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With so many battery electric buses in operation, why are fuel cell electric buses more relevant than ever?

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Executive Summary

The bus industry has been a frontrunner in the adoption of zero emission vehicles and their operation. In 2022, zero-emission buses accounted for approximately 12.7%[1] of new bus registrations in the European Union, with the uptake growing year on year. Fuel Cell Electric buses (FCEB) and Battery Electric buses (BEB) are complementary zero-emission technologies, and while both offer advantages for fleet operators, there are significant differences that can impact the choice of vehicle:

- BEBs often require changes to bus depot activities to accommodate charging time and infrastructure, which can result in schedule changes and reduced asset utilisation for the operator. To gain – or improve - the range of a BEB, opportunity charging along longer routes may be required, which can impact scheduling of buses further.
- With their longer range and fast refuelling time, FCEBs can be a 'drop in' replacement for a diesel bus and does not suffer from the infrastructure and range issues that affect the service and depot operation of BEBs.

When transitioning to zero-emission buses, it is important for the operator to choose the correct technology for the specific route characteristics to ensure that the core purpose of the bus - to move passengers safely and on time - is completed without compromise.

Introduction

The bus industry is leading the way in decarbonising heavy-duty vehicles and Europe has been a leader in the implementation of zero-emission buses. Over the last 20 years, trials have taken place with zero-emission buses, both battery electric buses (BEBs) and fuel cell electric buses (FCEBs). Thanks to these trials and

[1] https://www.acea.auto/fuel-cv/fuel-types-of-new-buses-electric-12-7-diesel-67-3-market-share-full-year-2022/

demonstrations, the introduction of zero emission buses is becoming an increasingly frequent and important part of the transport network in European towns and cities. Now zero-emission buses are proven as a critical contributor to meet net zero targets, many cities are insisting that only zero emission buses are purchased. The European Commission has proposed that all new city buses should be zero emission from 2030.[2]

There are currently two core zero emission technologies available for buses: battery or fuel cell electric. It is often stated that combustion engine (ICE) solutions using either hydrogen or biogas as a fuel, can be made to be a zero-emission option. However, these are not considered in this paper as ICE will always emit some NOx due to combustion being involved.

Both battery and fuel cell technologies have their merits, and each has their disadvantages. Currently, the more mature BEB technology is often the choice of bus operators and authorities over the newer FCEB solution; this paper sets out why – now more than ever - FCEBs should be considered an equal alternative for a zero-emission solution.

Difference and similarities between BEBs and FCEBs.

The driveline, of a hybrid architecture, is very similar between BEBs and FCEBs. Both BEBs and FCEBs are electrically propelled buses; the main difference is that BEBs need to be charged by an external source while FCEBs generate electricity on board, via a fuel cell, using hydrogen as the fuel. This means the energy storage system (ESS), normally a battery, is much smaller in a hydrogen FCEB, approximately a tenth of the size with a corresponding weight saving.

Battery Electric Bus Architecture

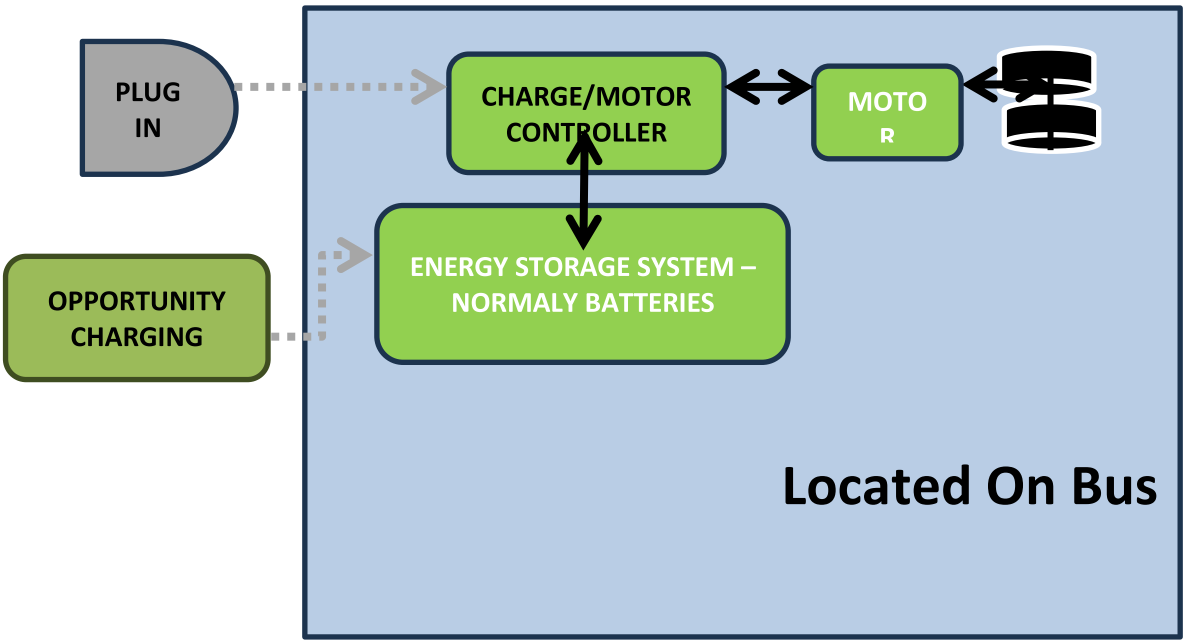

Figure 1 – Battery electric bus architecture

[2] https://www.sustainable-bus.com/news/eu-commission-proposal-zero-emission-buses-2030/

Fuel Cell Electric Bus Architecture

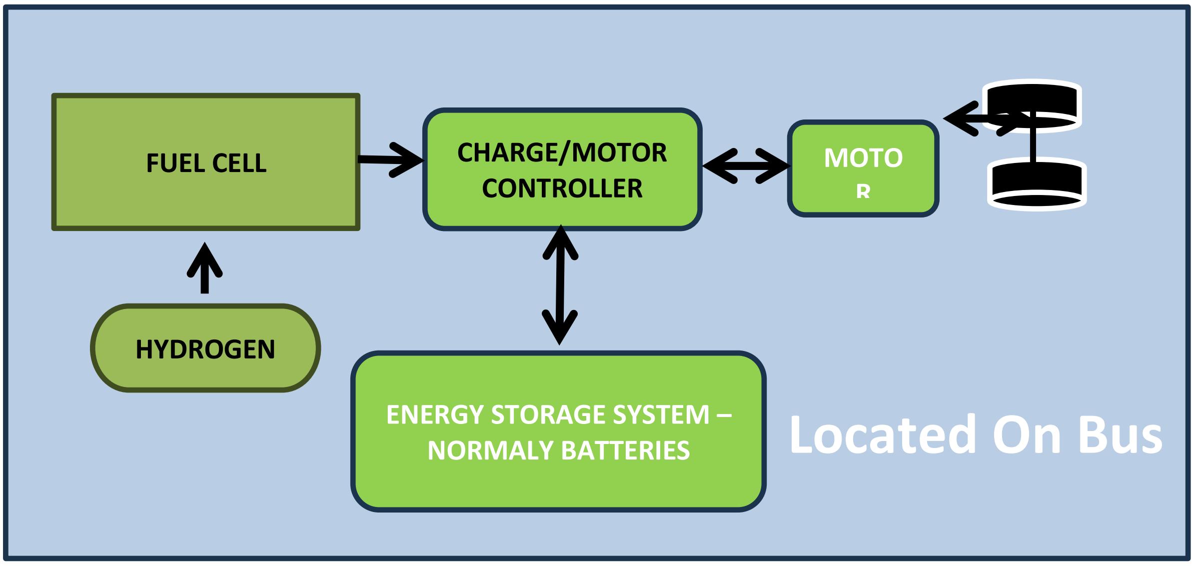

Figure 2 - Similarities of BEB and FCEB architecture

As both BEB and FCEB architectures use an electric driveline, both can be defined as an *electric bus*. Both have a series hybrid architecture, consisting of an energy source, energy storage system (ESS), control electronics, and an electric motor that drives the wheels. The motor can be a single motor that connects to the axle or hub motors. When the bus slows, the motor acts as a generator, producing electricity which is stored in the ESS. This energy can now be used in addition to the primary fuel source - saving hydrogen in the case of a FCEB, or power in a BEB. This energy storage and usage is what makes the vehicle a hybrid architecture.

As the drivelines of both BEBs and FCEBs are very similar, what is the difference between the two technologies and why choose one over the other?

Advantages and disadvantages of zero emission bus technologies

Recognising there are certain advantages and disadvantages of both technologies, a comparison between BEBs and FCEBs is outlined in Table 1:

Battery Electric Buses	Fuel Cell Electric Buses
Eco-friendly	Eco-friendly
Robust design	Robust design
350 km range	up to 550 km range
4-6 hour overnight charge	6-12 minutes fill time
Range decreases over life of the batteries	Range consistent over the life of the batteries & fuel cell
Range decreases in extreme weather	Range consistent every time of day and in every season
One charger per 2-3 buses	Fill station scalable by fleet size
Diesel auxiliary heater recommended for cold climates to maintain range	No secondary auxiliary heater required, fuel cell provides cabin heat

Table 1 – Similatities and differences between BEB and FCEB.

However, Table 1 only offers part of the picture and there are further considerations when adopting zero-emission buses into a fleet.

Range
Normally a BEB carries around 350 – 400kWh of batteries on board that can give a range of over 350km, this would be about 1.25km/kWh. Note that not all the kWh on a bus is useable, so a bus with 350kWh would only use around 80% of that power.

Consistency in range
One of the major disadvantages experienced with BEBs is the inconsistency of range over different temperature conditions. It has been found that the range can severely decrease during temperature below 0^{o} Celsius (C) and very hot conditions can also be challenging. This can have a serious effect on the scheduled duty of the bus and may require the bus to be swapped mid schedule. It has been seen that on cold winter days that a 12m BEB can require as much as 2.2kWh/km, drastically dropping the range to around 150km.[3]

Refuelling / Charging time
A FCEB can refuel in a matter of minutes - longer than a diesel bus - but in minutes. Therefore, the depot process for refuelling is the same as a diesel depot. The bus operates all day, returns, refuels, is washed and parked ready for service the next day.

A BEB requires charging, so the first challenge is getting sufficient power to the depot. If there are 50 buses that each require 200kWh, it means that 10MWh is required, assuming all buses are charged at the same time. If chargers are 100kW, all buses would have to be charged for two hours each. Smart charging can be employed in scenarios where the buses only charge according to their need, reducing the required amount of power at the depot. However, if the operator has an 8-hour charging window, the requirement would be to have at least 2.5MW of power available for this period, but in total 10kWh will still be required to fully charge all the buses.

[3] https://www.sustainable-bus.com/news/electric-bus-range-electricity-consumption/

The ultimate power requirement does not change even if you have fast charging. For example, if the same depot has 300kW fast charging capability per bus, you may be able to charge a bus in less than an hour but the overall power requirement at the depot does not change. Moreover, fast charging ability does depend on the chemistry of the batteries. Just having a charger capable of delivering high power does not mean the vehicle be charged at that rate.

When connecting BEBs to charging stations, this is an extra activity that need to take place. Plus, there is a space requirement for the charging infrastructure that may take valuable parking area from the buses. Within the depot there may also have to be a “first-in-first-out” parking regime that can seriously restrict the available movement within the depot.

Opportunity Charging

Often seen as a solution for shorter routes, opportunity charging is viewed as a way of extending the range of a BEB. Opportunity charging is normally a high-power fast charge to give the ESS energy to enable the bus to complete the route. The power has to be available on the street via a pantograph. This can work very effectively for shorter and less demanding routes. However, permissions are need for the charger to be positioned in the street and, alongside the pantograph, there is also some form of power unit required to sit alongside.

Charging time has to be scheduled into the operation of the bus. If there is a delay on the route, the bus still has to be charged, so an early morning delay can have a knock-on effect on the full day’s schedule. Delays can also incur if the charger is not readily available when the bus arrives, for example when the charger is shared between more than one route.
The maintenance of the pantograph also needs to be factored in. If the pantograph is out of service for maintenance, the route cannot work.

Figure 3 – Pantograph opportunity charging and infrastructure.

Efficiency

It is often stated that battery electric vehicles (BEV) should be chosen over fuel cell electric vehicle (FCEV) as the driveline and charging of a BEB is more efficient than a FCEB. At a simple, superficial, glance this seems to be the case, however deeper analysis shows this is not necessarily correct.

A bus operation is complex, and it must always be remembered that the job of a bus is to move people. The driveline is important in emission terms but not in the fundamentals of moving people, so when talking about efficiency we must also account for the efficiency of operation.

Energy Carrier

The difference between hydrogen and electricity from the grid is that hydrogen is an energy carrier. Hydrogen can store energy, move that energy and convert it back to electricity. The charging of electric vehicles directly from the grid does not take account of any energy storage, so to make a comparison, energy storage has to be added to the equation. When you fill a bus with hydrogen some energy storage has already taken place, this is not calculated in the simple BEB efficiency.

Electricity Generation

Today zero emission electricity is produced by three methods:

1. Solar
2. Wind
3. Nuclear

Solar is now widely used for zero emission generation of electricity, but power can only be generated in daylight. Solar can be brought online and taken offline when required.

Wind is also a growing source of zero-emission power. Again, wind cannot be guaranteed 100% of the time, but use of turbines can be brought online and taken offline when appropriate for peak power.
This disadvantage of solar and wind is that the capability may be there to generate, but if the power is not required on the grid, the asset is not used. Often there are tariffs for when the facility is not producing power. For both solar and wind, hydrogen offers an opportunity to utilise the asset when the electricity is not required on the grid. Using electricity and water as inputs, an electrolyser breaks the water in to its constituent parts, hydrogen and oxygen. The complete chemical process of a fuel cell is:

$$2H_2O \rightarrow H_2 + {}^{1}/_{2}\,O_2$$

Utilising power generation assets when they are not required for the grid, hydrogen can be produced and used in several applications, including transport.

There is an argument that nuclear should not be included in the net zero debate due to safety concerns and long-term storage of spent nuclear materials, but it is true to say that it is carbon neutral. The advantage of nuclear is that it produces a stable amount of electricity consistently, but it is hard to vary the amount produced quickly. Therefore, nuclear is used for base load within a grid system and not for peak power.

Today, there are still limited sources of ‘green’ electricity. Most power taken from the grid is a mix of fossil fuel and renewable electricity. Hydrogen, when using an electrolyser, is renewable as the power can be taken directly from the renewable source, stored and used when needed.

Most renewable electricity is either solar or wind. Most BEB charging takes place overnight, when solar is not available, and if there is a lack of wind then fossil back up is required. Well to wheel, the zero-emission calculation is not straight forward if BEBs are getting renewable electricity. When looking at a zero-emission energy source, there has to be a storage solution in the network, hence adding inefficiency in the source to wheel.

Hydrogen, produced using an electrolyser, can be undertaken in periods when there is an excess of wind or solar meaning that the renewable source can be utilised 100% of the time - not just when there is a grid power requirement. An asset, such as a wind turbine, not being used is not efficient (it is often the case that subsidies are paid to stop the production of renewable if not required at a certain time). Therefore, the efficiency question is not just restricted to the fuelling and the driveline of the vehicle, if extended to the source of renewable energy and power, the picture is far less clear.

Choosing the correct zero emission buses

Although the uptake of zero-emission buses is good, there is still a long journey before the city bus network is fully zero emission. In the transition to zero emission, most uptake so far has opted for BEBs, but these buses have often been put on router that are simpler to electrify. Recently there have been larger BEB bus deployments, but in many cases just adding more BEBs to a fleet is not as simple as it seems on paper. It is imperative that when choosing a zero-emission bus, the correct choice is made as the assets will be in service for 10 to 15 years. Below are some items that must be debated, when making the zero-emission choice.

Power Requirements

The power requirement for a large fleet of BEBs is great. For charging at 100kW for 100 BEBs, the peak requirement for power would be 10MW. While smart charging techniques can reduce this requirement, as a 350kWh bus would need about 3 hours charging per night and the charging window could be greater than that.

Some depots do not have access to such high-power connections, and it is possible that an extensive power infrastructure will be required to connect to an electricity grid network. This can be costly and also involve difficult land access discussions.

Hydrogen fuelling is analogous to diesel fuelling, and if a delivered option is used, there are few power requirements required. If an electrolyser is deployed onsite, more power will be required.

Connection issues

All BEBs in the depot are required to be connected to a charger, if this is a plug in connect via a cable from a charger, a robust process must be in place to ensure that the buses are connected. With many cables trailing in the depot, there is a high chance of trips for personnel and potential damage to the cables. Some depots have avoided a physical connection by installing a pantograph system. This is a costly infrastructure.

For a FCEB, the depot process is the same as a diesel: the bus finishes the route, is fuelled cleaned then parked and ready to go in to service the next day.

Reduction in parking space

Charging infrastructure takes up space, so there is a reduction in parking space available for the buses. This can become a major issue in cities where land costs and space are at a premium.

A FCEB does not need any overnight charging infrastructure so the there is no reduction in parking space.

First in, first out

After a bus has been in service and returns to depot, the process for a diesel bus is normally that the bus is fuelled, washed, and then parked ready for service in the morning. Buses can 'run in' during the evening, but for buses servicing an inner-city route, this can be the early hours of the morning. When taking an inner-city route in to account, buses depart the depot on the 'run out' from as early as 4 or 5 am. For a diesel bus or a FCEB, the short 4-hour window doesn't cause an issue for which bus arrives at the depot last and which bus leaves the depot first. However, with a BEB, charging time can be extended and a first in, first out system may need to be employed. This can be complex in a busy bus depot where space and time are at a premium.

A FCEB is fuelled in minutes, avoiding the first in first out process, making a FCEB a direct replacement for a diesel, as far as the depot operational process is concerned.

Range variation

BEBs are very susceptible to range variation, which can be due to a number of reasons. Weather conditions can cause the range of a BEB to vary during the year. A particularly cold spell can have a detrimental effect on range, as can a period of hot weather. In severe cases, this can cause problems where the BEB may not be able to complete the daily scheduled service.

During the buses' lifetime the state of charge of the battery will reduce, therefore reducing the range that the bus can achieve later in its life.

There is little range variation on a FCEB over the different seasons so there is no concern on the range changing during the year.

Opportunity charging

Opportunity charging is often thought as a solution to range issues; however, this is not a panacea to solve the problem.

Opportunity charging is normally performed using some form of fast charging via a pantograph. This is often located at the end of a route at the bus terminus. There are many issues in installing this infrastructure in the street. Positioning of the charger will have to be suitable, and the correct power will need to be connected to the pantograph; again, this could cause issues in gaining access to the grid.

Maintenance of the charger must be considered. If the charger is not operating, it could have serious consequences for the ability to operate the whole route. Who is responsible for this maintenance, who owns the charger, what happens when routine maintenance is being undertaken are questions that need to be considered. But there are also unforeseen issues that could occur with opportunity charging pantographs, these could include:

- The infrastructure is accessible to the public and could be subject to graffiti and vandalism.
- Noise issues can cause a problem if the charger is in a pedestrian or residential area, often there are cooling fans associated with the pantograph chargers.
- Many buses will stop at the same point, so it also must be ensured that the road is maintained and does not sink.

If a certain route requires opportunity charging, it can restrict the flexibility of buses in the depot and may require BEBs to be 'route tied'.

In contrast, it is possible for a FCEB to carry enough hydrogen to complete a whole day's duty on a city bus using hydrogen.

Schedule Changes

Changes to schedules may have to be introduced to make sure that the BEB is able to operate the route to the required level. To ensure that the charging takes place, well established depot processes may have to be adjusted and could take time to adjust to.

No schedule changes are required for a FCEB, it is a drop-in replacement for a diesel.

Charging standards
There are currently few standards around BEV charging protocols. As standards progress and are adopted, it may render existing infrastructures redundant for new BEVs, including BEBs. As BEB technology progresses, there may be large infrastructure improvements required for the ability to fast charge.

Hydrogen fuelling compounds are easy to upgrade if necessary, there is less risk of obsolescence.

Fuel Cell Electric Buses – the Hidden Benefits
Alongside the items outlined in Table 1, the 'hidden' benefits of FCEBs should not be forgotten. The depot process does not have to change, the bus goes out in service, returns to the depot, fuels within minutes, is cleaned and parked ready for service the next day. The issues highlighted above for the operation of BEBs do not occur for FCEBs - indeed a FCEB can be considered a 'drop in' replacement for a diesel bus. The time to fuel a hydrogen FCEB is measured in minutes, so equivalent to a diesel vehicle. No first in, first out protocol needs to be adopted and no overnight parking protocol needs to be changed in the bus depot compared to a diesel bus.

Hydrogen fuelling
As stated above the time to fuel a hydrogen FCEB is minutes, not hours as required by a BEB charging. The fuelling of a FCEB is slightly longer than a diesel bus, but not enough to make a difference in depot processes. The hydrogen fuelling infrastructure can be installed and is easily expandable to the fleet size that is required. Space required for the fuelling is not much larger than traditional diesel fuelling.
Hydrogen can be made onsite using an electrolyser, or delivered into the depot in the same way as diesel. The hydrogen is dispensed in minutes enabling the bus to be ready for the next day's service in a similar amount of time as a diesel. This could be important if there is little time from when the bus runs in at night and then departs in the morning. Twenty-four-hour routes would mean that extra BEBs are required to keep the service operating, this is not the case with a FCEB.

Flexibility
As there are no restrictions on the fuelling of the bus, it can be used on any route and is not route tied in the way that a BEB could be. It might be that the flexibility of being able to use any bus on any route could be a big advantage. There is no restriction on where a bus is parked overnight in the depot, no first in, first out situation arises.

Conclusion
Both BEBs and FCEBs will play a part in the future of zero-emission travel, however one technology does not fit all situations. When choosing the zero-emission technology, it is important to ensure all the options are explored, and all scenarios are looked at. What appears, at first look, to be the route to take may not be the same when you project 5, 10, 15 years into the future. Key factors to consider is the range required, the space available in the depot, the flexibility needed for the fleet; and the weather the buses will be operating in.

Critical investment can be wasted by choosing the wrong zero-emission option and subsequently trying to adjust this to work in an incorrect operating environment.

It is vital for the growth in the uptake of zero-emission buses over the rest of the decade, that the correct technology is chosen for the route characteristics, the depot and schedule, so the adoption of BEBs and/or FCEBs does not compromise the movement of passengers compared to diesel buses.

There are a several examples were FCEB are a good choice for a zero-emission future, these include:
- Longer routes and high asset utilisation

- Locations with varying temperatures.
- Routes where a fast turnaround is required.
- Where depots do not have access to high grid power.
- Where the depot space is at a premium.

The most important aspect is that Public Transport Authorities and Public Transport Operators consider all zero- emission options, what that will require to operate an efficient city bus in the zero-emission world. Decisions made today will be influencing the operation of the buses for the next decade or more.

Case Study: Aalborg Fuel Cell Electric Buses

Introduction

Aalborg, in the North Denmark Region, operated the first FCEBs in Denmark. The three buses were part of the Clean Hydrogen Partnership (previously the Fuel Cell and Hydrogen Joint Undertaking) "3Emotion" project that demonstrated a total 29 FCEBs in 5 cities across Europe. The buses in Aalborg operated for 2 years (2020 – 2022).

Partners in the project are:

- North Denmark Region (NDR) - decides on the service level and is financing the regional Public Transport in North Denmark.
- Aalborg Municipality (AAK) - decides the service level and is financing local Public Transport in the City of Aalborg.
- Nordjyllands Trafikselskab (NT) - North Denmark Public Transport Authority.
- Arriva, Keolis and Tidebus - operates bus services for NT.

Why Fuel Cell Electric Buses in Aalborg

There were three main reasons for the project and the region to want to trial FCEBs:

- To generate knowledge and experience.
- A project where green hydrogen is produced from surplus wind energy, and so used as an alternative green fuel for buses.
- To strengthen and support innovation and industrial development in North Denmark.
- Promote the green transition.
- Generating the required knowledge for changing heavy duty transport from fossil fuels to green hydrogen solutions.

The Buses

Three Van Hool A330 fuel cell buses were used in the demonstration. The demonstration included:

- Ballard FCvelocity HD85 fuel cell modules.
- 12metre buses with a capacity of 79 people.
- 38kg of hydrogen storage.
- A hydrogen refuelling station
- The hydrogen refuelling station (HRS) was provided by Green Hydrogen Solutions, Denmark. An electrolyser was employed to produce hydrogen on site. Other features of the HRS were:
- Electrolyser produces 90kg / day.
- 350 bar dispensing.
- Optimised to run on electricity from renewable sources.
- Meets fuel cell hydrogen standards.

- Site is scalable.

Results and Lessons learned from the demonstration

The three buses drove nearly 315,000km during the 2-year demonstration in revenue service. Following the demonstration, it was found that:

- The drivers were extremely happy with the buses.
- Passengers were generally happy driving on a fuel cell electric bus.
- Less time was spent on maintenance.
- The availability of the FCEBs was the same as diesel.
- The range of the buses was longer than expected.
- Workshops are easily adapted to undertake the maintenance of FCEBs.
- Permits for the HRS take longer than expected.
- The fuelling process was easy for drivers.

Figure 4 – The Van Hool A330 fuel cell electric bus in operation in Aalborg