Zero Emission

Fuel Cell Electric Refuse Collection Vehicles

March 2021

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1. Executive Summary

Globally, cities are working to decarbonize their transportation operations primarily by replacing older fleet vehicles with newer, low-carbon and zero-emission options to meet GHG emission targets and low emission zone requirements. A range of vehicle types are impacted, including refuse collection vehicles (RCV) – the focus of this report.

Traditionally RCVs are diesel powered, with a few compressed natural gas (CNG) trucks deployed. In addition to noise emissions, these internal combustion trucks emit air pollution and greenhouse gases. Even when fueled with renewable natural gas, CNG trucks are not a true zero-emission solution, still generating NOx and /x, along with potential methane leaks. The emissions from these trucks pose a hazard to our climate, citizens, homes and the crews that work around the vehicles all shift.

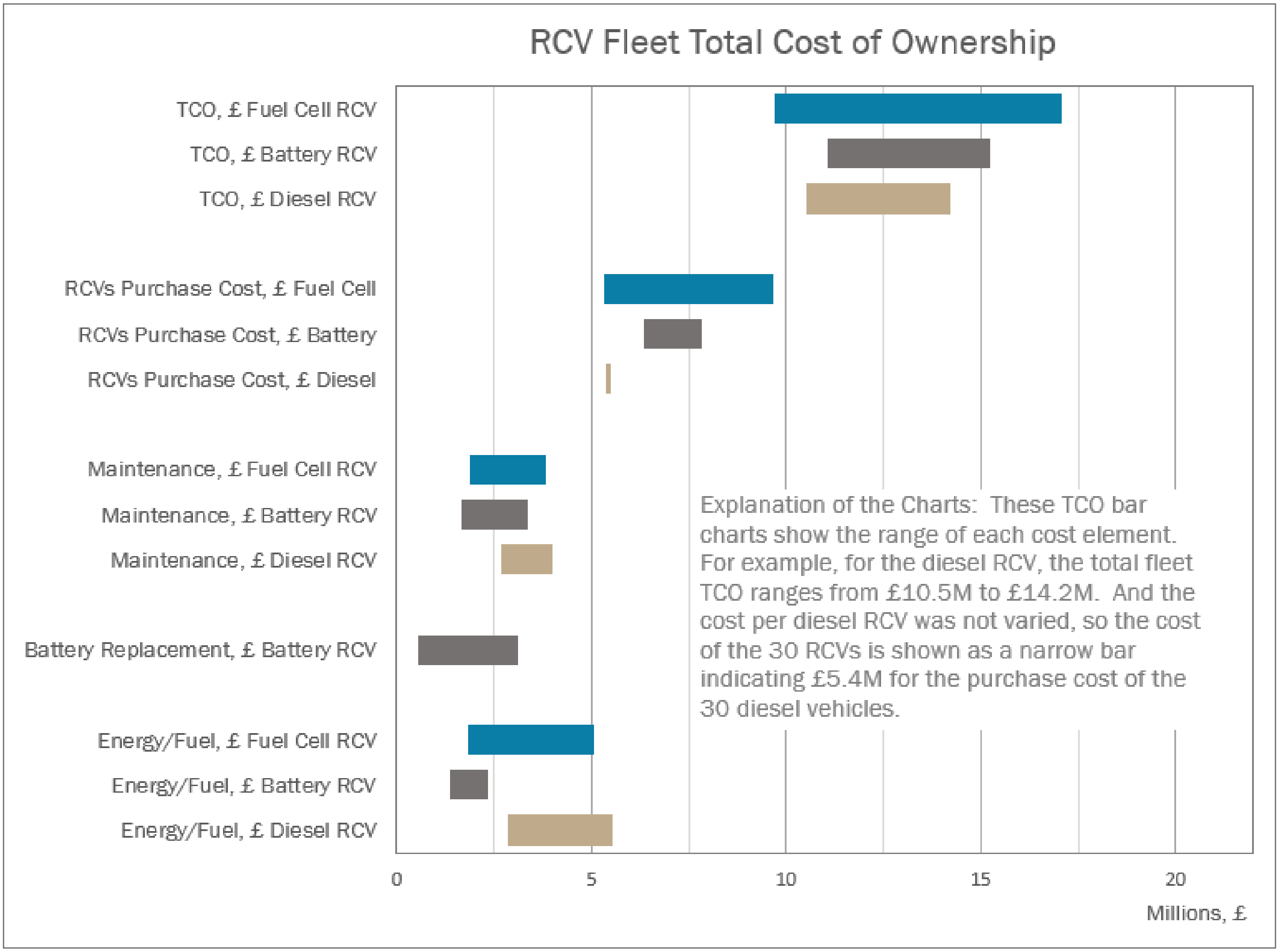
The ideal RCV must be a full-service zero emission truck with capabilities for heavy payload, high utilisation, and sustained high power operation. Using actual data collected from diesel powered RCVs operating in the United Kingdom, Glasgow and the Midlands, this report examines the capability of fuel cell powered RCVs to meet the cost and performance requirements of the waste management application. To this end, performance and operational requirements were reviewed and cost and performance of the fuel cell solution were compared.

Results show that the fuel cell RCV is a full service zero-emission vehicle that can reproduce and improve on the performance of current diesel fleets as a like-for-like replacement.

Benefits of a fuel cell RCV include:

- Flexible, full-service vehicle capable of both short city routes and extended suburban and rural routes. Flexibility and long range can reduce total fleet size requirements.
- 2.5 tonne better payload over battery electric RCV for 16 hours or more of operation. Virtually equivalent payload to diesel with path to higher payload with technology improvements and improved vehicle integration.
- Thirty kilograms of hydrogen onboard enables a duty cycle of more than 125 kilometres containing more than 3,000 bin lifts. Extended double-shift operations are possible with 3000 bin lifts.
- Fast refuelling in under 10 minutes for thirty kilograms of hydrogen. This enables high utilisation of the vehicle asset, possibility for extended shift operation or back-to-back shifts without downtime for recharging, and efficient operations and use of the labour force.
- The cost of the fuel cell RCV can be lower than the diesel RCV once commercial maturity is reached. Path to lower total cost of ownership (TCO) compared to both pure battery and diesel RCV.

Zero Emission Fuel Cell Electric Refuse Collection Vehicles



Importantly, the TCO indicates that the fuel cell RCV fleet can be lower cost than current diesel RCV fleets. While the estimated cost of battery RCV fleets have higher certainty and therefore a tighter range, the pure battery RCV has limited performance and operational capabilities compared to the diesel and fuel cell RCV. Furthermore, there could be large unaccounted-for costs associated with opportunity charging, grid upgrades, and labour associated with charging infrastructure.

Hydrogen fuelling infrastructure has the benefit that it scales well – increasing the capacity of the station to larger fleets is easy and cost-effective. Location of refuelling at depots on industrial estates can open up a wide potential group of other users in logistics or public services to share the costs of infrastructure and reduce hydrogen price at the pump. We recommend local authorities consider leveraging the scaling benefits of hydrogen infrastructure by locating fuelling assets at transfer stations or other strategic locations where multiple fleets of hydrogen vehicles routinely converge.

The fuel cell RCV offers fleet managers and local authorities flexibility in operation and the opportunity to reduce costs of refuse collection while improving health and the environment. We anticipate waste management companies and local authorities will recognize the benefits of fuel cells and hydrogen and launch the first deployments of fuel cell RCVs.

2. Introduction

This paper is a partnership between leading fuel cell supplier Ballard Power Systems and experienced system integrator Arcola Energy to present the hydrogen fuel cell refuse collection vehicle as a full service zero emission truck capable of the busiest operations.

We describe the technology and its benefits for both domestic and commercial refuse collection operations, showing through data analysis and modelling how the practical requirements of power, payload, range, utilisation and lifetime can be met by this technology.

Combining Ballard and Arcola's experience, for the first time this paper presents a detailed total cost of ownership (TCO) calculation that shows a pathway to parity and better, compared to both diesel and battery electric technology.

Finally, the paper discusses the practical aspects of hydrogen infrastructure and refuelling and the similarity of depot operations to current diesel vehicles.

3. Background

Management of residential and commercial refuse, including curbside collection, is an integral part of our modern society. Crews, with their trucks, collect our rubbish, compostable materials, and recyclables – often in wheelie-bins right at our curbside or in large bins in alleyways – and transport these loads to centralized centers where the waste is properly managed. The complete refuse management system includes different types of trucks including refuse collection vehicles (RCV), traditional heavy-duty transfer trucks moving large containers of refuse, and off-highway heavy duty yard trucks working at centralized waste management centers. This study investigates refuse collection vehicles, with a focus on operations in the United Kingdom.

Supported by public tax revenues, local authorities manage refuse collection for citizens and either perform this "residential" refuse collection themselves or contract the work, typically with 5 to 7 year terms, to third-party companies specializing in waste management. Businesses, such as retail or industrial, are responsible for their own refuse and so-called "commercial" collection services are either provided by waste management companies or through "paid-for" services by local authorities.

In this paper we report on these two types of collection duty cycles – residential and commercial collection. Residential refuse collection is typified by the RCV travelling from the overnight depot to a neighborhood where the crew moves from one collection stop to the next, and these stops are generally in close sequential proximity with low average speed between the stops; we call this type of route an "arc" duty cycle. These arc routes are configured to utilise the full payload of the RCV and minimize the number of trips to the transfer center to dump the load; in other words, payload is important.

We found that commercial collection routes are different in that the trucks travel to an area to make one or more collections, then travel to the next area where additional collections are made, and then back to a depot which is often some distance away. The commercial route features fewer stops, with higher speeds between stops, frequently a single operator/driver, and often significant periods of highway travel; we call this type of route a "node" duty cycle. These node routes require a RCV capable of high sustained power to travel at highway speeds with full loads. However, payload is not so important, as the duty cycle finishes when the collections are complete, not when the vehicle is full.

Refuse collection vehicles are available in any number of configurations, but most modern trucks include a system – the bin-lift – to lift the refuse can or container and empty it into the body of the truck as well as a system – the compactor – to compact the refuse once it has been emptied into the body. Power for operation of the bin lift and compactor is traditionally supplied by the RCV engine through a power take-off and hydraulic system. Truck configurations include rear loader, front loader, side loader, bodies with one or more compartments to maintain separation of, for example, rubbish and recyclables, and linear or roto-compactor systems. RCV gross weight ratings include 7.5, 18, 26, and 32 tonne, with 26 tonne being most common. There are approximately 2,000 new RCV registrations in the UK annually.[1]

Due to narrow, tight streets RCV crews for residential collection in the UK often consist of a driver plus an additional 2 to 3 operators who bring bins back-and-forth to the truck and help spot for the driver. Therefore, labour costs per RCV are high, and it is important that the number of trucks and their crews is optimized, and utilisation of trucks while on-duty should be high.

We additionally found that RCVs should have high availability to align with staff availability and to replace a failed truck on short notice. Holidays and special events call for high utilisation of the RCV fleet due to the possibility for increased flow of refuse. Weather-related events such as a sunny spring weekend, which enables mowing and gardening by homeowners, can result in heavy loads of compost requiring full RCV payload.

Traditional RCVs in the UK are typically diesel powered, with a few compressed natural gas (CNG) trucks deployed. In addition to noise emissions, these internal combustion trucks emit air pollution including NOx and particulate matter (PM), and green house gases (GHG) including CO_2 and methane. With these trucks working in close proximity to homes and businesses, and with crews working around the vehicle all shift, the importance of zero emission RCVs cannot be over-stated.

4. Fuel Cell Electric RCV Solution

Heavy duty transport applications, including refuse collection, are viewed as ideal applications for emerging fuel cell solutions. These heavy-duty applications require long hours of operation – sometimes nearly continuous operation, long lifetime – 25,000 hours and more between engine rebuilds, high power for heavy payloads and high sustained speeds, and costs which meet the requirements of these demanding commercial applications. Internal combustion engines (ICEs) have long been the solution for many heavy-duty applications, but fuel security and the damaging impacts of combustion on health and the environment has led the world to increasingly tighter emission requirements and outright bans[2] on ICEs in many locations.

Clearly, the ideal RCV should be a full-service zero emission truck with capabilities for heavy payload, high utilisation, and sustained high power operation. The only zero emission RCV architectures available are pure battery and fuel cell-battery hybrid designs. Therefore, it is important for waste management companies and local authorities to understand how these zero emission options compare against each other, as well as to the incumbent diesel solution.

The objective of this report is to investigate the capability of a fuel cell powered RCV to meet the cost and performance requirements of the waste management application. To this end, performance and operational requirements will be reviewed and cost and performance of the fuel cell solution estimated.

The fuel cell RCV is represented by Figure 1, with the key subsystems and the flow of power for traction and auxiliary loads identified. Note that the RCV is a hybrid architecture including both a fuel cell and a battery.

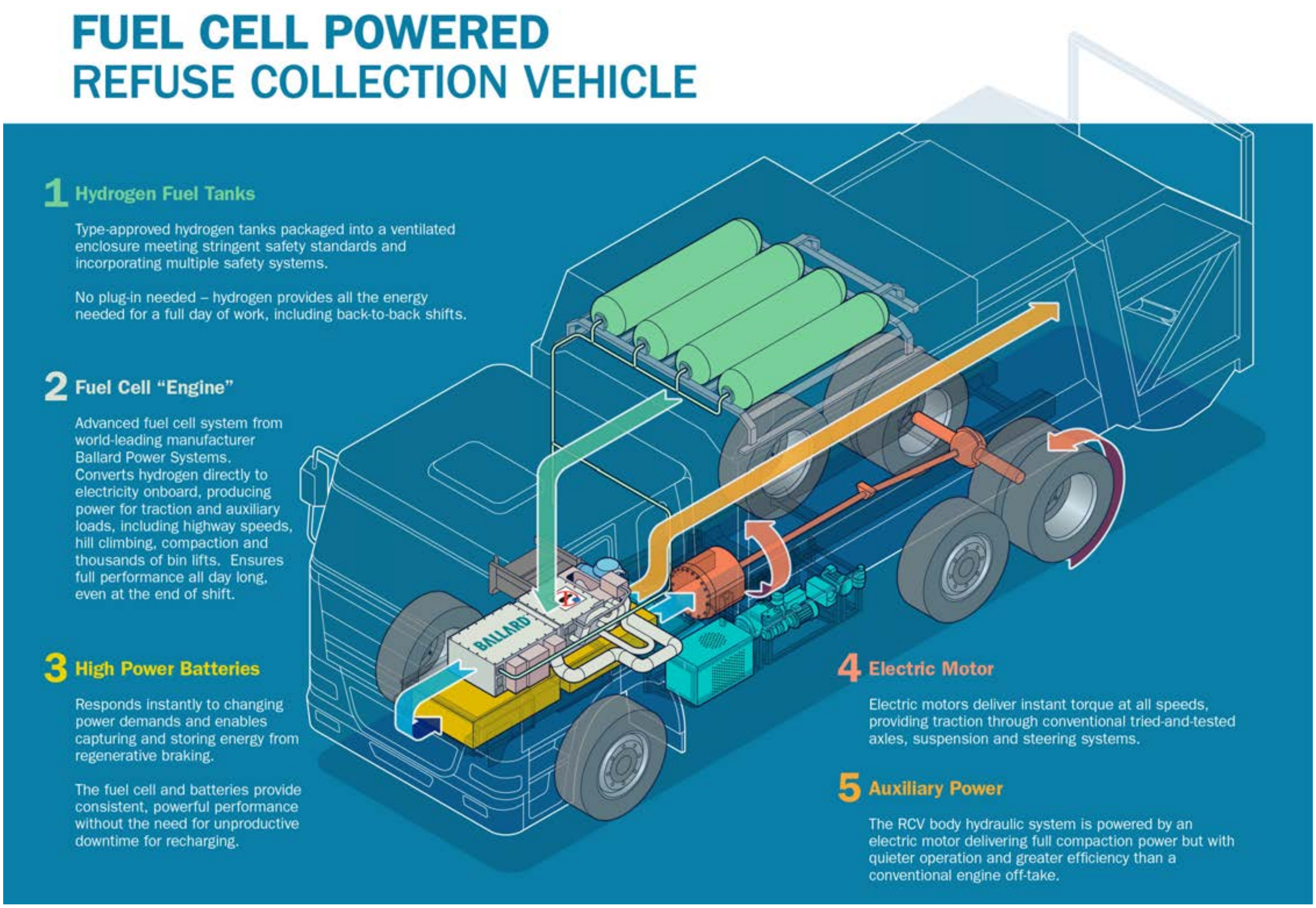
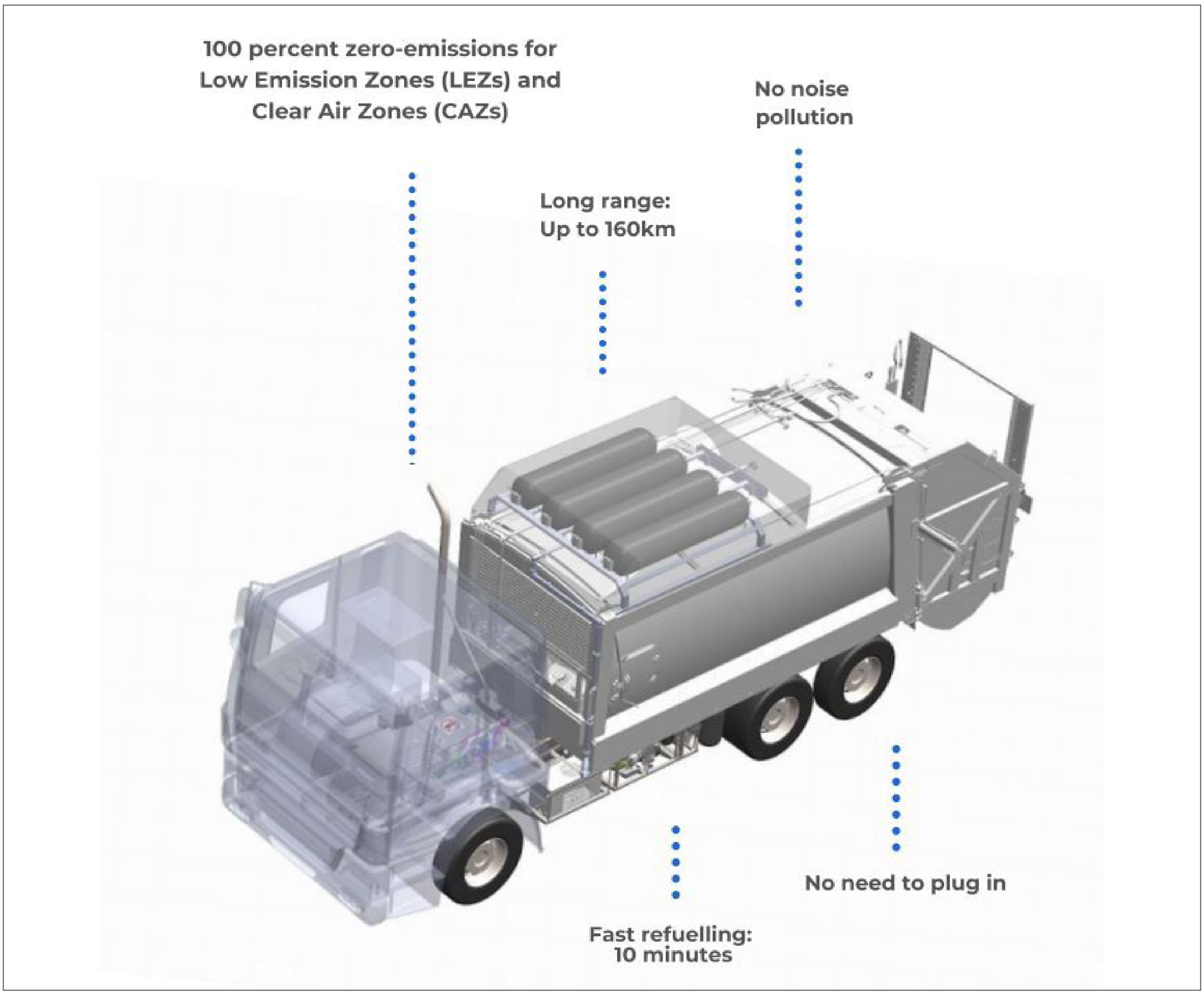


Figure 1: Fuel Cell Powered RCV Key Subsystems

Key components and features of the fuel cell RCV include:

- **Hydrogen and storage tank.** Twenty (20) kg of hydrogen (H2) will provide all the energy needed for a full 8 hour RCV shift, with 30kg potentially enabling extended or double-shift operations. No plug-in to the electric grid is required, which means that, other than the few minutes needed for refuelling, the RCV is always available. Due to the low volumetric density of hydrogen, the fuel is compressed and held in composite tanks on the RCV. But hydrogen has extremely high gravimetric energy density (about 3 times higher than diesel), enabling a lighter weight solution, and therefore heavier payloads, compared to a pure battery RCV.
- **Fuel cell.** The fuel cell converts energy in the hydrogen fuel into electric power. (This is similar in concept to an internal combustion engine attached to a generator, but in one, highly efficient device). Heavy duty fuel cells from 30kW to 100kW are commercially available, with higher power engines in development.
- **Energy storage system (ESS), typically batteries (for the hybrid system).** Less than 60kWh is required for most RCV applications. The ESS is used to store energy from regenerative braking and meet transient power requirements of the duty cycle.
- **Traction and auxiliary loads.** Together, the ESS and fuel cell provide all the zero emission power needed for traction, the bin lift and compactor, and all other auxiliary loads including cab heating, steering, radios and other vehicle electronic accessories, compressors, etc.



Advantages of an electric powertrain RCV include:

- Zero emissions at the tailpipe gives air quality benefits immediately.
- The clean, quiet, powerful electric drive with lower noise emissions reduces local disruption on city streets, and possibly enables operation in neighborhoods during evenings or other traditionally quiet times.
- Better acceleration with maximum torque at low speed means routes are completed more quickly, or can be lengthened meaning more effective use of staff time and reducing fleet size.
- Better driver and crew experience and zero emission operations improves staff welfare.

Additional benefits of a fuel cell electric RCV:

- Use of hydrogen as a fuel gives a route to zero carbon emissions, including on a well-to-wheel basis when using green hydrogen as fuel.
- Equivalent power performance throughout the shift, as battery state of charge is maintained by the fuel cell. There is no performance fade and the fuel cell RCV can operate at highway speeds with a full load, even at the end of a shift.
- Fast refuelling in under 10 minutes, and often no more that 5 minutes.
- Range and shift length capability for a full day of operation – no need for on-route charging.
- Depot operations and parking are the same as diesel – no need to plug in, and no need for space-consuming charging stations in the depot.
- Flexible, full service vehicle capable of both short city routes and extended suburban and rural routes. Flexibility can reduce total fleet size requirements and simplify fleet composition.
- Capability to do double shifts without refuelling.
- Virtually equivalent payload to diesel with path to higher payload with technology improvements and improved vehicle integration. Payloads exceeding diesel RCV payloads are possible with alternative fuel derogation allowance.
- Path to lower total cost of ownership (TCO) compared to both pure battery and diesel RCV.

The fuel cell RCV is a full service zero-emissions vehicle that can reproduce and improve on the performance of current diesel fleets as a like-for-like replacement.

5. Design Approach and Modelling

Arcola Energy has developed several fuel cell electric heavy duty vehicles, their first prototype RCV is in build at the moment and they are starting work on their first production fleet for deployment in 2022, working with chassis from a leading OEM. Arcola takes a system engineering approach to powertrain and vehicle design starting with comprehensive requirements capture to ensure that the final vehicle meets customer needs. As a key part of this process Arcola captures detailed duty cycles from vehicles in operation to understand both the power demands for effective operation and the full energy demands of a shift.

Working with Glasgow City Council and a commercial operator in the Midlands, Arcola Energy instrumented diesel powered RCVs from those fleets with remote data collection systems. The data collected included engine speed, torque and fuel use to calculate the traction power and energy demand as well as hydraulic power and bin lift and compaction counting to calculate the energy requirement for the body systems. All of this is combined with GPS tracking to provide mapping, speed and elevation profiles of the routes.

This study is an analysis of 20 routes representing a mix of city centre domestic collections, mixed city-suburban domestic collection and commercial collection routes around Glasgow and Birmingham.

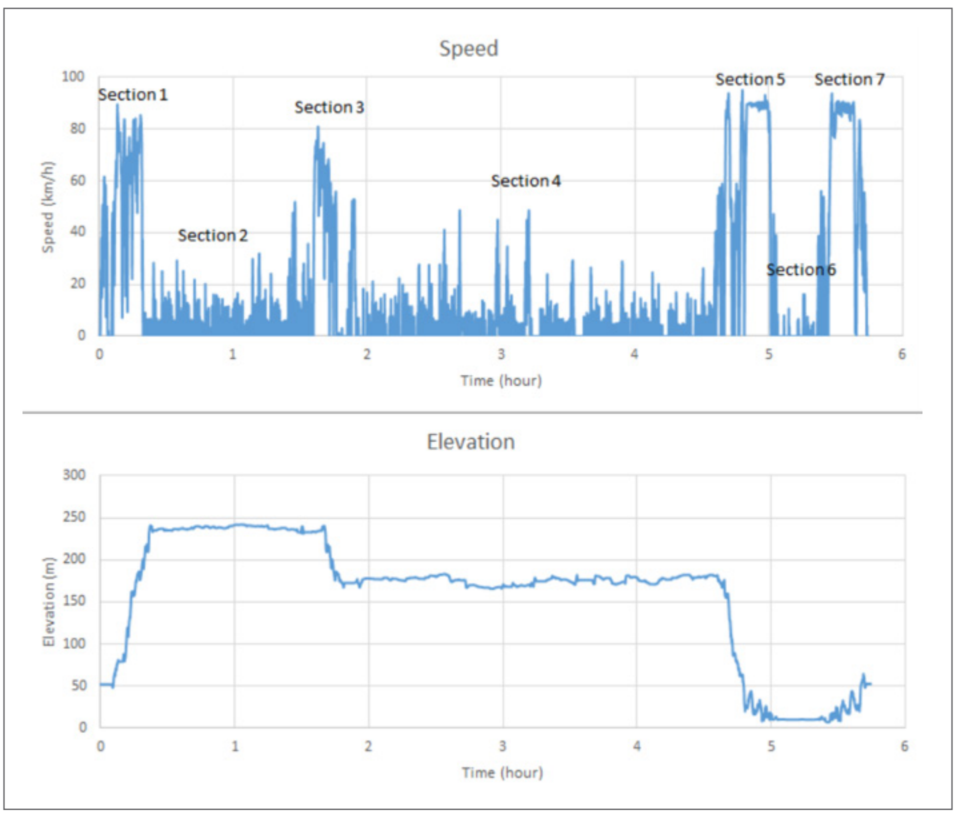


Figure 2: Example of an arc duty cycle representing residential collection

Data from this effort was used to build duty cycles of speed and elevation versus time. One such arc duty cycle, Figure 2, is described in Table 1 where distinct periods of operation are apparent. This duty cycle requires a full 10 tonne payload and durations of 6 to 9 hours are typical.

Table 1: Description of a Duty Cycle

Section	Activity
1	Depart from depot and travel to first collection area
2	Collection
3	Depart first collection area and travel to second collection area
4	Collection
5	Depart second collection area and transfer to dump station
6	Dumping at transfer station
7	Depart transfer station and return to depot

A node duty cycle representative of commercial collection is shown in Figure 3. This duty cycle shows clear differences from the arc duty cycle, with fewer stops and bin lifts, but long periods of sustained highway speeds. Payload requirement for this duty cycle is 8.2 tonnes and a 4 hour duration duty cycle is often combined with an 8 hour duty cycle for a total requirement of 12 consecutive hours of work.

Data collected by Arcola enabled deep understanding of RCV power requirements for traction, bin lifting, compaction and auxiliary loads, as well as requirements for payload, rates of energy consumption and magnitude of brake regenerative energy available. Understanding of requirements is necessary to inform the design of the fuel cell hybrid powertrain, as well as identify opportunities for further gains through electrification of auxiliary components and systems.

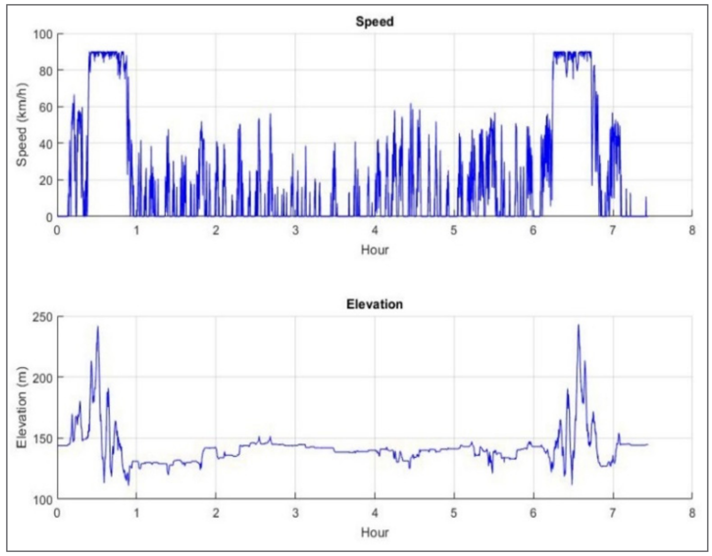


Figure 3: Example Node Duty Cycle

There are key outputs of this modelling work, summarized in Table 2 which feed into the total cost of ownership (TCO) modelling to compare the fuel cell hybrid solution to pure battery and diesel solutions.

Table 2: Modelling parameters for TCO analysis

Parameter	Value
Fuel Cell Power, kW	70
Battery Capacity, kWh	30 to 60
Duty Cycle Duration, h	8 to 12
Fuel Cell Energy Consumption Rate, kWh/h	46.5 to 53.6
Total H2 Consumption, kg/day	< 30

6. Demonstrating Capabilities of FCE RCV

a. Power

In the fuel cell-battery hybrid architecture, the fuel cell and battery work together to provide all the power needed for traction and auxiliary loads. (This concept is similar to a diesel hybrid vehicle where the diesel engine and battery work together to power the vehicle.) Typically, vehicle controllers operate the fuel cell at relatively constant power output, while allowing the battery to deliver power for short-term transient loads and capture energy from regenerative braking. This strategy enables operation of the fuel cell at higher efficiency in order to minimize hydrogen fuel consumption and thereby reduce the total cost of ownership (TCO). Additionally, the fuel cell maintains the battery at a relatively stable state of charge (SOC), thereby maintaining power performance throughout a shift and benefitting battery lifetime which again delivers a positive impact on TCO.

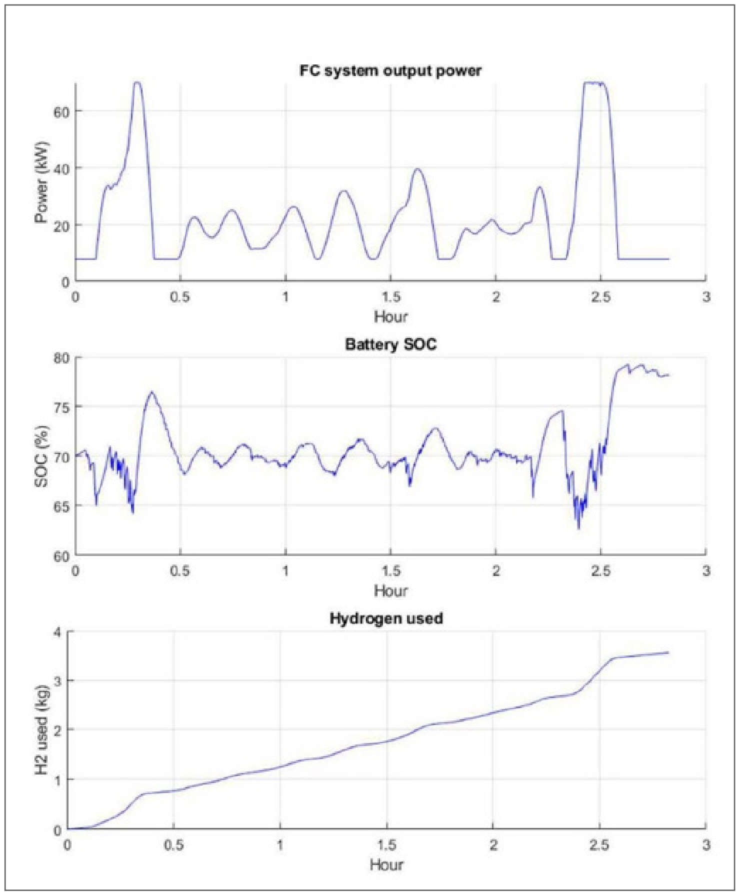


Figure 4: Example Model Output

We modeled a 70kW fuel cell, which is commercially available and satisfies the power needs of most RCV duty cycles, with a 30kWh battery for the arc duty cycles and a 60kWh battery for the node duty cycles. Example model output, Figure 4, for the arc duty cycle indicates the battery is maintained within a healthy state of charge, average fuel cell power is appropriate to enable reduced hydrogen consumption, and the powertrain delivers ample power even at the end of the shift, thereby avoiding performance fade and providing a consistent operator experience over the entire duty cycle.

In contrast to other zero emission solutions, the fuel cell hybrid architecture delivers consistent power and performance over the range of operating conditions – including high and low temperature, steep grades, and highway speeds – and throughout the entire work shift.

It is understood that, as commercialisation of fuel cell engines accelerates, there will be future additional choices for engine power (for example, fuel cell engines of 350kW and higher) and the optimum solution could be an as-yet-to-be-developed higher power fuel cell engine paired with a smaller battery, pointing to the need for expanded hybridisation studies to inform the best performing solution at the lowest cost.

b. Range

Hydrogen fuel provides all the energy needed by the zero emission fuel cell refuse truck to meet the range requirements without encumbering the RCV with heavy batteries (which can reduce payload).

For refuse collection, with high energy requirements despite typically very low speed and distance, we found that required duration (hours) of operation is a better metric than range (km) of operation. This is reflected in the TCO work presented later in this paper.

For this study, we modeled fuel cell RCVs with 30kg of hydrogen to provide more than 16 hours of refuse collection for both the arc and node duty cycles, Table 3.

Based on typical energy requirements of the arc duty cycle, Arcola estimates the fuel cell RCV with 30kg of hydrogen can complete a duty cycle of more than 125km containing more than 3,000 bin lifts before reaching 90% depletion of the hydrogen tanks. Just 30kg of hydrogen opens the possibility of zero emission operation over multiple shifts without unproductive stops for opportunity charging of batteries. And 30kg of hydrogen requires less than 10 minutes to refuel. This high-utilisation capability of the RCV asset is an important differentiating characteristic of fuel cell solutions.

The flexibility of the fuel cell RCV to complete short and long duration arc and node duty cycles coupled with the capability to operate multiple consecutive shifts per day presents opportunities for waste management companies to complete the workload with fewer vehicles and a consistent mix of trucks, thereby reducing the total cost of operations. This is an important point that we recommend operators and local authorities study for potential cost savings.

Table 3: Operating Duration of Fuel Cell RCV

Duty cycle	Energy consumption rate, kWh	Available energy in 30kg hydrogen, kWh	Operation to 90% depletion of 30kg hydrogen tank, hours
Arc	47	1000	>19
Node	54	1000	>19

c. Payload

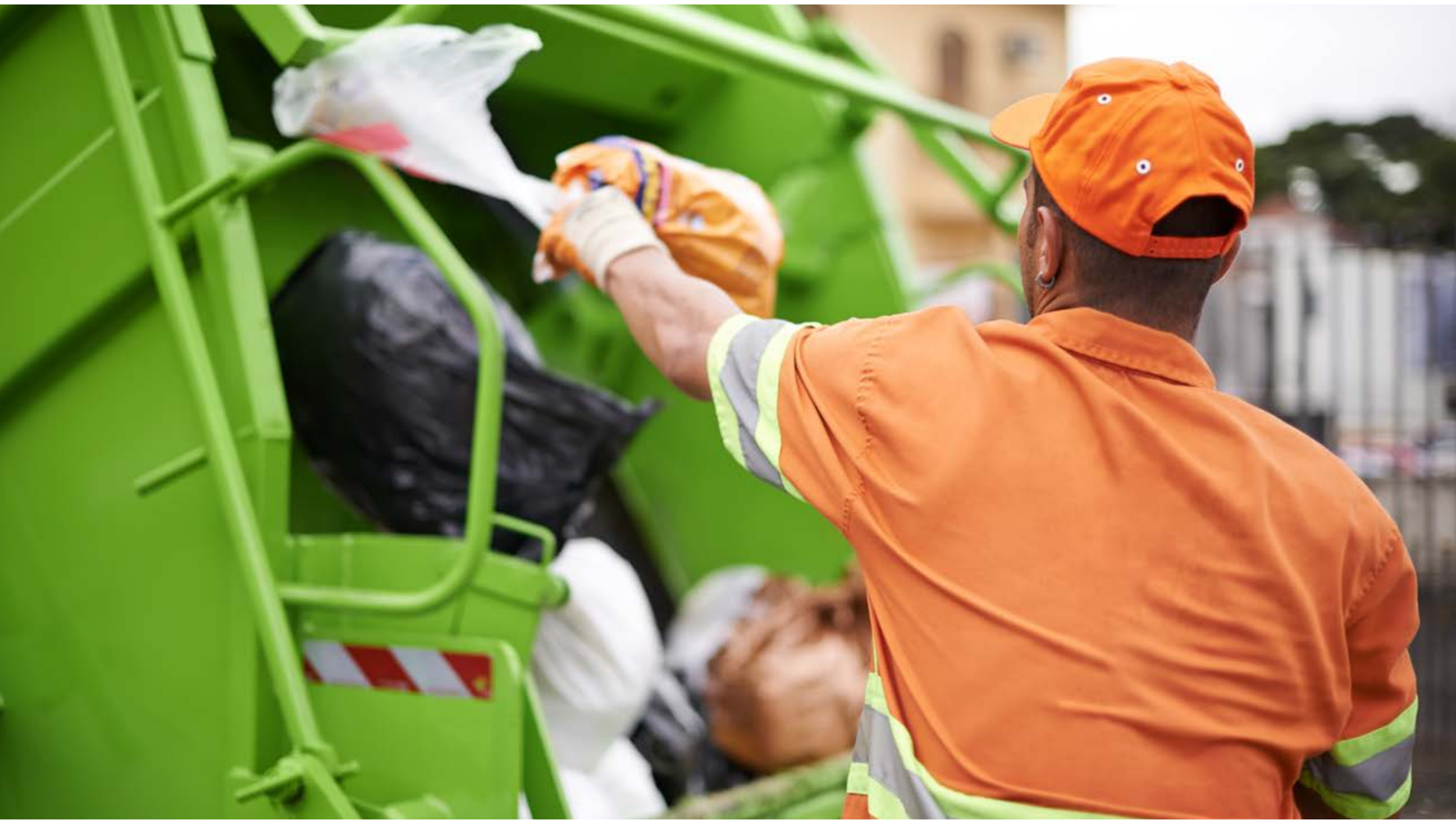
The conventional 26 tonne diesel RCV has a payload capability of 10 tonnes, and this is the target for zero emission fuel cell RCVs, otherwise there will be negative impact on cost and operations to the operator. Trucks without the capability to haul the required payload cause the waste management company to deploy additional vehicles, pay overtime labour rates for extended hours, operate multiple shifts, or take the risk of operating their vehicles over the legal weight limit.

We estimate the fuel cell RCV with 30kg of hydrogen has a payload between 9.6 and 9.8 tonnes, depending on whether the truck is configured with 60kWh or 30kWh batteries. This compares to an estimated payload loss of up to a tonne for a pure battery RCV with 300kWh battery.

We believe that the fuel cell RCV can achieve full 10 tonne payload with 30kg of hydrogen with implementation of forthcoming technology improvements, improved vehicle integration, and light-weighting measures. However, if an operator desired a fuel cell RCV today with full 10 tonne payload, the hydrogen capacity could be reduced to 20kg, still providing between about 11 and 13 hours of operation, depending on the duty cycle.

In addition, there is a derogation in the UK allowing alternatively fuelled vehicles to operate up to an additional 1000kg on the gross vehicle weight. This derogation could allow additional payload for these vehicles further extending the capabilities above diesel trucks.

The 30kg of hydrogen offers capability for 16 hours or more of operation, and the mass of the whole system only increases by around 150kg. This contrasts to a 16-hour battery system that would weigh more than 3.5 tonnes, sacrificing more than 2.5 tonnes of payload compared to the fuel cell RCV, resulting in additional unproductive transfers to the dumping station and contributing to either the need for additional battery RCVs in the fleet or longer duration shifts (and higher labour costs) to complete the collection. However, the reality we anticipate is that most pure battery RCVs will be configured with an approximate 300kWh battery, but these RCVs will require charging if more than 8 hours of operation



is needed. This could mean that either the pure battery RCV will not be capable of multiple consecutive shifts, or that on-route "opportunity charging", for example in the middle of the day, will be required to extend operations of the RCV. But opportunity charging carries significant burdens of construction, often in the city core, high demand charges, possible requirements for costly electric grid upgrades, poor proximity of chargers to the routes, impact on the lifetime of the battery, and inefficient utilisation of the RCV asset, driver and crew.

For a fleet of 30 battery vehicles, with a charging window of 10 hours using 100kW chargers, a depot would require a network connection of around 1MW, assuming some losses and power for other operations on site is required.

Effective fleet management requires trucks with payload capability to manage collections without exceeding weight limits or adding extra trips to the transfer center, which extends the collection cycle and impacts labour requirements. The fuel cell RCV is a capable, high-payload vehicle that supports efficient fleet use and reductions in fleet size overall.

d. Lifetime

Evaluating the durability of the fuel cell engine is important to gauge if it will meet the RCV application lifetime requirements. It is generally believed by experts[3] that a lifetime of 25,000 hours for fuel cells is the correct requirement for heavy duty applications. Ballard has designed their heavy duty fuel cell engines to enable long life (and lower life cycle costs) and has already demonstrated lifetimes of more than 30,000 hours[4] of operation without major maintenance.

Fuel cell engine lifetime is generally defined as a 20% loss in power, but could also be defined in terms of increasing fuel consumption or other metric. At this nominal end-of-life the fuel cell is refurbished, re-using components as much as possible, to achieve the same performance specifications as new fuel cells. They are then shipped back to the customer. During the refurbishing process, we integrate a new membrane electrode assembly (MEA) with the re-used bipolar plates and hardware. Used MEAs are sent to a specialized facility that reclaims 95% of the platinum. Every year, Ballard recycles and refurbishes thousands of fuel cell stacks. This rebuilding process reclaims valuable materials, minimizes waste, and reduces costs to the vehicle owner. To learn more about this process, read Ballard's blog post titled "Benefits of Fuel Cells: Refurbishing Leads to Zero-Waste."

Operational lifetime of the fuel cell is estimated based on 260 operating days per year and 25,000 hours lifetime, Table 4.

Table 4: Operational Lifetime of Fuel Cells

Duty cycle h/day	Lifetime between fuel cell rebuild, years
8	12
12	8
16	6

The body of the RCV also experiences heavy wear and is often rebuilt on a 7 to 10 year cycle. We note that the 8 year rebuild cycle of a fuel cell operated 12h/d matches quite well with the rebuild cycle of the RCV, and see the opportunity to extend the life of the RCV to 15 years with a mid-life rebuild of the fuel cell and RCV body. Alternatively, operating the RCV 8 hours per day should enable the fuel cell to last well into the second life of the RCV, which would contribute to higher residual value or enable use of the fuel cell RCV as a reliable spare.

As the lifetime of the fuel cell extends to 30,000 hours3 between rebuilds over the next few years, an opportunity exists to extend the powertrain of the fuel cell RCV to nearly 15 years without rebuild.

The fuel cell RCV, with long life and possibility for affordable mid-life rebuild, offers managers and local authorities flexibility in operation and the opportunity to reduce costs of refuse collection while improving health and the environment.

The fuel cell RCV lifetime compares favourably with battery vehicles. Current battery benchmarks assume around 2500 to 3000 cycles in heavy duty operation before capacity is degraded to 80%, or 7-8 years, assuming a single daily charging cycle, and significantly shorter if fast opportunity charging is used. Even as this improves, this means that to extend life beyond 8 years will require a new battery system, reducing residual values or incurring a significant mid-life cost. Range and performance are also significantly curtailed within this lifetime by this reduction in capacity to 80%, while any performance loss for the fuel cell vehicle would only be in extreme duty cycles.

e. Utilisation

An important feature of fuel cell vehicles is the capability to carry large amounts of fuel energy and operate long hours without sacrificing payload, and refuelling time is comparable to diesel vehicles – 30kg of hydrogen can be refueled in under 10 minutes. This enables high utilisation of the vehicle asset, possibility for extended shift operation or back-to-back shifts without downtime for refuelling, and efficient operations and use of the labour force.

With quick refuelling, the fuel cell RCV is always ready to deploy if another truck has been taken out of service, or collections are needed on an emergency basis (e.g., special events, storms, snow removal, etc.). Availability of trucks to meet this requirement is important because it reduces the required number of “reserve” trucks.

Additionally, fuel cell RCVs are expected to operate more quietly than diesel RCVs. This quiet operation coupled with capability to operate back-to-back shifts may enable extended working hours in neighborhoods and city centers.

7. Costs

a. TCO Basis

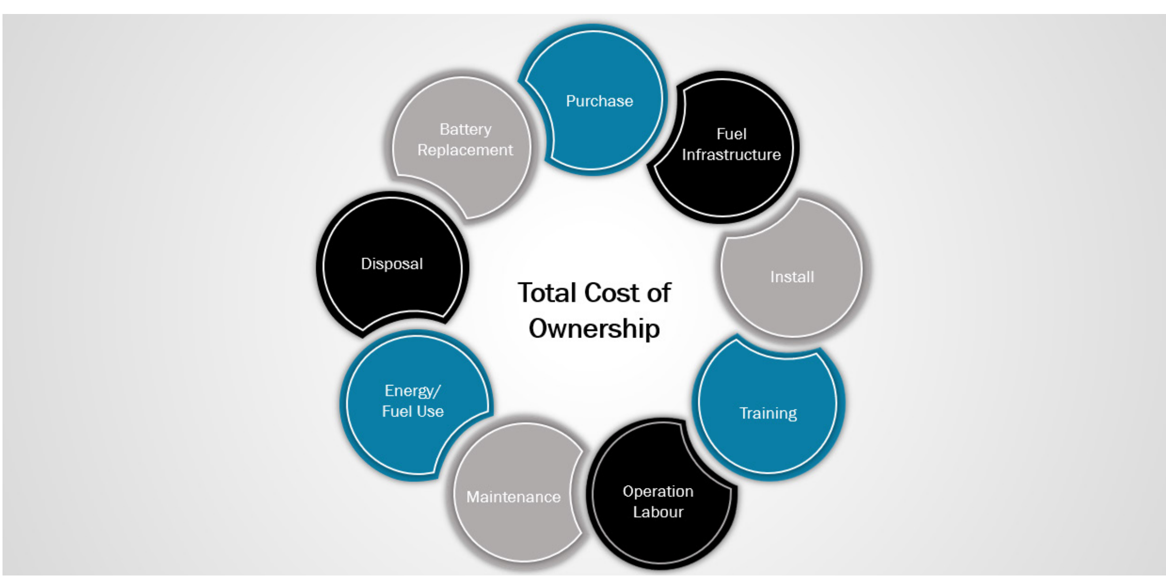
Combining Arcola's detailed modelling of real-world routes and Ballard's experience of fuel cell powertrains in operation for many years has enabled, for the first time, a detailed, realistic calculation of the costs of fuel cell RCVs and comparison to the cost of diesel and battery RCVs. We used a total cost of ownership (TCO) calculation, estimating the purchase cost of vehicles, infrastructure costs, cost of battery replacement, fuel and maintenance costs, and studied the sensitivity of these costs to expected declining costs of hydrogen fuel, and fuel cell and battery technology, and increasing cost of diesel fuel.

The TCO calculations were based on a base fleet size of 30 RCVs. The capability of fuel cell and pure battery RCVs to carry the payload required by the duty cycle was evaluated and, if the RCV could not carry the required payload, additional vehicles were added to the base fleet. The costs of these additional vehicles was accounted for in the TCO. We found that, for the arc duty cycle which requires a full 10 tonne payload, 1 additional fuel cell RCV and 3 additional battery RCV were required to complete the workload, and for the node duty cycle which requires 8.2 tonnes payload, no additional fuel cell or battery RCV are required due to payload. We believe that weight parity of the fuel cell RCV with the diesel RCV will soon be achievable, pointing to future improvement in the fuel cell TCO. UK gross vehicle weight derogation was not considered in the TCO, as it is not certain when this will be available.

Also, for duty cycles longer than 8-hour duration, we tracked the capability of the pure battery RCV to complete the duty cycle. For those conditions where the 300kWh battery is not sufficient, we added a 1 hour opportunity charge (1 hour was selected to account for some lost time in travelling to-and-from the charger, the possibility for queueing time, and time spent charging). When opportunity charging is required, we applied a utilisation penalty, consisting of the ratio of the lost time for charging to the required duty cycle duration, and calculated the number of additional RCVs required. We estimated that no opportunity charging is required for the battery RCV to complete an 8 hour duty cycle, but additional battery RCVs are required for the 12 hour and longer duty cycles. There is likely also a negative impact (higher cost) on the TCO if the battery RCV utilises opportunity charging due to shortened lifetime of the battery causing a need for a battery replacement within 10 years, possibly at 5 years.

Since the required number of diesel, fuel cell and pure battery RCVs can be different (due to payload and utilisation penalties) for each scenario in our study, we tracked the total project cost which is simply the product of the TCO per RCV and the number of RCVs required to complete the work.

Importantly, we did not estimate or account for labour costs associated with additional vehicles or the costs associated with opportunity charging, which would include cost of the equipment, installation, possible grid upgrades, electricity, demand charges, and maintenance of the charging equipment.



b. Capex

We estimated capital cost of the diesel RCV at £179,360 ($236,000), and accounted for costs of the fuel cell, hydrogen storage, batteries, electric powertrain and miscellaneous components, as well as the cost of the diesel powertrain to estimate the cost of the fuel cell and battery RCVs.

For the pure battery RCV, the cost of batteries was varied from a high of £266/kWh to a low of £114/kWh ($350 to $150/kWh), resulting in a vehicle cost of £237,641 to £192,041.

The fuel cell RCV is at a lower state of commercial maturity than the battery RCV and the expected cost decrease of several components are interesting to study. For the fuel cell RCV, we assumed newer, high performance batteries would be utilised, with a cost of £760/kWh today to a future low of £114/kWh ($1,000/kWh to $150/kWh). Cost of the fuel cell was modeled from £912/kW to £76/kW ($1,200 to $100/kW) and hydrogen storage from £27/kWh to £7/kWh ($35 to $9/kWh) (future costs are consistent with the US DOE report on Hydrogen Class 8 Long Haul Truck Targets). These costs resulted in a cost range for the fuel cell truck between £295,678 and £177,518 ($389,050 to $233,576). The higher end of the range is for low volumes of trucks produced for demonstration fleets (i.e. 10 to 20 RCVs). The lower end of the range is for high volumes of trucks produced, expected later this decade through an amalgamation of demand from different truck applications (tens of thousands of vehicles). Note that the cost of the fuel cell RCV can be lower than the diesel RCV once commercial maturity is reached.[1]

c. Maintenance

The cost of maintaining the diesel RCV was set to £3.80/operating hour ($5/hour). This cost accounts for maintenance of the complete truck including powertrain, chassis, bin lift, compactor, etc. Maintenance costs of the battery and fuel cell RCV were calculated by applying a multiplier to the diesel maintenance cost.

The battery RCV is at a higher state of maturity than the fuel cell RCV and we therefore applied factors of between 100% and 75% of the diesel maintenance cost, for an estimated cost of between £3.80 to £2.85/operating hour ($5 to $3.75/hour) for the battery RCV.

The cost of maintaining the fuel cell RCV was estimated at between 125% and 90% of the diesel RCV, for an estimated range of £4.75 to £3.42/operating hour ($6.25 to $4.50/hour). [1]

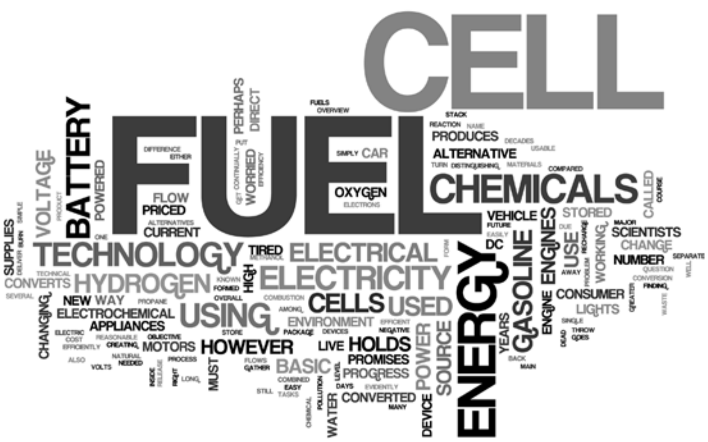
(1) GBP values have been converted to USD

d. Fuel

We have seen the cost of diesel fuel rise and fall several times over the past 15 years and there are wide differences in fuel cost between regions and countries. Globally, the world average cost of automotive diesel has remained relatively flat[6] from 2005 to 2019. However, for the UK, there has been an approximate 60% increase[7] in diesel pump price from 2003. We set the cost of diesel to £0.099/kWh and evaluated the impact of an increase to £0.111/kWh (£0.98 to £1.10/liter; $4.90 to $5.50/gallon).

The cost of electricity for battery charging was set to £0.114/kWh ($0.150/kWh) and was not varied. Although demand charges could be enforced and would add significantly to the battery RCV energy cost, we did not include them in the TCO.

Significant reductions in the cost of hydrogen[8] are expected to 2030 and beyond. We allowed the cost of hydrogen fuel at the dispenser to range from £0.150/kWh to £0.091/kWh (£5.00 to £3.04/kg; $6.60 to $4/kg).[1]



e. Battery Lifetime

For the battery RCV, the impact of battery lifetime was investigated by including costs for 100% battery replacement after 4 and 8 years of operation. These replacements add £1,710 to £9,423 per vehicle per year ($2,250 to $12,398) to the battery RCV TCO.

The fuel cell RCV maintains the batteries within a healthy state of charge and battery replacements were therefore not considered.

f. Infrastructure

Costs of infrastructure for both battery charging and hydrogen fuel depend on a number of factors including size of the fleet, required charging power level, condition of the electric grid, available space at the deport for chargers, cost of civil works, and more. It is generally observed that the cost of infrastructure to charge one heavy duty battery vehicle is low compared to the cost of setting-up the fuelling infrastructure for one heavy duty fuel cell vehicle. However, the situation flips as the size of the fleet increases. Studies in California, where large fleets of zero emission buses are planned, are finding that the cost of infrastructure for electric vehicles can be 2.5 times higher than the cost of hydrogen infrastructure.

For this study of a fleet of 30 RCVs, the cost of the charger including installation was set to £57,000 ($75,000) and it was assumed that one charger would service two RCVs. Additionally, a one-time cost of £760,000 ($1,000,000) was applied to the TCO to account for site and grid upgrades, although it is thought that this cost could in fact be 2 to 3 times higher[9] on average for charging of heavy duty battery vehicles.

Different options exist for consumers of hydrogen. In some cases the fleet owner may choose to own their own hydrogen generation, storage and dispensing equipment, or just the storage and dispensers. Alternatively, the fleet owner can contract with a third-party to install and maintain the hydrogen fuelling station at the fleet depot (or other convenient location, for example a transfer station). Our TCO assumes this last model where the cost of hydrogen fuel includes all infrastructure costs. Therefore, no additional costs for hydrogen infrastructure are assigned to the fuel cell RCV fleet.[1]

(1) GBP values have been converted to USD

g. Labour

The number of RCVs in the fleet as well as the maintenance and charging or fuelling requirements will influence the workforce demands. We did not estimate or account for labour costs associated with extra vehicles, higher or lower maintenance intensity, costs of establishing new depots to enable fleets of battery RCVs, or costs associated with opportunity charging.

Note that a full service zero emission RCV meeting the range, payload, and maintenance requirements will not require additional labour over the incumbent diesel fleets.

These TCO inputs are summarized in Table 5.

Table 5: TCO Inputs

Diesel RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	179,360	179,360
Energy/Fuel Cost, £/kWh	0.099	0.111
Maintenance Cost, £/h	3.80	3.80
Payload Capability, kg	10,000	10,000
Required number of RCV	30	30
Energy consumption rate, kWh/h	68.72	79.68
Battery RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	192,041	237,641
Energy/Fuel Cost, £/kWh	0.114	0.114
Maintenance Cost, £/h	2.85	3.80
Battery Lifetime, years	4	8
Payload Capability, kg	9211	9211
Required number of RCV	33	33
Energy consumption rate, kWh/h	20.1	23.1
Fuel Cell RCV Costs	**low**	**high**
Duty Cycle Duration, h	8	12
RCV Cost, £/RCV	177,518	295,678
Energy/Fuel Cost, £/kWh	0.091	0.183
Maintenance Cost, £/h	3.42	5.70
Payload Capability, kg	9570	9823
Required number of RCV	30	31
Energy consumption rate, kWh/h	46.5	53.6

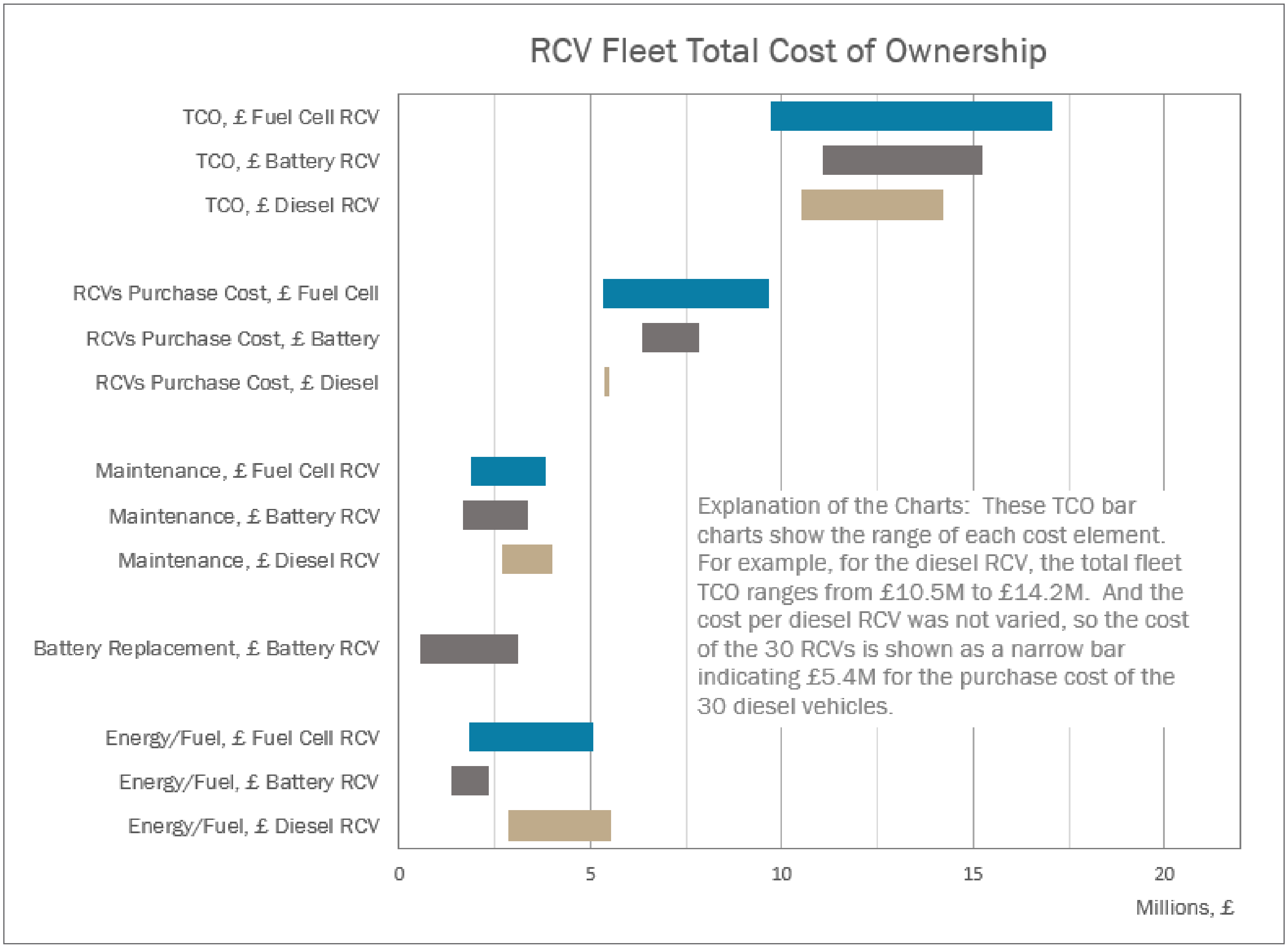


Figure 5: TCO Results (Million £)

These results indicate that the fuel cell RCV fleet has the widest range in estimated costs. This is because fuel cell RCVs are at a lower state of commercialisation with higher uncertainty in the costs, but with a projected steep decrease in costs of the vehicles and hydrogen fuel[10]. Importantly, the TCO also indicates that the fuel cell RCV fleet can be lower cost than current diesel RCV fleets.

While the estimated cost of battery RCV fleets has higher certainty and therefore a tighter range, the pure battery RCV has limited performance and operational capabilities compared to the diesel and fuel cell RCV. Furthermore, there could be large unaccounted-for costs associated with opportunity charging, grid upgrades, and labour associated with additional RCVs if longer duty cycles are desired.

8. Infrastructure

a. Hydrogen Refuelling

Hydrogen infrastructure has an initial CAPEX cost and as a rule this means that it is not cost-effective to install for one or two vehicles. However, a fleet of 20 RCVs configured with 30kg tanks and each consuming an average of 25kg per day requires 500kg per day of hydrogen and at that scale a dedicated refuelling station is viable. Hydrogen infrastructure has the benefit that it scales well – increasing the capacity of the station to larger fleets is easy and cost-effective and reduces the final fuel cost.[11] Hydrogen stations can simply and cost-effectively increase capacity from 10 to 100 or more vehicles by upgrading the compression and storage equipment and adding dispensers.

Sharing refuelling with other vehicles and fleets can also contribute to station utilisation and reduce costs by amortizing station costs over a higher through-put of fuel. Local authorities often have mixed fleets and adoption of hydrogen for RCVs can provide a baseload of demand to enable conversion of other vehicles to zero emissions. Location of refuelling at depots on industrial estates can open up a wide potential group of other users in logistics or public services to share the costs of infrastructure and reduce hydrogen price at the pump. We recommend local authorities consider leveraging the scaling benefits of hydrogen infrastructure by locating fuelling assets at depots, transfer stations or other strategic locations where multiple fleets of hydrogen vehicles routinely converge.

Like many heavy duty fleet-based applications, hydrogen refuelling brings benefits to waste management operators including centralized fuelling stations, compact station footprint, fast refuelling, reduced capital investment, avoidance of costly and disruptive infrastructure construction typical of battery chargers, flexibility in hydrogen-sourcing, minimized load on the electric grid, avoidance of operational and workforce disruptions, and opportunity for low and zero carbon well-to-wheels operation. In many cases, fleet depots can install hydrogen refuelling infrastructure with a similar footprint to CNG refuelling. Different flexible and scalable options, from gas or liquid delivery, to on-site production are available to meet specific site and operator requirements. A 2019 study by the Brussels-based Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) illustrates several of these benefits in a comparison of charging battery trucks versus fuelling hydrogen trucks, Figure 6.

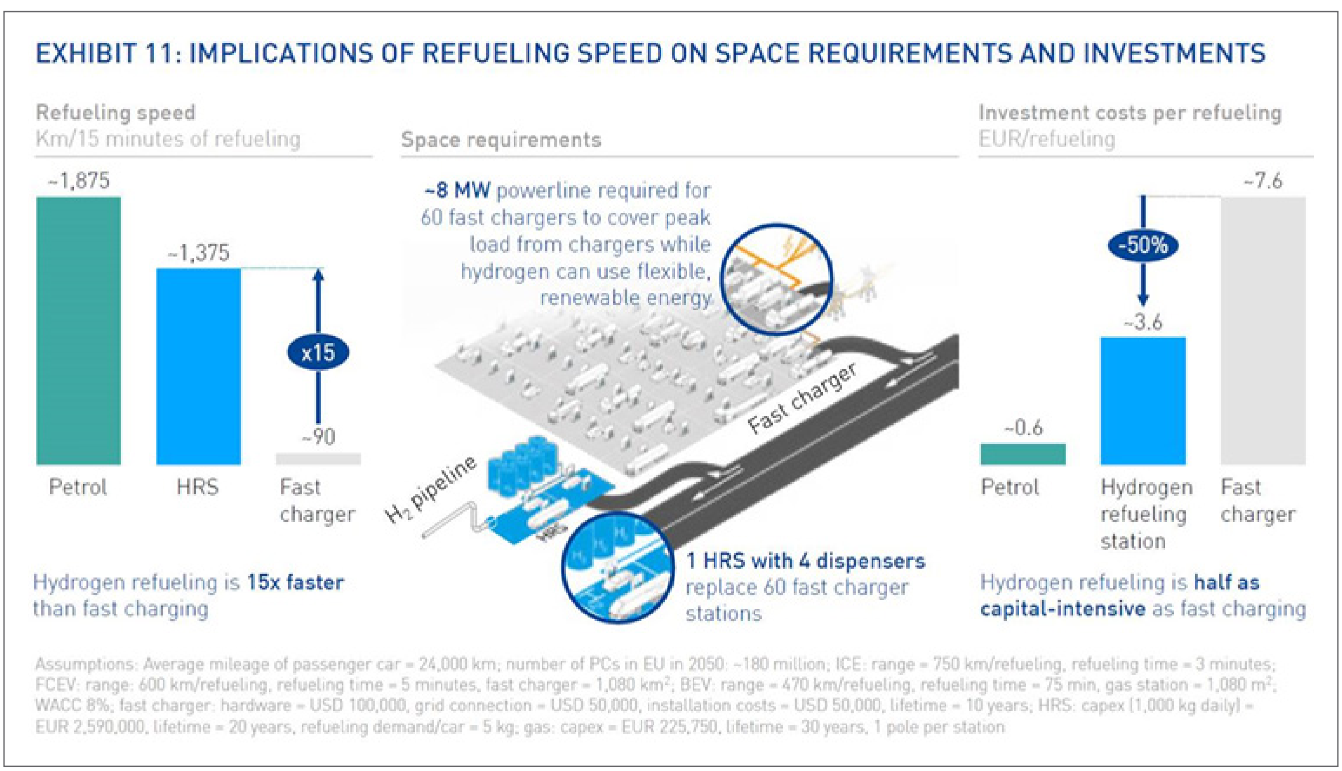


Figure 6: Comparison of hydrogen fuelling versus battery charging. [Hydrogen Roadmap Europe, FCH-JU, 2019][12]

In compliance with state law, transit agencies in California are completing implementation studies for 100% zero emission bus fleets. Many of these studies conclude that implementing fuel cell buses with hydrogen fuelling can be a lower cost solution compared to pure battery buses. These cost and operational benefits are expected to translate to other heavy-duty fleet-based applications, including refuse collection. With hydrogen and fuel cell costs forecast[13] to continue decreasing, we advise waste management companies to evaluate hydrogen and fuel cells in their zero emission plans.

When sourcing hydrogen fuel, fleet operators can put out a tender for companies to supply the hydrogen and even operate and maintain the hydrogen station. There are a variety of companies that will compete for the opportunity, which keeps the price of the fuel down. The price of fuel is fixed over a period of time, and the fleet operator pays in pounds or dollars per kilogram. This fuelling model enables the local authority or waste management company to accurately forecast their fuel budget and frees them up from the burden of managing a fuel station so they can focus on refuse collection.

The estimated cost of the hydrogen station and dispensing equipment (including capital, property, energy, and operational costs) for a fleet of 30 RCVs is between £1.16/kg to £2.82/kg ($1.53 to $3.71/kg) depending on factors including the state of commercial maturity, method of hydrogen delivery, station configuration, fuelling rates, and RCV fuelling schedule (costs are estimated for a USA case in 2016 dollars using Argonne National Laboratory's Heavy Duty Refuelling Station Analysis Model (HDRSAM), Version 1.0)[14]. Depending on ownership of the refuelling station, margin might also be applied to these costs. The full cost of hydrogen fuel is estimated by adding these station costs to the production cost of hydrogen, which can be produced today for between £0.53/kg to £5.85/kg[15] ($0.70/kg to $7.70/kg) depending on the production method and region. For this application, we anticipate the all-in cost of hydrogen, not including margin (if applicable), is between £1.69/kg and £8.67/kg ($2.23/kg to $11.41/kg).[(1)]

b. Depot Parking

Today, a typical RCV depot holds many vehicles generally parked very close together due to limited space.

A challenge fleet operators will face with a battery electric vehicle fleet is that these battery RCVs require expanded physical depot space for charging infrastructure. The space needs to be available for at least four-to-six hours for these vehicles to fully charge their batteries. This additional space requirement can lead to the need for costly construction of new depots.

In comparison, fuel cell electric vehicles are quickly refuelled at a central station in the same way as diesel RCVs. They don't require the charging infrastructure that takes up that extra space, enabling the fuel cell RCVs to be tightly parked in the same space as diesel vehicles.

c. Maintenance Facilities

To create a safe environment for hydrogen fuel cell electric vehicles, existing workshop buildings will have to be adapted and upgraded. Workshop upgrades are designed to detect a potential hazard, dilute the gas to reduce ignition risk, and then extract the gas for safe re-entry. Although maintaining fuel cell RCVs is not widespread, there is a lot of experience of maintaining hydrogen fuel cell electric buses (FCEV). FCEVs have been in revenue service since the early 2000's and during that time many lessons have been learnt on the maintenance area of fuel cell heavy duty vehicles generally. Anyone that has had experience of CNG fuelled vehicles will be accustomed to the types of adaptions that are required.

A Ballard white paper titled "Adapting Bus Depot Facilities for the Maintenance of Hydrogen Fuel Cell Electric Buses," reviews best practices in hydrogen bus maintenance facilities for fleet operators. It includes safety and infrastructure factors to consider when transitioning to servicing and maintaining fuel cell electric buses. Many of these considerations are equally applicable to the maintenance of fuel cell RCVs.

(1) GBP values have been converted to USD

10. State of the Industry

The development of fuel cell solutions for heavy duty applications has been underway at Ballard Power Systems for more than 40 years. The first demonstration of a transit bus by Ballard in 1993 was a milestone that led to follow-on public demonstrations of buses from the wintry environments of Oslo and Whistler to the hot, dry conditions of Palm Desert. There are now approximately 7,500 fuel cell buses and trucks deployed globally from China to Europe and North America logging millions of kilometers in revenue service. Recognizing the advantages of fuel cells and hydrogen, and witnessing the decline in bus pricing and operational costs, transit companies and fleet operators, alongside local authorities are now scaling their fleets. Approximately 40,000 fuel cell buses and trucks are expected to be deployed globally by 2025[16] with both traditional and new start-up companies developing solutions to meet this rising demand. For the transit bus application, the market is on the threshold of large scale commercialisation.

Transit is the first heavy duty fuel cell application to be commercialised and this will be followed by other fleet-based applications, including refuse collection, where heavy payload, high utilisation, and long duration and affordable operation are required. Demonstrations of fuel cell RCVs are already underway in Europe[17]. In Korea[18], a 5-tonne fuel cell powered refuse truck was introduced in 2021. We anticipate waste management companies and local authorities will recognize the benefits of fuel cells and hydrogen and launch the first deployments of fuel cell RCVs. However, in contrast to the many years of bus commercialisation, the learnings from transit can be applied to refuse collection to allay the unknowns and reduce the risks, thereby enabling a faster scale-up and aggressive response to environmental, health, and climate damage. We expect the first fleet deployment of Arcola RCVs in 2022.

11. Conclusions

Providing true zero-emissions and noise reduction are some of the benefits of fuel cell technologies, benefits that are vital when operating refuse collection vehicles in densely populated urban areas with strict emissions regulations. Refuse trucks are a particularly attractive first application for the commercialisation of heavy-duty fuel cell-based trucks for a number of performance and economic reasons.

For this paper, refuse collection vehicles operating on distinctly different duty cycles was collected, analyzed, and models of fuel cell RCVs operating over these same routes simulated, demonstrating that fuel cell technology is highly capable of meeting refuse collection requirements at costs which can be competitive and eventually lower than current diesel RCVs.

The flexibility of fuel cell RCVs to complete short and long duration arc and node duty cycles coupled with the capability to operate multiple consecutive shifts per day presents opportunities for waste management companies to complete the workload with fewer vehicles and a consistent mix of trucks, while avoiding operational and workforce disruptions, thereby reducing the total cost of operations. Additionally, with long life and the possibility for affordable mid-life rebuild, the fuel cell RCV offers managers and local authorities the opportunity to affordably extend the life of the RCV, contributing to reduced life cycle costs.

Opportunities for centralized hydrogen fuelling of fuel cell RCVs with other fleets of transit buses, municipal vehicles, and trucks should be investigated, as this shared infrastructure can reduce the costs of hydrogen and support wider and more rapid adoption of zero emission fuel cell solutions.

Fuel cell powered RVCs will be lower cost to own and operate than diesel or CNG vehicles by the end of the decade.

The zero emission fuel cell solution for refuse collection is ready now. The technology is mature, sustainable, and affordable, as the time is right to deploy fuel cell refuse collection vehicles.

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Arcola Energy is a leader in hydrogen and fuel cell integration, specialising in zero-emission solutions for heavy-duty vehicles and transport applications. As a systems engineering specialist and Tier 1 integrator, Arcola addresses the deployment gap between rapidly evolving low-carbon technologies and efficient real-world applications by developing market-ready solutions, reducing development cost and time to market.

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