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MODELLING THE ELECTRIFICATION OF ROYAL MAIL'S DIESEL VAN FLEET.

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Abstract

Electrification of Royal Mail's diesel van fleet is necessary to comply with the UK government's pledge for net zero carbon emissions by 2050. Various investment strategies are considered in order to find the most time and cost efficient solution. The main scope for optimisation is found in the charging infrastructure. Three parameter corner cases are derived, minimising charger expenditure, minimising electricity expenditure, and minimising the peak power drawn from the National Grid. A comparative cost analysis is presented during and after electrification, yielding the optimal charging method. Additional revenue streams and power generation methods were analysed and found to be infeasible ventures for Royal Mail at this time. A fleet conversion algorithm takes the price of an electric van and the optimal charging method to calculate the maximum number of vans that can be bought in any given year. The algorithm continues until electrification is complete, calculating any effects on Royal Mail's carbon dioxide emissions throughout. Provided with an annual budget of £50million, savings are reinvested on a yearly basis. The annual investment is then divided into electric vehicles and chargers to achieve full electrification in a 17 year time frame.

Contents

1 Introduction

Royal Mail is a UK based postal service founded in 1516 [1]. They deliver post every day except for Sundays and Bank Holidays [2], aiming to deliver all first-class post by the next business day [3]. They have 1,164 depots and deliver approximately 13 billion letters each year [4]. In the past, to deliver post house by house, Royal Mail used bicycles and postal workers on foot. With advancements in fuel-powered vehicles, delivery vans provide a large cargo hold for large amounts of post to be distributed in fewer trips. However, over the past five years, there has been an increasing movement towards sustainable fleet management for companies and organizations with large fleets. The managers of said fleets are generally required to optimise their operations to meet sustainability targets defined by ISO 14001 [5] or Corporate Social Responsibility programs. Electrification has been the fundamental aspect of this change and electric vehicles are emerging as a viable alternative to conventionally fuelled vehicles. Environmental regulations are only going to become more strict in the coming years, therefore a staged procurement strategy will enable them to effectively future-proof their operations and ensure business continuity.

Vehicle fleet electrification projects are becoming more prominent with the development of new electrical vehicles. An ongoing project, which inspired the model in this report, is the recent changes of Transport for London's (TfL) buses. To combat London's high carbon emissions, TfL has implemented 3,669 hybrid buses, 155 electric buses, and 10 hydrogen buses out of a total fleet of 9,142 [6]. This is a clear indication that it is now possible to convert fleets from conventional fuel-powered vehicles to electric. An analysis of the performance of bus operations for a bus depot in London is investigated in 'Techno-economic Analysis of Charging and Heating Options for an Electric Bus Service in London' [7]. In this report, the power requirements of electric buses over defined drive cycles are estimated using simulation. The drive cycles use operational data about speed, GPS coordinates, and motor performance to define these drive cycles. A key finding from this paper is that these changes created a financial saving of £1.7million over a 14-year lifetime in comparison to diesel-fueled buses. This report is significant to this study as it implies that conversion from diesel to electric vehicles has possible financial benefits as well as environmental. Similarly, this mirror focuses on the financial aspect of fleet conversion. One major focus of this study is to optimise the purchase of electric vehicle chargers and schedule vehicle charging to minimise cost. Royal Mail's predetermined shift schedule is a key constraint to the optimisation.

The analysis in this report aims to provide Royal Mail with an investment and savings strategy to electrify their fleet of small delivery vans. The main problem that comes with electrifying Royal Mail's small fleet is the economic viability of such a change. Electric vehicles have many advantages over conventional fossil fuel vehicles, seen in Section 2.1, however, the focus in this report is the economic aspect. This change needs to have a clear financial benefit to be considered over the current state. To achieve this, different corner cases are studied and optimised for a particular depot over the purchase of electric vehicles and maintenance, along with the purchase of charging facilities. An increase in electric vehicles implies an increased demand for electrical power from the National Grid which is also considered in the model.

2 Background Information

2.1 Electric Vans

Electric vans are better for the environment in comparison to their diesel counterparts as they do not release greenhouse gases when in use. They also produce less noise pollution, as the engine on an electric vehicle is quieter than that of a fuel-powered vehicle [8]. Electric vehicles are often more expensive up front, but the maintenance costs are far lower, thereby making them a cheaper investment than the current diesel fleet over time [9]. The upfront cost of electric vehicles is likely to decrease through product innovation. A large disadvantage of electric vehicles is the range of limitation. The average range for an electric vehicle is 100 miles which, smaller than that of a diesel van [10]. Although, similarly to the cost disadvantage, as technology improves, so will the range.

2.2 Chargers

To solve the problem of comparatively small range of electric vehicles, electric charging stations are used. Chargers are used domestically, commercially, and publicly and are separated into three categories - slow, fast, and rapid. A charger's type is defined by its power output and, in turn, the rate at which its able to charge a vehicle. Slow chargers have a power output of approximately 3kW and can take 8-12 hours to charge an electric vehicle fully [11]. These are typically used for charging vehicles overnight. Fast chargers are similar, however the power output varies from 4-22kW, meaning that a high powered fast charger could potentially charge a 40kWh electric vehicle in 1-2 hours [11]. They cost around £1,000 each [4]. Rapid chargers have a power output of 50kW or higher and are usually installed for commercial or large-scale use because of their high cost. Their minimal charging time (of as little as 20 minutes for an 80% charge) make them ideal for businesses using vehicles that travel a considerable distance in a day, or that need to be sent on routes multiple times a day. The drawback of rapid chargers is their expense; they can cost more than 15 times as much as a fast charger. Additionally, frequent use of rapid chargers can increase battery degradation reducing the lifespan of an electric vehicle, and therefore, increasing cost of maintenance in the long term. Although theoretically, the higher the power output is, the faster an electric vehicle will charge, each model of electric vehicle has a maximum power input for an AC or a DC charger. This means that regardless of the of the power of the charger, an electric vehicle will be limited to minimum charge time. To ensure a fleet of electric vehicles is effective for Royal Mail and their unique route schedule, charging is an essential factor to consider.

2.3 National Grid

The National Grid is the operator of the United Kingdom's electricity and gas supply. Distribution Network Operators (DNO) of the National Grid are responsible for transferring electricity from the transmission lines to the consumer and each DNO operates a different area of the country. Substations are a key component of distribution as they step down the voltage from transmission lines and make it suitable for consumption. Substations are built with an upper limit to the amount of power they can distribute. The DNOs ensure the limit is not surpassed by monitoring the power installations in a particular substations catchment area. Monitoring is done through DNO applications which the consumer (in this case Royal Mail) sends off for approval before creating a new development. The figure for power requirement is taken as the maximum power demand the installations will draw from the National Grid [12] . The fast and rapid chargers described above are very power intensive so there is potential to breach the substation upper limit and therefore it is important to find a combination of these chargers which ensures that this limit is not surpassed. The limit differs depending on location so presenting a range of options equips Royal Mail with a method for every scenario.

2.4 Carbon Dioxide Emissions

One of the main motivations of fleet electrification is to reduce carbon dioxide (CO_2) emissions. This is inline with the UK governments target to reduce net CO_2 emissions to zero by 2050 [13]. A necessary step is converting to electric vehicles, which do not require the burning of fossil fuels to operate. Therefore, if the electric vehicles are run on 100% zero-carbon electricity the operational CO_2 output would be zero.

The CO_2 statistics quoted in this section come from the Department for Business, Energy and Industrial Strategy's report for 'Updated energy and emissions projections 2018' [14]. Currently, around 45% of the electricity generated in the UK comes from fossil fuels but this number is declining fast. CO_2 emissions from major power producers were projected in 2019 to fall 80% between 2010 and 2020. This trend is expected to continue, with the total CO_2 emissions from power generation expected to fall from 170 gCO_2e/kWh (grams of CO_2 emissions equivalent per kilowatt hour of generation) in 2017, to 41 gCO_2e/kWh in 2035. The aforementioned government document does not provide data for the yearly reductions but a figure found on page 35 indicates a roughly linear trend between 2017 and 2035. The linear trend is interpolated and used to approximate CO_2 emissions throughout the electrification process, see Section 3.6.

3 Modelling and Results

Of the 1,164 UK Royal Mail depots, 7% are in rural areas and 93% in urban areas [4]. The depots are either small, medium or large with the number of vans in each centre being 18, 32, and 120 respectively. Each diesel van will be replaced by at least one electric van. Depots of each size, in both urban and rural areas, are modelled and the optimal financial strategy for fleet conversion is derived. The optimal strategy converts the diesel fleet to an electric one in the shortest possible time without surpassing the specified budget. Once converted, the fleet has a far lower running cost so achieving this in the shortest possible time saves money over an extended period. The CO_2 emissions for each approach is calculated but this figure does not have weight in the optimal strategy calculation.

The depot distribution above tells us that roughly 88% of all Royal Mail depots are medium sized and also located in an urban area [4]. The second most common intersect consists of small depots in urban locations, representing around 7.76% of all depots. For this reason, the most significant results lie in analysing the behaviour of the former as the process of electrification takes place. The fleet conversion algorithm that was chosen for this process was one that minimises electricity expenditure (MEE), seen in Section 3.3.2. The MEE method was found to minimise investment on electricity by utilising the Economy 7 scheme [15]. This was achieved by increasing power usage at off-peak times in order to lower costs, seen in Figure 2.

Implementing the MEE fleet conversion algorithm initiates a 17 year process, seen in Figure 6, where implementation in 2021 would lead to the conclusion of the electrification of Royal Mail's diesel fleet taking place in 2038. This provides Royal Mail with a relaxed window in which to carry out proceedings, with the deadline of completion being 2050 in accordance with UK government guidelines [13]. If the DNO application for a particular depot is rejected, a modified approach is necessary to ensure the fleet can still be fully electrified. Solar installation, National Grid reinforcement and an increase in the number of vans in the depot are all presented as options.

3.1 Investment and Savings Strategy

The strict government guidelines influence a change in the usual Royal Mail savings strategies. Savings from the conversion will be reinvested to ensure compliance, rather than paying dividends to shareholders. However, the project is non-integrated with other ongoing Royal Mail dealings, therefore in all other cases Royal Mail will behave in the usual manner.

An annual input of £50million has been assigned across Royal Mail to support the electrification of its entire fleet, where each depot receives an allocation equal to the proportion of vans it holds in comparison to the total number of Royal Mail vans [4]. Small, medium, and large depots hold 18, 32, and 120 vans respectively, where the total number of Royal Mail vans is 37,300 [4]. Therefore, the annual initial budget for each size of depot is £24,128.69, £42,895.44, and £160,857.91. The savings per annum are calculated using the money left over after investment plus the net saved in maintenance and running costs. As electric vehicles (EVs) are bought, an equal number of diesel vans can be sold, and the net saved in maintenance costs is defined as the difference between the fuel and maintenance costs of n diesel vans, and the electricity and maintenance costs of n EVs (including the chargers that sustain them). At the start of each financial year, the previous year's savings are added to the annual input to make the net annual investment. This value is used to purchase new EVs, install EV charging stations, and cover the maintenance and electricity costs for both. The method of electrification is carried out in accordance with a predefined fleet conversion algorithm, seen in Section 3.5.

3.2 Additional Costs of Diesel and Electric Vans

To calculate the savings over a financial year, running and maintenance costs for the fleet were incorporated. This includes calculating the maintenance costs of both diesel and electric vehicles, as well as the costs of diesel and electricity.

3.2.1 Maintenance Costs

Maintenance costs of EVs can be up to 23% less than those of diesel vehicles [16]. The number of moving parts in an electric motor is significantly less than the number in an internal combustion engine, meaning fewer parts need to be replaced. Regenerative braking also allows less strain to be put on the brakes and therefore they have to be replaced less frequently. For a fleet of approximately 40,000 vans (as needed by Royal Mail), all of which travelling more than the average distance, the maintenance costs can have a significant impact on cost analysis. Initially, a set value was given for maintenance costs for the average electric vehicle per year. This provided an approximation based on the fact vehicles travel an annual average distance of 7,134 miles [17]. Each Royal Mail van travels 24,000 miles a year on average - over 3 times the national average. To overcome this problem, the cost for maintenance and repairs was calculated per mile that the vehicle was expected to have driven. An electric vehicle driving 60,000 miles over the course of a three year period has an average maintenance cost of £1,200 to £1,400 [18]. The cost of maintenance and repair for an electric vehicle per mile driven (C_{mr}) is calculated below:

$$C_{mr} = \frac{£1,400}{60,000 \text{ miles}} = £0.023/\text{mile}. \tag{1}$$

To avoid unexpected costs, as these values are not specific to any model of EV, the higher bound of the range was used in calculations for a conservative estimate. To find the maintenance cost for each electric vehicle in the fleet at any moment in time, C_{mr} was multiplied by the expected distance travelled by that vehicle from the time of purchase. Warranties were not considered as they can vary for commercial vehicles. The assumption was made that the maintenance cost per mile does not vary over time and can be taken as a constant value.

The average maintenance cost for each vehicle in the current fleet of diesel vans (which consists of Peugeot Experts, Vauxual Vivaros, and Ford Transit Customs) was calculated. Given that the number of vans of each type in the fleet are unknown, the assumption that there is an equal number of each type is made. The maintenance cost per mile of each van (£0.025, £0.024, and £0.035 per mile driven [19]) is averaged to find the final value used in the model; £0.028 per mile driven. As for the maintenance cost of an electric vehicle, this value is assumed to remain constant.

3.2.2 Running Costs

The cost of charging an electric vehicle with electricity varies due to type of vehicle, type of charger used, and time of day when said vehicle is being charged. This model uses the Economy 7 scheme which prices electricity at £0.153/kWh in peak hours and £0.087/kWh in off peak hours [20]. To calculate the cost of charging a vehicle is to multiply the number of kWh's used by the hours taken charging multiplied by the price at that hour.

As of the 1$^{\text{st}}$ May 2020, the average price of diesel fuel in the UK is £1.17/L [21]. The price varies by approximately £0.10 depending on location in the UK. Diesel fuel in Sunderland costs £1.14/L whereas in West London it costs £1.24/L [21]. However, due to the COVID-19 epidemic, both petrol and diesel costs have dropped substantially as the UK has been under lockdown, therefore the population are not driving as much as travel is prohibited. This can be seen as on the 27$^{\text{th}}$ January 2020 diesel cost £1.33/L, where on the 27$^{\text{th}}$ April it cost only £1.15/L [22]. The fuel cost of running a diesel van fluctuates as fuel prices rarely stay stagnant. Both petrol and diesel follows the fluctuations of crude oil; the global price of crude oil reduces, so does petrol and diesel. There are other factors that impact the cost of fuel such as the fuel duty (currently £0.5795/L), pound to dollar exchange rate, and valued-added tax (VAT, currently 20%) [23]. Fuel duty plus VAT means the lowest possible price of fuel even if the fuel itself cost nothing would be £0.6945/L [23]. The highest price recorded in recent history was on 13$^{\text{th}}$ April 2012 where diesel fuel cost £1.4793/L. For this model, the price of diesel has been set to £1.30/L. This decision was made as it is similar to the price in January, before much of the COVID-19 situation had impacted the UK. It was also chosen as fuel prices in general increase over time, as seen between 2006 to 2012 [24], and £1.30/L is on the higher end of fuel prices, allowing an increase in price over the time-span.

3.3 Charger Implementation

The electricity expenditure and charging times presented in this study assume all electric vans return to the depot with no charge left in the battery. This assumes the worst case scenario for both variables and so prepares Royal Mail for maximum charging time and electricity expense. This study uses Mercedes E-vito vans as the model vehicle which can drive a minimum of 93 miles per charge. Data from Royal Mail suggests the average shift is 65.7 miles long [4]. Royal Mail were unable to disclose shift length distribution data and so this study assumes no van exceeds 93 miles in one shift.

Royal Mail's shift scheduling dictates that 90% of the vans in a depot must carry out the morning shift (6am - 2pm) and 25% must carry out the afternoon shift (2pm - 10pm) [4]. Therefore, 15% of the vans must be charged between shifts. Alternatively, the approach of buying 15% extra vans is also considered, seen in Section 3.3.3. Even though each shift is 8 hours long, vans are only driven for 6 of these. Therefore, there is a maximum of 4 hours where vans are in the depot in the working day (which runs from 6am - 10pm). Fast chargers are not adequate for charging vehicles between the shifts as these take 6 hours to charge the EVs. Rapid chargers can charge the EVs in around 40 minutes. Three 55 minute charging slots using the rapid chargers are scheduled between shifts, from 12:30pm to 3:15pm. The extra time allocated for each charging slot accounts for charger turn over time between vans. Three charging slots are allocated to minimise the number of rapid chargers that need to be purchased. The number of rapid chargers needed to charge 15% of the fleet between shifts is

$$N_r = \left\lceil \frac{\lceil N_{EV} \times 0.15 \rceil}{3} \right\rceil, \tag{2}$$

where N_r is the number of rapid chargers, N_{EV} is the number of electric vans in the depot and the $\lceil x \rceil$ function represents rounding up to the nearest integer. The necessity to charge between shifts sets this value of N_r as a constraint. From this constraint two parameter corner cases are considered. The first, minimises the expense on chargers. The second, minimises the cost of electricity. The long term savings of each method is calculated in Sections 3.3.4 and 3.3.5. The results for the modal depot type (a medium sized depot with 32 vans) are presented. Despite this, the methods outlined are scalable to any size of depot and are applicable across the whole Royal Mail fleet.

3.3.1 Corner Case One: Minimising Charger Expenditure (MCE Method)

A medium sized depot with 32 vans requires 2 rapid chargers, calculated using Equation 2. After charging 15% of vans between 12:30pm and 3:15pm, 90% of the fleet must now be charged ready for the morning shift at 6:00 am the next day. 90% of 32 is 28.8 which is rounded up to 29. Each charging slot is 55 minutes long and there is 14 hours and 45 minutes between 3:15pm and 6:00 am. The number of charging slots available is defined by

$$\text{Charging Slots} = \left\lfloor \frac{(14 \times 60\text{mins}) + 45}{55} \right\rfloor, \tag{3}$$

where $\lfloor x \rfloor$ represents rounding down to the nearest integer. Equation 3 yields a value of 16. Two rapid chargers could charge 32 vans in this time, when only 29 vans are needed. Therefore, it is possible to charge the entire fleet with only two rapid chargers. Each rapid charger costs £15,000 giving a minimum expense of chargers to be £30,000 using Equation 4 below:

$$\text{Minimum charger expense} = N_r \times 15,000. \tag{4}$$

3.3.2 Corner Case Two: Minimising Electricity Expenditure (MEE Method)

The most common way to price electricity is at a flat rate throughout the day (24 hours). However, many suppliers offer the Economy 7 scheme which prices electricity differently depending on the time of day [20]. Energy is more expensive than the flat rate alternative at peak times but cheaper than the flat rate at off peak times. The hours of the day which fall in either pricing bracket vary depending on the supplier [15]. Off peak times is taken as between

12:00am and 7:00am in this study. Aside from the necessary charging between 12:30pm and 3:15pm, this corner case considers the long term savings of carrying out all other charging between 12:00am and 7:00am. The following optimisation problem minimises the expenditure on chargers while operating under the time and charging constraints. The objective function to minimise the expenditure on chargers is

$$\min\{N_f + 15N_r\}, \tag{5}$$

where N_f is the number of fast chargers, and N_r remains the number of rapid chargers. The constraints are

$$N_r \geq 2, \quad 7N_r + N_f \geq 32. \tag{6}$$

The second constraint is derived from the necessary charging of 32 vans in the 7 hour window between 12:00am and 7:00am. Every N_r can charge 7 vans in this window and every N_f can charge 1 van in this window. The sum of vans that can be charged must be equal to or greater than 32. The optimisation problem is solved using the graphical methods shown in Figure 1. The optimal ratio of the two types of charger is 18:2 for N_f:N_r. The value of N_r indicates that increasing the value of N_f to a maximum and only purchasing the minimum required rapid chargers is optimal. The cost of chargers for the MEE method is £48,000.

3.3.3 Corner Case Three: Minimising National Grid Power (MGP Method)

A third corner case considers purchasing 15% more EVs. This case reduces the maximum power that is drawn from the National Grid to a minimum value and so could be employed if the feedback from the DNO application restricts other methods being implemented. In the case of medium sized depots, 15% of the the 32 electric vans is 4.8, which is rounded up to 5 thus 37 vans are required. An additional 15% of EVs prevents the previously necessary charging between 12:30pm and 3:15pm and therefore the purchase of rapid chargers. Each fast charger can charge 4 vans in a 24 hour period meaning a minimum of 10 fast chargers are required to charge 37 vans in one day. 10 fast chargers also allow Royal Mail to operate under the constraint that 29 vans must be charged by 6:00am and 8 vans must be charged by 12:00pm. This method significantly reduces the maximum power drawn from the National Grid. Therefore, the long term cost analysis of this method is presented.

3.3.4 Cost Analysis of Charger Implementation Methods After Complete Electrification

The power drawn from the National Grid over a day for each of the three methods previously described is given in Figure 2. Each method's power consumption is shown after the fleet has been fully electrified. The graph corresponds to a medium sized depot. The MEE method uses the maximum amount of electricity between 12:00am and 7:00am. The only energy used outside this period is used to carry out the necessary charging between 12:30pm and 3:15pm. The MCE method carries out the same charging as the MEE method in the 12:30pm to 3:15pm window but has less flexibility outside of it. This results in a large percentage of electricity being used at peak times. The MGP method has an almost constant draw from the National Grid at all times. The only fluctuation is caused by N_f not dividing N_{EV} to make an integer. Therefore, marginally more power is drawn during off peak times to minimise cost.

The price for peak and off peak power is taken as £0.153/kWh and £0.087/kWh respectively. Additionally, the price for flat rate electricity is given is £0.138/kWh. These prices are the average rates available on the market for the Economy 7 scheme [25]. Integrating under the the lines shown in Figure 2 gives the energy used. The integral between 7:00am and 12:00am gives the peak energy used for each method. Integrating between 12:00am and 7:00am gives the energy used at off-peak times. The data for each method is provided in Table 1 alongside the total electricity expenditure in one day and charger expenditure for each method. Here it is shown the MEE method requires the least expenditure on electricity. The MEE method is £45.56 cheaper than the MCE method and £60.15 cheaper than the MGP method per day. Conversely, the MEE method involves spending £18,000 more than the MCE method and £38,000 more than the MGP method on chargers. However, the savings on electricity over two years results in a greater net saving in the MEE method compared to the MGP method. When comparing the MEE and MCE methods, the time period for a net saving is only one year and three months. Therefore, when the fleet has been fully electrified the MEE method will quickly pay back the added expense needed for chargers, providing superior savings in the long term.

3.3.5 Cost Analysis of Charger Implementation Methods During Electrification

The algorithm discussed in Section 3.5 divides the yearly budget for a given depot by the price of an electric vehicles to calculate the upper limit of the number of EVs that can be bought in a given year. The added expenditure on chargers and electricity needed to support the increase of the number of EVs is calculated. This expenditure is minimised by purchasing chargers at the right time in order to prevent electricity being used at peak times. This is done so in the MEE and MCE methods. Evidence of minimising expenditure throughout the electrification process can be found in Figure 3. Figure 3 shows the MCE method for a medium sized depot in which two rapid chargers are needed to run a fully electric fleet. The spikes in yearly investment found in years 1 and 7 are from the purchase of a rapid charger. One rapid charger can charge 7 EVs during off peak times and in year 7 the 8$^{\text{th}}$ EV is bought. Therefore, to avoid using electricity at peak times a second rapid charger is bought in year 7. The MEE model performs the same action during the 13$^{\text{th}}$ the 15$^{\text{th}}$ year as seen by the spikes in the bar chart.

The three models return the expenditure on chargers and electricity needed to support the increase of the number of EVs in the depot from one more EV, to the upper limit of additional EVs calculated in the aforementioned algorithm. From this, the greatest number of EVs that can be purchased are added to the fleet of existing EVs. The process continues until the entire fleet has been electrified. Figures 3 and 4 show the MEE method plotted against the MCE and MGP methods respectively. The bar chart ends when the entire fleet has been fully electrified, which is 17, 18 and 20 years for the MEE, MCE and MGP methods respectively. The area under the charts show the total expenditure of each method to fully electrify the fleet. By inspection, this is considerably lower for the MEE method than both the MCE and MGP methods. The final bar for each method shows the total expenditure for running the fully electric fleet. The charts show this number is significantly lower in the MEE method than both other methods. Additionally, Table 1 consolidates this fact. Therefore, the MEE method is optimal during and after the electrification process and so is the correct method to implement. Table 2 details the charging and shift schedules for a medium sized depot employing the MEE method, after full electrification. The numbers 2 and 18 in the 'Number of Vans Charging' column are equal to N_r and N_f for the given depot size (Section 3.3.2).

Royal Mail could avoid installing rapid chargers by making use of the growing network of publicly available rapid chargers. However, the network is still in the early stages of development and so we assumed the depot would not have reliable and sufficient access to a rapid charger station. Access to a rapid charger station may save additional funds but the availability of a station is unknown and so is not included.

3.4 Minimising Electricity Expenditure with Solar Power

The optimal solution for converting fleets of diesel vans to electric vans is detailed above but does not factor in the substation upper limit being surpassed. In most scenarios, if the limit is exceeded, there is the option for the applicant to pay to reinforce the National Grid. An assumption has been made that the cost of reinforcement will be significantly larger than the cost of any solution to reduce the maximum power output. For any given limit of maximum power output, the viable solutions for charging the vehicles throughout the day can be found in Figure 2. The lines whose peak fall below the limit are the viable solutions, and if all solutions have a peak above the limit value, then the fleet cannot be charged without needing to reinforce the threshold. The model does not account for this eventuality as the cost of reinforcing the National Grid varies significantly depending on the area and so there is no accurate way to model reinforcement. Solar energy provides an alternative power source to avoid paying to reinforce the National Grid.

The median solar panel cost in 2019 was £1,078/kW of generation capacity [26]. Moreover, each kW of solar panel will generate around 900kWh of electricity annually and has a lifespan of about 25 years [27]. The price of solar energy per kWh can therefore be calculated as approximately

$$\text{Solar Energy Generation Cost (£/kWh)} = \frac{£1,078}{900\text{kWh/year} \times 25\text{years}}, \tag{7}$$

yielding £0.048/kWh. This is £0.038/kWh and £0.104/kWh cheaper than the off peak and peak rates respectively. However, because the best method for vehicle charging (MEE method) involves using 86.5% of electricity at night (when no solar energy is being produced), implementing solar panels would involve more charging at peak times. Any electricity which is drawn from the National Grid at this point costs £0.066/kWh more than it would otherwise. To avoid this, enough solar panels must be purchased to ensure they can fully facilitate the required charging needs. If less energy is produced than is needed £0.153/kWh must be paid.

If more is generated than needed, electricity must be sold back to the National Grid. As of May 2019 this is not a cost effective practise as solar energy export and generation tariffs where scrapped [28]. The new scheme, named the 'Smart Export Guarantee', obligates licensed electricity suppliers to offer a tariff to small-scale low-carbon generators for electricity exported to the National Grid [29]. The only company so far to do is is Octopus Energy, which offers a fixed rate of £0.055/kWh and a flexible rate which depends on day ahead wholesale prices [30]. This study uses Octopus Energy's flat rate figure as it is the only case of this scheme in existence today. Therefore, under-generating is 278% more expensive than over-generating is rewarding. The best case scenario assumes the exact power demand is meet resulting in the best possible payback time. Royal Mail operates 312 days of the year and saves £0.087/kWh of solar produced, on Sundays they are selling back to the National Grid and receiving £0.055/kWh. The payback time is therefore

$$\text{Payback Time (years)} = \frac{\pounds 1,078}{\frac{312}{365} \times 900\text{kWh/year} \times \pounds 0.087/\text{kWh} + \frac{53}{365} \times 900\text{kWh/year} \times \pounds 0.055/\text{kWh}}, \tag{8}$$

yielding 14.5 years. Therefore, the best case scenario would start saving money after 14.5 years. Despite this as shown in Figure 12 the electrification process is now extended to 19 years. This makes the implementation of solar questionable even in the best case scenario. Furthermore, given the large fluctuation between winter and summer in terms of daylight hours, the probability of anything close to the best case scenario is virtually zero. Therefore, the solar scheme will mean electrification will take longer, and likely be more expensive. For these reasons the installation of solar power to supply electricity to EVs has not been included in our modelling.

3.5 Fleet Conversion

The overview of the savings and investment strategy is visualised in Figure 5. In the first year, the investment limit is the initial annual input evaluated in Section 3.1, as no savings have been made through electrification as of yet. Here, an electric van is purchased, alongside a fast charger to sustain it. From this point onwards, money is saved annually as the maintenance costs of the electric vans are less than those of the current diesel vehicles. The sum of the initial annual input and the previous year's savings is the new investment limit. Each bar in the bar chart (Figure 5) then represents how much of this new limit is spent on new EVs and chargers, after the electricity costs of the current fleet are covered. The annual net investments vary due to the number of EVs and chargers bought fluctuating between each year. However, the general trend of the graph shows net investment to increase over time. This occurs as although the contributions from Royal Mail remain the same, their savings increase over time as more of the diesel fleet is electrified.

A medium sized Royal Mail depot in an urban area currently holds 32 diesel vans and no EVs. The aim of the process with the chosen algorithm is to maintain the total number of vehicles, converting all diesel vans to EVs. This transition is visualised in Figure 6. Initially, the net investment can only purchase one vehicle a year for a medium sized urban depot, with a small portion left over as savings. As this savings pot builds, eventually a second EV can be bought in one year, first seen in year 5. The frequency at which two EVs can be purchased in a year then increases as savings increases over time with electrification. This phenomenon is shown in the graph as the increasing gradient of the electric cars plot.

The MEE method (Section 3.3.2) to minimise investment on electricity provides an optimum strategy in the purchasing of chargers. Figure 7 details how the number of chargers owned of each charger type changes over the 17 year process. The number of fast chargers grows proportionally with the total number of EVs in the depot until year 12, when there are 18 fast chargers and 18 EVs. After this point, the number of EVs exceeds the amount that can be charged efficiently by fast chargers at off-peak hours, and rapid chargers are purchased to combat this.

The behaviour of Royal Mail as a whole can be seen to be similar to that of the most common depot, and occurs in the same timeframe. Having modelled for all possible Royal Mail depots, plots were produced for the entire Royal Mail fleet, in Figures 8, 9 and 10. The same behavioural patterns are shown here, however the results appear generalised without noise and fluctuation. This is due to variations in the number of EVs bought in a single year being relatively insignificant in comparison to the entire fleet. Therefore, the trend of the investment strategy can be seen for the company as a whole.

3.6 Carbon Dioxide Emissions

The Department for Business, Energy and Industrial Strategy's report for 'Updated energy and emissions projections 2018' shows that the carbon intensity of the National Grid is decreasing [14]. In 2017 the carbon intensity of the National Grid was 170 gCO_2e/kWh (grams of carbon dioxide equivalent per kilowatt hour of generation), which is projected to decrease to 41 gCO_2e/kWh in 2035. Linearly interpolating between these two points provides an estimate for carbon intensity on a yearly basis. Multiplying the gCO_2e/kWh by the number of kilowatt hours consumed in a depot yields the CO_2 output of all the EVs in the fleet. This is summed with the CO_2 output of the diesel fleet to achieve the total fleet CO_2 output.

As previously mentioned in Section 3.2.1, there are three different models of diesel van in the Royal Mail fleet with an approximately equal number of each. The CO_2 output of each van, for each mile driven, was found and an average was calculated to be 0.185kg/mile [31]. Multiplying the averaged CO_2 emissions figure by the total miles driven by diesel vans in one year achieves the total emissions from diesel vans. The sum of emissions from both EVs and diesel vans from across the whole Royal Mail is shown for the 17 years taken to fully electrify the fleet in Figure 11. Year 0 on this graph is taken as 2021, with the final year being 2038. The projections for CO_2 emissions found in the aforementioned government document terminate in 2035. The carbon intensity of the National Grid is assumed to be constant for the final three years of electrification. Given the negative trend in carbon intensity displayed by the projections, a constant rate from 2035 to 2038 is deemed a modest approximation. Figure 11 shows a parabolic decrease in CO_2 emissions. The trend is explained by the parabolic decrease of diesel vans shown in Figure 9. The final year of Figure 11 shows a gradient increase, explained by the fewer diesel vans that are replaced in the final year, shown in Figure 9. Overall, Figure 11 shows a reduction from 162.5kt to 35kt over the course of the fleet electrification. The remaining 35kt will be reduced to zero by the complete de-carbonisation of the National Grid, which is targeted for 2050 [13].

4 Discussion

4.1 Alternative Solar Energy Usages

Although solar energy has been incorporated into the model to mitigate the power taken from the National Grid for charging the EVs, solar panels could also be installed to power the lighting and heating inside the depot. An example of where this change has been successful is South Croydon station in London. The installation of 42 photovoltaic (PV) solar panels has aided the CCTV and lighting energy requirements [32]. Alternatively, photovoltaic-thermal (PV-T) hybrid panels could be used to provide a direct source of electricity and heat. A cost model is needed to explore whether PV-T panels are financially viable or whether conventional PV panels are more suited to Royal Mail's depot and depots. Unfortunately, Royal Mail where not able to disclose their electricity requirements so modeling PV-T or PV installation for this use is not possible in this study.

4.2 Alternative Revenue Streams

Vehicle-to-grid power is a new technology which allows EV owners to sell electricity back to the National Grid during periods of high demand [33]. This could mean a potential additional income for Royal Mail, however, battery degradation occurs after many cycles of charge and discharge increasing the maintenance costs. The Mercedes eVito vans only have a range of 96 miles and so maintaining the capacity of the battery is a concern. Additionally, vehicle-to-grid charging is a technology in its infancy and so deploying it on a national level is unrealistic at this stage. Despite this, the technology could induce a considerable revenue stream for Royal Mail so we advice they are aware of this during the electrification process.

Demand side response (DSR) incentives gives opportunities to large consumers of electricity [34]. Renewable energy accounts for a growing percentage of electricity generation in the UK. Technologies such as wind and solar power are temperamental in their outputs, meaning the supply capacity of the National Grid can change on a daily basis. To mitigate this problem, large consumers of electricity can sign up to DSR incentives schemes which allow their supplier to fluctuate the power draw if necessary. These schemes could provide a new revenue stream in future but are not developed enough to consider at present.

4.3 External Factors Mitigation

The investment strategy assumes Royal Mail is able to work at full capacity over the 17 year period, maintaining the annual budget of £50million. In practice, external factors impact the ability of a business or investment to achieve its strategic goals and objectives. The current COVID-19 pandemic is an appropriate example of such an external factor. Royal Mail are 'open for business', however they are experiencing increased levels of employee absence due to illness and self-isolation [35]. This has resulted in a reduced service [36], therefore, work is no longer being carried out at full capacity. The advice to Royal Mail to mitigate unforeseen crises would be to initiate the implementation of the 17 year electrification process at their earliest convenience, as any setbacks would still allow a great deal of time for completion before 2050.

5 Conclusion

This study offers Royal Mail a detailed and thorough investment strategy to electrify their fleet of small delivery vans. Correspondence with a Royal Mail representative [4] provided a number of bespoke assumptions for the model, while all algorithms used in the design of the model were built to fit around the current daily structure of Royal Mail's work. Therefore, all results produced are custom-made to Royal Mail's needs and represent a realistic approach in how Royal Mail could electrify their diesel fleet before 2050 [13]. The investment strategy is supplied for Royal Mail as a whole (Figure 8), showing how much is to be invested annually and how to treat any savings from a financial year. Furthermore, how to invest this money is detailed (Figures 9 and 10). In addition to the overview, Royal Mail has small, medium, and large depots, in urban and rural areas. The model allows Royal Mail to specify the location and size of an individual depot and view the investment strategy on a micro-level in the same way they would for the company as a whole. From this, Royal Mail can set annual goals in which to follow, where adhering to the guidance sets them up for a comfortable transition into the carbon net zero era.

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A Appendix

A.1 Tables

Charger Implementation Method	Electricity used at Peak Times (%)	Electricity used at Off Peak times (%)	Total Electricity Expenditure in one Day (£)	Total Expenditure on Chargers (£)
MEE	13.5	86.5	146.92	48,000
MCE	58.7	41.2	192.48	30,000
MGP	73.0	27.0	207.07	10,000

Table 1: *Table showing energy usage at peak and off peak times for three charger methods employing the Economy 7 scheme. The total electricity expenditure and total charger expenditure for the three methods is given.*

Time	Vans in the depot (%)	Vans out Doing Deliveries (%)	Number of Vans Charging
06:25	90	10	0
–	90	10	0
12:30	75	25	2
–	75	25	2
15:30	75	25	0
–	75	25	0
21:00	100	0	0
–	100	0	0
00:00	100	0	2 + 18
–	100	0	2 + 18
06:00	85	15	2
–	85	15	2

Table 2: *Table showing the distribution of electric vans in and out of a depot on an average operational day at a medium sized Royal Mail depot, when employing the MEE method. The number of vans charging in the depot at any time is also detailed.*

A.2 Figures

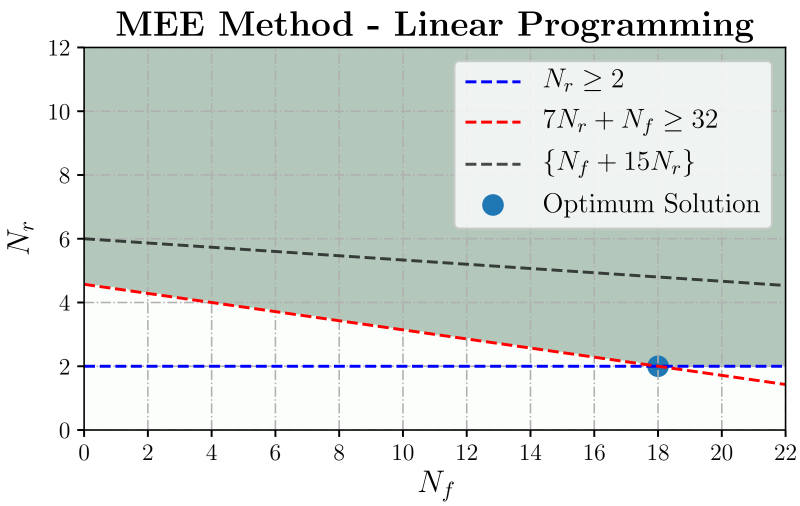

Figure 1: *Linear programming plot visualising how the optimal solution for the MEE method was found.*

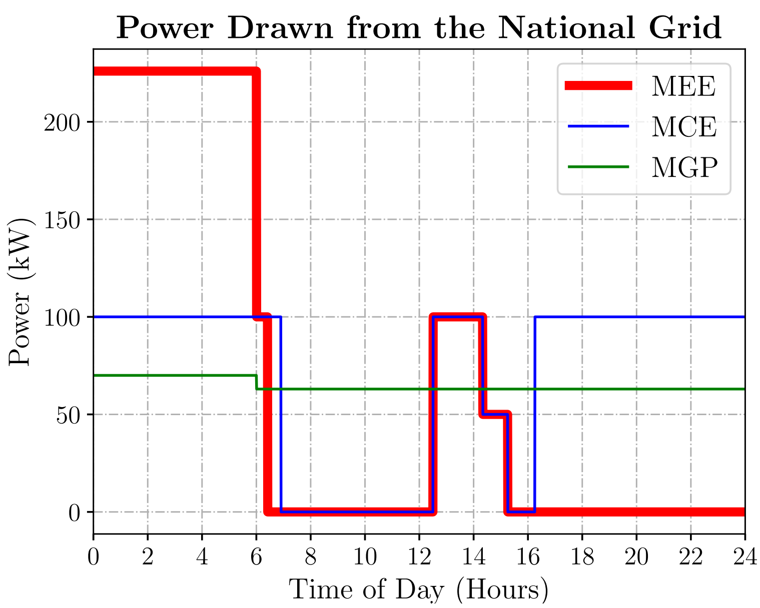

Figure 2: *Graph showing the power (kW) drawn from the National Grid over a day for each of the 3 proposed charger implementation methods. Daily activity remains the same over a year.*

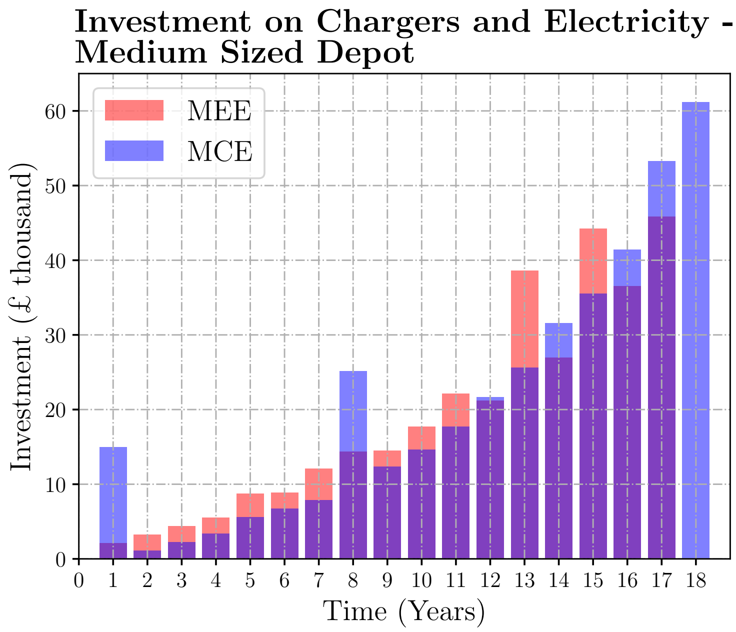

Figure 3: *Bar chart showing the annual investment (£ thousand) spent on chargers and electricity for the MEE and MCE methods. This chart represents the planned expenditure for a medium sized depot, the depot location does not affect this chart.*

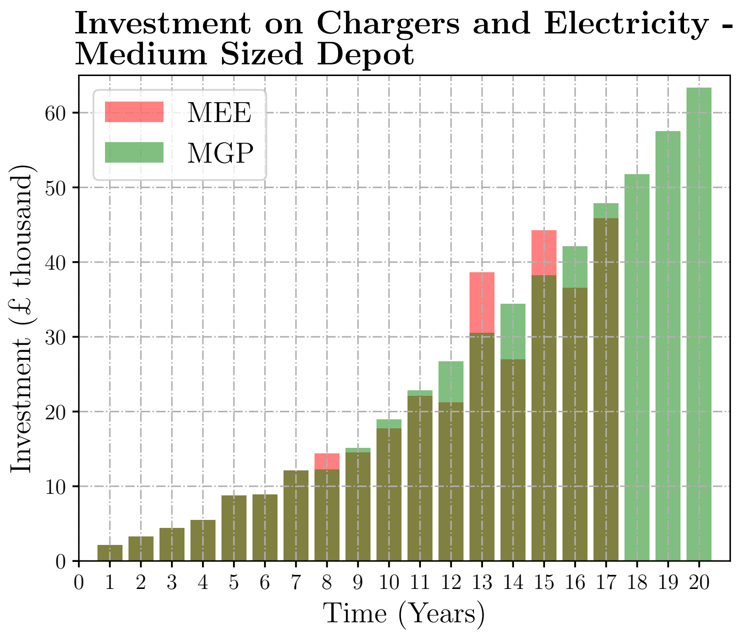

Figure 4: *Bar chart showing the annual investment (£ thousand) spent on chargers and electricity for the MEE and MGP methods. This chart represents the planned expenditure for a medium sized depot, the depot location does not affect this chart.*

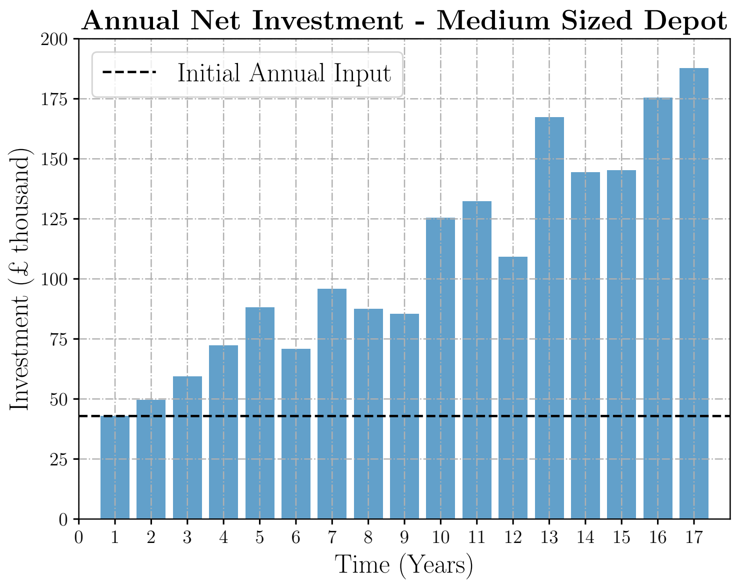

Figure 5: *Bar chart showing the net annual investment (£ thousand) for the chosen MEE method. The previous year's savings are added to the initial annual input to make the net annual investment. This chart represents the planned expenditure for a medium sized depot in an urban area, hence an annual initial budget of £42,895.44 (Section 3.1).*

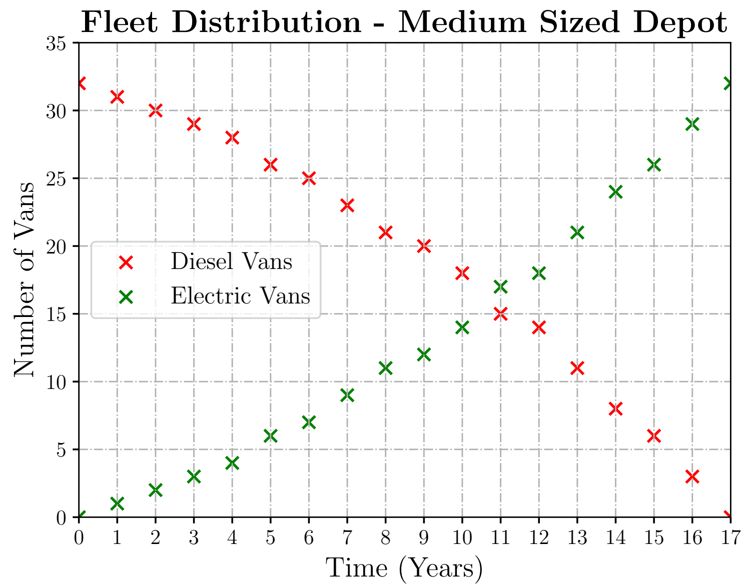

Figure 6: *Scatter plot showing the distribution of a depot's fleet over the electrification process using the chosen MEE method. This graph represents the distribution of a fleet belonging to a medium sized depot.*

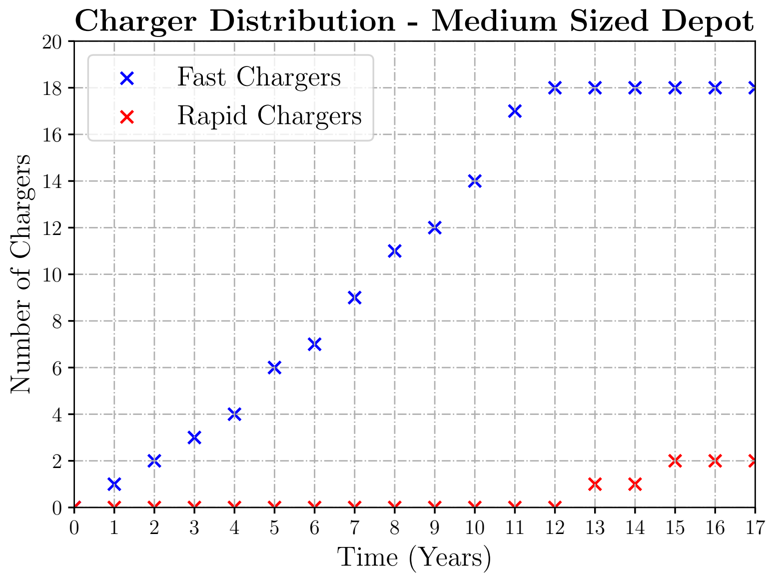

Figure 7: *Scatter plot showing the distribution of a depot's chargers over the electrification process using the chosen MEE method. This graph represents the distribution belonging to a medium sized depot.*

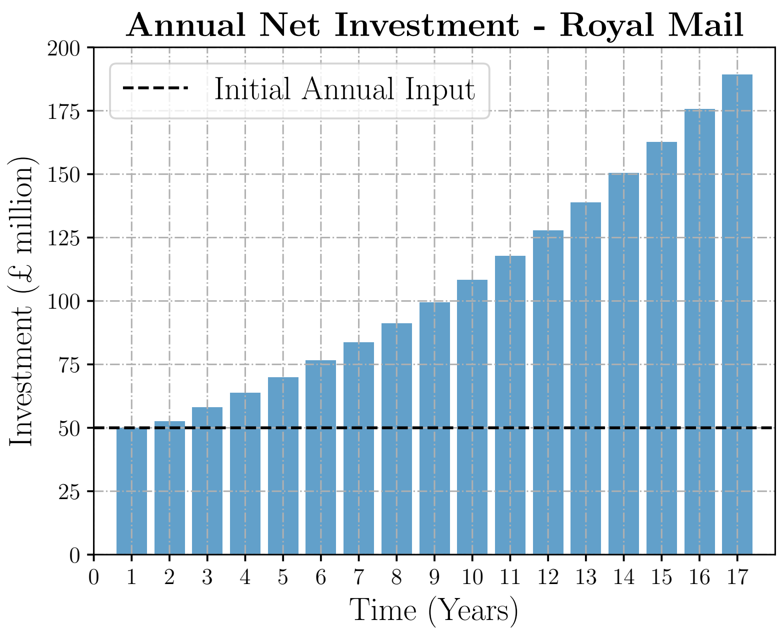

Figure 8: *Bar chart showing the net annual investment (£ million) for the chosen MEE method. The previous year's savings are added to the initial annual input to make the net annual investment. This chart represents the planned expenditure for the entire Royal Mail, hence an annual initial budget of £50million [4].*

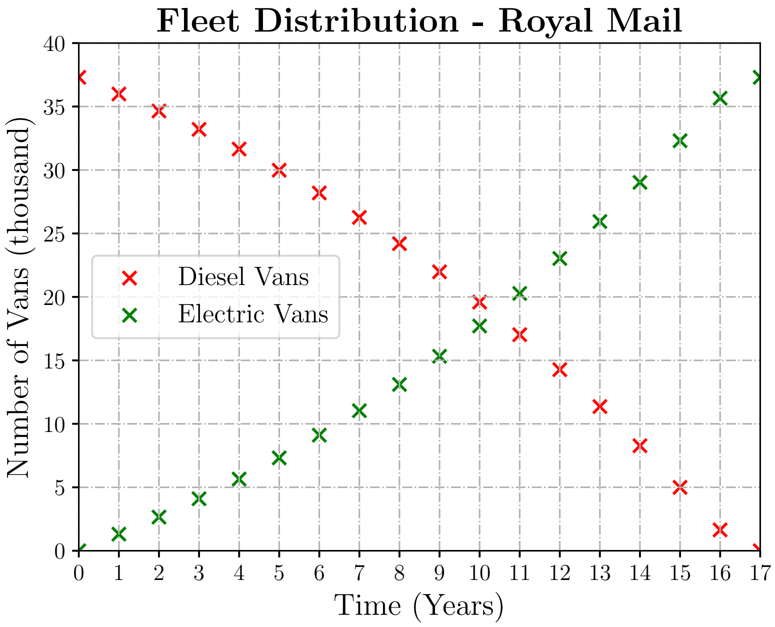

Figure 9: *Scatter plot showing the distribution of a depot's fleet over the electrification process using the chosen MEE method. This graph represents the distribution of Royal Mail's entire fleet.*

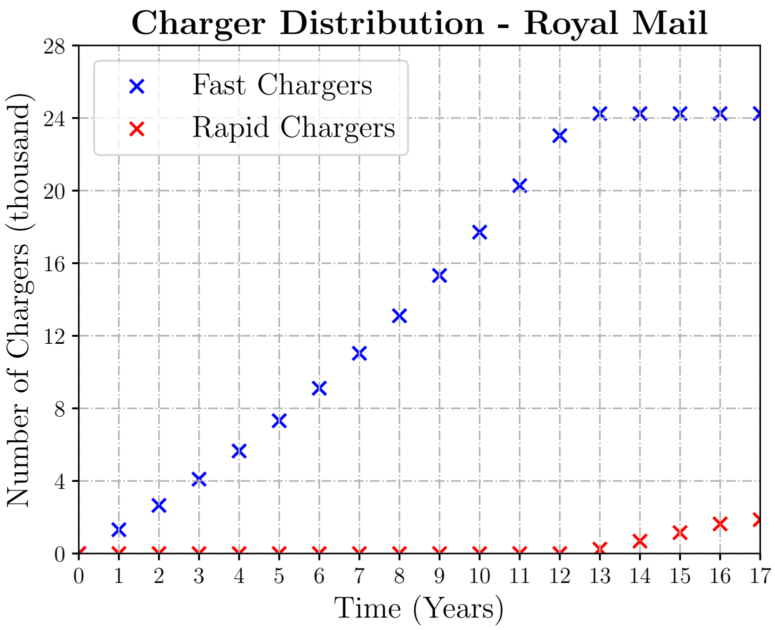

Figure 10: *Scatter plot showing the distribution of Royal Mail's chargers over the electrification process using the chosen MEE method. This graph represents the distribution of the entire Royal Mail.*

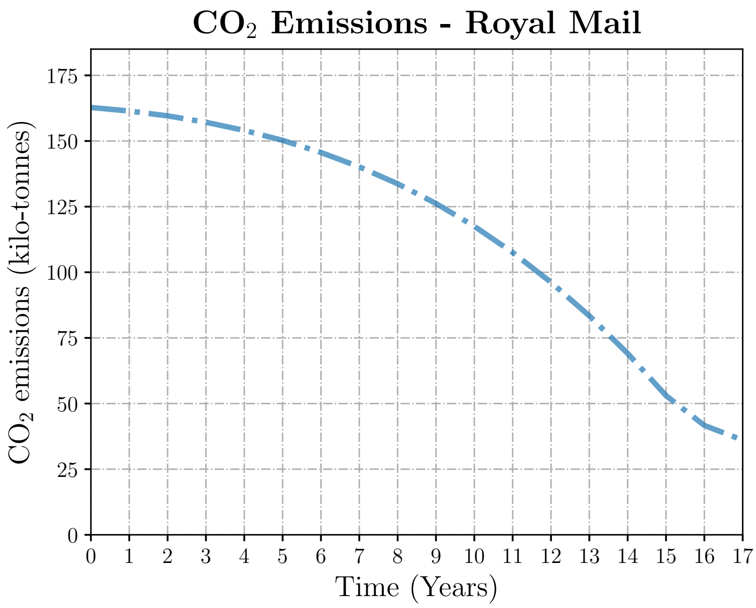

Figure 11: *Line graph showing how the total CO_2 emissions of Royal Mail vary over time. The effect is shown using the MEE method of fleet conversion.*

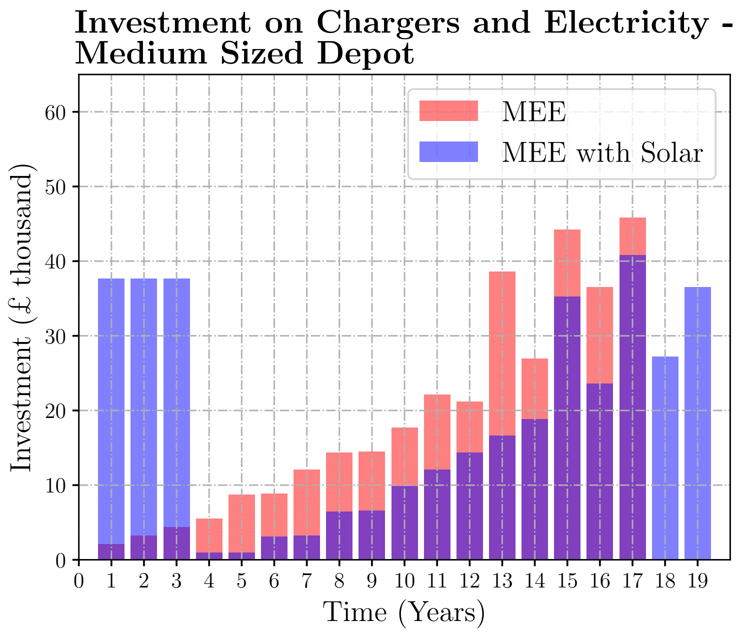

Figure 12: *Bar chart showing the annual investment (£ thousand) spent on chargers and electricity for the MEE method with and with solar assistance. This chart represents the planned expenditure for a medium sized depot, the depot location does not affect this chart.*

B Mitigation Appendix

Due to the COVID-19 pandemic, our group did not have an in-person meeting after the 13th of March 2020. This meant that all communications had to be online using group messaging and video calling. Meetings via video calling hold more complications than in-person ones for a manner of reasons. Weak internet connections meant that people froze, or were not heard, and in some instances members had to leave the meeting as their internet connections could not keep up. This meant that not everyone was informed of what was discussed, and ideas were not conveyed or developed as well as they could have been. Video calling is also difficult as it is easy to talk over one another, delaying productivity.

Working on this project from home was a challenge as some of our group did not have a space sufficient to work in, meaning meetings had background noise and occasionally family members in the background. Furthermore, research, modelling and writing were not completed as easily due to inadequate environments.

We were not given the correct contact information for Royal Mail until 3 weeks into the project. We were initially given an email address that we continued to email, with our supervisor cc'ed in, for 3 weeks without getting any replies. After 3 weeks, we were informed that the contact information we were given was wrong and should have been another member of Royal Mail team. This meant that none of our questions were answered and we received no data until after the university was closed on the 27th of March. Therefore, no productive in-person meetings were held with the appropriate tools.

We also were not given our marks and feedback for our second MDM3 projects of before the deadline of this project, the third. As we submitted our second projects on the 20th February 2020, we expected to have had our feedback and marks by now to know what we did well and what to improved on. This is extremely useful to know for future projects otherwise how are we expected to improve if we have not been told what we did well or not. As no one in this group was in a group together in the second round of projects, comparing each others constructive criticism and praise from these reports would have significantly help.