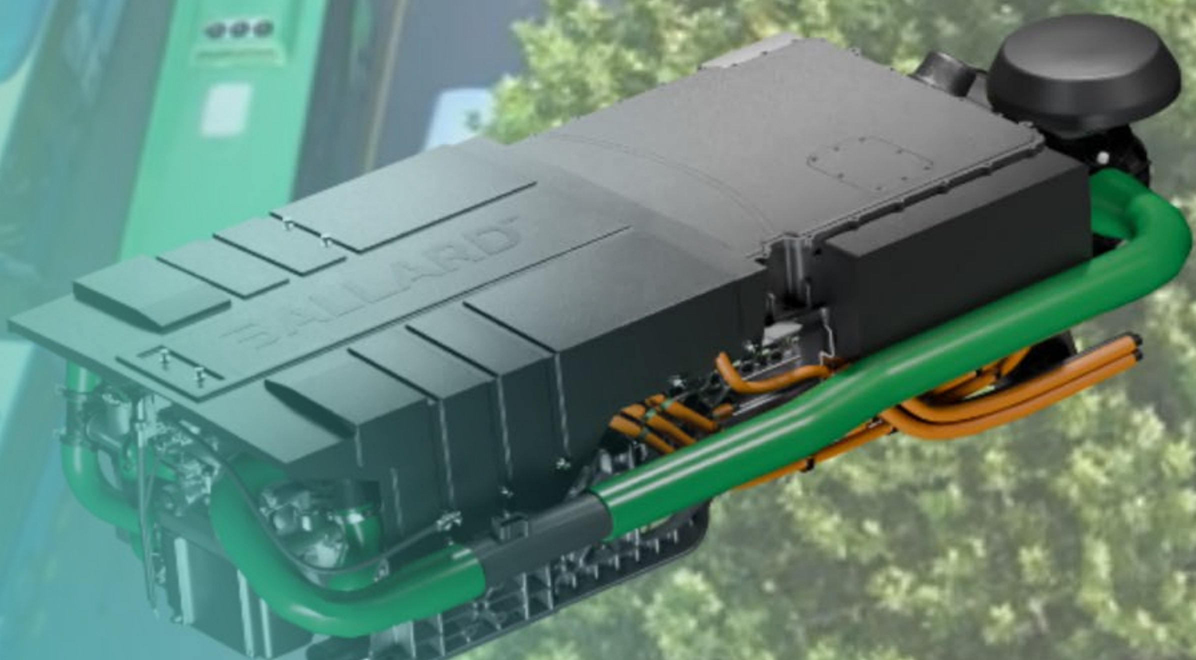


FCmove®–SC: The path to TCO parity for fuel cell buses

How innovative fuel cell module engineering, simplified vehicle integration, and smarter telemetary narrow the TCO gap

November 2025

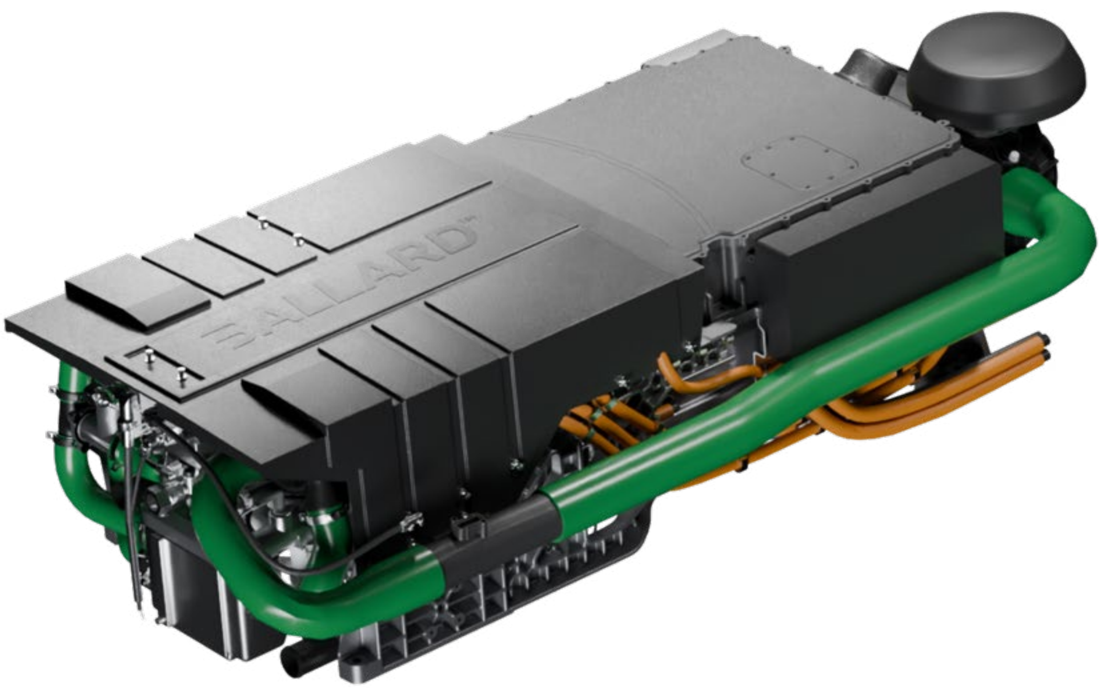
Executive Summary

Fuel cell electric buses (FCEBs) are moving beyond pilots into growing commercial fleets. They deliver operational strengths – rapid refuelling, long range, and consistent performance across hot and cold weather – but historically carry a total cost of ownership (TCO) premium compared to diesel, and in many cases, versus battery electric buses (BEBs). That premium depends mainly on hydrogen price, vehicle acquisition cost, and operational requirements. Less obvious, but decisive, is how fuel cell module design and powertrain architecture can impact those inputs.

Ballard's FCmove®-SC – the company's ninth-generation fuel cell platform – is designed for transit buses and demonstrates how efficient module design with simpler vehicle integration directly contributes to TCO improvements. The FCmove®-SC module incorporates learnings from Ballard's market-leading operational base which includes OEM and operator feedback from over 250 million service kilometers.

FCmove®-SC packages module-level innovations and pairs them with telemetry-enabled fleet services. Together, these changes reduce integration cost, lower hydrogen consumption on many duty cycles, and reduce maintenance and downtime impacts – moving many challenging routes into or toward parity territory as hydrogen supply scales and vehicle procurement becomes more standard and repeatable.

This paper outlines how product-level improvements reduce capital expenditure (CAPEX) and operating expense (OPEX), how hybridization with the battery, controller, and HVAC system impacts hydrogen consumption, and the key powertrain and operational actions bus OEMs and fleet operators can take to capture these savings.



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Introduction

Market context and the TCO challenge

Supported by EU-funded programs such as JIVE/JIVE 2, the introduction of FCEBs has scaled up with over 1,100 buses now deployed in Europe. Coordinated public transport projects and OEM bus platforms are now transitioning to commercial operations, generating operational data – duty cycles, refuelling patterns, and service events – that are being fed back into product design and fleet support services.

The overall result is a more mature picture of where fuel cell technology fits in the low-emission transit mix. It is not a single “better” choice for every route, but it is increasingly the preferred option for challenging routes where range, elevation, rapid refuelling and consistent performance across all seasons matter.

FCEBs can now be considered as a mature technology with multiple OEMs offering 10-meter to 18-metre vehicle platforms, as well as double-deckers. The value proposition of hydrogen for transit buses is validated; long range, quick refuelling, consistent performance, and scalable refuelling infrastructure can deliver true 1:1 replacement for diesel buses in an operator’s fleet.

Despite these strengths, FCEBs remain more expensive than legacy solutions, with TCO around 20% higher. However, as vehicle prices continue to fall (FCEB price has been halved in the past 10 years) and hydrogen costs decline as new production capacity comes online, the gap is expected to close in the coming years.

The TCO premium arises from three central inputs to any fleet model:

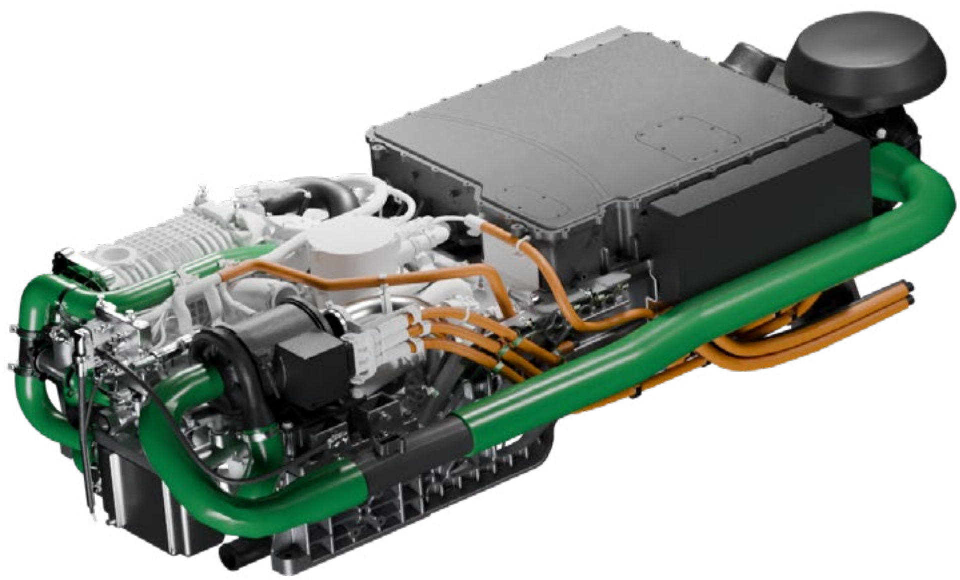
- Hydrogen cost
- Vehicle price
- Operational requirements (number of vehicles/route)

What is less obvious, but critically important, is how much influence fuel cell-level engineering can exert on those inputs. A well-designed fuel cell module changes not only the module’s own performance but also the vehicle’s thermal, electrical, and service architecture – so the benefits multiply across the lifecycle.

FCmove®-SC: Fuel Cell Level Improvements & Impact on Lifecycle

Designed specifically for city transit duty, the FCmove®-SC has key advancements that provide improvements in integration, operation, service, and cost. The module targets a rated power capability of 75kW, optimized for consistent in-service output and higher thermal margins for improved efficiency.

Efficient subsystems and state-of-the-art membrane electrode assembly (MEA) support an expected service life of approximately 25,000 operating hours under standard transit duty cycles.



The FCmove®-SC offers several enhancements for bus OEMs and operators:

- Stable lifetime optimized power – allowing for improved system integration and optimization with retained capability at end-of-life
- Integrated DC/DC – simplifying mechanical, electrical, and controls integration, while achieving a 25% increase in volumetric power density
- Open architecture – designed to allow for improved maintenance enabling faster and simpler servicing
- 40% reduction in total part count for higher reliability, as well as lowering failure modes and spare parts inventory
- 25% increase in maximum radiator temperature, from 60°C to 75°C outlet temperatures to reduce cooling (radiator) requirements
- 20%-30% expected lifecycle cost reduction with preventive and corrective maintenance*

** Ballard projects that the combination of module design and telemetry-enabled predictive maintenance can reduce lifecycle maintenance and downtime costs by 20–30% in fleet scenarios – an effect that directly reduces OPEX per km.*

Mechanically	Higher power density and higher thermal margins reduce the vehicle's packaging premium. Integration of the DC/DC converter and other balance-of-plant elements result in fewer custom harnesses and less bespoke thermal routing for the OEM, directly shortening integration cycles and reduces engineering hours and bill-of-materials cost. It also means fewer discrete parts to fail and fewer complex interfaces to validate during vehicle qualification.
Operationally	Improved module efficiency and lower parasitic loads translate into fewer hydrogen kilograms consumed per 100km, and more usable heat reduces auxiliary loading in cold climates – both of which lower fuel expense and reduce duty-driven volatility in range.
Service-centric design	smaller numbers of field-replaceable units, improved access and predictive telemetry, reduces spare-parts inventory, workshop hours and unplanned downtime.

FCmove®-SC's Impact – from Integration to End-Use

The FCmove®-SC fuel cell module provides a useful case study of the multiplier effect when reduced product and vehicle integration cost, increased power, and reduced parts count results in lower lifecycle cost for the fleet operator.

To leverage the full capability of a fuel cell and realise the benefits it enables, it is essential to consider hybridization and TCO together. These elements are tightly linked – how the fuel cell is sized and operates affects not only efficiency and durability, but also the lifecycle economics that determine fleet viability.

POWERTRAIN HYBRIDIZATION: THE FUEL CELL & BATTERY TRADEOFF

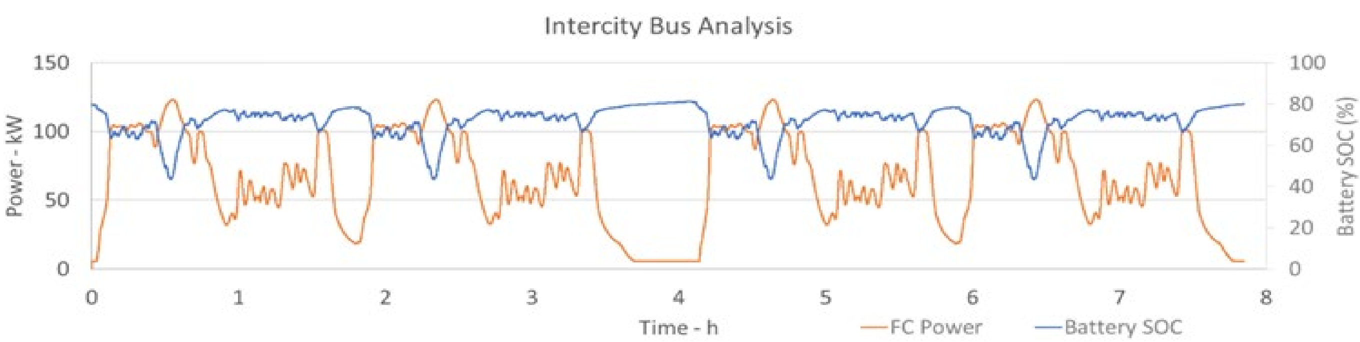
The fuel cell and battery together represent approximately 15–20% of the total cost of a FCEB and up to 70–80% of the powertrain cost.

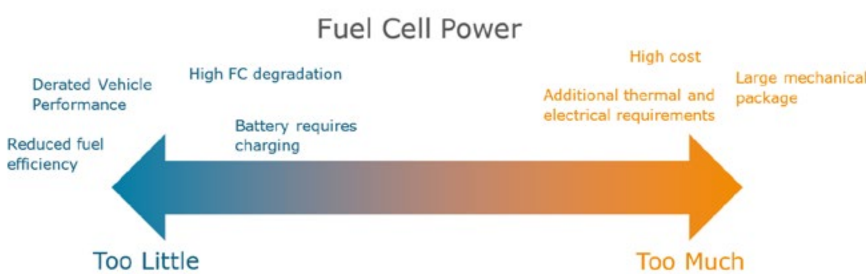
The hybridization strategy – the sizing of the fuel cell and battery and the associated control methodology – directly influences vehicle cost, efficiency, and performance. Operating the fuel cell within its optimal efficiency range can significantly improve system performance, but this must be balanced with battery behavior to mitigate degradation.

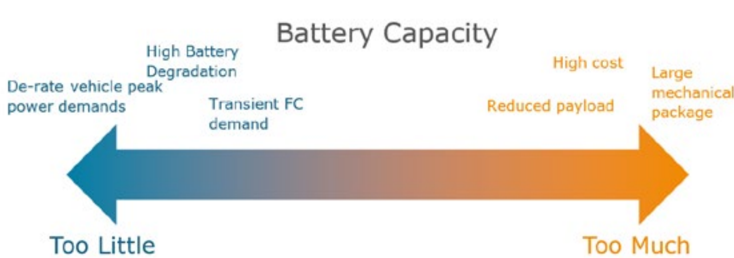
Modelling shows that modestly increasing fuel cell size relative to a baseline can lower kg H_2/100km because the fuel cell operates at a lower relative load (higher efficiency).

The optimal balance depends on measured route data: duty cycles, average speeds, HVAC demand, and depot refuelling patterns. Key considerations for bus OEMs, transit agencies, and end-users when choosing a bus with the lowest lifecycle costs include:

Achieving the optimal balance between fuel cell power and battery capacity and/or power is essential for each bus use case. Modelling several fuel cell and battery combinations converge real-world usage data to identify the most effective configuration for performance and efficiency.







TCO Considerations

Optimizing FCEB TCO to compete in this saturated market demands not only the component level improvements and cost reduction that FCmove®-SC offers but also a system and route-level approach that combines module innovation, vehicle integration, and fleet operational strategy. CAPEX, OPEX, system lifecycle, and duty considerations are four key elements impacting the TCO of FCEBs when compared to competing technologies such as battery electric.

1. CAPEX: Component and integration costs

Current FCEB purchase prices in Europe are around 20% higher than BEBs, with ongoing cost reductions expected to reduce the gap to 10%. FCmove®-SC supports ongoing cost reduction with design features that reduce upfront vehicle and system costs:

- Integrated DC/DC allows for direct power demand, simplifying mechanical and electrical integration while reducing control complexity. The integrated DC/DC requires fewer custom harness and less bespoke thermal routing
- Stable lifetime net output power means OEMs can optimize component selection for a consistent fuel cell performance across the whole system's lifecycle
- Reduced part count lowers module cost and improves reliability
- Increased radiator temperature allows for a more efficient, smaller fuel cell radiator, lowering cost and simplifying packaging
- Latest automotive protocols (J1939, UDS) streamline OEM integration and reduce engineering overheads

These features will simplify the fuel cell module integration in the vehicle and shorten the assembly time. Cost reduction of other key components such as the hydrogen tank system and battery pack is required to meet the above targets.

2. OPEX: Operational and maintenance costs

Hydrogen cost is a pivotal driver of OPEX. By optimizing hybridization and leveraging fuel cell design improvements, operators can reduce hydrogen consumption and service costs, shifting emphasis from fuel price to overall system performance. Ballard's analysis indicates that for certain applications, such as high-duty city transit routes, FCEBs are viable at roughly €8-9/kg of hydrogen, with cost parity against diesel buses likely around €6-7/kg.

- Increased operating temperature: A more efficient radiator requires a lower parasitic load to achieve the same heat rejection. Additionally, more usable heat reduces auxiliary loading in cold climates when integrated with HVAC - this lowers fuel expense and reduces duty-driven volatility in range
- Open architecture: Simplified maintenance allowing for improved fleet up time while lowering cost
- Reduced total part count: Improved serviceability, with fewer parts, and optimized packaging for better access to parts and field replaceable units (FRUs)
- Lifecycle cost reduction: Ballard's modelling for FCmove®-SC shows lifecycle maintenance and downtime improvements (~20-30% reduction) when telemetry-enabled predictive maintenance services are applied; this fleet-specific impact should be validated against local labour rates and duty profiles

3. Lifecycle: Serviceability

Module lifetime, refurbishment, and residual value materially affect lifecycle economics. FCmove®-SC modules are designed for 12-14-year bus lifetime, with a stack life expectancy of 25,000 hours under standard transit duty cycles.

At end-of-life, modules can be refurbished in-situ:

- MEA replacement and stack reassembly re-using existing components (bi-polar plates and stack enclosure)
- Balance-of-plant component exchange (e.g., compressors, pumps, humidifiers)

Because refurbishment is feasible, FCEB powertrains can retain a residual value at the end of a bus's first service cycle (8-12 years). Depending on operating hours and refurbishment strategy, that residual value of the fuel cell module will improve vehicle financing and fleet TCO when accounted for in lifecycle models.

DUTY CONSIDERATIONS & TCO: ROUTE-LEVEL OPTIMIZATION FOR FCEB v BEB

FCEBs offer distinct advantages on high-duty, challenging routes where BEBs face limitations. Comparing FCEBs and BEBs requires a route-level lens: BEBs typically perform best on short routes with reliable depot charging and sufficient grid capacity, while long-range or high-duty routes often favor hydrogen because of range, payload, and operational resiliency considerations. As route length, duty intensity, and fleet size increase, capital and operational constraints become decisive.

Key operational advantages and constraints

- FCEB advantages on challenging routes:
  - FCEBs enable rapid refuelling and long range, allowing 1:1 replacement of diesel buses on many routes
  - Lighter vehicles compared to BEB with large battery banks
  - For larger fleets, hydrogen refuelling infrastructure can scale more cost-effectively per vehicle (see infrastructure point below)

- BEB constraints on challenging routes:
  - BEBs need larger battery packs for long or intensive routes, increasing weight, reducing payload, and accelerating component wear
  - Deploy additional vehicles to meet route requirements
  - Depot fast charging and/or opportunity charging can require costly substation upgrades, civil engineering work, and complex charger management
  - In some locations, adequate grid capacity may be unavailable for years, constraining BEB deployment

Four TCO levers that determine parity between FCEBs & BEBs

Hydrogen Price	Break-even with diesel is typically in the region of ~€8/kg; achieving parity with BEBs is likely nearer ~6€/kg. Regional variance exists today
Vehicle Price	Typical FCEB purchase prices in Europe remain higher than BEBs (order of magnitude +20% today), though ongoing cost reductions target vehicle price gap to 10% or less
Operational Requirements	The number of zero-emission buses required to preserve service levels matters: FCEBs can often be deployed one-for-one with diesel replacements, while BEB deployments on some routes may require an additional 10-20% of vehicles (and drivers) to maintain service
Infrastructure Cost	Upfront refuelling/charging infrastructure and grid upgrades affect TCO. Operator studies indicate that, above fleet sizes of roughly 30-50 buses, the per-vehicle infrastructure cost tends to become more favorable for hydrogen refuelling compared with high-capacity charging installations

Procurement & Operational Recommendations

To capture the savings benefits described in this paper, fleet planners should:

1. **Model at the route level.** Require measured duty cycles (including HVAC and payload effects throughout all seasons) and run candidate pairings through standard control strategies to estimate hydrogen consumption, battery Depth of Discharge profiles and expected degradation.

2. **Demand standardized simulations in tenders.** Require suppliers to declare fuel cell sizing and power output at end-of-life, battery chemistry and capacity, control windows (fuel cell efficiency bands and SOC bands), and predicted hydrogen consumption on provided cycles. This prevents apples-to-oranges comparisons.

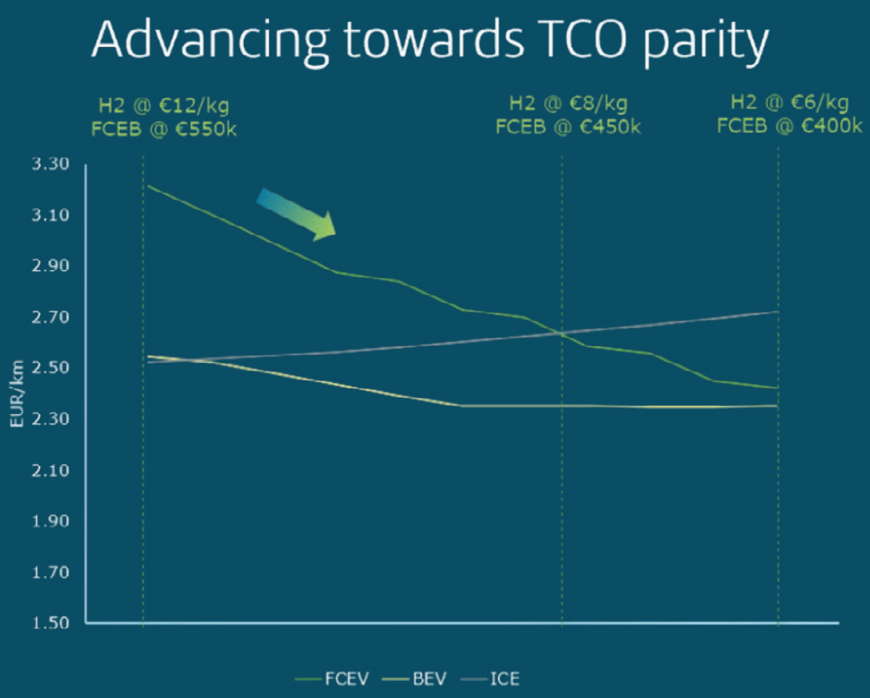
3. **Buy hydrogen and infrastructure at scale.** Hydrogen refueling station (HRS) per-vehicle economics improve with fleet size; long-term hydrogen contracts reduce fuel price volatility. Explore depot sharing and regional HRS consortia where feasible. Consider the future state with full depot conversion and associated costs when selecting bus powertrain technology. Access to energy, charging/refuelling infrastructure as well as depot space and weight constrains should be considered as zero-emission bus fleets will scale-up over time.

Conclusion

Bringing FCEBs to parity with diesel and battery electric solutions is not a single technological milestone but the result of coordinated advances across product engineering, powertrain architecture, vehicle integration, and procurement practice.

The FCmove®-SC case study shows that targeted module engineering – higher operating temperature, integrated DC/DC power conversion, reduced parts count, and service-centric design – produces benefits that can be multiplied: lower component and vehicle integration cost, materially lower maintenance and downtime when combined with telemetry-enabled predictive services. These effects act on both CAPEX and OPEX and therefore on fleet TCO in ways that component-level improvements alone cannot achieve.

Quantitatively, the paper demonstrates near-term TCO improvements: stack lifetime objectives (~25,000 operating hours), simplified bus integration, module refurbishment, and projected lifecycle maintenance and downtime improvements (~20-30% reduction) with predictive services. When coupled with declining electric drivetrain costs and scaled hydrogen supply, these levers make parity a realistic outcome on high-duty challenging routes within the coming years.



For procurement and operators, the implications are practical and immediate:

- Evaluate zero-emission options at the route level
- Require standardized, transparent simulation inputs in tenders (fuel cell sizing, battery capacity, control windows, and predicted hydrogen consumption)
- Standardized bus specifications to capture repeatable integration savings
- Include telemetry and service KPIs in supplier evaluations

These measures help to convert technical improvements into verifiable lifecycle savings and reduce the sensitivity of TCO to external factors such as short-term hydrogen price volatility.

In summary, fuel cell module innovation plus disciplined systems-level deployment and scaled procurement create a credible pathway to TCO parity for more challenging routes. The FCmove®-SC example illustrates how engineering choices and technical innovation, when paired with appropriate operational practice, can shift FCEBs from a niche alternative to a competitive, scalable solution for many city transit bus networks.

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