1 Stakeholders consulted across the value chain

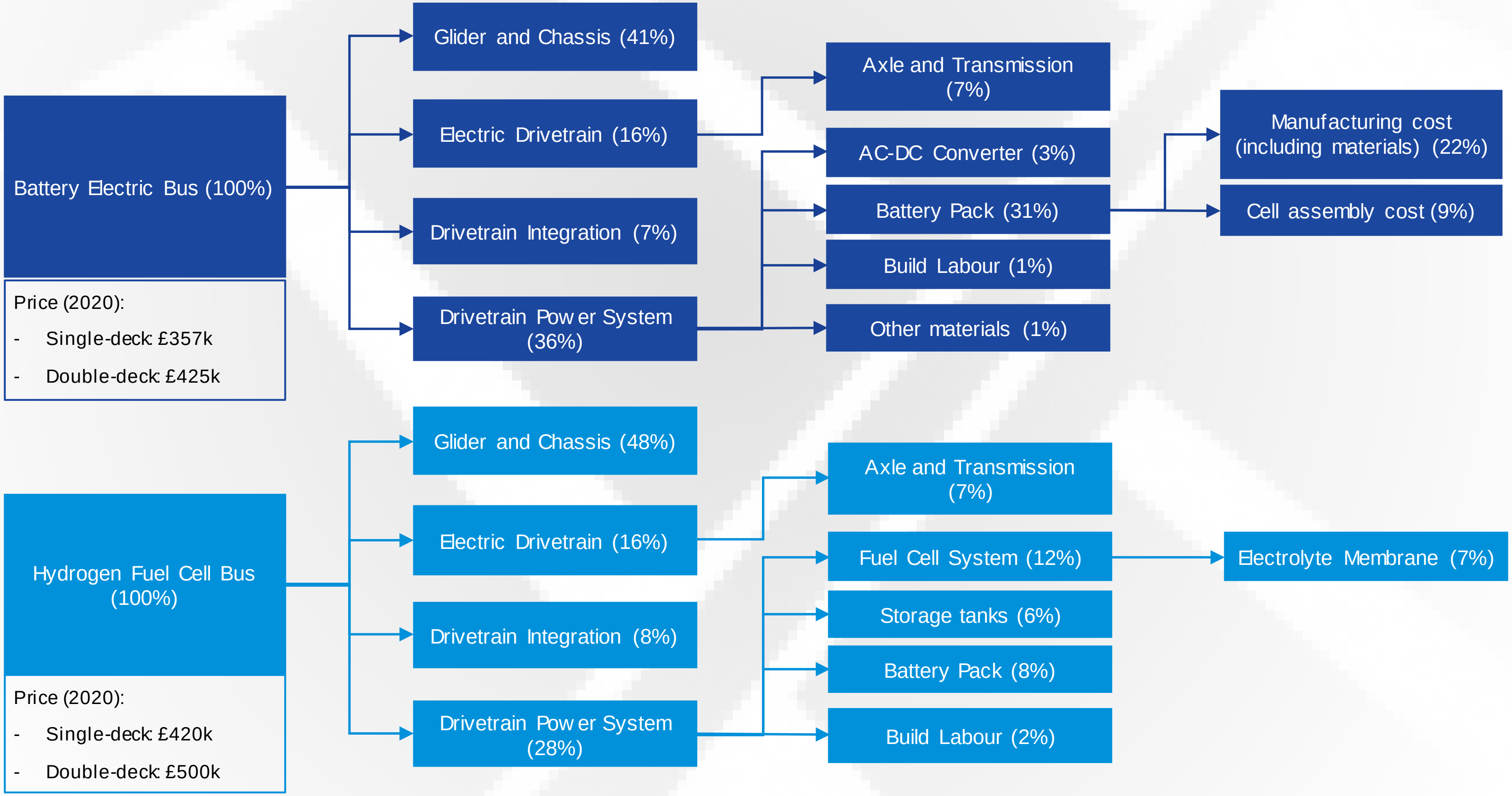
A range of stakeholders across the supply / value chain were consulted and engaged with, in order to ensure an informed and representative view of cost drivers for zero emissions buses, was obtained and presented. The figure below illustrates stakeholders consulted across the industry. It is not intended to be an exhaustive list of all stakeholders in this market but those who participated in the study.

Vehicle (and its constituent parts)		Infrastructure			Others
Vehicle manufacturers and distributors	**Battery and fuel cell manufacturers**	**Battery charging infrastructure and management**	**Hydrogen re-fuelling infrastructure and management**	**Bus operators**	**Industry bodies**
▪ Alexander Dennis ▪ Wrightbus ▪ Pelican Engineering (Yutong)	▪ BritishVolt ▪ Arcola Energy	▪ Zenobe ▪ NEOT Capital ▪ Hitachi	▪ Arcola Energy ▪ Logan Energy	▪ Dundee Express ▪ First Group ▪ Stagecoach ▪ Tower Transit	▪ SMMT

2

Zero Emission Bus Cost Component Breakdown

Based on a combination of desktop research and outputs from stakeholder interviews, a cost breakdown structure (at a component level) is presented below. It is important to note that this structure is not fully exhaustive but captures elements which are deemed to be the most significant cost components associated with zero emission buses and their infrastructure.



- Battery Electric Bus (100%)
  - Glider and Chassis (41%)
  - Electric Drivetrain (16%)
    - Axle and Transmission (7%)
  - Drivetrain Integration (7%)
  - Drivetrain Power System (36%)
    - AC-DC Converter (3%)
    - Battery Pack (31%)
      - Manufacturing cost (including materials) (22%)
      - Cell assembly cost (9%)
    - Build Labour (1%)
    - Other materials (1%)

Price (2020):
- Single-deck: £357k
- Double-deck: £425k

- Hydrogen Fuel Cell Bus (100%)
  - Glider and Chassis (48%)
  - Electric Drivetrain (16%)
    - Axle and Transmission (7%)
  - Drivetrain Integration (8%)
  - Drivetrain Power System (28%)
    - Fuel Cell System (12%)
      - Electrolyte Membrane (7%)
    - Storage tanks (6%)
    - Battery Pack (8%)
    - Build Labour (2%)

Price (2020):
- Single-deck: £420k
- Double-deck: £500k

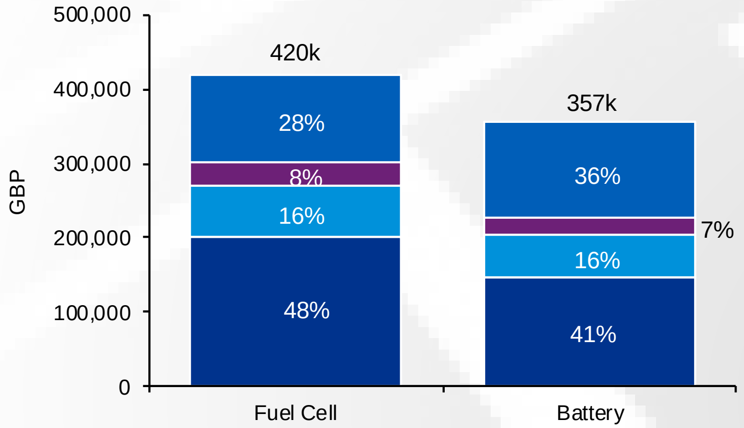
Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. Stakeholder interviews

Note:
All percentages are expressed in terms of the entire cost of the vehicle. Proportions for each cost component have been presented based on sale prices, which are inclusive of the suppliers' profit margin(s) and overheads.

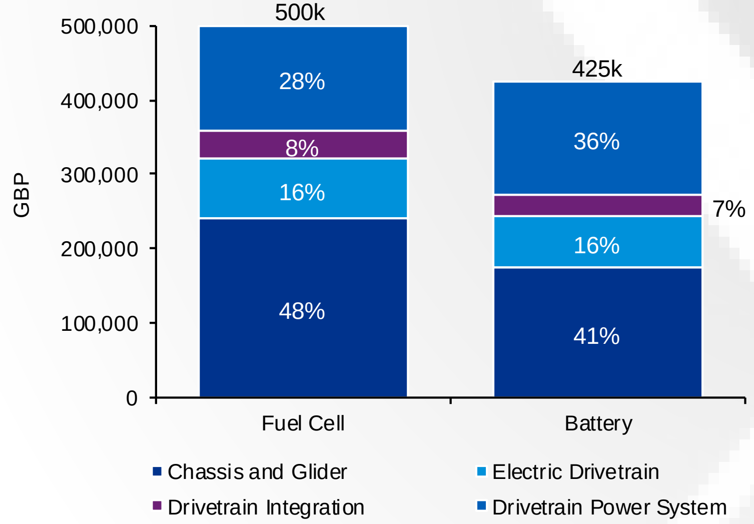
3

Vehicle Cost: Battery Electric vs. Hydrogen Fuel Cell

Single Decker Bus Component Cost comparison



Double Decker Bus Component Cost comparison



Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. Stakeholder interviews

Definition

1. **Chassis** refers to the base frame of the vehicle onto which wheels, the engine and other metal structures are fixed.
2. **Glider** refers to the part of the vehicle in which the weight load (passengers or goods) is situated. In buses, this usually refers to the front end of the vehicle and in trucks it is at the back.
3. **Electric Drivetrain** refers to the part of the vehicle which transfers energy from the power system to the wheels and is operated with electrical energy (e.g. battery or fuel cell).
4. **Drivetrain Power System** refers to the engine which transforms chemical or electrical energy to kinetic energy for the vehicle (e.g. battery or fuel cell system).
5. **Drivetrain integration** refers to the engineering work required to integrate all of the different parts of the vehicles together.

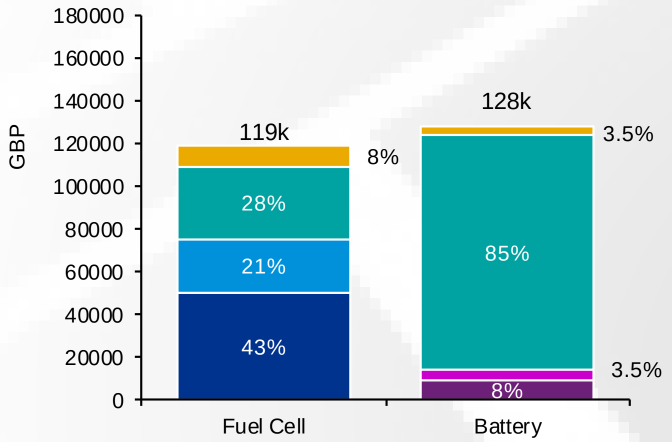
Main observations

- **At a high level, the cost of a zero emission bus can be broken into four major components:** 1) chassis and glider; 2) electric drivetrain; 3) drivetrain power system; and 4) drivetrain integration.
- **Comparing the two types of buses, it is clear that at present a hydrogen fuel cell bus still costs more than a battery electric cell by approximately 20%.** It is noteworthy that this is not a comment on the cost-effectiveness of delivering bus services because this varies based on route requirements and associated operating costs.
- Contrary to a popular misconception, **the cost driver** which makes a fuel cell bus more expensive than its battery counterpart does not lie in the drivetrain power system. **In fact, the smaller battery pack and fuel cell combined in a hydrogen bus is cheaper than the large battery pack in a battery electric bus.**
- **The cost drivers** in a hydrogen fuel cell bus relative to its battery counterpart are:
  - **Electric drivetrain:** More constituent electronic parts are involved in putting together the drivetrain. This leads to an approximately £9k-£10k cost difference.
  - **Drivetrain integration:** The more complex engineering work required leads to an approximately £8k-£10k cost difference.
  - **Chassis and Glider:** More constituent parts involved in building a fuel cell drivetrain means that the glider and chassis have to be designed and made to accommodate these greater engineering complexities. At small scale, these components have to be custom-made which could lead to a cost difference of £55k-£65k.
  - **R&D**: A significant amount of R&D is still taking place to improve fuel cell technology. The costs of these R&D projects have been partially passed on to the buyers (via the supply chain), which contribute to the higher component costs.

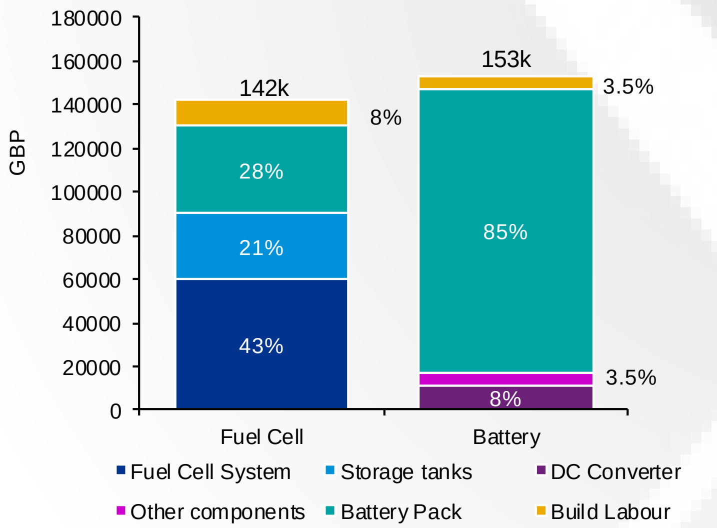
4

Power Systems: Battery vs. Hydrogen Fuel Cell

Single Decker Power Systems Component Cost Comparison



Double Decker Power Systems Component Cost Comparison



Battery Systems

1. The battery pack comprises the majority (approximately 85%) of the cost of a battery system. Of this:
   - 70% of the costs can be attributed to the costs of manufacturing and raw materials; and
   - 30% can be attributed to the costs associated with cell assembly.
2. A large portion of the costs of raw materials is attributed to the prices of precious metals used in making EV batteries, such as manganese, cobalt, nickel, and lithium.
3. Furthermore, this means that the cost of the battery system is contingent to the size of the battery which needs to be increased proportionately to the level of utilisation (e.g. range and power).

Hydrogen Fuel Cell Systems

1. On the other hand, the cost of components in a hydrogen fuel cell system is more evenly distributed among the different components.
2. The three main components which drive cost are the fuel cell unit, storage tanks and the battery pack.
3. Zooming in closer on the fuel cell unit, it is notable that the (platinum) electrolyte membrane is the main cost driver of a fuel cell. The membrane constitutes 60% of a fuel cell unit and is the part which needs to be replaced every 7 to 10 years.
4. The cost of storage tanks, battery pack, other ancillary components, and engineering work required to put the various parts together drive a lot of the fixed costs within a hydrogen fuel cell. This is highlighted by the build labour cost which is almost twice that of a Battery Electric Bus. The higher fixed cost means that cost parity can only be achieved when it is spread over greater level of utilisation (i.e. range and power).

Assumption

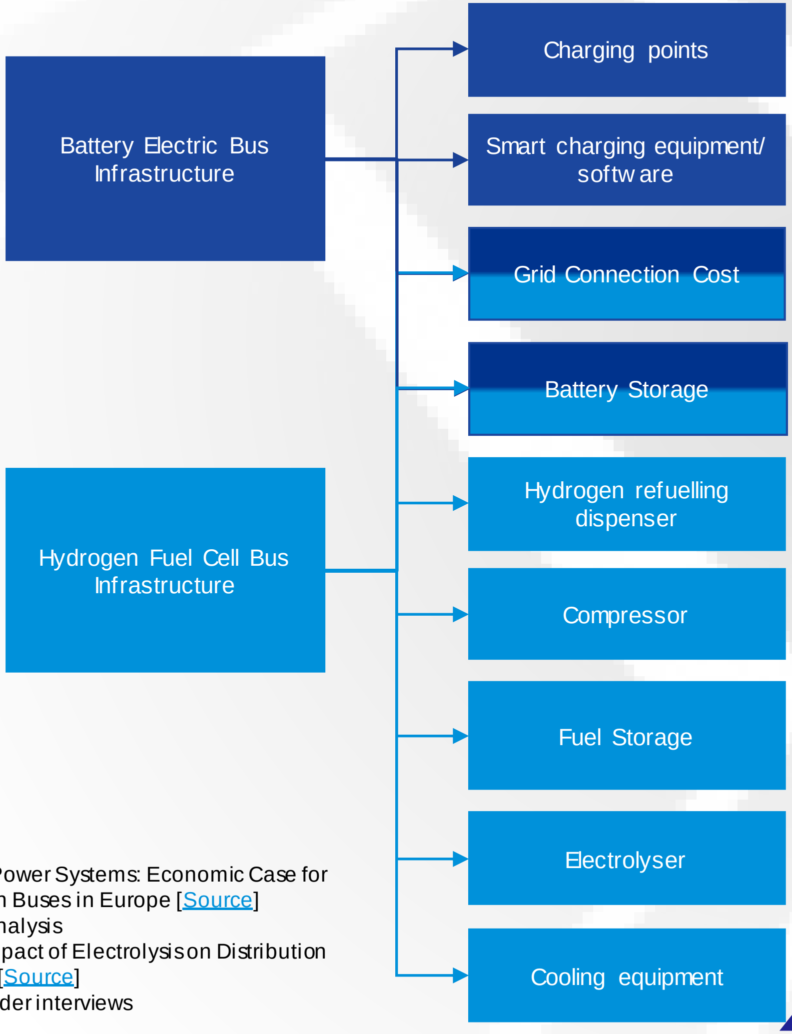
1. In the absence of information to suggest otherwise, it is assumed that the proportional share of costs of the different components is the same for a single and double decker bus.

Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. Stakeholder interviews

5

Zero Emission Bus Infrastructure Cost Breakdown

Costs drivers for infrastructure are largely site-dependent. The majority of the costs may sit in grid connection at one depot but this may not necessarily be the case for all depots. Therefore, as opposed to expressing them as relative percentages, the main factors influencing these cost components are presented below, and further analysed. A more detailed breakdown is presented in the following slides.



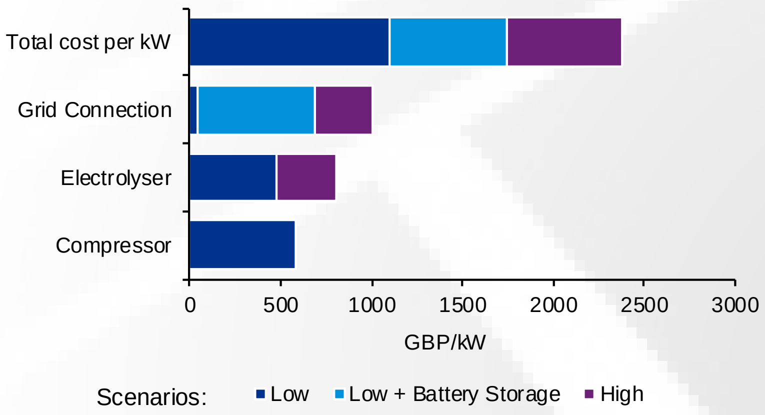
	Top influencing factors
Charging points	At present DC (direct current) charging points are approximately 5-6 times more expensive than AC (alternating current) chargers.
Smart charging equipment/ software	The cost of smart charging equipment/software is weighed against the savings it promises to justify its procurement in the first place.
Grid Connection Cost	This depends on the distance between a depot and the nearest grid network. It also depends on whether (local) reinforcement to that nearest network is required.
Battery Storage	The capital cost of battery storage is usually incurred by the service provider. However, the cost varies dependent on the energy capacity of the storage site.
Hydrogen refuelling dispenser	The cost of a dispenser is fairly fixed. The total cost of installing dispensers will usually depend on the size of the refuelling site and the number of dispensers installed.
Compressor	The cost of a compressor is largely dependent on its capacity (i.e. the volume of hydrogen fuel it can compress within an hour).
Fuel Storage	The cost of fuel storage is dependent on its size, although larger storage tanks are cheaper on a per volumetric unit basis. There is, however, a key trade off between size of a tank vs. cost of cooling (which is an operating cost).
Electrolyser	The cost of an electrolyser largely depends on its capacity and the type of technology it uses (i.e. PEM vs. alkaline electrolyser).
Cooling equipment	The cost of cooling equipment is also dependent on capacity (e.g. the amount of fuel storage capacity as well as the amount of hydrogen fuel that needs to be dispensed).

Sources:

1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. ZEMO Analysis
3. SSEN Impact of Electrolysis on Distribution Network [Source]
4. Stakeholder interviews

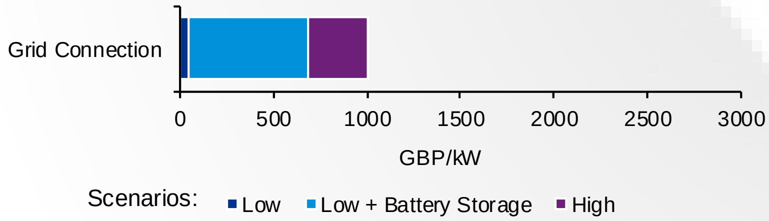
6 Infrastructure Costs: Battery vs. Hydrogen Fuel

Cost range of key components of hydrogen fuel infrastructure



Non kW-standardisable components	Estimated cost provided by industry
Cooling equipment	5% of a refuelling station

Grid connection range for a battery electric bus depot



Non kW-standardisable components	Per unit cost for equipment & installation
AC Charging Point (40-80kWh) DC Charging Point (120-150kWh)	GBP 6,000 GBP 35,000

Sources:

1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. ZEMO Analysis

Definition of scenarios:

1. **Low:** Additional capacity from the grid network can be obtained at a low cost.
2. **Low + Battery Storage:** Additional capacity can be obtained at a low cost but incremental or occasional gaps in energy need to be filled by battery storage.
3. **High:** High cost of grid connection, battery storage and/or electrolysers.

NOTE: *The costs illustrated here are Capital costs only (i.e. supply and installation costs).*

Hydrogen Fuel Infrastructure: Electrolyser and Compressor*

1. **Electrolyser:** There are two types of electrolysers: alkaline electrolysers and PEM (polymer electrolyte membrane) electrolysers. On its own, a PEM electrolyser is more expensive to build than alkaline. However, PEM electrolysers occupy less space which may change the calculus in a space-constraint facility. Manufacturers also claim that PEM electrolysers last for 60,000 hours whereas Alkaline electrolysers last for only 30,000 hours. For the purpose of this study, the need for a PEM electrolyser is categorised as a “High” scenario.
2. **Compressor:** The cost of the compressor to pump and adjust the pressure of hydrogen fuel makes up a significant portion of the infrastructure cost.

Battery and Hydrogen Fuel Infrastructure: Grid Connection and Battery Storage

1. **Grid Connection:** The cost of grid connection introduces the greatest element of uncertainty in infrastructure cost. Based on stakeholder interviews, an addition of 1.5MW in capacity (to accommodate an additional fleet of 40 electric buses) can range from £60k(“Low”) - £1.5m(“High”). This depends on the distance from the depot to nearest grid network and the requirement for local reinforcement. It is also noteworthy that an electrolyser requires more energy to produce hydrogen fuel (approx. 4 times compared to using electricity directly which is stored in batteries) which is very likely to add to the cost of grid connection. However, electrolysers can be located where there are larger supplies of (renewable) energy and the hydrogen fuel transported by land or pipes to grid-connection-deprived areas.
2. **Battery Storage:** Battery storage is a less costly solution to address energy deficiency in depots and is perceived as the recommended “first-stop” for operators before going to (I)DNOs to request for local reinforcement. Since the cost of grid connection varies widely, it is worth performing a cost-benefit analysis on a case-by-case basis to assess if a particular depot is better off with a battery storage site or capacity expansion from the grid.

Battery Infrastructure: Charging Points

1. **Charging points:** Charging points have a fixed supply & installation cost per unit. There are currently two types of chargers in the market: DC chargers are more expensive as they require more complex engineering to manufacture, and include an AC-to-DC converter. It is understood that the market is shifting towards DC chargers with CCS (combined charging system) 2 as the standard.

Sources:

3. SSEN Impact of Electrolysis on Distribution Network [Source]
4. Stakeholder interviews

7

Cost Driver Analysis (Vehicle)

Cost Driver	Powertrain	Current Drivers	Industry Trends	Opportunities for cost reduction
Labour (in manufacturing buses and associated components)	Fuel Cell	Complex engineering involved in integrating the different component parts.	Potential to reduce in future with transition of skills from other industries e.g. oil and gas.	Provide relevant education, training and upskilling opportunities and embed into necessary curricula / qualifications.
	Battery	Labour costs have reached a relatively stable point.	Labour costs will likely remain as they are for the near term.	Limited opportunity for cost reduction (other than efficiencies in administrative resource). Training and upskilling will however allow manufacturers to hire from a larger workforce pool (reducing costs).
Raw Materials & Component Parts (please also see Tariffs and Taxes on next page)	Fuel Cell	The platinum electrolyte membrane comprises up to 60% of the cost.	Expected to reduce in the future with increasing recycling capacity for platinum.	R&D to improve the quality and reliability of fuel cells (acclimatise fuel cells to their application as opposed to laboratory environment).
	Battery	Raw materials - in particular the cost of precious metals which is increasing due to demand.	Operators think the price of batteries will fall but manufacturers and industry analysts now believe they are likely to rise.	Limited opportunity due to batteries becoming a commodity market but some opportunities include shifting away from using precious metals as resources or securing domestic, cheaper sources of supply. Scaling up secondary use and recycling capacity is key but will be costly at first (please refer to recycling/reclamation on next page).
Production / Manufacturing / Integration	Fuel Cell	Customisation of processes / products (which can add 10% to costs) to meet different automaker / operator needs but also the higher engineering complexity required to integrate the different (and more) parts, compared to battery electric buses, sometimes increasing the amount of time and skill required.	The complexity of parts and engineering required will likely remain.	Increased R&D and improvement/standardisation of manufacturing equipment and processes could result in decreased line-time requirements and complexity for the integration and manufacture of different components (i.e. a standardised process to manufacture all types of fuel cells, limiting the number of variations thereby limiting potential for increased costs).
	Battery	Customisation of processes / products (which can add 10% to costs) to meet different automaker / operator needs.	Customisation is likely to stay in place due to differing needs unless regulation mandates otherwise.	Future proofing of standards can help to reduce costs (e.g. health and safety, and regulatory standards / requirements associated with battery packs such risk of fire etc.). Standardisation of processes in manufacturing can also help to reduce costs.

Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. ACEE – Battery cost reduction report [Source]

Sources:
3. SSEN Impact of Electrolysis on Distribution Network [Source]
4. Stakeholder interviews

8 Cost Driver Analysis (Vehicle) - Continued

Cost Driver	Powertrain	Current Drivers	Industry Trends	Opportunities for cost reduction
Recycling / Reclamation	Fuel Cell	Recycling of platinum membranes is understood to be a simpler and less costly process than recycling of cells themselves.	Cost of platinum membrane recycling will likely reduce in the future as the volume of fuel cells increase (unless alternative membranes start coming to market).	Limited opportunity. Onshoring manufacturing/remanufacturing capabilities may reduce logistical costs but this needs to be first driven by sufficient scale to justify the investment. R&D to lengthen the life of fuel cell and scaling up of fuel cell recycling capacity & capabilities.
	Battery	Initial costs of setting up battery recycling plants.	With more used EV batteries coming onto the market in the next 5-8 years, industry expects a similar lead time for scaled reclamation and recycling facilities.	R&D to lengthen the cell lifetime, identification of secondary use cases, and/or refurbishment of individual cells (or replacement of modules).
Taxes, Duties and Tariffs	Fuel Cell	Import duties for cells. These are mostly originating from the Far East (Japan, S. Korea, and China) where tariffs applicable are in between 5-10%.	Bilateral agreements such as UK-Japan CEPA have allowed for exemption from such tariffs. Moving forward, UK's trade deals with East Asian countries will be key in reducing the costs for these components.	Trade and inward investment promotion activities could be done to attract investors to set up sites in Scotland (or other areas of the UK), however, scale of domestic and near-shore demand is a critical factor to unlocking cost competitive production of fuel cells and batteries. Increase in international demand also helps existing businesses to scale up Increasing the local content of parts in an FCEV bus could help reduce the tariff/taxes/logistics costs associated with importing and bringing them together. It should be noted that this will largely be driven by strong demand and be dependent on the ability to achieve economies of scale.
	Battery	The import duty rate for electric buses from China is 10%.		Limited opportunities – as above.

Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. ACEE – Battery cost reduction report [Source]

Sources:
3. SSEN Impact of Electrolysis on Distribution Network [Source]
4. Stakeholder interviews

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Cost Driver Analysis (Infrastructure)

Cost Driver	Powertrain	Current Drivers	Industry Trends	Opportunities for cost reduction
Charging / refuelling equipment	Fuel Cell	Infrastructure developers identified that **the compressor is the biggest cost driver** of a hydrogen refuelling station. This is then followed by the cooling equipment.	Many governments around the world are upscaling the use of hydrogen fuel. As scale increases, costs are expected to fall.	**Shared, multimodal use of a facility** will allow for greater utilisation and justification for a larger facility, which reduces the cost of per unit capacity.
	Battery	**Lack of interoperability among the chargers of different manufacturers.** This will influence the type of charging points that need to be installed in depots as well.	There is a shift towards DC charging and standards such as CCS 2.	Requirements for standardisation of chargers **(e.g. DC and CCS 2 in government-subsidised/funded procurements, bus market reform, etc.)** could help drive cost down by an industry-estimated 15%-20%.
Grid connection	Fuel Cell	**Due to the higher energy requirements,** grid connection cost of a hydrogen refuelling station is expected to be higher.	To overcome this, hydrogen fuel production facilities are usually located where there is easy access to grid connection and large supplies of renewable energy. Hydrogen fuel is then transported via freight.	**There is an opportunity to increase the supply, affordability, and accessibility of renewable energy** by utilising the excess capacity of windfarms in Orkney Islands, in order to meet increased demand across multiple use-case applications.
	Battery	**Local reinforcement costs** and **lack of knowledge of energy capacity (including costs)** required by a specific depot (information asymmetry challenge).	Grid connection costs are likely to decrease as operators become more aware of the true nature of their requirements and likely costs.	**Regulatory review:** establishing a fairer and more transparent relationship between (I)DNOs and operators regarding the ownership and costs of infrastructure. A regulatory review of (I)DNOs business activities and structures could help to ensure fairer prices and quotes are being provided to operators for use and access of required infrastructure. **Education:** Operators often overestimate the need for increase in energy demand for their fleets, resulting in higher infrastructure costs.

Sources:
1. Ballard Power Systems: Economic Case for Hydrogen Buses in Europe [Source]
2. ACEE – Battery cost reduction report [Source]

Sources:
3. SSEN Impact of Electrolysis on Distribution Network [Source]
4. Stakeholder interviews

10

Conclusion and summary

Vehicles

Drivetrain integration and skills: While cost drivers do lie in key components such as powertrain systems (e.g. battery packs and fuel cell), the labour and engineering cost of integrating different components also add significantly to overall cost of the vehicle. This is attributed to the complexity of technology, especially in fuel cell systems, involved and therefore the niche pool of skills that manufacturers look for.

Raw materials: The cost of raw materials is also a significant driver to the overall cost of a zero emission bus. The industry does not yet have an answer on how to recycle used batteries effectively, and the depleting supply of precious metals, coupled with rapidly increasing demand for them, indicates that prices are expected to increase (rather than decrease) in the future.

Trade barriers: Currently many components of a zero emission bus, such as its battery pack, fuel cell, and for some suppliers the entire vehicle itself, are imported from all across the world. Such tariffs can add up to 10% to the cost of the vehicle depending on the rules of origin which determine the trade tariffs applicable to any particular product.

Infrastructure

Grid connection cost: Grid connection costs can make up a significant portion of infrastructure cost, especially for depots which are located far from an existing grid network. The cost for adding energy capacity to such depots can be reduced by exploring solutions such as battery storage or having hydrogen fuel delivered to depots, depending on their situation and fleet profile.

Hydrogen fuel generation and refuelling station: The infrastructure cost to enable hydrogen fuel remains a key driver. Currently the industry is trying to agglomerate as many use cases as possible so as to justify a large facility which can reduce capital cost per unit of capacity through economies of scale.

Information asymmetry: Operators commonly need tailored advice on depot upgrades because there is no one-size-fits-all answer to every depot. Some depots will require additional connection capacity but others may be better off with battery storage or converted into a hydrogen bus depot. Such tailored advice to operators will allow them to opt for the most cost-effective measures in undertaking infrastructure upgrade.