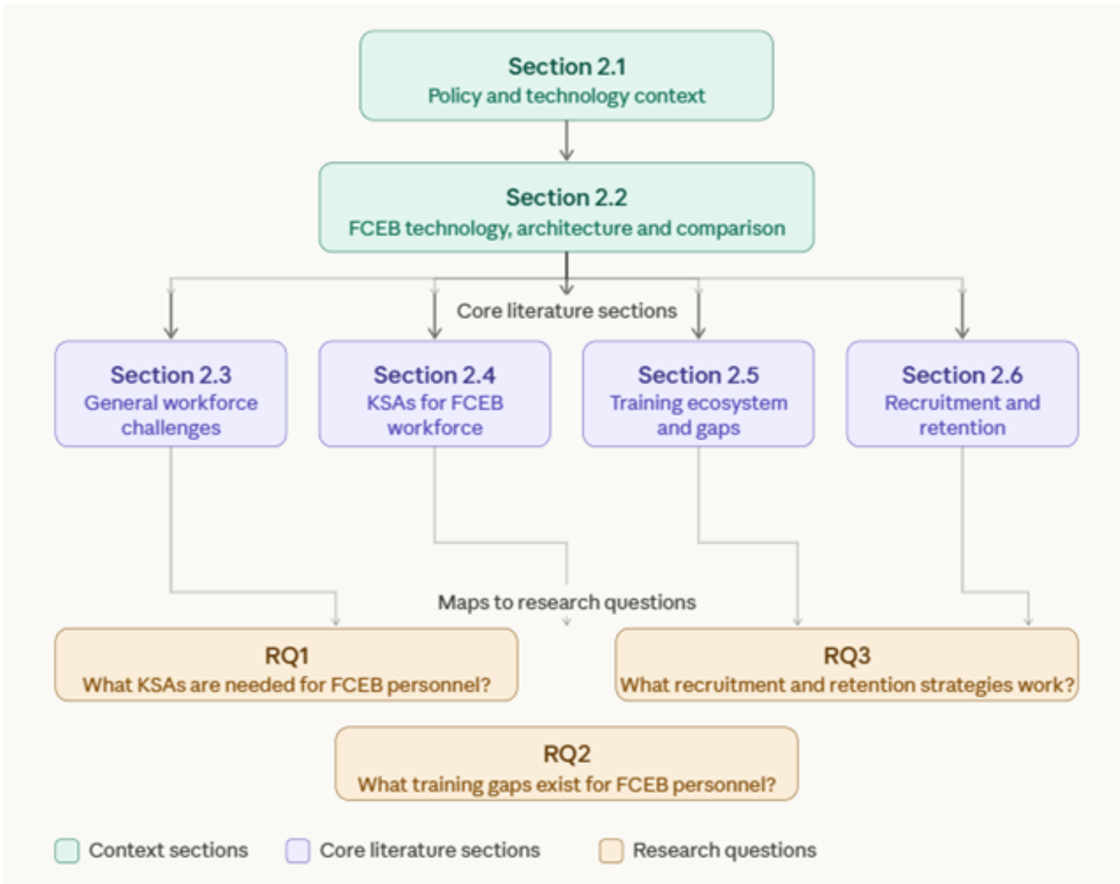
2. Literature Review

This literature review was conducted through a systematic search of academic, governmental, and practitioner sources to identify and synthesize existing knowledge relevant to FCEB workforce development. The search drew on multiple databases and repositories including academic engineering databases (e.g., ASCE Library), academic business databases (e.g., PMI Virtual Library), the Transportation Research Board's TRIS Online database, transit training organizations (e.g., TCRP, CTTC), scholarly research databases (e.g., Google Scholar, Web of Science, Pro Quest), international databases (e.g., Austroads, Highway England, NZTA), public transit agency libraries and websites, and the websites and publications of key federal agencies, including the U.S. Environmental Protection Agency, the Federal Transit Administration, the California Air Resources Board, and the U.S. Department of Energy.

Search terms were developed around four thematic clusters aligned with the study's research questions: (1) hydrogen fuel cell electric bus technology and deployment; (2) transit workforce development, recruitment, and retention; (3) knowledge, skills, and abilities for zero-emission bus personnel; and (4) training programs, curricula, and gaps for FCEB and ZEB transitions. Boolean operators were used to combine and refine search terms, and results were screened for relevance, recency, and credibility. Priority was given to peer-reviewed journal articles, government reports, and publications from established transit research institutions. Other literature, including agency reports, OEM documentation, and practitioner guides, were included where it provided operational insights not captured in academic literature.

The literature review is organized into six sections as illustrated in Figure 1, which maps the conceptual structure of the review and shows how each section connects to the study's research questions.

Figure 1. Literature Review Concept Map



2.1 The Transition to Zero-Emission Transit: Policy and Technology Context

The transition of public transit bus fleets toward zero-emission technologies is being driven by a convergence of regulatory mandates, federal investment, and growing environmental urgency. In the United States, California has led the way with the most comprehensive regulatory framework to date. The California Air Resources Board (CARB) adopted the Innovative Clean Transit (ICT) regulation in December 2018, requiring all public transit agencies operating buses above 14,000 pounds gross vehicle weight to transition to 100% zero-emission bus fleets by 2040 (CARB, 2018). Under the ICT regulation, large transit agencies were required to begin purchasing zero-emission buses starting in 2023, with 100% of all new bus purchases mandated to be zero-emission by 2029 (CARB, 2018). Additionally, each agency is required to submit a Zero-Emission Bus Rollout Plan demonstrating how it will achieve full fleet transition, including infrastructure development and workforce training (Alternative Fuels Data Center, 2019).

At the federal level, the passage of the Bipartisan Infrastructure Law (BIL) in 2021 significantly amplified investment in zero-emission transit. The Infrastructure Investment and Jobs Act made approximately $5.6 billion available for the Low or No Emission (Low-No) Grant Program for fiscal years 2022 through 2026, funding the purchase of low- and zero-emission buses and related infrastructure. In fiscal year 2024 alone, the Federal Transit Administration (FTA) awarded $1.5 billion in bus grants supporting nearly 120 projects across 47 states, with approximately $390 million allocated specifically to hydrogen-powered transit buses and supplementary facilities (Ballard Power Systems, 2025).

The zero-emission bus landscape currently encompasses two primary technologies: battery-electric buses (BEBs) and hydrogen fuel cell electric buses (FCEBs). While BEBs currently constitute the majority of zero-emission bus deployments in the United States, FCEBs are gaining significant traction, particularly for transit agencies operating longer routes, hilly terrain, or high-frequency service where range and refueling speed are critical (ETA Transit, 2025). The choice between these technologies is shaping workforce development needs in distinct and complex ways. Understanding the technical characteristics of FCEBs is therefore essential to understanding the workforce competencies they demand.

2.2 Hydrogen Fuel Cell Technology in Public Transit

FCEB Architecture: How Fuel Cell Buses Work

A hydrogen fuel cell electric bus (FCEB) is fundamentally an electric vehicle that generates its own electricity on board through an electrochemical reaction, rather than drawing from a stored battery charge. At the core of this system is the fuel cell stack, which comprises an assembly of individual membrane electrode assemblies (MEAs) that react hydrogen and oxygen in the presence of a catalyst (Alternative Fuels Data Center, 2019). During this proton exchange membrane (PEM) process, hydrogen molecules are split into protons and electrons at the anode; the protons pass through the membrane to the cathode, while the electrons are directed through an external circuit, generating electric current. On the cathode side, the protons, electrons, and atmospheric oxygen combine to produce water vapor, the bus's only tailpipe emission (Karsan, 2023). The electricity produced by the fuel cell stack is supplied to an electric traction motor that drives the wheels.

Most modern FCEBs employ a hybrid architecture that pairs the fuel cell with a smaller auxiliary battery or supercapacitor (Fuel Cell Electric Buses, 2021). In this configuration, the fuel cell serves as the primary energy source for sustained operation, while the battery provides peak power during rapid acceleration and captures energy through regenerative braking (Fuel Cell Electric Buses, 2021). Hydrogen is stored onboard in high-pressure compressed tanks, typically rated at 350 or 700 bar, mounted on the roof or in purpose-built compartments. Each tank is equipped with a multifunctional safety valve system including solenoid valves, emergency temperature-activated shutoffs, and overload valves to prevent uncontrolled hydrogen release (Karsan, 2023).

This hybrid architecture, integrating a fuel cell stack, high-pressure hydrogen storage, power electronics, auxiliary battery, and electric drivetrain, represents a significant departure from diesel, CNG, and even battery-electric propulsion systems. They carry profound implications for the technical competencies required of the workforce that maintains and operates these vehicles.

FCEB vs. BEB: A Comparative Analysis

While FCEBs and BEBs share an electric drivetrain and zero tailpipe emissions, they differ substantially across several dimensions critical to transit operations: range, refueling time, infrastructure requirements, environmental performance, and total cost of ownership. Table 1 presents a structured comparison across these dimensions.

Table 1. Comparative Analysis: FCEB vs BEB

Dimension	**Fuel cell electric bus (FCEB)**	**Battery electric bus (BEB)**
Operational range	Up to 450 miles per fill; suitable for long routes, hilly terrain, and high-frequency service	150–250 miles per charge; range reduced further by cold weather and high auxiliary loads
Refueling / charging time	7–10 minutes; comparable to diesel/CNG; minimal operational disruption	Several hours for full charge; fast charging available but costly and grid-intensive
Infrastructure requirements	Centralized hydrogen station at depot	Significant electrical upgrades required
Weather performance	Consistent power and range in extreme hot or cold temperatures; less sensitive to ambient conditions	Range and battery capacity reduced in cold weather; heating loads further diminish operational range
Tailpipe emissions	Zero; emits only water vapor during operation	Zero; no tailpipe emissions during operation
Vehicle acquisition cost	Higher per vehicle; costs declining with scale; lower mid-life maintenance costs noted	Lower per vehicle for small fleets; battery replacement costs affect lifecycle total cost of ownership
Operational cost per mile	~2.3× higher per mile than BEB currently, primarily due to hydrogen fuel cost	Lower per mile; cheaper electricity and simpler mechanical maintenance
Best fit service conditions	Long routes, hilly terrain, high-frequency BRT, mixed climates, emergency resilience needs	Short urban routes, predictable schedules, mild climates, depot charging feasibility
Workforce training complexity	High; requires hydrogen safety, fuel cell diagnostics, high-pressure systems, and high-voltage expertise	Moderate; requires high-voltage electrical training; less complex than FCEB but beyond diesel skills

Note. Data were compiled from Transit Workforce Center (2022), ETA Transit (2025), and Alameda-Contra Costa Transit District ZEB Report (2025).

In terms of operational range and refueling, FCEBs hold a distinct advantage. FCEB models have driving ranges of up to approximately 450 miles, making them more suitable for longer routes, hilly terrain, and routes with heavy heating or air-conditioning demands (Environmental Resources Management, n.d.; Kurtz et al., 2019). Standard BEBs typically have ranges of approximately 150 to 250 miles depending on battery size, and their range is further reduced by cold weather and heavy auxiliary loads. Furthermore, FCEBs can be refueled in approximately 7 to 10 minutes, comparable to conventional diesel or CNG buses, while BEBs may require several hours for a full charge (Karsan, 2023). One modeling study of a mixed transit fleet found that BEBs could adequately serve approximately 73% of service blocks, while FCEBs were operationally necessary for the remaining 27% involving longer or higher-frequency routes (ETA Transit, 2025).

From an infrastructure perspective, BEBs require substantial electrical upgrades to depot facilities, while FCEBs require a centralized hydrogen refueling station at the bus depot with minimal electrical grid upgrades (Fuel Cell Electric Buses, 2021). FCEBs have a higher per-vehicle acquisition costs and higher per-mile operational costs primarily due to hydrogen fuel pricing, though lifecycle analyses present a more nuanced picture. Foothill Transit's analysis found that operating BEBs on one of its routes (Line 486) would cost $12.9 million more than FCEBs over a 12-year lifecycle (California Hydrogen Business Council, 2024). As green hydrogen production scales, the cost gap is expected to narrow substantially. Beyond production costs, hydrogen fuel expenditures include upstream compression, storage, and delivery costs that vary with local supply chain maturity. For BEBs, peak versus off-peak utility rate differentials represent an often-overlooked operational cost driver.

The operational characteristics of FCEBs make them a compelling choice for transit agencies facing specific service conditions and regulatory requirements. For agencies operating routes that exceed the range capabilities of available BEB models, particularly in hilly terrain, extreme climates, or high-frequency service, FCEBs offer a viable and operationally compatible zero-emission alternative (Farahmand, 2024). Their rapid refueling capability allows transit agencies to maintain existing scheduling and depot operations with minimal disruption (Farahmand, 2024). FCEBs also offer grid resilience advantages by remaining operational during grid outages, an increasingly important consideration as climate-related disruptions affect electricity supply. For many transit agencies, the most practical approach is a mixed-fleet strategy that deploys BEBs on shorter urban routes and FCEBs on longer, more demanding routes (ETA Transit, 2025). Regardless of fleet composition, the introduction of FCEBs fundamentally changes the skills, training, and organizational structures required of the transit workforce.

2.3 Workforce Development in Public Transit: General Challenges

Public transit agencies across the United States face a persistent and worsening workforce crisis that predates the zero-emission transition but is significantly amplified by it. The transit workforce has been aging for decades, with a considerably older age profile than comparable industries; for example, the median age of transit workers is 50.8 years, compared with 42.2 years for the overall U.S. workforce. This has contributed to an accelerating rate of retirements that agencies have struggled to offset through recruitment (APTA, 2022). This is compounded by the post-COVID-19 pandemic labor market, in which transit agencies face intensified competition from private sector employers offering higher wages and more flexible working conditions (MTI, 2024).

Recruitment challenges are further exacerbated by structural barriers including the declining interest of younger workers in skilled trades, the complexity of Commercial Driver's License (CDL) requirements for bus operators, and competition from adjacent industries such as logistics, construction, and renewable energy sectors (Noland et al., 2021). Retention is equally challenging, with transit agencies reporting that workers are attracted to higher pay, better scheduling, and a better pay progression structure in other organizations. Public sector employment has had a history of ineffective early-career workers' retention in an increasingly competitive labor market (APTA, 2022).

The Government Accountability Office (GAO) has highlighted that transitioning to ZEBs will most significantly transform traditional mechanic roles, shifting them from hands-on mechanical trades toward technician roles that require the use of electronic diagnostic equipment and software to interpret error codes and identify system faults (GAO, 2025). This role transformation requires not only the retraining of existing workers but a fundamental rethinking of how transit agencies recruit, develop, and retain technical talent. These challenges form the context within which the specialized workforce demands of FCEB adoption must be understood.

2.4 Knowledge, Skills, and Abilities (KSAs) for the FCEB Workforce

The introduction of hydrogen FCEBs into transit fleets creates distinct and role-specific knowledge, skills, and ability (KSA) requirements across multiple occupational categories. Unlike the transition from diesel to CNG, which involved familiar mechanical principles with modified fueling systems, the shift to FCEBs introduces fundamentally different propulsion technologies that demand competencies not covered by conventional transit training curricula (Jakovich & Reeb, 2022). The Transit Workforce Center (2022) notes that moving to ZEBs requires significant commitment to additional skills training. For FCEBs specifically, the high-voltage environment is compounded by the added complexity of hydrogen systems, making the KSA demands even more specialized.

Vehicle operators working with FCEBs require foundational knowledge of hydrogen safety principles, including the properties of hydrogen as a fuel, leak detection procedures, and emergency response protocols specific to hydrogen incidents (SamTrans, 2022). Maintenance technicians face the most substantial KSA expansion in the transition to FCEBs, requiring deep competencies in fuel cell stack diagnostics, high-pressure hydrogen storage systems, high-voltage electrical system safety, power electronics, and the use of electronic diagnostic tools (Transit Workforce Center, 2022; GAO, 2025). The APTA *National ZEB Maintenance Training Standards* define the essential KSAs needed for technicians to perform maintenance and diagnostic tasks safely on zero-emission buses (Transit Workforce Center, 2022).

Across all occupational categories, several cross-cutting KSAs emerge as critical: a strong hydrogen safety culture, systems-level thinking about integrated electrical and hydrogen systems, regulatory compliance awareness, and the ability to adapt to rapidly evolving technology (Ahuchogu et al., 2024; Wijayasekera et al., 2024). Table 2 organizes the KSAs identified in the literature across the two primary occupational categories, vehicle operators and maintenance technicians.

Table 2. KSAs for FCEB Workforce by Occupational Category

KSA type	Vehicle operators	Maintenance technicians
Knowledge	• Properties of hydrogen as a fuel (flammability, dispersion behavior) • Hydrogen safety principles and emergency procedures • Operational differences between FCEBs and diesel/CNG/BEB buses • Fuel cell system status indicators and warning signals • Safe refueling procedures at hydrogen dispensing stations	• Proton exchange membrane (PEM) fuel cell stack operation • High-pressure hydrogen storage systems (350/700 bar) • High-voltage electrical system principles (up to 800V) • Hydrogen fuel line, fitting, and valve specifications
Skills	• Pre-trip vehicle inspection for hydrogen-specific components • Recognition and response to hydrogen leak indicators • Safe execution of hydrogen refueling process • Emergency response and passenger evacuation procedures in hydrogen contexts	• Fuel cell stack diagnostics and performance testing • High-voltage system safe working practices (lockout/tagout) • Hydrogen system inspection, leak testing, and repair • Use of electronic diagnostic tools and OEM software • Preventive and corrective maintenance of fuel cell components
Abilities	• Apply hydrogen safety culture consistently during operations • Adapt to operational changes as FCEB technology evolves • Communicate effectively with dispatch and maintenance on system issues • Exercise sound judgment in novel or emergency situations	• Apply systems-level thinking across integrated hydrogen and electrical systems • Continuously update skills as fuel cell technology advances

Note. Data were compiled from Transit Workforce Center (2022), GAO (2025), Jakovich & Reeb (2022), SamTrans (2022), and Alternative Fuels Data Center (2019).

2.5 The Current Training Ecosystem for the FCEB Workforce

Training Programs, Curricula, and Modalities

The current training ecosystem for FCEB workforce development is fragmented and still maturing. Several key institutions and programs have begun to address the gap, but no comprehensive, standardized national framework currently exists that aligns training content with the full operational requirements of transit agencies deploying FCEBs (Jakovich & Reeb, 2022).

The Transit Workforce Center (TWC), established as the first FTA-funded technical assistance center dedicated to transit workforce development, has worked with APTA, transit agencies, labor unions, and bus manufacturers to develop the national *ZEB Maintenance Training Standards* (Transit Workforce Center, 2022). Notable training facilities have also emerged at the agency level: SunLine Transit Agency hosts the West Coast Center of Excellence in Zero Emission Technology (CoEZET) in Thousand Palms, California, while AC Transit has developed the Zero Emission Bus University at its Emeryville facility (California Hydrogen Business Council, 2024). Training modalities across the existing ecosystem include classroom instruction, online and self-paced eLearning, hands-on activities, simulation-based training, on-the-job mentorship, and train-the-trainer programs (Hydrogen Era, 2025). Table 3 summarizes the key training programs and modalities currently available for FCEB workforce development, including their target audiences, content focus, and structural limitations.

Table 3. Current FCEB Training Programs, Modalities, and Limitations

Program / organization	**Target audience**	**Modality**	**Content focus**	**Key limitations**
FTA *National ZEB Maintenance Training Standards*	Technicians	Standards framework; classroom; hands-on exercises; assessments	ZEB maintenance and diagnostics; safety fundamentals;	Framework only; not a delivered course; implementation varies by agency
SunLine Transit Agency	Technicians	In-person; hands-on; simulation; in-service management workshops	ZEB fueling system operations; fleet maintenance; diagnostic tool use; hydrogen infrastructure	Geographic access limited; capacity constraints; primarily California-focused
Zero Emission Bus University; AC Transit, Emeryville, CA	Technician; Operators	In-person; classroom; laboratory; integrated maintenance facility	FCEB and BEB maintenance; safety protocols; system diagnostics; workforce upskilling	Single agency; limited external access; still scaling as of 2025
OEM Training: New Flyer, and Ballard Power Systems	Technicians	In-person workshops; on-site delivery; manufacturer facility tours	Product-specific fuel cell system operation; maintenance procedures; proprietary diagnostics	Product-specific only; not transferable across platforms; not sustained post-delivery; inaccessible for smaller agencies
DOE H2Tools; U.S. Department of Energy	Technician; Facility staff	Online; self-paced e-learning; reference materials	Hydrogen safety training; properties of hydrogen; leak detection;	General hydrogen content, not transit-specific
Rio Hondo Community College – Alternative Fuels Technician Program	Technicians	In-person; classroom; laboratory; vocational certification	Alternative fuels including hydrogen fuel cell technology	Limited depth of FCEB-specific content; not replicated at sufficient national scale

2.6 Recruitment, Retention, and Workforce Pipeline Strategies

Building and sustaining a qualified FCEB workforce requires transit agencies to address not only training but also the upstream challenges of recruitment and the downstream challenges of retention. Table 4 summarizes several evidence-based strategies across these dimensions as identified in the literature.

Table 4. Recruitment and Retention Strategies for Transit Workforce

Strategy	Focus	Description	Applicability to FCEB context
Educational institution partnerships	Recruitment	Collaboration with community colleges, vocational schools, and technical institutes to build entry-level pipelines with relevant foundational skills	Critical for FCEB context; develops pre-trained talent pool with hydrogen and electrical systems knowledge, reducing agency training burden from zero baseline
Apprenticeship and earn-while-you-learn programs	Both	Structured pathways allowing workers to gain transit-relevant skills while earning; FTA-supported network for sharing apprenticeship models across agencies	Particularly effective for attracting workers from non-traditional backgrounds; allows agencies to grow FCEB capacity incrementally aligned with fleet deployment timelines
Succession planning and knowledge transfer	Retention	Structured mentorship, documented procedures, and cross-training to manage retirement-related knowledge loss	Critical as transit workforce ages, agencies risk losing scarce FCEB expertise
Inter-agency collaboration and regional consortia	Both	Regional partnerships between agencies, educational institutions, and OEMs to develop shared training infrastructure and recruitment pipelines	Particularly valuable for smaller agencies that cannot independently fund FCEB training programs

Note. Data were compiled from Transit Workforce Center (2022) and MTI (2024).

Partnerships with educational institutions represent one of the most promising pipeline strategies. Collaborations between transit agencies and community colleges, vocational schools, and technical institutes can produce entry-level workers with relevant foundational skills, reducing the burden on agencies to provide all training from scratch (Transit Workforce Center, 2022). Several agencies have pursued such partnerships in the context of FCEB adoption. For example, the North County Transit District received FTA funding specifically to develop a workforce development program in partnership with a local college as part of its FCEB procurement (*The Coast News*, 2023). In addition, inter-agency collaboration and regional workforce consortia allow smaller agencies to pool training and recruitment resources that would otherwise be prohibitively expensive to develop independently (CARB, 2018; Transit Workforce Center, 2022).

Apprenticeship and earn-while-you-learn models offer another effective pathway, particularly for attracting workers from non-traditional backgrounds who may not have prior exposure to transit or hydrogen technology. Compensation and career pathway clarity are consistently identified in the literature as critical retention factors. Workers in the transit sector, particularly skilled technicians, face competitive offers from the private sector, renewable energy industry, and hydrogen production companies (Freeman et al., 2018). Transit agencies that have successfully improved retention have done so by offering clearer progression pathways, transparent pay scales tied to skill development, and early investment in new employee experience (MTI, 2024). Additionally, succession planning and knowledge transfer are particularly urgent given the aging of the existing transit workforce (Transit Workforce Center, 2022; MTI, 2024), ensuring that institutional expertise is retained as experienced workers retire.

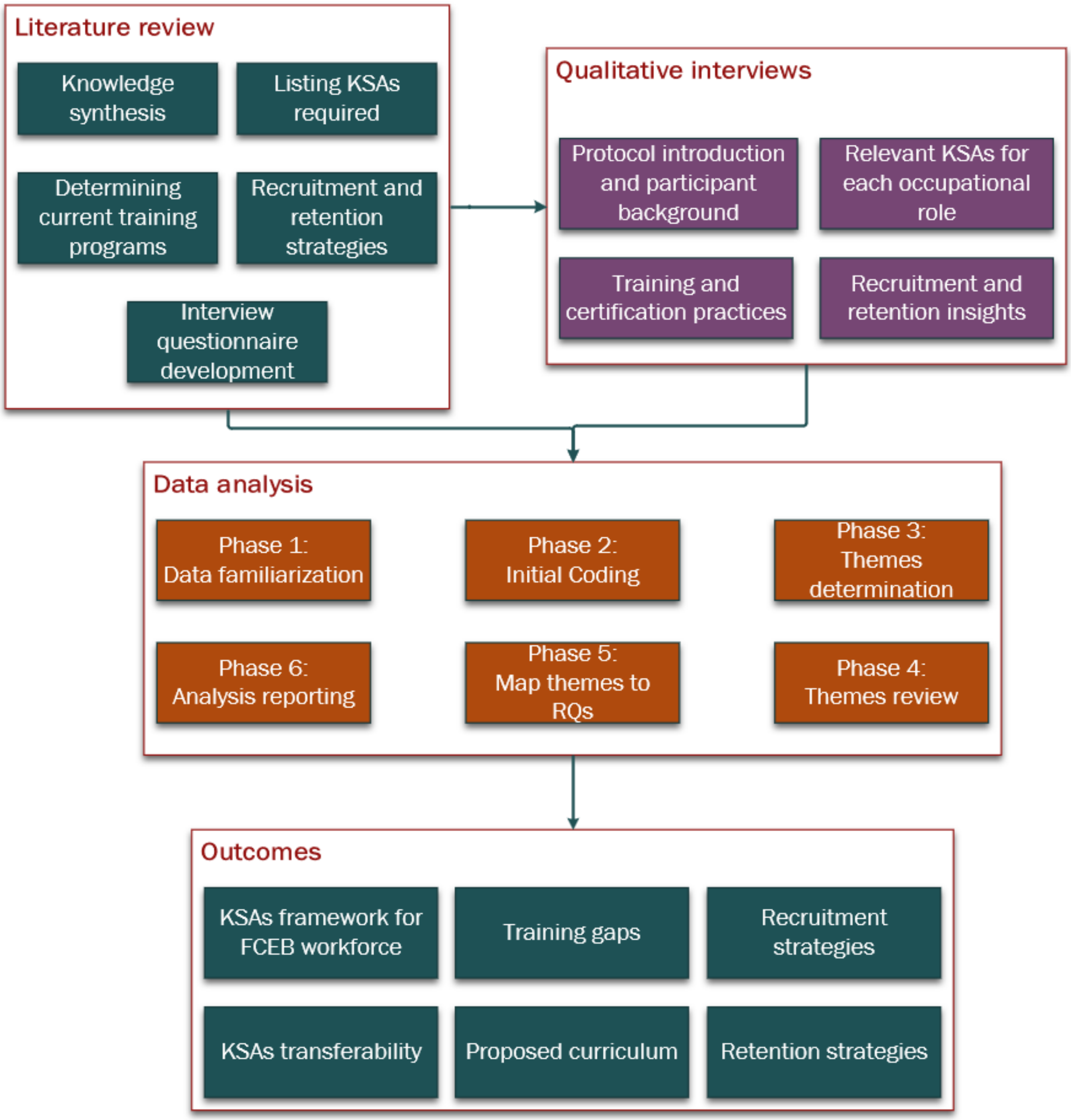
3. Research Methodology

3.1 Research Design

This study employed a qualitative research design to investigate the workforce development challenges, knowledge, skills, and abilities (KSAs), training gaps, and recruitment and retention strategies associated with the adoption of hydrogen fuel cell electric buses (FCEBs) at transit agencies. A qualitative approach was selected because the nature of the research questions demanded in-depth exploration of participants' professional perspectives and institutional knowledge (Creswell & Poth, 2018). Given that FCEB workforce development is an emerging and rapidly evolving area for which little standardized data exists, a qualitative design was particularly appropriate, as it allows researchers to construct meaning from the perspectives of those directly involved (Creswell & Creswell, 2018). Qualitative methods have been applied extensively across workforce development and organizational research contexts (Celoza et al., 2023), demonstrating their established utility for exploratory purposes investigating complex professional and institutional phenomena.

To address the study's research questions comprehensively, data were collected and analyzed through (1) a systematic literature review and desk scan and (2) semi-structured qualitative interviews with FCEB stakeholders. The literature review (Section 2 of this research report) and desk scan provided the conceptual and empirical foundation for the study, establishing what is already known about FCEB technology, workforce challenges, KSAs, training programs, and recruitment and retention strategies. The qualitative interviews then extended and deepened this foundation by capturing the professional experiences, operational realities, and institutional perspectives of practitioners actively engaged in FCEB deployment. Together, this enabled a rigorous triangulation of documented knowledge with current operational reality, producing findings grounded in both the scholarly evidence base and frontline practice (Creswell & Poth, 2018). Figure 2 illustrates this study's overall research methodology framework.

Figure 2. Research Methodology Framework



3.2 Literature Review and Desk Scan

The first step in the research methodology was to perform a literature review and desk scan. The primary purpose of literature review was to (1) synthesize existing knowledge on FCEB technology, policy context, and deployment trends; (2) identify what the literature documents about KSAs required for FCEB workforce roles; (3) examine existing training programs, curricula, and their limitations; and (4) review evidence-based strategies for workforce recruitment, retention, and pipeline development. The literature review directly informed the development of the semi-structured interview protocol, ensuring that interview questions were grounded in existing knowledge and targeted toward documented gaps.

The literature (Section 2 of this report) was organized thematically into six sections corresponding to the study's conceptual framework: (1) policy and technology context; (2) FCEB architecture and comparison with battery-electric buses; (3) general transit workforce challenges; (4) KSAs for the FCEB workforce; (5) the current training ecosystem, including OEM training and training gaps; and (6) recruitment, retention, and workforce pipeline strategies. This structure ensured that the literature review directly mapped to the study's research questions and provided a structured basis for the development of the interview protocol.

3.3 Qualitative Interviews

The next step in the methodology employed semi-structured, in-depth interviews with a diverse set of stakeholders involved in FCEB operations, maintenance, workforce development, and policy. While the literature review established what has been documented in the scholarly and practitioner evidence base, the qualitative interviews were designed to capture what practitioners know from direct operational experience, including perspectives, challenges, and strategies that have not yet been formally documented in the literature. Semi-structured interviews ensured that each interview addressed the core thematic areas (Braun & Clarke, 2006)—KSAs, training and certification, and recruitment and retention—while also allowing the interviewers to follow participant responses with probes and follow-up questions, enabling participants to elaborate on topics leveraging their experiences, introduce perspectives not anticipated in the interview guide, and share experiential knowledge in a naturalistic and conversational manner (McIntosh & Morse, 2015). Semi-structured interviews are widely recognized as the most appropriate data collection method for workforce-focused qualitative research as they produce rich, context-sensitive data that can illuminate both the technical and institutional dimensions of workforce challenges (Creswell & Creswell, 2018; Creswell & Poth, 2018).

Data Collection

The interview protocol was developed collaboratively by the research team and was directly informed by the findings and gaps identified in the literature review. Questions were designed to understand practitioner perspectives regarding KSAs, training, and workforce strategies. The protocol contained questions organized into four thematic sections: (1) protocol introduction to establish context and gather participant background, (2) KSAs relevant to the occupational roles (operators and mechanics/technicians), (3) training and certification practices and gaps, and (4) recruitment, retention, and workforce pipeline strategies. Interviews then concluded with a standardized set of closing questions soliciting participants' recommendations for improving FCB workforce development across the sector. Follow-up probes were embedded throughout the protocol to encourage depth and specificity of response.

Qualitative interviews were conducted remotely via videoconference (Zoom) between October and December 2025 to capture a wide geographic distribution of participants. Each interview lasted between 50 and 115 minutes. With participants' consent, all interviews were recorded to support accurate transcription. Where video conferencing platforms provided automatic transcription, researchers utilized these transcripts as a starting point and subsequently made corrections by reviewing the audio recordings, a process consistent with Celoza et al. (2023). Where automatic transcription was unavailable, audio recordings were manually transcribed. All transcripts were reviewed for accuracy before analysis commenced. Participants were informed that audio recordings would be used solely for research purposes and would not be shared beyond the research team.

Participant Recruitment

Participant recruitment followed a purposive sampling strategy, which is the predominant approach in qualitative research and involves the deliberate selection of participants who possess particular experiences, expertise, or perspectives relevant to the research questions (McIntosh & Morse, 2015). Within the overarching purposive framework, the study employed a maximum variation sampling strategy to ensure that the participant pool captured a broad range of organizational types, geographic contexts, fleet sizes, and FCEB adoption stages (Creswell & Poth, 2018). Transit agencies were selected to represent both large and smaller systems, California-based and out-of-state agencies, agencies with established FCEB fleets and those in the early implementation phases, and agencies operating under different fleet management models, including direct agency operation and contracted service providers. OEM and industry stakeholders were similarly selected to represent different segments of the FCEB ecosystem, including vehicle manufacturers, fuel cell system providers, transit industry associations, and training intermediaries.

For the inclusion criteria, the participants were eligible if they had direct professional involvement with fuel cell electric buses (FCEBs). This included (a) transit agency personnel involved in operations, maintenance, facilities, workforce development, or fleet transition planning at agencies operating or planning FCEBs, with at least one year of experience; (b) OEM representatives from bus manufacturers, fuel cell providers, or hydrogen infrastructure companies engaged in the U.S. transit market, with roles in FCEB training, technical support, or workforce development; and (c) industry and policy stakeholders involved in FCEB-related policy, advocacy, training, or workforce initiatives. Individuals without direct FCEB involvement were excluded. A total of 20 participants were recruited. Table 5 summarizes participant characteristics.

Table 5. Research Participants

ID	Participant type	Geographic area	FCEB experience
P01	Transit Agency (Large, Implementing)	California	10 years
P02	Transit Agency (Mid-size, Implementing)	Ohio	10 years
P03	Transit Agency (Mid-size, Implementing)	Ohio	4 years
P04	Transit Agency (Mid-size, Implementing)	California	5 years
P05	Transit Agency (Mid-size, Implementing)	California	2 years
P06	Transit Agency (Mid-size, Implementing)	California	1.5 years
P07	Transit Agency (Large, Scaling)	California	2 years
P08	Transit Agency (Small, Implementing)	California	5 years
P09	Transit Agency (Mid-size, Implementing)	Illinois	5 years
P10	Transit Agency (Small, Planning Stage)	California	1 year (planning only)
P11	OEM / Manufacturer	North America (multi-site)	10 years
P12	Training Organization	California	3 years (FCEB focus)
P13	OEM / Manufacturer	North America	10 years (ZEB total)
P14	Training Organization	Washington	5 years
P15	OEM / Manufacturer	North America	10 years
P16	Industry Association	California	5 years
P17	Industry Consultant	National / multi-region	5 years
P18	Transit Agency (Large, Implementing)	California	5 years
P19	Transit Agency Contractor (Small, Implementing)	California	3 years
P20	Industry Association	California	8 years

The participant pool spanned transit agencies actively deploying FCEBs, OEMs, transit industry training organizations, a state regulatory agency, and a workforce development firm actively supporting FCEB deployments at transit agencies. This multi-stakeholder composition was intentional, reflecting the study's recognition that FCEB workforce development is a shared challenge requiring coordinated action across transit agencies, manufacturers, training providers, and policymakers. The geographic spread included agencies in California, Ohio, Washington, and Illinois, capturing both California-led adoption patterns and the growing national FCEB market.

The stopping criterion for data collection was the achievement of saturation combined with reaching a minimum participant threshold. Saturation occurs when no new ideas, themes, or information emerge from additional interviews and when identified concepts are sufficiently well-defined to be comprehensively explained (Creswell & Poth, 2018). Creswell and Poth (2018) recommend 20 to 30 participants to achieve saturation in qualitative studies employing systematic coding procedures. This study with 20 participants meets this and achieved the study's criterion for saturation.

This study was conducted in full compliance with the ethical standards governing human subjects research. Institutional Review Board (IRB) approvals were obtained from both California State University, Fresno, and California Polytechnic State University, San Luis Obispo, prior to the commencement of data collection. Informed consent was obtained from all participants prior to their participation in the study. Oral re-confirmation of consent was obtained at the beginning of each interview prior to recording. Participants were informed that no individual would be identified in association with specific sensitive statements without explicit permission. Data were stored securely on password-protected institutional systems accessible only to the two principal investigators.

Data Analysis

Interview data were analyzed using thematic analysis as outlined by Braun and Clarke (2006), one of the most widely used and methodologically robust approaches to analyzing qualitative data across workforce development and organizational research contexts (Nowell et al., 2017). All 20 interview transcripts were imported into NVivo, which was used to develop, apply, and organize codes throughout the analysis. The analysis followed Braun and Clarke's (2006) six-phase framework, implemented as an iterative and reflexive process in which both researchers moved back and forth between phases rather than progressing through them in a strictly linear sequence.

Phase 1: Familiarization with the Data

Both principal investigators independently read and re-read all 20 transcripts in their entirety prior to any formal coding, making initial notes and observations about recurring ideas, striking phrases, and patterns of response. This immersive engagement with the data served to build familiarity with the breadth and depth of participant accounts before formal coding commenced (Braun & Clarke, 2006).

Phase 2: Generating Initial Codes

Each researcher independently coded the full dataset within NVivo, assigning descriptive labels to segments of text that captured meaningful units of data relevant to the research questions. Coding was conducted both inductively and deductively, allowing codes to emerge organically from participant language and experiences while remaining anchored to the study’s research questions ensuring that the analysis remained anchored to the study’s research questions (Braun & Clarke, 2006).

Phase 3: Searching for Themes

Initial codes were collated and sorted into potential themes. In this phase, the discrepancies between the two researchers’ codes were discussed and, following independent coding, the two coders compared their coding of all 20 transcripts. Discrepancies clustered in three areas: (1) the level of abstraction at which a segment was coded (e.g., whether information on hydrogen-sensor calibration was coded under a broad "diagnostic skills" code or a more specific "hydrogen system instrumentation" code); (2) the placement of segments that plausibly belonged to more than one code (e.g., between training-gap and workforce-strategy content; and (3) divergence between inductively generated and deductively anchored labels. Each discrepancy was resolved through discussion against the source transcript until both coders reached consensus on the code assignment and, where needed, the coding structure was revised accordingly. This consensus process functioned as a reflexive check on interpretation, strengthening the credibility and confirmability of the analysis (Nowell et al., 2017), rather than as a measure of inter-rater agreement, consistent with the reflexive orientation of the chosen method (Braun & Clarke, 2006).

Phase 4: Reviewing Themes

The researchers revisited the NVivo coding structure and the original transcripts during this phase to verify that each theme accurately captured a meaningful and identifiable pattern in participant accounts and that no important nuance was being lost through over-aggregation (Braun & Clarke, 2006). Themes were refined, merged, or disaggregated as necessary throughout this iterative review process.

Phase 5: Defining and Naming Themes

Each theme was clearly defined in terms of its scope, central organizing concept, and relationship to the study's research questions. Theme names were crafted to be both descriptive and analytically precise, capturing the essence of what each theme conveys without reducing it to a simplistic label (Braun & Clarke, 2006; Nowell et al., 2017). At this stage, the mapping of themes to specific research questions was finalized to ensure that the findings directly and comprehensively address RQ1, RQ2, and RQ3.

Phase 6: Producing the Report

The final themes were woven into a narrative account of the findings, supported by representative quotations drawn from participant interviews. Quotations were selected to illustrate the breadth and depth of each theme, representing the range of participant perspectives rather than privileging any single viewpoint. Additionally, a triangulation approach was employed wherein themes identified in the interview data were systematically compared with evidence drawn from the literature review, enabling the research team to identify areas of confirmation, extension, and divergence between documented knowledge and practitioner experience (Creswell & Poth, 2018).

Researcher(s) Positionality

Qualitative inquiry is shaped by the perspectives researchers bring to it, and acknowledging this positionality supports trustworthiness (Braun & Clarke, 2006). The research team comprised investigators in construction management and workforce development at California State University, Fresno, and California Polytechnic State University, San Luis Obispo, who approached FCEB workforce development as workforce-and-training researchers rather than transit insiders. This outsider position aided foundational questioning but required care in interpreting operational terminology, which the team verified against participant accounts and the literature. The team also began expecting FCEB readiness to be largely a technical-training problem, but engagement with the data revised this toward the system-level interpretation that organizes the findings.

4. Findings and Discussion

The findings are organized around the three research questions: KSAs for the FCEB workforce (RQ1); training gaps between current programs and operational needs (RQ2); and effective workforce recruitment, retention, and development strategies (RQ3).

4.1 RQ1: Knowledge, Skills, and Abilities Required for the FCEB Workforce

The first research question asked the following: What knowledge, skills, and abilities (KSAs) are essential for vehicle operators and maintenance technicians responsible for FCEBs? Analyses revealed distinct competencies for each occupational category. Consistent with the literature (APTA, 2023; Fechtner et al., 2017), findings confirmed that FCEBs demand a uniquely tri-disciplinary integration of mechanical, electrical, and hydrogen chemical safety competencies.

KSAs for Vehicle Operators

Participants consistently described operator KSA requirements as more tractable than technician requirements, with the critical differences from diesel and CNG operations concentrated in three areas: energy management behavior, emergency response, and hydrogen safety awareness. Table 6 presents the full operator KSA framework with frequency data.

Table 6. KSA Framework for FCEB Vehicle Operators

KSA Type	Competency	Description	Frequency (*n* = 20)
Knowledge	FCEB propulsion architecture	• Relationship between the fuel cell, traction battery, inverter, and electric motor; • Operational difference of FCEB from ICE, CNG, and BEB buses.	19
	Hydrogen safety principles	• Hydrogen properties • Hazard identification and alarm indicators NFPA 2 awareness	19
	Range and energy management	• PSI gauge reading and FCEB range relationships • Route-specific range planning	18
	Dashboard indicators	• FCEB-specific warning lights: battery state-of-charge, fuel cell status, hydrogen pressure, sensor alerts	18
	Emergency Response Readiness	• Safe vehicle de-energization procedures • Emergency Responder Guide delivery to first responders and Emergency passenger evacuation procedures	19
Skills	Energy-conscious and eco-driving technique	• Regenerative braking, smooth acceleration, relative HVAC use, terrain and weather conditions driving, and coasting to maximize range	18
	Enhanced pre-trip inspection	• Walk-around for hydrogen system anomalies, panel security, and fuel system indicators • Document pre-departure conditions and confirm readiness with dispatch	18
	Hydrogen fueling protocols	• Familiarity with fueling facility layout: dispenser locations, emergency shutoffs, grounding points, restricted zones	15

KSA Type	Competency	Description	Frequency (*n* = 20)
		• Fueling sequence and operator verification steps • Safe handoff procedures with fueling staff	
	Proactive PSI monitoring and reporting	• Monitor hydrogen pressure throughout shift • Report threshold readings to dispatch before fuel is critically low • Active dispatching and communication skill	14
Abilities	Situational awareness	• Recognize warning signs: unusual system behavior, unexpected vapor, sensor alerts, contamination odors • Respond proportionately without panic	15
	Communication	• Communicate PSI readings, warning conditions, and incident details to dispatch and maintenance • Document pre-trip findings, mid-shift anomalies, and end-of-shift observations • Communication loop with maintenance	15

The operator KSA framework presented in Table 6 reflects a consistent finding across all participants: The transition from conventional transit bus operations to FCEB operations demands meaningful retraining, but the scope and depth of that retraining is lower than what is required for maintenance technicians. Operators require a targeted set of adaptations concentrated in three functional areas: safety awareness specific to hydrogen, energy management behavior, and procedural discipline during fueling and emergency events.

Emergency response readiness and hydrogen safety awareness emerged as a core competency requirement, with 19 of 20 participants identifying it as non-negotiable for safe FCEB operations. Effective operation of fuel cell electric buses requires operators to possess specialized knowledge of hydrogen system behavior. This includes awareness that hydrogen flames may be invisible, that normal exhaust may appear as steam-like vapor, and that improper vehicle positioning can significantly increase risk during emergency situations. From a knowledge standpoint, operators must understand the unique hazard profile associated with hydrogen systems, including the implications of high-pressure storage and rapid fuel release.

From a skills perspective, operators must be able to apply this knowledge in real time by executing appropriate emergency positioning strategies. This was expressed by P07, a safety director at a transit agency in California:

If you're in a fuel cell electric bus and you break down, don't pull under trees, don't pull into parking spots or under underpasses. If there is a thermal event, stay downwind by 100 feet, because you know that toxic smoke's coming out.

This reflects the critical operational skills related to emergency response execution under uncertain conditions. The operators must demonstrate consistent behavioral compliance with these safety protocols in dynamic, real-world environments.

Energy management behavior was cited by 18 of 20 participants as the most operationally consequential operator gap. Operators who previously drove diesel or CNG buses tend to carry over aggressive acceleration habits, which significantly increase hydrogen consumption and reduce the effective range of FCEBs. P02, an Operations leader at a transit agency in Ohio with over a decade of FCEB experience, described this pattern with operational specificity:

They [drivers] tend to drive it like it was a diesel bus, where they just put the pedal to the floor and don't realize the degradation they're causing to the bus for the duration of the day. I have a route here in town that's a few hundred miles. I can only get about 11–12 hours out of it (FCEB), and that's because of ICE like driving.

To mitigate this behavior-driven variability in fuel consumption, P02's agency implements a protocol in which operators are trained to report when the bus reaches 1,000 psi, allowing the vehicle to return to the depot before fuel is critically low. This threshold-based monitoring approach represents a replicable operational best practice that has not yet been formalized at most agencies. P01, a maintenance director at a large transit agency in California, reported that their operators experience fewer driving management problems, attributing this to the agency's decade of FCEB familiarity, but cautioned that agencies transitioning from diesel-only fleets face a meaningful re-training challenge with respect to operator behaviors.

KSAs for Maintenance Technicians

Maintenance technician KSAs represent the most complex and consequential workforce competency challenge in FCEB deployment. Every participant agreed that the FCEB maintenance workforce requires a depth and breadth of competency significantly exceeding any predecessor transit technology. Table 7 presents the comprehensive KSA framework for maintenance technicians with full frequency data and evidence from thematic analysis.

Table 7. KSA Framework for FCEB Maintenance Technicians

KSA type	Competency	Description	Frequency (n = 20)
Knowledge	Electrical fundamentals	• Ohm's Law, Watt's Law, series and parallel circuits • Multimeter operation; reading schematics and ladder logic • AC/DC theory and insulation principles	20
	PEM fuel cell fundamentals	• PEM electrochemical reaction and stack architecture • Degradation modes • How degradation appears in telemetry and fault codes	20
	High-pressure hydrogen storage and safety devices	• Composite tank design; 350 and 700 bar pressure ratings • PRDs: design, activation conditions, and inspection requirements • Hydrogen sensors and alarm systems	19
	High-voltage and hydrogen safety standards	• Arc flash recognition; PPE selection; LOTO and BLOTO procedures • NFPA 70E, OSHA 1910, and NFPA 2 requirements for transit facilities • Ventilation, hydrogen embrittlement, and confined-space standards • Regulatory differences between NFPA 52 (CNG) and NFPA 2 (hydrogen)	20
	FCEB telematics	• Reading FCEB telematics data and OEM fault code logs • Distinguishing fuel cell chassis faults through data	16
	FCEB preventive maintenance	• Manufacturer-recommended PM intervals and procedures • Deionized water, glycol, air filter, and fuel cell filter maintenance	17

KSA type	Competency	Description	Frequency (n = 20)
		• System calibration and component replacement sequences	
Skills	Safe de-energization and hydrogen system isolation	• HV de-energization: live-dead-live testing and zero-voltage confirmation	20
	Root cause troubleshooting and fault isolation	• Fault isolation using electronic data, not visual or mechanical inspection • Distinguish faults via fault code trees • Identify root cause before any parts replacement	17
	OEM diagnostic	• Navigate OEM platforms; follow fault trees and interpret severity ratings • Post-repair validation before returning bus to service	16
	Hydrogen safety inspections	• Leak detection • Ventilation operations • Inspect PRDs, shutoff valves, and vent lines per OEM schedule	16
	Mentorship and knowledge transfer	• Guide junior technicians through live troubleshooting	8
Abilities	Critical thinking and data-driven diagnostic reasoning	• Analyze multi-system fault data without visible mechanical indicators • Pursue unresolved faults until root cause is identified	11
	Cross-system communication	• Communicate bus status and restrictions to operations staff • Coordinate with facility staff on hydrogen fueling system readiness • Follow OEM instructions precisely during remote diagnostic support	10

KSA type	Competency	Description	Frequency (n = 20)
	Adaptability and continuous learning	• Treat FCEB competency as a continuously updating knowledge domain • New stack models, software versions, and PM requirements emerge every 2–5 years	9

The KSA framework for maintenance technician presented in Table 7 highlights the most complex workforce challenge in FCEB deployment. Unlike operators, whose training focuses on behavioral adaptation, technicians must develop entirely new competencies spanning electrical systems, hydrogen safety, and data-driven diagnostics. Across all participants, there was clear agreement that FCEB maintenance requires a tri-disciplinary integration not produced by any prior transit technology.

The most consistent finding is the role of electrical fundamentals as a non-negotiable prerequisite. Participants emphasized that the gap is not in advanced theory but in basic application, which directly limits technicians' ability to troubleshoot FCEB systems. As P01 explained, "the big one was the electrical. That's why we developed an ohmmeter class. We had to go back to basics to Ohm's Law, resistance because FCEBs require a lot of troubleshooting electrical resistance type setups."

This finding is reinforced at the curriculum level. P12 described how this gap reshaped training design:

Even though there is definitely a lack of hydrogen fuel cell bus training…we chose to do electrical fundamentals before hydrogen fuel cell buses. Without that foundation, everything else is noise. You can't teach someone how a fuel cell charges a battery if they don't understand what a battery is.

A second critical knowledge domain is PEM fuel cell operation and degradation. Technicians must understand not only how fuel cells generate power, but how they degrade and how those degradation patterns appear in telemetry. P06's reflection illustrated a broader shift toward predictive, data-informed maintenance, where system understanding directly affects asset life:

We've been rebuilding our own fuel cells. I didn't understand it, my predecessors didn't understand it. We made changes to the preventive maintenance (PM) program because we were missing things we shouldn't have been missing. You need to take better care of these things from the very beginning. If you don't, it will bite you quicker than you want it to.

From a safety perspective, FCEB maintenance introduces a unique requirement: dual system isolation. Technicians must complete both high-voltage de-energization and hydrogen system isolation before beginning work, increasing procedural complexity and risk. P11 emphasized this:

We give them a very deep dive into safety. We teach them how to de-energize the bus, how to do zero-voltage verification, and then how to re-energize the bus when they're done working on it. Lockout, tagout. That is non-negotiable, before they touch anything.

In the skills domain, root cause troubleshooting emerged as both critical and underdeveloped. Unlike diesel systems, FCEB faults must be diagnosed through data rather than physical cues. P11 described a common pattern:

So many of the technicians are just parts changers. A bus is down, they think it's this part…okay, let's change that part. Oh, that didn't work, so let's change this part. It is so important…to get to the root cause and understand what's happening and why that system is failing.

P02 further highlighted the mindset required for effective diagnostics:

Somebody who can understand schematics, multiplex systems…who comes into work saying: this bus has an engine code, I'm gonna trace all these wires…You have a 40-foot bus with about 50 foot of wire running through it. The guy you want is the one who's like: I've checked 900 connections and I know these last 100 has to be one of them.

At the ability level, two competencies distinguish fully prepared technicians: integrating multiple safety frameworks simultaneously and cross-system communication that involves coordination with operations staff, facility personnel, and OEM representatives during diagnostics and repair. This ability ensures that technical findings are translated into operational decisions and timely resolutions.

Overall, the findings indicate that the FCEB workforce challenge is not simply a shortage of technicians, but a shortage of technicians with a specific and evolving competency profile. Developing this profile requires a structured progression from foundational electrical knowledge to advanced diagnostic reasoning, supported by hands-on experience, mentorship, and continuous learning in a rapidly evolving technological environment.

Comparative KSA Analysis: ICE, CNG, BEB, and FCEB

Understanding how FCEB competency requirements relate to prior technology experience is essential for designing efficient, targeted training programs. Table 8 presents a structured comparison of FCEB KSA requirements for each prior technology background, organized by occupational category.

Table 8. Comparative KSA Transferability: ICE, CNG, BEB, and FCEB

Category	**FCEB competency**	**ICE / Diesel**	**CNG**	**BEB**	**Transferability to FCEB**
Vehicle Operators	FCEB architecture, hydrogen safety, and fueling protocols	Basic mechanical; liquid fuel only	Mechanical + gas systems; no electrical	Electric propulsion, HV safety; no hydrogen	Strong from CNG; Moderate from BEB; None from ICE
	Pre-trip inspection, energy management, and system monitoring	Fluid checks only; range management unfamiliar	Pressure checks, gas indicators; range unfamiliar	Battery checks, regen braking, energy management—transfers directly	Strong from BEB; Moderate from CNG; None from ICE
	Emergency response and passenger evacuation	General procedures only; no gas or HV context	Gas leak response; no HV or invisible-flame training	HV thermal event, evacuation; no hydrogen context	Moderate – all backgrounds require hydrogen-specific additions
Maintenance Technicians	Electrical fundamentals	Negligible—visual/mechanical only; no multimeter or schematics.	Negligible—gas expertise only; no electrical diagnostics	Fully present—transfers directly	Strong from BEB only.
	PEM fuel cell fundamentals	Combustion only; no electrochemical context	High-pressure gas, PRDs; no fuel cell context	Electric motors, inverters; no fuel cell or hydrogen context	None from any background—new learning required for all

Category	FCEB competency	ICE / Diesel	CNG	BEB	Transferability to FCEB
	High-pressure hydrogen storage	No high-pressure systems	High-pressure cylinders, PRDs, NFPA 52—strong foundation	no hydrogen storage experience	Strong from CNG only
	High-voltage safety	Mechanical lockout only; no HV or arc flash.	Gas shutoff, pressure relief; no HV training	LOTO/BLOTO, arc flash, NFPA 70E—fully trained	Strong from BEB; Partial from CNG; hydrogen system isolation is new for all
	OEM diagnostics	Visual/mechanical only; high parts-changing risk.	Basic; limited electronic diagnostic depth	OEM software, fault code interpretation—strong foundation.	Strong from BEB; Partial from CNG; ICE highest risk of parts-changing behavior

This table reveals that, for maintenance technician roles, CNG and BEB backgrounds are complementary, and their combination provides the strongest preparation for FCEB work. CNG technicians bring expertise in high-pressure systems and gas safety, while BEB technicians contribute high-voltage knowledge, electrical fundamentals, and diagnostic software experience. As P13 explained, "if I were to put the other vehicle technologies in a hierarchy…hybrid probably is going to translate the most skills…then CNG…because you have high-pressure tanks on both…." P01 reinforced this while emphasizing the growing importance of electrical systems: "A mechanic that has worked on hybrids has an advantage…because there is so much more electrical…. The high voltage side is the one that requires a much deeper knowledge to diagnose the problem…." These findings suggest that while gas system knowledge is important, electrical competency is often the limiting factor in FCEB maintenance.

At the same time, several competencies do not transfer from any prior background, including PEM fuel cell operation, degradation behavior, and integrated safety across mechanical, electrical, and chemical domains. As P13 noted, "the propulsion unit sits at the intersection of things that can shock you, burn you, and asphyxiate you at the same time. No prior technology makes you think in three different safety frameworks at the same time." These represent irreducible new-learning requirements that must be developed through dedicated training and experience.

In summary, for operators, the primary transferability gap is not safety knowledge but energy management behavior. BEB operators transfer efficient driving practices directly, while ICE and CNG operators must unlearn ingrained habits.

The Aptitude Profile of the Ideal FCEB Technician

A finding not anticipated in the study's conceptual framework emerged consistently across 17 of the 20 participants: The most reliable predictor of FCEB technician success is not a specific prior technology background, but a cognitive and motivational profile. Across interviews, participants converged on a shared description of the technicians who succeed in FCEB environments: individuals who are analytically oriented, persistent in problem-solving, and intrinsically motivated to engage with complex, data-driven systems. P02 articulated this profile with operational specificity:

> Someone who can understand schematics, multiplex systems, who can track down the gremlins…somebody who comes into work saying, this bus has an engine code, I'm gonna trace all these wires, I'm gonna punch in all this data, and I'm gonna sit here and diagnose it that way. You want somebody who is technical savvy, a gamer…. The guy who just wants to come in and change oil will never make it.

This characterization shifts the definition of technical competence away from routine mechanical tasks toward diagnostic reasoning and digital engagement. P11, director of training at an OEM, reinforced this pattern and emphasized mindset over experience, drawing on their experience across approximately 200 agencies:

It's more to do with mindset than experience. You want somebody who has that drive to learn…who isn't going to just swap a part because it seems likely. The technicians who excel are the ones who find it interesting…and take it personally.

Importantly, this is operationalized in hiring practices. P06 described how their agency evaluates FCEB maintenance technician candidates based on thought process rather than correct answers: "We're looking for that spark…. We ask questions we don't expect them to get right. We look for how they think…if they take a stab at it, that tells me they have the mindset I want."

These findings suggest that FCEB workforce development should not focus solely on technical upskilling, but also on selecting and cultivating specific cognitive attributes including systems thinking, persistence, and comfort with digital diagnostics. This represents a shift from experience-based hiring toward aptitude-based workforce development, with significant implications for recruitment, training design, and long-term talent pipelines.

4.2 RQ2: Training Gaps and Proposed FCEB Training Curriculum Framework

Original equipment manufacturers (OEM) play a central role in FCEB workforce training. The findings reveal that OEMs provide product-specific training to transit agency technicians, covering the operational characteristics, maintenance procedures, and diagnostic protocols of their particular fuel cell systems and busses. This OEM-led training provides technicians with direct, authoritative instruction on the proprietary architecture of the vehicles they will be maintaining. However, as many participants mentioned, OEM-led training carries significant structural limitations:

- First, it is inherently product-specific and does not transfer across manufacturers, creating dependency and limiting the development of generalizable competencies.
- Second, OEM training is typically conducted at the time of vehicle delivery and may not be sustained or refreshed as systems evolve.
- Third, OEM training is often delivered at manufacturer facilities in large-group sessions that may not be accessible to smaller transit agencies with limited travel budgets or to workers on operational shifts.
- Fourth, the proprietary nature of OEM training content makes it difficult to incorporate into standardized curricula or community college programs, limiting the ability to develop a broader pipeline of FCEB-qualified workers independent of manufacturer relationships.

Table 9 summarizes the major training gaps identified through thematic analysis. Drawing on perspectives from transit agencies, OEMs, training organizations, and industry stakeholders across multiple regions and experience levels, the findings indicate that FCEB workforce training is fragmented, uneven, and structurally constrained.

Table 9. Summary of Training Gaps in the Transition to FCEBs

Gap	Roles affected	Severity	Implication for transit agencies
No comprehensive, standardized national training framework or FCEB certification	All roles	High	Agencies must develop training independently without a unified curriculum benchmark, leading to inconsistency in competency levels and safety preparedness across the sector
Operator and facility staff training underdeveloped	Operators; Facility staff	High	Most existing programs (OEM offered) focus on maintenance technicians; operators and facility staff receive insufficient structured training, creating safety risks in daily operations and fueling management
No structured framework for OEM-to-in-house maintenance transition	Technicians	High	Agencies lack guidance on when and how to transition from OEM dependency to in-house FCEB maintenance capability, delaying self-sufficiency and increasing long-term costs
Limited FCEB content in community college and vocational programs	Technicians	Medium	The educational pipeline produces insufficient entry-level workers with FCEB-relevant foundational knowledge, placing the full training burden on transit agencies and OEMs
Inequitable access to training resources for smaller agencies	All roles	Medium	Smaller and rural transit agencies lack access to training infrastructure available to large urban systems, creating a two-tier workforce readiness landscape that may slow FCEB adoption

Gap	Roles affected	Severity	Implication for transit agencies
Training not sustained post-vehicle delivery	Technicians; Operators	Medium	Initial OEM training at delivery is not refreshed as systems evolve; workers may become outdated as software, components, and safety protocols change over the vehicle lifecycle

The most fundamental gap is the absence of a comprehensive, standardized training framework spanning all occupational roles involved in FCEB deployment. Nearly all (18 out of 20) participants, regardless of agency size, geography, or role, highlighted that no national curriculum, certification pathway, or structured progression currently exists. As a result, agencies are required to independently design training programs, leading to inconsistent competency levels and uneven safety preparedness across the sector.

Closely related is heavy reliance on OEM-delivered training as the primary and often only source of workforce development, a limitation identified by all participants, including both agency representatives and the OEM itself. From the OEM perspective, P11, an OEM training director with visibility across North America, described the structural constraints:

They (OEMs) are making the vehicles as fast as possible, but they're (OEMs) not developing trainers…. We (OEMs) have a handful of instructors for the United States. That's not enough at all…we (OEMs) didn't get our first manual probably until after two years we had the bus.

From the agency and industry perspective, participants consistently emphasized the downstream consequences of this model. P17, a consultant working across multiple agency deployments nationally, noted such consequences: "The buses show up. And then that's it. There's no follow-up…. The warranty runs out two years later and they're (transit agencies) on their own with buses they (transit agencies) barely understand." Similarly, P14, representing a training organization, highlighted the lack of scalable training capacity: "You need to train the trainers…right now, the manufacturers are overwhelmed…we need to start training people systematically."

A critical issue compounding this gap is training timing misalignment (n = 17/20), particularly among agencies in early- and mid-stage implementation. OEM training is typically delivered at or near vehicle deployment, during the warranty period when OEM technicians perform most maintenance. As a result, agency technicians receive training but have limited opportunity to apply it independently, leading to knowledge decay. As P11 explained, "our (transit agencies) technicians got trained when the bus arrived…. Great. Two years later, the warranty ran out…now what? The training is gone. It landed on top of nothing." P10, representing a small agency, described the same issue: "They (technicians) get trained when the bus arrives but don't touch the bus for two years because it's under warranty, what do they actually know at the end of that warranty period when they have to starting fixing themselves?" Together, these findings demonstrate that OEM training is necessary but structurally insufficient and misaligned with practical application.

A third major gap is the lack of a structured transition from OEM-supported maintenance to in-house capability, identified across agencies with varying levels of FCEB experience (from approximately 1.5 to 10 years). Agencies reported little guidance on when to assume maintenance responsibility, how to sequence skill development, or how to manage knowledge transfer. P02, a COO at a mid-size agency with a decade of FCEB experience, described how this transition is currently managed through informal, experience-based approaches: "We had technicians working alongside OEMs…six to eight months before we felt comfortable letting them work independently." However, such approaches are not standardized and are largely unavailable to agencies at earlier stages of deployment. P07, representing a large agency scaling its fleet, similarly described building maintenance capacity in real time as warranties expire, underscoring the absence of a formal transition framework.

Another significant and underexplored finding is the behavioral compliance gap in operator training. While agencies across the dataset have delivered training on energy management and FCEB-specific driving practices, none reported reliable mechanisms to verify whether operators consistently apply these behaviors in service. As stated by P08, a representative from a small transit agency, "Did we teach them? Yes. Are they doing it? Not so sure…no one's monitoring it." This gap reflects a disconnect between training delivery and actual behavior, indicating the need for monitoring and feedback mechanisms alongside instruction.

The analysis also confirms a two-tier disparity in training capacity across agencies (n = 15/20). Larger, well-resourced agencies, primarily those with established FCEB programs in California, have developed internal training infrastructure, instructional capacity, and, in some cases, advanced simulation tools. In contrast, smaller and rural agencies remain heavily dependent on OEM support. As P01, a maintenance director at a large agency, observed, "There's two tiers—agencies that have the capacity, and agencies that do not have the capacity." P16, representing an industry association supporting multiple agencies, further emphasized the implications: "What about the agency with 12 FCEB buses and two mechanics? They need the same training…but they have none of the infrastructure to build it themselves."

This structural inequity results in significant differences in workforce readiness, safety culture, and operational independence across agencies adopting the same FCEB technology. Without policy support and intervention, this gap is likely to widen as FCEB adoption scales, with smaller agencies falling further behind in both technical capacity and safety preparedness. These findings point to the need for coordinated policy support and investment, particularly in shared training infrastructure, regional training centers, and standardized curricula that can be accessed by smaller agencies. Such approaches would help reduce duplication of effort, improve consistency in workforce preparation, and ensure that safe FCEB deployment is not limited by agency size or resource availability.

Additional gaps include the limited integration of FCEB content into community college and vocational programs, noted by both training providers and agencies, which constrains the development of an entry-level workforce pipeline. In addition, training is often not sustained beyond initial delivery, leaving workers unprepared to adapt to evolving technologies, software updates, and changing safety protocols. Participants also emphasized that training remains heavily technician-focused, with operators and facility staff receiving comparatively limited structured preparation despite their critical role in safe system operation.

A related and distinct gap concerns hydrogen fueling infrastructure maintenance, a specialized function that requires dedicated technical training beyond what is covered in standard operator or technician programs. Two agencies have developed in-house staff focused exclusively on hydrogen infrastructure maintenance; however, this capacity remains rare overall. Nineteen of the study's participants 95% of study participants indicated that fueling infrastructure maintenance is outsourced to third-party contractors. However, despite multiple outreach attempts, the research team was unable to obtain data from those contractors, leaving this domain underrepresented in the current study. This gap represents a priority area for future research and curriculum development.

Collectively, these findings demonstrate that current FCEB workforce development and training approaches are fragmented, reactive, and unevenly distributed, highlighting the need for a coordinated, multi-level strategy to support safe and scalable FCEB deployment.

Proposed FCEB Training Curriculum Framework

Drawing on the RQ1 KSA analysis and the training gaps identified, this study proposes a structured FCEB training curriculum framework for both vehicle operators and maintenance technicians. Unlike generic zero-emission bus (ZEB) frameworks that treat battery-electric and fuel cell buses interchangeably, this framework is explicitly designed for FCEBs, reflecting the tri-disciplinary integration of electrical, mechanical, and hydrogen safety competencies required by fuel cell technology. Table 10 presents the framework, while Appendix A provides detailed curriculum content for operators and technicians, respectively.

Table 10. Proposed FCEB Training Curriculum Framework

ID	Module / Level	Delivery guidance	FCEB-specific content
		PART A: Vehicle operators (OP-1 to OP-3)	
OP-1	FCEB Safety and Hydrogen Familiarization	All operators; required before first FCEB route	FCEB vs. ICE/CNG/BEB architecture; FCEB-specific pre-trip checks
OP-2	FCEB Operational Characteristics	All operators; refresher every 2 years or new model	Electric drive behavior and range management; PSI threshold monitoring; FCEB dashboard indicators;
OP-3	Emergency Response and Incident Protocols	All operators; annual refresher required	Hydrogen thermal event emergency response; Emergency Responder Guide; passenger evacuation procedures; incident reporting chain for hydrogen events
		PART B: Maintenance technicians (MT-0 to MT-5)	
MT-0	Electrical and Electronics Foundations	PREREQUISITE— gate before MT-1; required for ICE and CNG backgrounds; competency test only for BEB	Electrical Fundamentals; reading electrical schematics and ladder logic; insulation principles. Skills assessment gate: must demonstrate competency before advancing
MT-1	FCEB Familiarization	All technicians;	FCEB architecture vs. ICE/CNG/BEB; hydrogen fuel cell electrochemical reaction; HV safety; FCEB subsystems: fuel cell stack, high-pressure H_2 storage.
MT-2	FCEB Systems and Theory of Operation	All technicians	PEM fuel cell electrochemistry; stack architecture and degradation modes telematics: de-energization on live vehicle; dual de-energization process
MT-3	FCEB Maintenance, Troubleshooting, and Repair	All technicians; 2-week hands-on live FCEB bus capstone is required	FCEB PM procedures; H_2 system maintenance; H_2 leak detection

ID	Module / Level	Delivery guidance	FCEB-specific content
			and ventilation verification; post-repair validation procedures
MT-4	Advanced Fuel Cell Stack Diagnostics and Repair	Select senior technicians only (with OEM authorization)	Stack health monitoring via telemetry; stack removal and replacement procedures; near-clean-room protocols; component rebuild assessment.
MT-5	Train-the-Trainer and Curriculum Development	Agency maintenance instructors; after MT-4 completion	Adult learning principles for technical instruction; structuring hands-on instruction in shop environments; mentorship techniques for junior technicians.

Vehicle Operators (OP-1 to OP-3)

The operator curriculum is organized into three modules (OP-1 to OP-3), covering safety, operational characteristics, and emergency response. These modules reflect a key finding from the study: While operator training is less technically complex than technician training, it is safety-critical and behavior-dependent.

OP-1 introduces foundational knowledge of FCEB systems, including hydrogen properties, system architecture, and pre-trip safety checks. OP-2 focuses on operational behavior, particularly energy management, regenerative braking, and psi monitoring, which directly influence vehicle range and performance. OP-3 addresses emergency response protocols, including hydrogen-specific hazards such as invisible flames and appropriate vehicle positioning during thermal events.

Maintenance Technicians (MT-0 to MT-5)

The technician curriculum is organized into six levels (MT-0 to MT-5), reflecting the progressive development of competencies required for FCEB maintenance, from foundational electrical knowledge to advanced fuel cell diagnostics and instructor development.

The most critical design principle is that the electrical prerequisite (MT-0) is non-negotiable. Participants consistently identified gaps in basic electrical competencies as a primary barrier to effective FCEB training. As such, MT-0 functions as a gate that must be completed before any FCEB-specific instruction. Subsequent modules (MT-1 to MT-3) develop core competencies in FCEB systems, diagnostics, and maintenance. Importantly, the framework emphasizes that hands-on application must be embedded throughout training, rather than deferred to a final stage. As P01 noted in describing their live-bus training model, “that’s the bread and butter, where they show that they know how to connect to the vehicles, pull codes, and regurgitate the information back to trainers.”

Embedding applied learning particularly at the MT-3 level ensures that technicians can translate diagnostic data into effective maintenance actions. Advanced levels (MT-4 and MT-5) focus on specialized competencies. MT-4 addresses fuel cell stack diagnostics and repair, which is currently limited to a small number of agencies with OEM authorization. MT-5 introduces a train-the-trainer model, identified as the highest-return investment for workforce development. As P12 demonstrated, training agency instructors rather than all technicians creates a scalable multiplier effect, while P14 emphasized that addressing OEM trainer shortages requires “training trainers, not waiting for OEMs to reach every agency.”

Overall, this curriculum framework translates empirical findings into a structured, scalable, and role-specific training model.

4.3 RQ3: Strategies and Best Practices for FCEB Workforce Development

The third research question asked the following: What strategies and best practices have transit agencies and OEMs found effective in recruiting, retaining, and developing a qualified FCEB workforce? Analysis produced a rich and consistent array of strategies. Table 11 presents the full strategy framework with frequency data, source participants, and direct participant evidence embedded in the description. This section synthesizes the findings into five core themes: (1) grow-your-own recruitment, (2) selection based on mindset, (3) pipeline development, (4) retention and workforce infrastructure, and (5) organizational readiness.

Table 11. Workforce Strategies for FCEB Recruitment, Retention, and Development

Strategy	**Focus**	**Description**	**Frequency (*n* = 20)**
Grow-your-own	Recruitment	Agencies recruit for mechanical aptitude and transit experience, then develop FCEB competency internally. No viable external market exists for FCEB-ready technicians.	20
Pay differential for FCEB-certified technicians	Recruitment	Tying compensation advancement to demonstrated FCEB competency, not seniority alone, serves as both a recruitment signal and a retention anchor.	15
Identifying internal candidates by electrical aptitude and mindset	Recruitment	The strongest predictor of FCEB success is a diagnostic mindset and the drive to pursue a fault to root cause, not prior technology background.	17
Three-level pipeline: CTE to community college to transit apprenticeship	Recruitment	A durable pipeline requires high school CTE programs, two-year community college technical preparation, and transit agency apprenticeships that bridge to FCEB systems.	14
Sector awareness and FCEB career visibility campaigns	Recruitment	FCEB technician careers are largely invisible outside transit. Proactive outreach through career fairs, school tours, and community partnerships expands the applicant pool.	12
Transparent career ladder with FCEB specialization	Retention	Technicians who see a clear progression from general mechanic to advanced FCEB specialist are more likely to stay through.	10

Strategy	Focus	Description	Frequency (n = 20)
Regional training consortia	Both	Pooling training resources across agencies allows all sizes to access FCEB curriculum without building it independently, directly addressing the two-tier capacity gap.	4
Change management and organizational readiness	Both	FCEB deployment fails as a workforce development initiative when frontline supervisors, maintenance directors, and senior operators resist or misunderstand the technology. Change management training directed at supervisors and mid-level managers: addressing the fear, uncertainty, and resistance that accompany new technology introduction is a precondition for the effectiveness of all training and retention strategies.	7

Grow-Your-Own: The Only Viable Recruitment Model

The most consistent finding is that transit agencies cannot recruit FCEB technicians from an external labor market because that market does not exist. Across all participant groups—agencies, OEMs, and training organizations—the conclusion was unanimous: Agencies must recruit for general mechanical and electrical aptitude and develop FCEB competency internally.

As P08 summarized, “you’re not recruiting for fuel cell buses. You’re recruiting mechanics that you end up training.” P02 reinforced this from a decade of operational experience: “We don’t recruit for hydrogen…. Hydrogen is something we grow our own.” This finding has immediate implications. Agencies that delay workforce preparation until buses arrive fall significantly behind. As P02 noted, “once the bus comes, they’re two or three years behind. You have to start before the buses show up.”

Selecting Workforce for Mindset: The Most Predictive Success Factor

Within the grow-your-own model, the most reliable predictor of technician success is not prior technology background, but diagnostic mindset and cognitive disposition. Participants consistently described successful FCEB technicians as those who are curious, persistent, and comfortable with data-driven troubleshooting. P02 described this profile in operational terms: "The person who likes puzzles and challenges, those are the ones who make it." P11 confirmed this from the OEM training perspective: "It's more to do with mindset than experience…the technicians who excel are the ones who find it interesting."

Building the Pipeline

While the grow-your-own model addresses current workforce needs, long-term sustainability requires a multi-level pipeline. Participants identified a three-stage structure:

- High school CTE programs introducing ZEB and hydrogen concepts
- Community college programs building foundational electrical, hydrogen, and mechanical skills
- Transit apprenticeships bridging education to real-world FCEB systems

The weakest link is at the high school level. At the community college level, structural barriers persist. P12 highlighted the mismatch between curriculum timelines and technology evolution, as well as financial aid limitations that restrict access to non-credit training.

Retention, Poaching, and Regional Workforce Models

Retention strategies center on mentorship, career progression, and compensation tied to skill development. For technicians, structured on-the-job mentorship—typically 6–8 months of supervised work before independent authorization—was identified as a critical mechanism for both skill development and retention.

However, a cross-cutting challenge is inter-agency poaching. Agencies that invest in technician development often lose trained staff to neighboring agencies that have not made similar investments. As observed by P14 and P15, this disincentivizes individual agencies to invest in workforce development. The most effective response identified in the data is the regional consortium model, which shifts workforce development from a competitive to a collaborative approach. As P12 explained, "if we all work together and pool our resources…we can deliver training at a much larger economy of scale."

Change Management as a Precondition for Workforce Success

A final and often overlooked finding is that technical training alone is insufficient without organizational readiness. Multiple participants described situations where training was delivered successfully, but adoption failed due to fear, resistance, or lack of cross-department coordination. P08 described this challenge following a bus fire incident within their agency: “You can train all you want, but if the emotional relationship with the technology is fear, training doesn’t land.”

In conclusion, the findings demonstrate that FCEB workforce development is not primarily a training problem, but a system design problem. The most effective agencies share a common approach: They recruit for aptitude rather than experience, develop competency through structured internal pathways, align training with career progression, collaborate regionally to share resources, and address organizational readiness alongside technical training. No single strategy is sufficient in isolation. It is the integration and sequencing of these strategies that enables agencies to achieve workforce readiness and long-term operational self-sufficiency.

5. Summary and Conclusions

The transition to hydrogen fuel cell electric buses (FECBs) constitutes a significant shift in US transportation while posing notable workforce and organizational challenges for transit agencies. FCEBs introduce new operational, maintenance, safety, and training requirements that must be addressed through coordinated workforce development strategies. This research examined the workforce implications of FCEB deployment by identifying the knowledge, skills, and abilities (KSAs) required for vehicle operators and maintenance technicians; assessing limitations in the current training ecosystem; and documenting strategies for recruitment, retention, and employee development. The study drew on semi-structured qualitative interviews with 20 stakeholders involved in FCEB deployment across the United States, including transit agency personnel, OEM representatives, training and curriculum developers, and workforce development professionals representing agencies in California, Ohio, Illinois, and Washington at varying stages of FCEB adoption. Interview data were analyzed using NVivo, with independent coding by two researchers, and triangulation against a literature review on FCEB technology, workforce development, training, recruitment, and retention.

Findings indicate that FCEB workforce readiness should be understood as a system-level issue rather than a discrete training need. It requires the integration of mechanical, electrical, hydrogen safety, fuel cell diagnostic, and emergency-response competencies.

For vehicle operators, the transition to FCEBs requires targeted retraining that include hydrogen safety awareness, adherence to fueling and emergency procedures, and driving practices that support efficient energy use. The findings suggest that operator behavior has direct implications for vehicle performance, particularly range and energy efficiency. Consequently, operator training should address not only technical awareness but also behavioral adaptation from prior diesel or compressed natural gas operating practices. Emergency preparedness is also a critical component, particularly with respect to hydrogen-specific hazard recognition, safe vehicle positioning, and communication with first responders.

The maintenance workforce faces a more substantial transformation. FCEB maintenance requires technicians to integrate competencies across high-voltage electrical systems, hydrogen storage and delivery, mechanical systems, fuel cell operation, and data-driven diagnostics. Electrical fundamentals appear to be a critical prerequisite for technician readiness, while fuel cell degradation, dual system isolation, and root-cause troubleshooting represent important areas of new learning. Prior experience with compressed natural gas or battery-electric buses offers partial transferability, but neither background is sufficient on its own. The findings therefore underscore the need for structured learning pathways that move technicians from foundational knowledge to supervised practice and, ultimately, independent authorization.

The study also identifies significant institutional gaps in the current FCEB training environment. The absence of a standardized training framework or certification pathway limits consistency across agencies. Manufacturer training, while important, is often product-specific, delivered at procurement, and insufficient to support long-term internal maintenance capacity. Training may also occur before technicians have meaningful opportunities to apply new skills, creating the potential for knowledge loss before agency self-sufficiency is required. In addition, limited FCEB content in community college and vocational programs constrains the entry-level workforce pipeline. These barriers are particularly consequential for smaller agencies, which may lack the resources to build internal training infrastructure.

A central implication of the findings is that transit agencies cannot rely on an external labor market to supply fully qualified FCEB technicians. Instead, agencies must develop internal capacity through a "grow-your-own" workforce model. This approach prioritizes recruitment for mechanical aptitude, electrical awareness, diagnostic orientation, and learning potential, followed by structured training, mentorship, and progressive skill development. Complementary strategies include skill-based compensation, apprenticeship pathways, partnerships with secondary and post-secondary education providers, regional training consortia, and career ladders that position FCEB specialization as professional advancement. Organizational readiness is also essential, particularly through supervisor engagement, labor participation, and early preparation before vehicles enter service.

Overall, the findings demonstrate that FCEB deployment is as much a workforce development challenge as it is a technological transition. The safe and reliable operation of FCEB fleets requires agencies to institutionalize new competencies, align training with operational timelines, and develop pathways for sustained internal expertise. Although the technical demands are substantial, the results suggest that agencies can improve readiness when workforce planning is integrated into fleet transition strategies from the outset.

At the policy level, broader deployment will require investment in standardized curricula, certification systems, regional training infrastructure, apprenticeship models, education-industry partnerships, and competency-based career progression. Such measures are necessary to ensure that FCEB workforce capacity is not limited to large, well-resourced agencies but is accessible across the transit sector. The policy recommendations can benefit from stronger partnerships between transit agencies and educational institutions. As zero-emission mandates continue to reshape public transportation, workforce development must be treated as a central condition for equitable, safe, and effective implementation of hydrogen fuel cell bus technology.

This research will help transit agencies to broaden their perspectives on workforce development to include improvements in system design, new training structures, and increasing institutional capacity. This research also prompts the decision-makers at the federal and state levels to increase funding capacity through grant programs which can facilitate the improvement of system design and institutional capacity challenges for efficient FCEB workforce development.

Despite the research rigor present, there were several limitations that provide an avenue for future work. Third-party contractor entities providing hydrogen fueling facility maintenance services could not be recruited for interviews and therefore, the study lacks the findings related to KSAs, such as training, recruitment, and retention for hydrogen fuel facility maintenance technicians at transit agencies. This could be a significant addition as they are the major players in hydrogen fueling infrastructure maintenance. The geographic coverage of this study is limited as it does not fully represent the US transit market. The proposed strategies in this research have not been through pilot testing and could be used as opportunities for future work.

Future work can assist with creating an FCEV workforce implementation roadmap to improve the system design and institutional capacity with a component to pilot these strategies in transit agencies. They can also assist with creating detailed training modules and universal toolkits for easy deployment that transit agencies and OEMs can customize for their organizational needs. As more of these training programs kickoff through the US, future studies can also look into determining the effectiveness of these programs and suggest improvements. Furthermore, the research could also seek to involve third-party contractors who are often tasked with fueling infrastructure maintenance. This would provide novel insights that were not captured in this study.

Appendix A

FCEB Maintenance Technician Training Curriculum

6 sequential levels: MT-0 through MT-3 are the core pathway; MT-4 is advanced tiers

MT-0 · Prerequisite

Electrical and electronics foundations

Gate — must pass before MT-1

- Ohm's Law and Watt's Law
- Series and parallel circuits
- Multimeter operation
- Reading electrical schematics
- Basic AC / DC theory
- Skills assessment gate

MT-1

FCEB familiarization

All technicians

- FCEB vs ICE / CNG / BEB architecture
- Fuel cell electrochemical reaction
- HV safety — NFPA 70E, arc flash, PPE
- LOTO and BLOTO procedures
- Hydrogen properties — NFPA 2
- PRDs, vent lines, H2 sensors
- FCEB PM intervals overview

MT-2 ·

FCEB systems and theory of operation

All technicians

- PEM fuel cell stack architecture
- Balance-of-plant — humidifier, HRV blower, coolant
- High-pressure H2 storage — tanks, PRDs, valves
- CAN / MUX diagnostics — J1939, PGNs
- Telematics — fault codes, data logs
- De-energization on live vehicle

MT-3

FCEB maintenance, troubleshooting, and repair

All technicians

- FCEB PM procedures — deionized water, glycol, filters
- Root cause analysis from fault trace data
- OEM diagnostic software — Ballard, New Flyer, etc.
- H2 system maintenance — PRD, solenoid, tank inspection
- Balance-of-plant component R&R
- 2-week hands-on capstone on live buses

MT-4

Advanced fuel cell stack diagnostics and repair

Select senior technicians only

- Stack health monitoring via telemetry
- Individual cell voltage and imbalance diagnosis
- Stack removal and replacement procedures
- Near-clean-room protocols

Note: OEM authorization required for this.

Appendix B

FCEB Operator Training Curriculum

3 sequential modules — all operators must complete in order before first FCEB route assignment

OP-1

FCEB safety and hydrogen familiarization

Required — all operators

- How FCEB differs from diesel, CNG, BEB
- Hydrogen properties — colorless, odorless, invisible flame
- High-voltage system layout — orange cable awareness
- FCEB startup and shutdown sequence
- PSI gauge identification
- Emergency Responder Guide overview
- H2 thermal event vs BEB thermal runaway
-

OP-2

FCEB operational characteristics

Required — all operators

- Driving behavior impact on hydrogen range
- Regenerative braking and coasting technique
- HVAC and temperature effects on range
- PSI threshold monitoring and reporting (1,000 PSI protocol)
- FCEB dashboard indicators and warning lights
- Hydrogen fueling
- Quiet operation and pedestrian safety awareness
-

OP-3

FCEB emergency response and incident protocols

Required — all operators

- Hydrogen thermal event handling and driving procedures
- Emergency Responder Guide delivery to first responders
- Passenger evacuation procedures
- Incident reporting chain for hydrogen events
- Invisible flame evidence recognition
- Annual refresher required
-

Appendix C

Semi-Structured Interview Guide

Advancing Clean Mobility: Preparing Transit Agencies for the FCEB Workforce

Participant ID	
Role / Title	
Interviewer(s)	
Recording consent	

Introduction (read aloud)

Thank you for taking the time to participate. This study is funded by the California State University Transportation Consortium and conducted by researchers at CSU Fresno and Cal Poly SLO. Our goal is to understand the workforce knowledge, skills, training gaps, and recruitment and retention challenges associated with hydrogen fuel cell electric bus (FCEB) adoption at transit agencies.

Your participation is entirely voluntary and confidential. You may skip any question or withdraw at any time. No individual will be identified by name in the final report. With your permission, we will record this interview to support accurate transcription. The recording will not be shared beyond the research team. Do you give us the permission to record the meeting?

The interview will take approximately 60–75 minutes and covers four areas: your background, KSAs, training, and workforce strategies. Not every question will apply equally to your role. Please feel free to focus on the areas most relevant to your experience.

Section 1: Background

1. Could you briefly describe your role and your organization's involvement with FCEBs?

    ↳ *How long has your agency / organization been working with FCEBs, and how many buses are in your fleet?*

↳ *What technology background did you come from before FCEBs — diesel, CNG, battery electric, or something else?*

2. How has your agency's workforce been affected by the transition to FCEBs in terms of staffing, skills, or organizational change?

↳ What surprised you most about what FCEB deployment required from your workforce?

Section 2: Knowledge, Skills, and Abilities (RQ1)

3. What are the most critical knowledge, skills, and abilities a person needs to work effectively with FCEBs, whether operating or maintaining them?

↳ *Which of these are genuinely new compared to diesel, CNG, or battery-electric buses?*

↳ *Which competency domains — hydrogen safety, PEM fuel cell diagnostics, high-voltage systems, compressed gas — require the deepest specialized knowledge?*

4. How do FCEB competency requirements differ between vehicle operators and maintenance technicians?

↳ *For operators: what does FCEB operation require that prior bus operation did not, particularly around energy management, fueling, and emergency response?*

↳ *For technicians: what has been the most significant competency shift and how does FCEB troubleshooting differ from diesel or BEB diagnostics?*

5. How well do prior technology backgrounds such as diesel, CNG, or battery electric transfer to FCEB work?

↳ *Which background provides the strongest foundation for technicians and why?*

↳ *Are there competency domains that no prior background adequately prepares someone for?*

6. When you think about the people who have succeeded most in FCEB roles at your organization, what do they have in common?

↳ *Is it prior technology experience, or more about how they think and approach complex problems?*

Section 3: Training and Certification (RQ2)

7. What FCEB training has your workforce received, and where did it come from?

↳ *How was training timed relative to vehicle delivery and how well did that timing work in practice?*

↳ *How effective has OEM-delivered training been and what are its limitations?*

8. What are the most significant gaps in current FCEB training?

↳ *Which occupational groups amongst operators, technicians, facility staff are most underserved?*

↳ *Is there a structured pathway for transitioning from OEM-supported maintenance to full in-house capability?*

9. If you were designing an FCEB training framework, what would it need to include and how would you structure it?

↳ *Should training be modular and background-specific, or a universal curriculum for all?*

↳ *Would standardized FCEB certification be valuable and what would it need to cover to be meaningful?*

Section 4: Recruitment, Retention, and Workforce Strategies (RQ3)

10. How does your organization recruit for FCEB operator and technician roles and what has worked?

↳ *Is there an external market for FCEB-ready workers, or are you building this workforce entirely in-house?*

↳ *When hiring for FCEB maintenance, what do you look for beyond credentials and prior experience?*

11. What keeps FCEB-trained workers at your organization and what causes them to leave?

↳ *What career pathway exists for an FCEB technician at your agency from entry to senior level?*

12. What strategies have you found effective in building FCEB workforce readiness?

Closing

13. What do you see as the most urgent workforce challenge the FCEB industry faces right now?

14. What single recommendation would you offer to policymakers, training providers, or transit associations to most effectively accelerate FCEB workforce readiness?

15. Is there anything we have not covered that you think is important for this research?

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About the Authors

Manideep Tummalapudi, PhD

Dr. Manideep Tummalapudi (Mani) is an Assistant Professor in the Department of Construction Management and Architectural Studies at California State University, Fresno. Dr. Tummalapudi's research interests include transportation project delivery, transportation workforce development, construction finance, emerging technologies in construction, transportation equity, and construction education.

Shantanu Kumar, PhD

Dr. Shantanu Kumar is an Assistant Professor at California Polytechnic State University, San Luis Obispo. His research spans disaster resilience and sustainability, project management, construction contracts, construction education, and mental health. Dr. Kumar has extensively worked on sustainability focused projects, and he brings insights into renewable energy sources and technologies, including their life cycle costs.

Jaskaran Preet Singh

Jaskaran Preet Singh is a graduate student in Construction Management at California State University, Fresno.

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