Techno-economic Analysis of Charging and Heating Options for an Electric Bus Service in London

The authors are with the Department of Engineering, University of Cambridge UK

Doros Nicolaides, corresponding author, e-mail: dn314@alumni.cam.ac.uk

Anil K. Madhusudhanan, e-mail: ak2102@cam.ac.uk

Xiaoxiang Na, e-mail: xnhn2@cam.ac.uk

John Miles, e-mail: jcm91@eng.cam.ac.uk

David Cebon, e-mail: dc@eng.cam.ac.uk

Abstract: This study explores electric bus operations for a bus depot in London. Operational data about speed, GPS coordinates and electric motor performance are used to define accurate drive cycles and validate simulations. A validated vehicle simulation tool is used to estimate the power requirements of electric buses over the defined drive cycles. The performance requirements for a practical system are set and appropriate charging infrastructures for electrified bus operations are proposed. The number and location of charging points required within the area of service, their power transfer rates and the capacity of the on-board battery for each charging option are determined. The effects of diesel heating versus electric heating are also analysed. The power demands are calculated and a cost model is built to assess the financial viability of the proposals. It is shown that electrification of the two routes is technically feasible and financially viable when the Opportunity Charging approach is adopted. Such a system (electric bus operations for the bus depot) results in financial savings of approximately £1.7 million over a fourteen-year lifetime when compared to conventional diesel buses. The use of electric buses would result in aggregated CO_2 savings of 48.2 kt between 2019 and 2050.

Index Terms— buses, charging infrastructure, electric vehicles, electrification, power demand, transportation

I.INTRODUCTION

Electric vehicles (EVs) offer significant environmental advantages over conventional vehicles. It was shown in previous studies that 90% reduction of freight-vehicle CO_2 emissions is feasible by 2050 (on a Well-to-Wheel basis including the carbon inherent in electricity) [1]–[3]; provided the current projections for decarbonisation of the electricity grid are realised [4]. This combined with zero tailpipe emissions and low operational noise make EVs an attractive solution particularly for urban areas.

Substantial progress towards more sustainable transport requires a significant contribution from the bus sector. There are approximately 160,000 buses and coaches on the roads of the UK [5] which are responsible for 2.5 billion vehicle-miles in a year [6].

An overview about electric bus (EB) developments and operations was conducted by the authors of [7]. That study shows that several EB systems have been developed and trialled around the world with the earliest systems introduced in 1907 in London UK. However, widespread electrification of bus operations around the world has not been achieved and one of the most significant factors is the limited operational range. Three main methods have been proposed so far to mitigate this problem and these are i) battery swapping, ii) regular (slow) charging at the depot combined with the introduction of backup buses and iii) opportunity charging [7]. Battery swapping has been proven to be inappropriate for electrifying bus operations mainly due to the large and expensive battery swapping station and the need for additional batteries; which result in a not-viable capital investment [7]. Regular charging at the depot and opportunity charging were found more attractive solutions for electrifying bus operations and they have been investigated more frequently by academia and industry.

Indeed, a recent study showed that shifting towards electric bus operations using periodic ‘Opportunity Charging’ (Opp Chg) is technically feasible [1], [2] and significantly more attractive than charging large batteries for an entire day’s operations – ‘Overnight charging’ (OnC). It was shown that the diesel-powered double-decker buses used on five Park and Ride bus routes in Cambridge could be replaced by fully electric buses (EB) that charge their batteries from charging points installed at either end of their routes [1], [2]. The opportunity charging approach significantly reduces the necessary battery capacity and vehicle costs which makes the shift to EB possible.

The Mayor's Transport Strategy for London, which was published in March 2018 [8], includes targets for zero emission buses from 2025. This will significantly improve air quality, improve customers' journeys and reduce the impact on the environment. Shifting towards EBs has been found to be a beneficial approach for achieving these targets [1], [2] but the technical and commercial feasibility of electric bus operations in London is still unclear. Indeed, the bus network of London carries around 2.3 billion passengers a year which is more than the rest of England combined [9]. There are approximately 8,500 buses in London and they operate 24 hours per day, 7 days a week; there are 19,500 bus stops, 700 routes and 6.4 million journeys are performed each weekday [10]. It is therefore important to investigate the technical and commercial feasibility of electrified bus operations in London.

This study investigates the technical and commercial feasibility of bus operations in London, which has not been considered before. In addition, an EB simulation model was developed and validated based on experimental data and the impact of diesel and electric heating on energy requirements was also explored. Moreover, real cost figures and feedback were obtained from the bus operator, the EB manufacturer, Transport for London (TfL) and the Low Carbon Vehicle Partnership (LowCVP).

The charging infrastructure for electric bus operations from a bus depot in London, UK, is explored in this study. The two bus routes at the depot, referred as Route A and Route B, are investigated. A prototype EB was trialled over the route for one week by a London bus operator. The bus was instrumented to gather operational data about speed, GPS coordinates and electrical performance. These were used to define accurate drive cycles and to validate a simulation of the vehicle. The simulation tool was then used to estimate the power requirements of EBs over the defined drive cycles. The performance requirements for a practical system were set and appropriate charging infrastructures for electrified bus operations were proposed. The number and location of charging points required within the area of service, their power transfer rates and the capacity of the on-board battery for each charging option were determined. The power demands were calculated and a cost model was used to assess the financial viability of the various options.

The analysis in this paper shows that the configuration and specification of the EB energy supply system is highly sensitive to operational factors such as the route, operating timetable and charging technology. Consequently, it is important to have technical and financial modelling tools, as described in this paper, to support decision-making. Use of the tools is illustrated via a case study of an EB service in London. However, the tools have general applicability to bus services with widely differing conditions, in other cities and countries.

The opportunity charging concept is illustrated here with an example taken from the study (More details of the methodology will be provided later). The stored energy on-board an electric bus for Route A, is shown in Figure 1 for the OnC and Opp Chg methods. A 435 kWh battery would be needed to run down through the day for the OnC approach. A significantly smaller 138 kWh battery would be sufficient for Opp Chg because it would be charged repeatedly through the day during around 10min stops at each terminus. This capacity difference of 300 kWh corresponds to approximately 1.5-3 t of mass and £20k-100k; assuming 6-8 kg/kWh specific energy of Lithium-Ion batteries [11] and costs around £70-330 per kWh[1] [11]. This means that smaller, lighter and significantly cheaper batteries can be used for electric bus operation when the Opp Chg method is adopted. This results in lower energy requirements and related CO_2 emissions. Having

[1] The lowest battery cost estimation which has been reported in the literature is $100/kWh by Tesla. This corresponds to approximately £70/kWh; hence, the lower limit of the battery cost range used in the text. Regarding the upper limit of £330/kWh, the actual prices of the bus manufacturer considered in this study were used. The bus manufacturer offers two versions of vehicles with 138 kWh and 250 kWh on-board batteries. The price difference between the two options is £36k (see Appendix) which can be used to estimate an average battery cost of £330 per kWh.

distributed charging also dramatically reduces the charging infrastructure needed at the depot and the charging bottleneck cause by having to charge many buses with large batteries overnight, as described later.

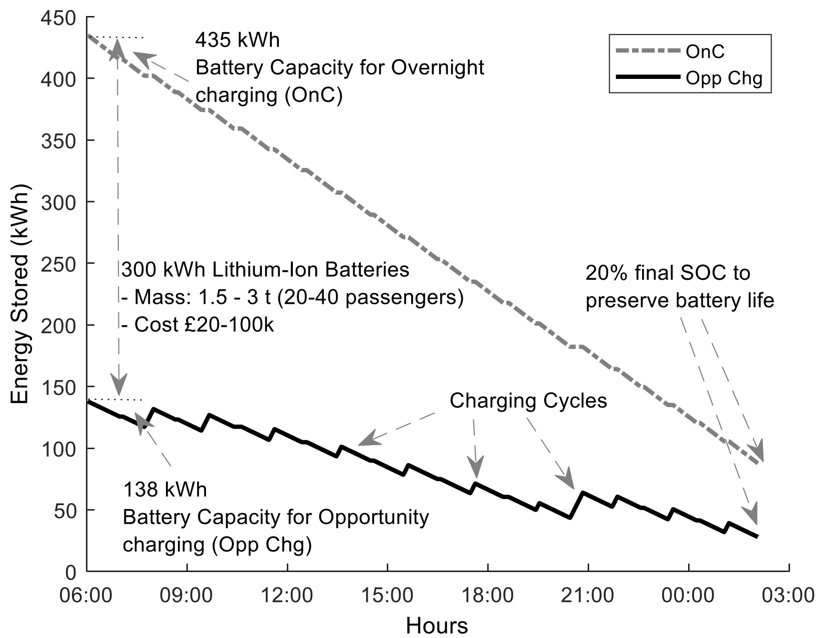

Figure 1: Route A – Stored energy in batteries for the OnC and Opp Chg options

Power transfer systems for EVs have been under development for decades. Conductive systems are well established and have high efficiency and reliability. Opportunity charging power delivery systems suitable for EBs have been developed by ABB, Siemens and others. SIEMENS' portfolio comprises up to 450 kW conductive overhead catenary systems for en-route opportunity charging and up to 150 kW plug-in charging solutions suitable for charging solutions at the depot [12]. Hamburger Hochbahn AG, which operates large parts of the bus system in Hamburg Germany, has demonstrated opportunity charging on its 'Innovation line 109' using SIEMENS' opportunity chargers [13]. Four conductive chargers at 300 kW power transfer rate were installed, two of which at either end of the route. Volvo hybrid and full electric buses have been running on the route since December 2014. In addition, Volvo has been operating an electric bus route 55, between Lindholmen and Johanneberg in Gothenburg Sweden, using SIEMENS' opportunity chargers since 2015 [14]. Similarly, ABB's technology offers power charging solutions up to 600 kW via an automated rooftop connection [15].

More recently, there has been considerable interest from academia and industry into non-conductive (wireless) power transfer suitable for EVs [16]. The ability to avoid plug-in cables and to use simple systems that are unaffected by weather conditions is likely to be attractive to drivers and fleet operators. The Electric Bus project in Milton Keynes is the first of its kind in the UK which demonstrates the concept of Opportunity charging for EBs. This is a fully commercial electric bus project which has been in service for four years. The project involves eight vehicles that receive a 10 min charge boost at wireless charging points located at either end of Route 7 in Milton Keynes [17]. Each of the charging points employs four 30 kW nominal rating units installed in the road to deliver a total 120 kW power transfer rate. 20 kW chargers at the depot are used to fully recharge the vehicles overnight. The performance of the eight buses was assessed retrospectively by Kontou and Miles [17] with the aim to identify any discrepancies between the designed and real-world performance. The results of the study suggest that ambient weather conditions (i.e., the need for on-board heating), route elevation and energy loss due to charging inefficiencies are significant factors to be considered at the early stages of system design. These factors are thoroughly considered in this paper. Useful data for this report was obtained both from [17] and direct links with the Milton Keynes project. This included operational requirements, technical specifications, capital cost figures, etc.

As a result of these pilot projects, the technology risk for implementing opportunity charging for electric buses is low. The technology (conductive and wireless) and operation have been proven in service for several years with many lessons learned from various systems around the world. Indeed, the two demonstrators conducted by Siemens and Volvo have shown that electrification of bus routes is feasible using opportunity charging achieving reduction of fuel consumption and CO_2 emissions by 80%, compared with Euro 6 diesel buses [13], [14]. The Milton Keynes project has been running since 2014 with an estimated capacity of 800,000 passengers a year without interrupting normal operations [17]. The technology of opportunity charging, for both conductive and wireless systems, has been proven to be reliable and financially reasonable.

Either conductive power chargers or wireless power chargers could be used with the proposed opportunity charging solutions. The ultimate choice of the opportunity charging technology to be used should be based on network-wide considerations and a detailed study of the available technologies.

The cost model in this work assumed wireless power transfer technology because real costs of the Milton Keynes electric bus project were available for extrapolation. Wireless charging also provides a worst-case scenario as wireless power chargers are expected to be more expensive than conductive power chargers.

II. MODEL DEVELOPMENT AND VALIDATION

The ‘Advanced Vehicle Simulator’ (Advisor) was used to model the EB. Advisor is an open source software tool developed at the National Renewable Energy Laboratory for the US Department of Energy [18]. Its latest version was released in 2003. Its accuracy has been verified by several authors and international laboratories [19], [20]. Advisor’s database includes a list of standard vehicle models, including light and heavy-duty vehicles with conventional and electric powertrain configurations. In order to model the performance, fuel economy and emissions of a particular vehicle, the user specifies components such as electric motor, battery pack, vehicle mass and additional electric loads. The simulations are executed over selected drive cycles, containing speed and elevation profiles.

The standard ‘Orion VI Transit Bus’ model in Advisor was adapted to match the performance of the prototype EB run in the field trial. Specific values were determined for the power rating of the electric motor, capacity of the on-board battery pack and overall/ unladen mass of the vehicle. The main parameters of the simulation model, ‘eBus’, were obtained from the actual trial EB and are summarised in Table 1:

Table 1: Simulation model parameters

Model Component	Parameters	
Electric Motor	Power: 150 kW	Torque: 2,000 Nm
On-board battery	Capacity: 138 kWh	Mass: 1,500 kg
	Nominal battery pack voltage: 340 V	

Mass	Gross Vehicle Weight: 13 t	Unladen Vehicle Wight: 9 t
Physical Specifications	Vehicle length: 10.8 m	Wheelbase: 5.8 m
	Vehicle Frontal Area: 5.7 m^2	Rolling radius: 0.41 m
	Fraction of total vehicle mass supported by the front axle: 0.35	

Electric Motor: The ‘Unique Mobility Electric Motor’ option in Advisor was chosen for the simulation model as it is recommended for large EV applications. Its maximum power was set to 150 kW and maximum torque to 2,000 Nm.

On-board Battery Pack: The ‘7.4 Ah Saft Lithium Ion battery’ option in Advisor was chosen for the simulation model. The nominal capacity of a battery unit, which has a nominal voltage of 10.65 V, is approximately 78.8 Wh. A single module of the battery pack contains 32 such units in series to achieve the nominal battery pack voltage of 340 V. The battery pack contains 55 such modules in parallel to achieve the nominal battery pack capacity of 138 kWh.

Overall/ Unladen Mass: The Gross Vehicle Weight (GVW) of the EB is 13 t, whereas the Unladen Vehicle Weight (UVW) is 9 t. The UVW includes the battery pack mass of 1,500 kg, which corresponds to approximately 10.5 kg/kWh. It is noted that the mass per unit energy storage of the most recent EB from the same manufacturer, with a 250 kWh battery pack is substantially lower at 4.5 kg/kWh. These figures were verified by the bus manufacturer and are similar to typical values of Lithium Ion batteries used in EV applications [11]. The 4 t difference between the UVW and GVW corresponds to the available passenger capacity which is 56 passengers; 29 of which can be seated based on the specifications of the vehicle.

Additional Specifications: The eBus simulation model includes the following additional specifications: i) Overall Length: 10.8 m; ii) Wheelbase: 5.8 m; iii) Vehicle Frontal Area: 5.7 m^2; iv) Fraction of total vehicle mass supported by the front axle: 0.35; v) Rolling radius: 0.41 m based on the 245/70/19.5 tyres.

Passenger Capacity: The maximum number of passengers that embark on a trip, anywhere along the route, was obtained from the existing bus operator. This averages 157 for Route A. However, the bus operator does not monitor how long passengers stay on board the bus. To this end, the maximum number of embarkations was combined with representative travel data for creating daily profiles. Figure 2 shows the daily profile (percentage) of people travelling to work according to UK National Travel data [21]. The same statistical profile was assumed for passenger loading on Route A and Route B. During the morning peak (i.e., 7am) a passenger load of 1,875 kg is included in the model assuming an average weight of 75 kg per passenger (75 kg *X* 25 passengers on-board).

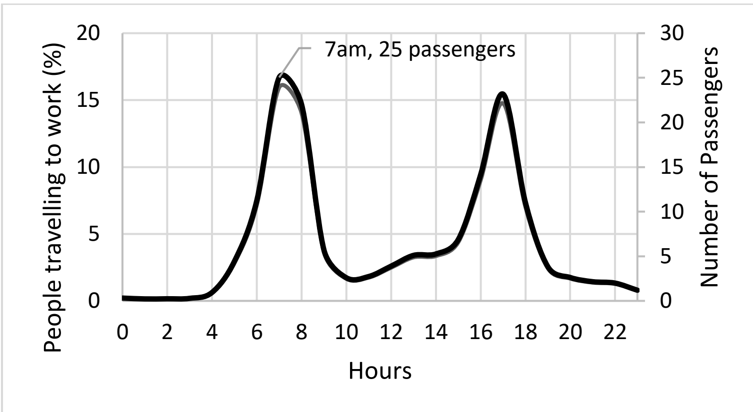

Figure 2: Daily profile and number of people travelling to work according to UK travel data [21]

A. On-road Data Collection

An EB, which was manufactured in the UK, was trialled by a London bus operator in Route A during the last quarter of 2017. Based on the experimental data that was collected during October and November 2017, the EB was evaluated. An electronic logging device developed at the Centre for Sustainable Road Freight (SRF), University of Cambridge, was used for logging the EB journeys. The logging device, known as 'SRF Logger', mainly consists of an Android smartphone and a VIACONT Bluetooth dongle. The Bluetooth dongle connects to the EB's On-Board Diagnostics (OBD) port and transmits the OBD data to the smartphone via the Bluetooth dongle. The dongle uses Bluetooth 2.1 communication protocol. In addition, a 'watchdog' module monitors the reliability of the communication and re-connects to the Bluetooth dongle if required. This maintains an effective and robust communication.

The OBD data includes the following: i) Accelerator pedal position, ii) Brake pedal position, iii) Battery pack current, iv) Battery pack State of Charge (SOC), v) Battery pack voltage and vi) Vehicle speed.

The logger senses the following EB data: i) GPS coordinates, ii) Translational accelerations along the x, y and z axes, iii) Angular velocities around the x, y and z axes and iv) Atmospheric pressure using the smartphone's integrated systems of GPS, accelerometer and barometer.

Once the EB's motor is started, the SRF Logger acquires and uploads the data to internet via a mobile data connection. This process continues until the EB's journey ends. The uploaded data is automatically downloaded and stored in a server at the University. Figure 3 shows the speed profile of the EB route on 11 October 2017. The elevation profile was determined from the logged GPS coordinates using elevation data from Google Maps, appropriately smoothed.

The collection of on-road data enabled the development of simulations tools and methods to calculate the power requirements of EBs for a bus depot in London, and exploration of appropriate charging infrastructures.

B. Model Validation

The performance of the modelled eBus was simulated over the logged drive cycles using Advisor and the results were compared to the EB performance using the measured data. The journey performed on 11 October 2017 was chosen to demonstrate the model validation, mainly because this was one of the longest routes performed by the EB over the trial period. The journey length was calculated to be 161 km using the logged GPS coordinates.

The power required by the electric motor to track the drive cycle of Figure 3 is shown in Figure 4 for a short segment of the drive cycle. The black line shows the measured power, whereas the grey line shows the simulation results using the eBus model. There is good agreement between the two data sets and any minor discrepancies are mainly due to missing data about the actual weight of the vehicle as a function of time. This is dependent on the number of passengers on the bus, which changes at every bus stop. Overall, the percentage error between the mean values of the measured and simulated power was less than 1.2%. This implies that the eBus simulation agrees well with the on-road energy performance of the bus. Such high accuracy has been achieved because: i) the real specifications of the trial bus were used in the simulation model; ii) calibration of the model was performed to align the measured data and simulation results (mainly the power demand from auxiliary services and the specifications of regenerative braking); and finally, iii) a dynamic passenger load profile was adopted in the simulation (see Figure 2).

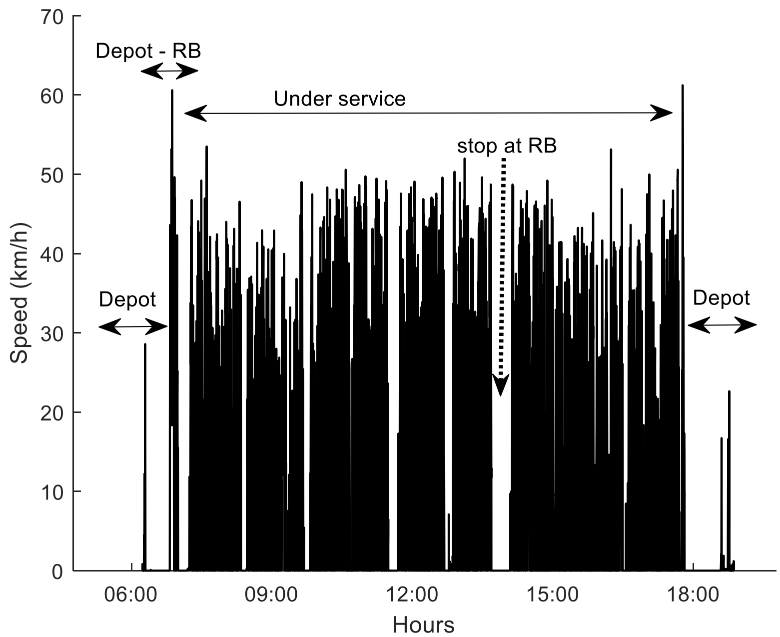

Figure 3: Speed profile of the logged route on 11 October 2017

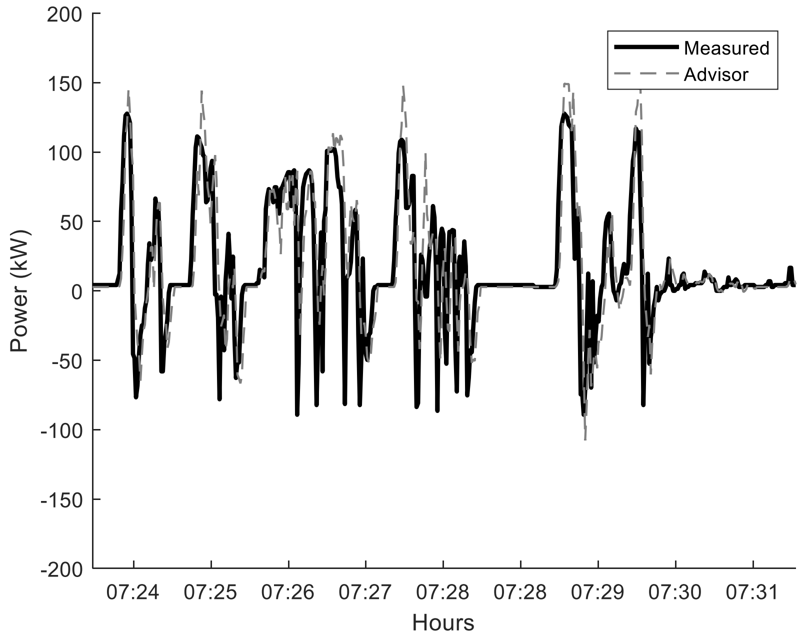

Figure 4: Measured and simulated power of the electric motor

The measured State of Charge (SOC) of the EB's battery pack was also compared with the simulation model's SOC. Although the SRF Logger can measure the SOC value directly by the OBD, this reading is not appropriate for the validation of the simulation model. This is due to the fact that each vehicle manufacturer adopts a slightly different technique for estimating SOC based on the chemical, voltage and current integration techniques. The measured and simulated SOC in this study were calculated using the same approach by integrating the battery pack current over time. This ensures a fair comparison between the measured data and simulation results. At a given time, t, the SOC is given as follows:

$$SOC(t) = 100\% - \frac{-\int_0^t I_B.dt}{3600 Q_B} \, X \, 100\% \, . \qquad (1)$$

Here I_B is the battery pack current, which was measured using the SRF Logger or obtained from the simulation. The battery pack current, I_B, is negative when the electric motor drives the EB, whereas it is positive when regenerative braking occurs. (During regenerative braking, the electric motor acts as an electric generator and the resulting electricity charges the battery). The factor of 3,600 converts the unit of the numerator from Ampere-seconds (As) to Ampere-hours (Ah). Q_B is the total charge content of the battery pack in Ampere hours (Ah), which can be calculated by

$$Q_B = {E_B}/{V_{B_{mean}}} \,. \quad (2)$$

Here E_B and $V_{B_{mean}}$ are the energy capacity (Wh) and mean voltage of the battery pack respectively. For the bus under trial, E_B equals 138,000 Wh and $V_{B_{mean}}$ equals 340 V. This results in a total charge content, Q_B, of 406 Ah.

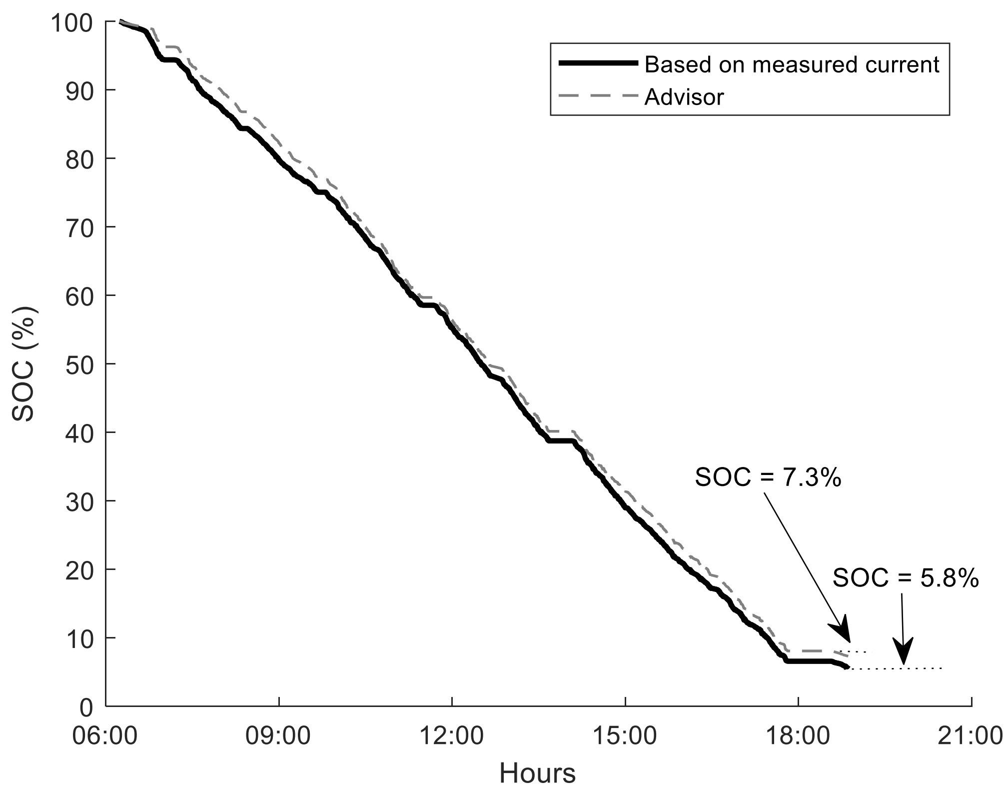

Figure 5: Measured and simulated SOC

Figure 5 shows the measured and simulated SOC for the test run on 11 October 2017. It is seen that the measured and simulated SOC are very similar, with 1.5 % difference on the final value of SOC after a day of driving.

Based on the measured data and simulation results, Table 2 summarises the electric energy consumption for some of the trial bus operations on Route A. Distance was calculated using the logged GPS coordinates of each route under investigation. The total energy consumed by the battery pack was calculated by integrating the power supplied by the battery as follows:

$$Energy = -\int_0^t I_B V_B . dt \,, \qquad (3)$$

where V_B is the battery pack voltage from either the measured data or simulation results. The average energy consumption was obtained by dividing the energy consumed by the distance travelled. The measured and simulated values are shown in the 4th and 6th columns of the table. These agree well. The overall average value was calculated to be 0.75 kWh/km for both cases. Again, the eBus simulation agrees well with the results from the on-road data.

Table 2: Average energy consumption based on measured data and simulation results

Date	Dist. (km)	Measurement Energy (kWh)	Aver. cons. (kWh/km)	eBus simulation model Energy (kWh)	Aver. cons. (kWh/km)	Average consumption error (%)
09/10/17	131.1	98.5	0.75	97.7	0.74	-0.81
11/10/17	161.5	126.9	0.79	127.7	0.79	0.63
12/10/17	126.0	98.9	0.78	98.3	0.78	-0.61
13/10/17	125.3	98.0	0.78	98.5	0.79	-0.51
25/10/17	78.7	49.7	0.63	50.1	0.64	0.8
26/10/17	49.6	35.1	0.71	35.2	0.71	0.28
Total	672.3	507.1	0.75	507.5	0.75	0.08

The bus manufacturer claims that their EB achieves an energy performance of 0.65 kWh/km, which is significantly better than the 0.75 kWh/km measured on Route A and simulated here.

In 2015, LowCVP tested a similar EB on a chassis dynamometer using the ‘Millbrook London Bus Cycle’ [22]. They measured an energy efficiency of 0.64 kWh/km, which is similar to the bus manufacturer’s claim.

This discrepancy was investigated by simulating the eBus performance over the Millbrook London Bus Cycle. The mass of the eBus model was set to 7,419 kg and all on-board electrical loads were removed from the simulation model to replicate the test conditions. The energy consumption of the eBus model was calculated to be 0.64 kWh/km, which is similar to the manufacturer’s claim and the LowCVP’s results. This increases the confidence in the simulation model and confirms that the EB energy consumption is 0.75 kWh/km on the real drive cycle.

The reason for the discrepancy between the two numbers (0.64 kWh/km and 0.75 kWh/km) is that the real drive cycle at the London bus depot is more arduous than the Millbrook London Bus Cycle. The Millbrook cycle has a different profile of starting and stopping, and does not include any elevation profile changes, passenger loading or other auxiliary loads on-board, which are important features of the real drive cycle. The measured energy economy of 0.75 kWh/km, which is based on the real drive cycle, is still considered to be good performance for an electric bus.

C. Duty Cycles

In this section, the validated eBus model is used to calculate the energy requirements of an electrified Route A and Route B. The impact of electric heating is also investigated.

1. Route A

The average energy consumption of the trialled EB performing Route A was measured and calculated at 0.75 kWh/km (Table 2) on the real drive cycle. These tests were conducted in October and no heating was needed on-board.

The bus manufacturer states that the additional power demand of electric heating averages 2 kW for cold weather[2]. The increase on the average energy consumption due to electric heating for cold weather can be calculated as follows:

[2] This power consumption is believed to be a conservative estimate, compared to the peak power demand of the bus manufacturer's electric heating system which is 14 kW. It appears likely that an air-source heat pump is used to provide sufficient heat using only 2 kW of electricity.

$$E_{eh}/_{km} = \frac{Pt}{\eta}/_{dist} = 0.14\ kWh/_{km}, \qquad (4)$$

where E_{eh} is the energy requirement for electric heating, P is the power rating of electric heating (kW), t the working time of heating (hours) and η the overall efficiency of the system. The additional energy demand for electric heating, E_{eh}, divided by the total distance travelled in the day, $dist$ (km) gives an estimation of the average energy consumption of electric heating per km travelled. For example, the first bus of Route A, referred as '101', performs 215 km in 11 hours and 41 minutes every weekday, according to the existing duty cycles. This, combined with a 2 kW constant load due to electric heating, and 81% overall efficiency of the system (assuming that the efficiency of both the heater and on-battery is 90%) results in an additional energy demand of 0.14 kWh/km. The validated eBus model was also adjusted appropriately to explore the impact of electric heating as explained in [23]. The corresponding average energy consumption was calculated to be 0.89 kWh/km.

Additionally, 1 kW heating power demand was assumed by the authors for 'cool' weather (instead of the 2 kW for cold weather). The corresponding average energy consumption was calculated to be 0.83 kWh/km. This number was used in the estimate of the total annual energy demand and the carbon savings of the buses. The required charging infrastructure for the bus depot was determined using the worst-case scenario which involves cold weather and the assumed power drawn for electric heating of 2 kW as stated by the bus manufacturer.

An alternative to electric heating is to burn diesel fuel to provide heat. This eliminates the need for additional electrical energy but generates emissions of NOx and particulate matter (PM). Consequently, it is not considered to be an acceptable future solution by many city authorities. Nevertheless, diesel heating was considered to be a possible option in this study.

The average energy consumptions of the trialled EB with diesel or electric heating were then combined with the daily duty cycles of buses on Route A to calculate the energy requirements of an electrified system. The duty cycles were generated using the 'bus graph' of the route which was obtained from the bus operator. The bus graph for Route A for Monday to Friday operations is shown in Figure 6. Table 3 shows the daily energy requirements (Monday to Friday) as a function of the bus number on Route A. It is noticed that the energy requirements vary for each bus because they perform slightly different daily duty cycles as a result of the different start and stop times as defined by the bus graphs.

The total daily energy requirement for Route A (12 buses) is approximately 2.5 MWh for operations performed between Monday to Friday when diesel heating is adopted. The adoption of electric heating increases the energy requirement to 2.9 MWh per day during cold weather.

Table 3: Daily energy requirements for Route A (Monday to Friday)

Bus no.	Dist. (km)	Diesel Heat. (kWh)	Electric Heat. (kWh)
101	214.9	161.2	193.4
102	351.0	263.3	315.9
103	346.8	260.1	312.1
104	206.5	154.9	185.9
105	241.2	180.9	217.1
106	315.6	236.7	284.1
107	324.3	243.6	291.9
108	254.2	190.6	228.8
109	250.0	187.5	225.0
110	241.2	180.9	217.1
111	285.0	213.8	256.5
112	245.8	184.3	221.2
Total	3,276.6	2,457.4	2,948.9

A similar analysis was performed for operations on Saturdays and Sundays and the results were combined with Table 3 to calculate the annual energy requirements for Route A. The results are summarised in Table 4. It can be seen that 842.5 MWh of electricity is needed to run 1,123,200 km per year when diesel heating is adopted on-board and 909.4 MWh for electric heating. This assumes that 20 weeks of the year have cool weather (i.e. 0.83 kWh/km) and 10 weeks have cold weather (i.e. 0.89 kWh/km). Mild or hot weather is considered for the remaining 22 weeks of the year which means that heating is not necessary. (Air conditioning was not used in hot weather.)

2. Route B

No trials were performed on Route B and therefore no experimental data was available for analysis. However, the GPS coordinates and speed profile of the route were logged using the SRF Logger, without connecting the device to the vehicle. The elevation profile was determined using Google Maps, as before and the validated eBus model was simulated over the measured drive cycle using Advisor to calculate the energy consumption.

The average energy consumption of the eBus traversing Route B was also estimated to be 0.75 kWh/km (the same figure as for Route A). The impact of electric heating was also investigated and again, the average energy consumption was found to increase from 0.75 kWh/km to 0.89 kWh/km during cold weather.

The bus graph of Route B was obtained from the bus operator to generate the duty cycles of the route. The performance of the eBus model was simulated over these duty cycles and the results are summarised in Table 4.

Overall, 1,463 MWh of electricity would be needed to run 1,951,372 km per year on Route A plus Route B, using diesel heating. With electric heating, 1,578.3 MWh of electricity would be needed per year (see Table 4).

The energy consumption of 1,578.3 MWh for the bus depot under investigation (22 buses) is scaled up for the entire county. The impact of a total shift towards electric bus routes, involving 160,000 buses and coaches in the UK [5], will be an additional energy demand of approximately 11.5 TWh. This corresponds to a less than 3% increase based on the UK’s electricity consumption of 400 TWh in 2015 [24]. The anticipated generation of electricity is estimated to increase by 100% by 2050 (from 400 TWh to 800 TWh per year) mainly due to the shift to EVs and electric heating [24]. This would allow a considerable margin for the electrification of bus routes in the future.

Table 4: Annual energy requirements for the bus depot

	Distance (10^3.km)	Diesel Heating (MWh)	Electric Heating (MWh)
Route A	1,123.3	842.5	909.4
Route B	828.1	621.1	668.9
Bus Depot	1,951.4	1,463.6	1,578.3

III. ENERGY AND CARBON

Possible charging infrastructures for electric bus operations from the bus depot are explored in this section. The analysis investigates the two main charging methods: Overnight Charging (OnC) and Opportunity Charging (Opp Chg). For the former, buses are equipped with a battery big enough to supply the energy requirements for the entire day. The batteries are recharged overnight when the vehicles return to the depot. By contrast, smaller batteries are used when opportunity charging is available because the buses get multiple small charging boosts during operation, from charging points installed along their routes. The stored energy in the batteries is shown in Figure 1 for both electrification options for the most demanding route performed out of the bus depot which is '102' on Sundays. This is a long route, combined with short duration stops. The adoption of electric heating is also explored for each charging method.

A. Overnight Charging

The main advantage of the OnC solution are that it is a direct substitution for diesel bus operations. The buses do not depend on charge being available en-route. The bus operator can potentially use the same buses for various routes. However, the capacity of the on-board battery must be sufficient for all buses operating on the route. This capacity is determined by the needs of the bus performing the most demanding duty cycle. For the bus depot under investigation, the most demanding duty cycle is 391 km performed by bus '102' on Sundays (Route A). This, combined with the average energy consumption of 0.89 kWh/km (based on the calculated energy consumption of the eBus with electric heating on-board) result in a battery size of 435 kWh.

A 20% safety margin is required to maximise the life span of the batteries and satisfy the manufacturer's warranty policy. This can be seen in Figure 1, where both vehicles return to the depot at the end of the day with 20% of their maximum energy storage still available.

The large batteries needed introduce significant practical and engineering issues that undermine the feasibility of the OnC system. The specific energy of the on-board battery used in the newer version of the bus manufacturer's EB with a 250 kWh battery on-board is 4.5 kg/kWh. This means that the 435 kWh battery needed adds approximately 830 kg to the vehicle – (435-250 kWh) X 4.5 kg/kWh. As a result of this, the bus operator would need to reduce the number of passengers on-board to avoid exceeding the maximum load limit. The additional mass of 830 kg corresponds to approximately 11 passengers (20% the capacity of buses), assuming an average weight of 75 kg per person.

Furthermore, the massive size of batteries (435 kWh) imposes technical concerns because the largest battery that has been used in the automotive industry to date is 324 kWh, on BYD buses [25]. Some vehicle manufacturers have announced plans for introducing larger batteries on their vehicles: 1 MWh battery on the Tesla Semi Truck [26] and 660 kWh battery on the Proterra Catalyst EBs [27]. Proterra estimates that mass production of the new product will start the second half of 2020. The bus manufacturer involved in this study offers two versions of EBs with 138 kWh and 250 kWh on-board batteries. This means that the only way to use these buses for the routes under investigation is to adjust the duty cycles and the size of the fleet to overcome the problem of limited mileage range. This approach is followed in this study.

1. Diesel Heating

The measured and simulated average energy consumption of EBs performing Route A and Route B with diesel heating is 0.75 kWh/km. This gives a maximum range of 267 km (significantly less than the desired range of 391 km), based on the 250 kWh battery and a minimum acceptable SOC of 20% (200 kWh of available energy).

It is shown in Figure 6 that the duty cycle performed by the first bus of Route A, referred as ‘101’, requires 161 kWh. An on-board battery of 250 kWh (200 kWh of usable energy) could deliver the energy needed for the duty cycle. By contrast, the energy required by the second bus of the route, ‘102’, is 265 kWh which goes beyond the available energy of 200 kWh. Fortunately, the vehicle has a one-hour break in the depot at approximately 21:30. A fast charger is therefore required at the depot to recharge the vehicle during the break. The fast charger provided by the bus manufacturer operates at 77 kW power transfer rate which means that the one hour break could deliver up to 77 kWh of energy to the vehicle (ignoring charging losses) which would be sufficient for the bus to complete the remainder of the duty cycle.

In a similar way, fast charging at the depot is needed for bus ‘106’. Although the break of ‘106’ lasts for one hour, only a 15 min charging boost is available because a charging boost is also needed by bus ‘102’ which returns to the depot around the same time (as described in the previous paragraph). The 15 min charging boost for ‘106’ does not deliver sufficient energy to the vehicle for completing the second part of its duty cycle. The solution is to install two fast chargers at the depot so they can be utilised simultaneously by buses ‘102’ and ‘106’.

Bus ‘103’ does not have any breaks, yet more than 200 kWh of energy is required. The on-board battery runs out of energy around 19:40. A possible solution to overcome this problem is to use other buses to complete the duty cycle. In particular, bus ‘105’ returns to the depot around 19:15. There is approximately a 30 min window for charging (a 10 min travel time is required to the changeover point) which is just sufficient to complete the duty cycle of bus ‘103’. However, any charging time lost due to plugging in the charger, signing in/ off at the depot or due to any bus delays would severely affect the performance of the system.

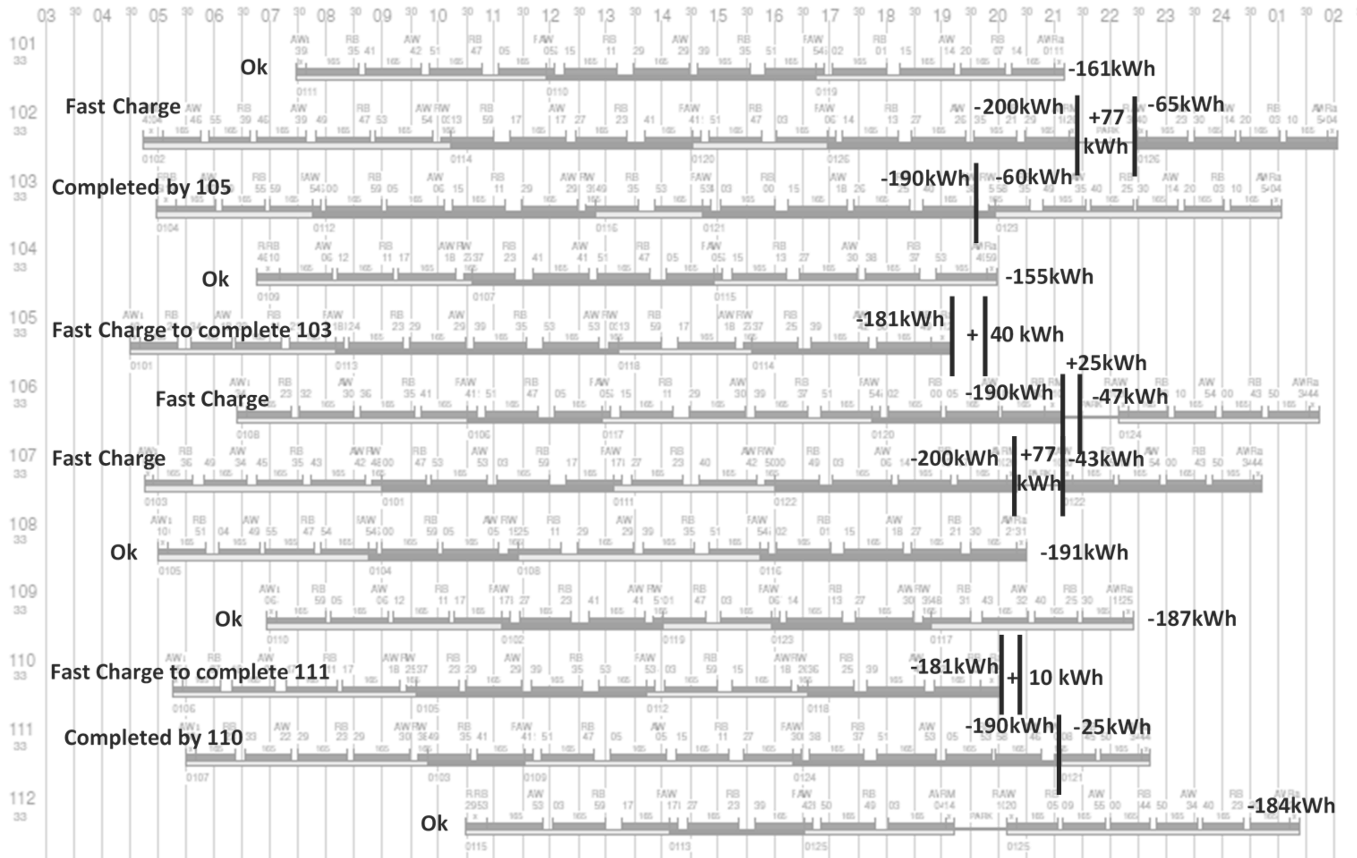

Figure 6: Scheduling adjustments on duty cycles for an electrified Route A when OnC and diesel heating are adopted

Some additional scheduling changes are shown in Figure 6 to allow the electrification of the route. The same analysis was conducted for the duty cycles performed on Saturdays and Sundays and for Route B. Overall, electric bus operations at the bus depot with diesel heating would involve 22 EBs (the same as the number of diesel buses) with the 250 kWh battery option, 12 of which are for Route A and 10 for Route B. 22 slow chargers at 44 kW are needed for overnight charging of these buses. In addition, 3 fast chargers at 77 kW need to be installed at the depot to deliver occasional fast charging boost to buses during breaks. The necessary charging equipment is summarised in Table 5.

Table 5: Charging infrastructure for electric bus operations

Cases	Equipment	Route A	Route B	Depot
OnC Diesel Heating	EBs (250 kWh)	12	10	22
	Extra Buses	0	0	0
	Fast Chargers (77 kW)	2	1	3
	Slow Chargers (44 kW)	12	10	22
OnC Electric Heating	EBs (250 kWh)	12	10	22
	Extra Buses	7	1	8
	Fast Chargers (77 kW)	1	1	2
	Slow Chargers (44 kW)	19	11	30
OnC, Electric Heating & rescheduled operations	EBs (250 kWh)	12	10	22
	Extra Buses	2	0	2
	Fast Chargers (77 kW)	0	0	0
	Slow Chargers (44 kW)	14	10	24
	Additional driver costs (£k)			120
OppC Diesel/ Electric heating	EBs (138 kWh)	12	10	22
	Extra Buses	0	0	0
	Fast Chargers (44 kW)	0	0	0
	Slow Chargers (22 kW)	12	10	22
	Opp chargers (120 kW)	2	2	4

2. Electric heating

The simulated average energy consumption of EBs performing Route A and Route B with electric heating is 0.89 kWh/km (compared to 0.75 kWh/km with diesel heating). The maximum range with heating drops from 267 km to 225 km, based on the 250 kWh battery with a minimum acceptable SOC of 20% (200 kWh of available energy).

As a consequence of the shorter range, most of the buses run out of energy mid-service before returning to the depot for a break. One solution is to employ additional buses to complete the duty cycles. Table 5 shows that this operation with electric heating on-board would require 30 EBs with 250 kWh batteries. This is because the opportunities for fast charging at the depot during breaks are limited. In addition, 2 fast chargers at 77 kW and 30 slow chargers at 44 kW (one for each bus) are needed.

The eight extra buses would significantly impact the way in which the bus operator schedules the operations. Things to be considered are the maximum driving hours on duty per driver, stand times at the depot, travel arrangements to changeover points, breaks, etc. Moreover, the physical capacity of the depot to accommodate eight extra buses and any additional staff needed due to the larger fleet (e.g. maintenance, administration, security, etc.) have to be considered. A financial evaluation of the OnC system is provided in section IV. It shows that this charging approach is very expensive compared to the alternative of Opp Chg and it does not ‘break even’ financially.

3. Electric heating with rescheduled operations

Re-scheduling the duty cycles entirely, considering the limited mileage range of EBs might be a possible solution to electrify Route A and Route B. This would involve scheduling breaks earlier in the day to allow buses return to the depot for charging boost before running out of energy. This possibility was investigated by the bus operator’s scheduling team and the results show that 2 extra EBs and 14 slow chargers at 44 kW for each bus would be required to electrify Route A. Additional driver costs of £120k per year would also be needed (see Table 5). This is because extra drivers would be required to move the empty buses back to the depot for charging or to replace them with fully charged vehicles on the route. This opposes the well-established approach of bus operations where drivers (not buses) change over on routes to minimise costs.

The total daily power demand profile at the depot for electrified Route A and Route B is shown in Figure 7 grey line. A maximum power demand of 600 kW is added on the grid overnight when all of the EBs are recharging their 250 kWh batteries. The additional power demand drops to zero during the day when all buses leave the depot and it gradually increases in the evening as buses return to the depot. This profile assumes that EBs are plugged-in two hours after they arrive at the depot, which gives time for maintenance, cleaning, etc. No further power is needed once each bus is fully recharged. A constant power demand of 77 kW is needed during some afternoon hours due to fast charging at the depot.

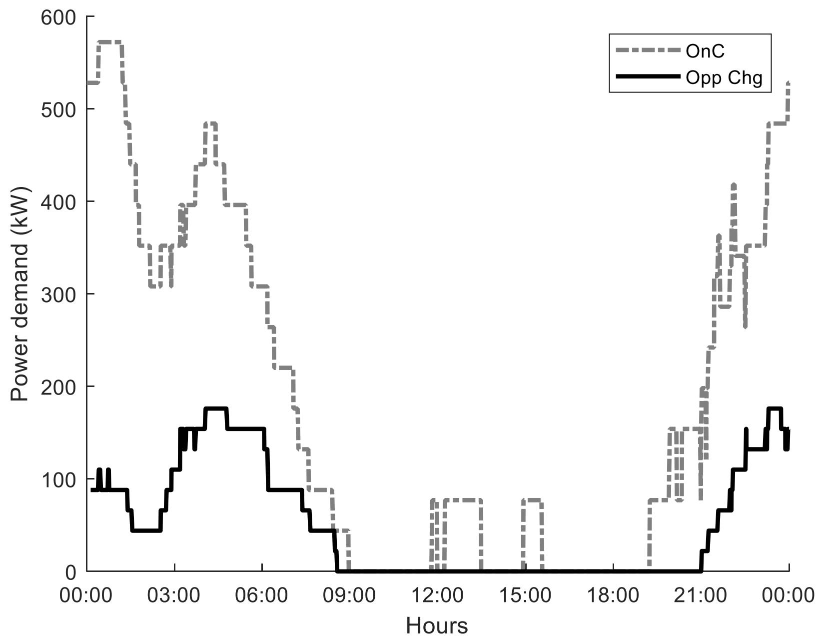

Figure 7: Power demand profile at the depot for OnC and Opp Chg

B. Opportunity charging

The Opp Chg approach is explored in this part of the paper. EBs could top-up their batteries from charging points, at key locations along their routes and therefore Opp Chg would significantly reduce the necessary battery capacity (see Figure 1). A maximum allowable charge rate of '0.9C' -charge the entire battery in 1.1 (=1/0.9) hours- and a minimum SOC of 20% are assumed in order to maximise the life span of the on-board batteries [28]. Buses with the manufacturer's smaller 138 kWh batteries on-board are assumed for this charging method.

The analysis shows that the installation of a charging point at either end of each route would deliver sufficient energy to the buses during their 10-15 min breaks throughout the day, to perform the existing duty cycles.

The SOC profile of the bus '102' (which performs the most demanding route out of the depot on Sundays) with opportunity charging is shown in Figure 8. The bus returns to the depot at the end of the day with 50% SOC when diesel heating is used and with 25% SOC when electric heating is adopted. Because the batteries are smaller, slow chargers capable of delivering 22 kW are used to fully recharge the buses overnight at the depot (compared to 44 kW charges needed for the OnC solution). Each opportunity charging point is rated at 120 kW which corresponds to 0.9C charge rate. The analysis allows half a minute lost charging time due to any alignment requirements and 'build up' of power electronics. It also takes into consideration the average stand layover times measured by the bus operator. On average these measured layover times are 79% of the scheduled layover times for Route A and 84% for Route B. The system would therefore be robust to bus delays of the duration that are typically observed on the routes. Even if 3-5 complete charging opportunities are lost at random intervals throughout the day[3], buses would have sufficient energy on-board to complete the duty cycles. As shown in Table 5, unlike OnC, Opp Chg does not require extra buses.

The total power demand profile of electrified Route A is shown in Figure 9. The power demand at the depot (dark line) reaches a maximum value of 110 kW when five EB are connected to the grid simultaneously (5 X 22 kW). It is zero during the day when all buses leave the depot. During the day, the opportunity power demand consists of ~10min 'spikes' of either 120 kW or 240 kW. The 2 opportunity chargers deliver power intermittently, with each providing a maximum power of 120 kW. Simultaneous operation at both ends of the route regularly demands up to 240 kW power from the electricity network of the city from two geographically spaced locations (i.e., probably different electricity sub-stations).

[3] The most demanding duty cycle involves 20 terminus stops in total (at either end of the route). 3-5 lost charging opportunities throughout the day corresponds to approximately 15-25% of all terminus stops. The analysis shows that a total energy of 220 kWh is delivered to the vehicle if none charging opportunities are lost. This corresponds to an average charging boost of approximately 11 kWh per terminus stop (i.e., 220 kWh / 20 terminus stops). 3-5 lost charging opportunities throughout the day result in a total energy loss of 33-55 kWh; or in other words, 24-40% battery SOC (based on the 138 kWh on-board battery). As it can be derived from Figure 8, there is sufficient battery headroom for up to 3 lost charging opportunities throughout the day when electric heating is considered in the analysis and up to 5 when diesel heating is assumed.

The combined power demand profile *at the depot* for Route A and Route B is shown in Figure 7, with a dark line. Electric bus operations based on the Opp Chg method requires a maximum power of 200 kW which is significantly lower than the power demand of 600 kW required for OnC. This means that the depot needs a much lower capacity electricity supply.

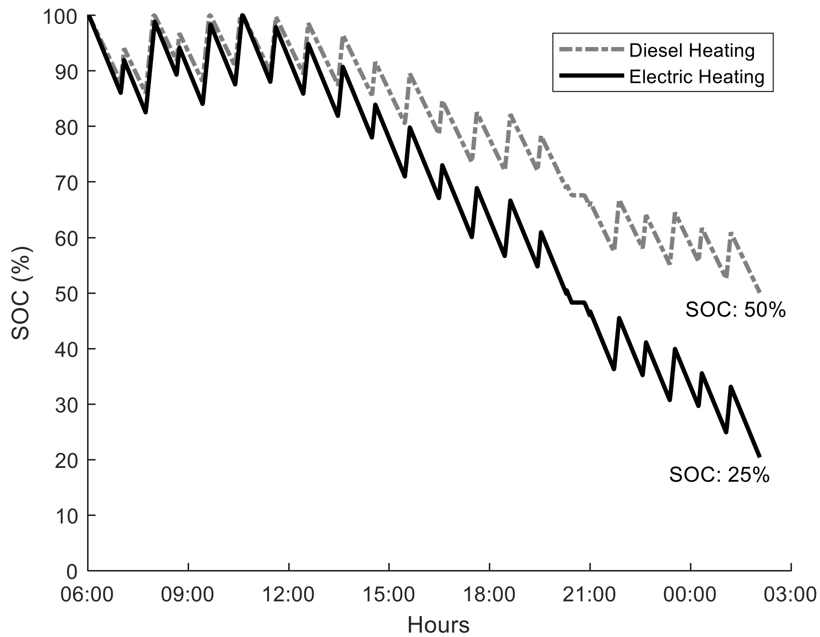

Figure 8: SOC profile of '102' (Route A on Sundays) based on the Opp Chg approach for diesel/ electric heating

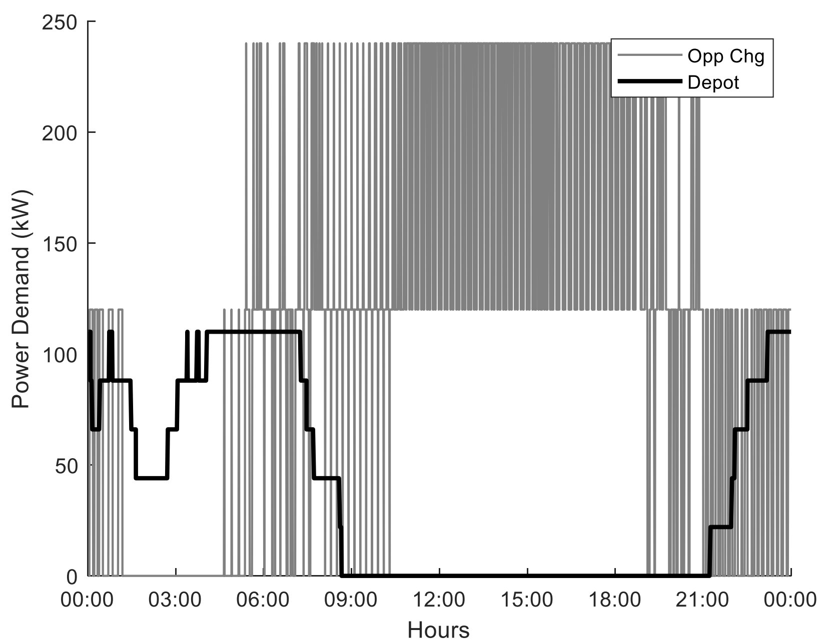

Figure 9: Power demand of Route A based on the Opp Chg

C. Carbon emissions

The fuel economy of the diesel buses currently operating from the bus depot under investigation (E200 Euro 5) is 9.10 mpg according to the bus operator. It was shown in [23] that a possible adoption of Euro 6 buses with 'smart electric steering' and 'start-stop' features could improve this to 9.44 mpg. About 13.6 kgCO_2 are produced from burning a gallon of diesel fuel on a Well-to-Wheel basis [29]. As a result, a conventional Euro 6 bus with 'smart electric steering' and 'start-stop' features under service in the depot would emit around 895 gCO_2/km. By contrast, the average consumption of 0.75 kWh/km of the eBus model combined with the carbon intensity of the UK electricity supply network in 2018 of approximately 300 gCO_2/kWh [30] results in approximately 225 gCO_2/km – which is 75% lower than that of the diesel vehicle. Using the UK Department of Energy and Climate Change's projected CO_2 intensity of 100 gCO_2/kWh [4] for the significantly decarbonised UK electricity grid in 2030, the CO_2 emissions of the EB would be only 75 gCO_2/km. This corresponds to a substantial reduction of 92% compared with the Euro 6 diesel buses. Using the CO_2 intensity of 50 gCO_2/kWh in 2050 [31], CO_2 reduction of 96% emissions is feasible.

In addition, there are emissions from the heating system on-board during cool/cold weather (30 weeks of the year). The fuel consumption of diesel heating is 227 mpg according to bus manufacturer. This, combined with the 13.6 kgCO_2 per gallon figure result in additional 37 gCO_2/km. By contrast, the impact of electric heating (0.08 kWh/km) would be 24 gCO_2/km at today's emissions rates and 4 gCO_2/km in 2050 with a significantly decarbonised electricity supply network.

Table 6: Carbon Emission savings for the bus depot based on different electrification options

	ktCO_2 savings per year			ktCO_2 saving
	2018	2030	2050	2019-2050
OnC – diesel heating	1.31	1.60	1.65	47.3
Opp – diesel heating	1.31	1.60	1.65	47.3
OnC – electric heating	1.31	1.63	1.68	47.7
OppC – electric heating	1.32	1.63	1.69	48.2

The CO_2 emission savings from an electrified Route A and Route B based on different electrification options are summarised in Table 6. The CO_2 emission savings are similar for all four solutions mainly because the weight of OnC/ Opp Chg buses (i.e. with 250/138 kWh on-board battery) is assumed to be the same[4]. A small improvement is possible when electric heating is adopted instead of diesel heating.

The OnC electrification option with electric heating involves extra journeys from the depot to the changeover points; because extra buses are required to perform the existing or the entirely re-scheduled operations. The additional distance travelled was calculated at 43,540 km per year which increases the energy consumption of the system and the CO_2 emissions compared to the OppC solution.

An electric system based on the Opp Chg approach (22 buses for the bus depot) with electric heating on-board would offer the greatest environmental benefits. The impact would be to save 1,322 tCO_2 per year at today's emissions rates[5] and 1,686 tCO_2 per year in 2050[6]. This corresponds to an accumulated saving of 48.2 $ktCO_2$, assuming a 0.8% annual improvement in the carbon content of the electricity grid in each year between 2019 and 2050.

[4] The bus manufacturer has stated that the newer 250 kWh vehicles have the same mass as the older 138 kWh vehicles, because of improvements in battery design. This means that the 138 kWh buses are heavier and use more energy than if they were to use more modern batteries.

[5] Based on an annual mileage of 1,951,372 km; 895 gCO_2/km for Euro 6 buses and 37 gCO_2/km for diesel heating; and 225 gCO_2/km for an EB and 24 gCO_2/km for electric heating

[6] Based on an annual mileage of 1,951,372 km; 895 gCO_2/km for Euro 6 buses and 37 gCO2/km for diesel heating; and 50 gCO2/km for an EB and 4 gCO2/km for electric heating

IV. FINANCIAL ANALYSIS

In this section, a cost model is developed to examine the financial viability of the proposed schemes. The key cost drivers of the model are divided into three main categories which are i) capital costs, ii) operating costs and iii) maintenance costs. Cost data was obtained from the bus operator, the bus manufacturer and UK Power Network (UKPN). The real costs of the Milton Keynes electric bus project (MK) [17] were also used in this study where possible, although the technology has been in operation for some years and prices should have improved since then. The cost assumptions of the model are summarised in the Appendix.

A. Basic Scenario

The annual expenditure F_a for each system is calculated using:

$$F_a = \frac{RC_c}{1-(1+R)^{-Y}} + C_{oa} + C_{ma}. \qquad (5)$$

where C_c is the capital cost; C_{oa} is the annual operating cost; C_{ma} is the annual maintenance cost; R is the annual interest rate and Y is the repayment period in years.

The capital cost C_c was calculated based on the cost assumptions in the Appendix which include the costs for the buses, the charging infrastructure at the depot and the charging infrastructure in the streets for opportunity charging. A 2.6% interest rate over a 7-year payment period was considered (see Appendix).

The operating cost C_{oa} includes the expenditures on fuel for both driving and heating purposes (diesel or electricity). Battery losses which are influenced by the charge rate are also considered in the model. According to [32], charging from slow chargers at the depot (0.15C) result in 7% battery losses, fast charging at the depot (0.3C) involves battery losses of 8% and charging from the opportunity chargers at streets (0.9C) results in 10% losses. The analysis assumes that these losses occur every time the bus gets recharged and the appropriate figure is considered in the calculations depending on the type of charging. Additional costs of £120k for drivers are included when OnC with rescheduled operations is adopted. Any additional staff costs due to the larger fleet (e.g. maintenance, administration, security, etc.) are not included in the study.

The maintenance figures (C_{ma}) for diesel buses were obtained from the bus operator and the same costs were assumed for EBs. It is assumed that an extensive mid-life maintenance task is performed in year eight for refurbishing the vehicle and servicing the engine and gearbox of diesel buses. It is also assumed that the same sum is required for the mid-life maintenance of EBs, for refurbishing the vehicles and servicing the traction drive and generator. In addition, the cost to replace the batteries of all EBs is included in the analysis. This was obtained from the bus manufacturer and stands at £40k per battery (single payment) regardless the size of the battery i.e. 138 kWh or 250 kWh. Although a 250 kWh battery would be more expensive to replace than a 138 kWh battery, the big battery would have more residual value in the end of its life, according to the bus manufacturer. Finally, 10% of the annual spend on charger costs is considered for charger maintenance.

1. Diesel Heating

The charging infrastructure required for the various electric bus operations are provided in Table 5. The two electric options are compared to the diesel option and the results are shown in Figure 10. Capital repayment stops in year 7, which accounts for the 'knees' in the curves. It is noticed that a payback-time of 11 years is possible when the OnC method is adopted and 12 years for the Opp Chg method.

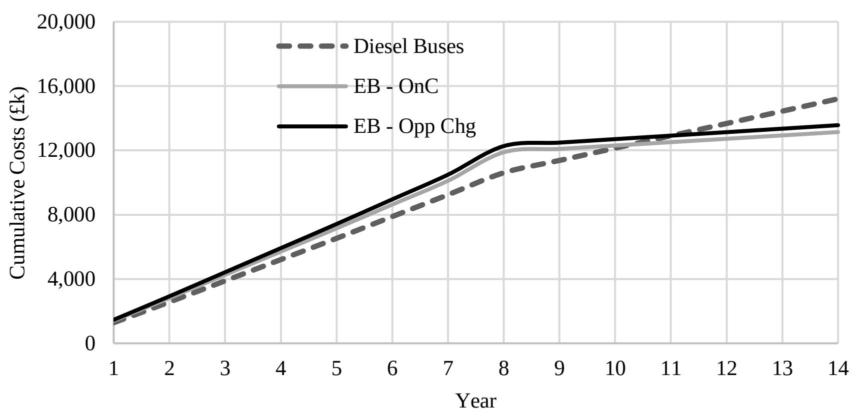

Figure 10: Cumulative costs for the bus depot in £k with diesel heating on-board

2. Electric Heating

A similar analysis was performed for the case of electric heating on-board. Eight extra buses and slow chargers, and two fast chargers are required to perform the existing duty cycles for the OnC approach (Table

5) which significantly increases the capital costs of the system. There is also an increase in energy costs as extra journeys are required between the depot and the changeover points. Such a system it is always more expensive to run (for a 14-year life) in comparison to the diesel system as shown in Figure 11. The electrified system based on the Opp Chg offers financial savings in the 12th year of operation, whereas the overnight charging system does not break even until approximately year 16.

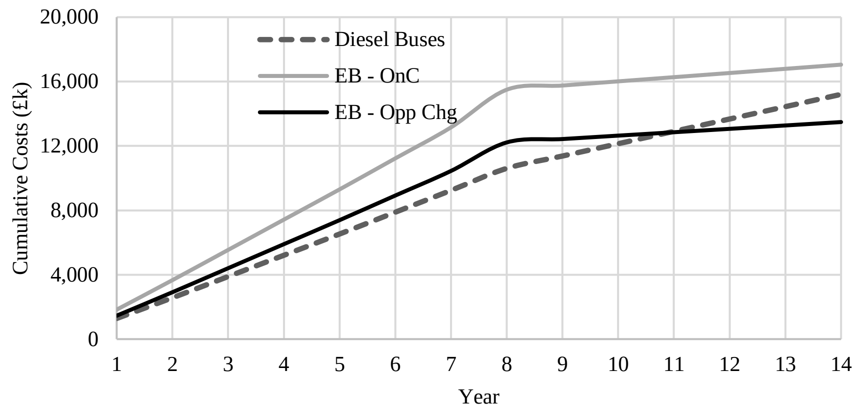

Figure 11: Cumulative costs for the bus depot in £k with electric heating on-board

The charging infrastructure for EB operations at the depot based on the entirely re-scheduled duty cycles involves two extra buses and slow chargers, based on the OnC approach. There is also an increase of £120k in labour costs due to the additional driver duties required for the extra journeys between the depot and the changeover points (Table 5). Such a system is again more expensive to run in comparison to a diesel system. It does not break even until approximately year 15, but it is financially more attractive than the OnC solution for the existing duty cycles (which break even in year 16). Hence, re-scheduled operations are further assumed in this study when the OnC solution is considered.

B. Sensitivity analysis

It is first assumed that the capital repayment period is increased to 14 years (instead of 7 years). The financial analysis shows that the lower annual spend on capital, combined with significant annual operating savings result in positive economic savings, relative to diesel from the first year of operation if the Opp Chg method is adopted. An electric system based on the OnC solutions is again more expensive than diesel operations.

In addition, the UK Office for Low Emission Vehicles (OLEV) ‘Ultra-Low Emission Bus Scheme’ [33] was considered which supports financially the shift towards ultra-low emission bus operations. The grant offers up to 75% of the cost difference between an ultra-low bus and diesel equivalent and 75% of the cost of the charging infrastructure. The analysis shows that an electric system (both Onc and Opp Chg) offers financial savings from the first year of operation over the conventional vehicle. The Opp Chg approach is financially more attractive than the OnC method.

An air quality economic analysis was also performed to quantify the impacts on air quality according to the Department for Environment, Food and Rural Affairs in the UK (Defra). The air quality economic benefits of an electric system over the diesel system were calculated using Defra’s “Air Quality Damage Costs Guidance” [34]. NOx damage costs vary according to the location and source of pollutant. For the “Transport Outer London” in particular, NOx damage costs stand at approximately £77.5k per tonne (2015’s figures).

In this study, it was assumed that diesel buses are responsible for 0.2 g of NOx emissions per km, according to a Transport for London (TfL) study which analyses in-service emission performance of Euro 6 vehicles using London drive cycles [35]. In addition, 20 g of NOx emissions were also included in the analysis for every litre of diesel used for diesel heating (DEFRA’s conversion factors obtained from [36]). The results of the air quality economic analysis show that the payback time for both OnC and Opp Chg is reduced by one year when compared to the results of an electric system) which does not include NOx damage costs.

Finally, higher cost assumptions are considered for some cost variables shown in Appendix because formal quotation have not been obtained from suppliers and the prices are location specific. The conservative cost figures for the basic and conservative scenario are shown in the last table in Appendix. The results show that the electrified system based on the Opp Chg and electric heating solution provides a financial savings in the 12th year of operation. This is essentially the same payback period as for the basic cost scenario, but a smaller financial saving is calculated over the entire life of the project. The overnight charging system does not break even until approximately year 15.

C. Financial Analysis Overview

Overall, the capital costs for the four electrification options, which are i) OnC with diesel heating on-board, ii) Opp Chg with diesel heating, iii) OnC with electric heating based on the re-scheduled operations and iv) Opp Chg with electric heating based on the existing operations are summarised in Table 7 for the Basic scenario (i.e. 7-year payment period without considering OLEV funding nor NOx damage costs). It is noticed that an electric system involves higher capital costs compared to a diesel system. Yet, significant operating savings are possible when shifting towards EBs. This is shown in second part of Table 7 where the annual total cost to run an electric system over the 14-year period (including capital, operating and maintenance costs) is smaller than the annual cost of a diesel system. An electrified system based on the OnC method (and electric heating on-board) is more expensive than the diesel system.

Table 7: Costs overview for the bus depot based on different electrification options

	Diesel	OnC - Diesel heating	Opp - Diesel heating	OnC - Electric heating	Opp - Electric heating
		Capital Costs (£k)			
Buses	4,032	7,944	7,800	8,606	7,800
Depot Infr.	0	398.5	108.5	174.5	108.5
Street Infr.	0	0	730	0	730
Total	4,032	8,342.5	8,638.5	8,780.5	8,638.5
		Annual Costs (£k/year)			
Capital	319	659	683	694	683
Operating	599	39	42	156	36
Maintenance	169	240	244	258	244
Total	1,087	938	969	1,108	963
		Overview for 14 years			
Battery (kWh)	-	250	138	250	138
Total Cost (£k)	15,218	13,132	13,566	15,511	13,482
Savings (£k)	-	2,086	1,652	-293	1,736
Payback (years)	-	11	12	NA	12
Savings (ktCO_2)[7]	-	33.2	33.2	33.3	33.8

The total costs to run bus operations for 14 years at the bus depot under investigation are summarised in third section of Table 7. The table does not include any financial support from low-emission schemes. Assuming that electric heating is required (last 2 columns of Table 7), it can be seen that the OnC system will cost £293k more than current diesel bus operations and so will never pay back financially. Conversely, the Opp Chg version will cost £1.7m less than the diesel and the investment will pay back in 12 years. If diesel heating is allowed (middle two columns in Table 7), the OnC solution could operate with a 250 kWh battery and no additional buses; a more feasible option. It would have a slightly shorter payback period than the Opp Chg scheme: 11 years instead of 12.

The impact of all of the electrification schemes on Carbon reduction would be a significant aggregated saving of approximately 33 ktCO_2 between 2019 and 2050. In practice, if the more advanced batteries were used

[7] Aggregate saving between the numbers calculated at 2019's norms and those calculated for 2050

on the Opp Chg vehicles[8], their mass would be lower, and their cost and carbon reductions would be greater than those shown in Table 7.

V. CONCLUSIONS

Electric bus operations for a bus depot in London were explored in this study. Operational data about speed, GPS coordinates and electric motor performance, were used to define accurate drive cycles and validate simulations of an electric bus. The resulting model was used to estimate the power requirements of electric buses over the defined drive cycles.

It was shown that electrification of the two bus routes based on OnC is a complicated solution. This is due to the fact that the capacity of the on-board battery (250 kWh) is not sufficient to perform all the duty cycles operated out of the bus depot. Scheduling adjustments, to enable fast charging at the depot during breaks and replacement of buses that run out of energy mid-service, are required to perform the existing operations. The financial analysis showed that such a system for the bus depot under investigation would be more expensive when compared to conventional bus operations using diesel buses by at least £293k over a 14-year life time.

An electrified system using the Opp Chg method would not involve any scheduling changes. Electric buses with 138 kWh on-board battery and electric heating could be used robustly on the same timetable as the conventional buses. It was shown that such a system would result approximately in £1.7 million savings over a 14-year life, compared to a conventional diesel system. The impact would be a significant aggregated saving of 48.2 ktCO_2.

VI. REFERENCES

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VII. APPENDIX: COSTS ASSUMPTIONS

Capital Costs			
Buses	£k	Notes	Source
Diesel	168	per bus	Bus manuf.
EB – 138 kWh	295	per bus	Bus manuf.
EB – 250 kWh	331	per bus	Bus manuf.
Wireless char. receiver	30	per bus	MK
Depot Infrastructure			
Slow smart chargers	5	Per 2 buses	Bus manuf.
Instal. of slow chargers	1	per unit	Bus manuf.
Losses - slow chargers	7%		
Fast chargers	50	per unit	Bus manuf.
Instal. of fast chargers	10	per unit	Bus manuf.
Losses - fast chargers	8%		
Grid Upgrade for OnC – 600 kW	100	Including a new substation	MK
Grid Upgrade for Opp Chg – 200 kW	40		MK
Opp Chg points			
Charger	0.85	per kW	MK
Installation	20	per unit	MK
Grid connection	35	per unit – average across locations	UKPN
Losses	10%		
Investment Loan			
Payment Years	7		
Interest rate	2.6%		

Operating Costs			
Fuel	£		
Diesel	1.00	per litre	Bus Oper.
Electricity	0.09	per kWh	MK
Battery Losses			
Slow charger	7%		[32]
Fast charger	8%		[32]
Charging point	10%		[32]
Subsidies			
Low Carbon Incentive	0.06	£ per km driven	Bus Oper.
Additional Costs			
Drivers	120	For extra journeys	Bus Oper.

Maintenance Costs			
Year 1, 2	2	per diesel/electric bus per year	Bus Oper.
Year 3, 4, 5	3.5		Bus Oper.
Year 6, 7, 8	5		Bus Oper.
Year 8 extra	27	per diesel/electr bus	Bus Oper.
Year 8 battery repl.	40	per electric bus	Bus manuf.
Year 9,10,11,12,13 & 14	7	per bus per year	Bus Oper.
Chargers maintenance	10%	annual spend on capital	

Capital Cost Variables	Basic Scenario (£k)	Conservative Scenario (£k)
Depot Infrastructure		
Installation of slow chargers	1	5
Installation of fast chargers	10	15
Grid Upgrade for OnC – 600 kW	100	150
Grid Upgrade for Opp chg – 200 kW	40	80
Opportunity Charging point		
Charger	0.85	1
Installation	20	40
Grid connection	35	75