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Use of data for electric transport network optimization. Optimal charging at bus depots.

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Summary

Following the development of lithium-ion battery heavy-duty vehicles for public transports, this study proposes a methodology to help operators conceive a cost-optimal and fully functional charging infrastructure network for electric vehicles. Simulations based on public data from various French city bus fleets helped design a methodology respectful of all operational constraints. Results show in-operation charging at regular bus stops to be sub-optimal and that overnight depot charging should be strongly encouraged. Developments include an extensive study of overnight bus charging strategies leading to better power management at the depot through reduction of the peak load.

Keywords: Public transports, BEV (Battery Electric Vehicle), Load Management, Battery Management, Case-Study

1 Introduction

Energy transition from gasoline engines to electricity motors is often seen as a successful way to tackle the rise of anthropological greenhouse gas emissions. This transition is made possible by the use of batteries, able to store energy in a chemical form and first developed on passenger cars. It was proved that a complete transition from the current two-third gasoline one third petrol energy mix for transport to a full electric solution would cut transport greenhouse gas costs by more than one third, assuming the electrical energy mix remains as it is now [1]. Energy transition in South-Korean transport study showed a potential nine fold cut in per kilometer CO_2-equivalent greenhouse gases in spite of a 62 % carbonated electricity mix (coal and gas) [2]. Furthermore, the use of electric vehicles is an effective way to significantly improve air quality in city centers, through the reduction of CO, HC, NOx and CO_2 emissions amid other particles and gases [3].

The ability to use batteries in electric buses has risen as a direct consequence of battery technology improvements. This lead to governments creating incentives, either legal or financial, to promote the use of electric vehicles. These showed a significant effect on electric passenger cars, regardless of the financial or practical measures taken [4]. In public transports, this study is to be taken in the context of France, where the government developed a mandatory diesel engine replacement by cleaner technologies in public transports. Electric and other clean technologies should start developing from 2020, when the replacement requirement begins [5]. To be accepted, electrical technology requires to create charging infrastructures and to guarantee their availability [6].

This paper therefore seeks at establishing a methodology to study urban transport systerms' ability to use electric motors in their busses. This goes through a comprehensive understanding of their operational constraints and of their internal organization [7-10]. Special attention should be paid to the vehicles' energy consumption. It was indeed proved that bus consumptions may greatly vary depending on their route, its characteristics, and the average journey's speed amongst other factors [11-14]. A study of 4,135 buses consuming 1.4 GWh per day showed that the daily vehicle consumption may vary by as much as 450 kWh, ranging from 100 kWh to 550 kWh for a complete day of operation and from 1.1 kWh/km to 2.2 kWh/km depending on the journey conditions [12]. New technology adaptation to existing bus fleets and existing operational constraints is required. Failures to adapt to the customer requirements may have highly negative impacts on a new technology acceptance [15].

All the electric vehicles hence have various energy requirements depending on their model or journeys. They may however be gathered in warehouses, where the power consumption may be important: peak load may form, leading to risks of constraints on the electricity distribution network [16] and increase in energy costs and risk of network instability. Energy issues have been studied in previous studies, aiming to understand the impact of charging choices on the electric load curve [16-23]. In the case of buses, it was shown that the impact of opportunity charging on the distribution grid is maximal while depot overnight charging is less impacting on the network and may be optimized [17]. Most significant use cases include a fleet of freight vehicles [18], the charging of individual electric cars [21-23] and Smart-Grid management problems [19]. This paper establishes a real-time charge management strategy to ensure charging costs and power may be controlled and optimized under all conditions.

Further concerns with regards to urban electric mobility include the impact of energy conversion on the depot and distribution network, through the rise in harmonic and perturbation levels [24], the rise of new storage technologies such as hydrogen in fuel cells [25] and the evolution of transport networks. Effects of electric mobility development also include effects on the energy market, through the reduction of volatility in the electricity spot prices [26].

2 Establishment of a bus fleet digital replica

2.1 Transport line analysis

The first step towards a good understanding of an urban transport network is to know what services must be travelled on a daily basis. Analysis of public data available from online sources for different French fleet operators show that the journey pool mostly remains unchanged from one day to another during the week [27-30]. This means that the operation is kept similar every day. This regularity shall be used to provide an analysis of what charging infrastructures should be purchased and how they must be piloted to obtain optimal energy performances.

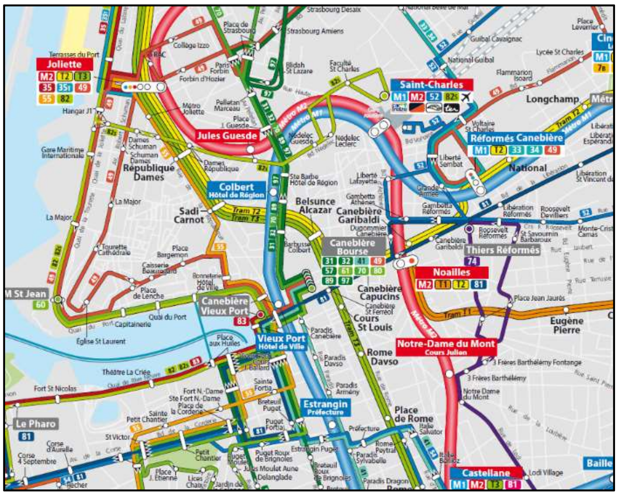

Figure 1 - Bus route definition in Marseilles' network

Consumption analysis showed the most influential bus route characteristics on the vehicle consumption to be the journey length, the number of stops and the operating conditions (e.g. traffic) [12]. It is therefore useful to know the typical path taken for each route in the transport network. This was done through an analysis of the official definition of the networks. For instance, figure 1 shows a French network bus routing map [27]. This piece of data allows the calculation of the path followed by each bus in the network as well as its altitude and number of stops as a function of time.

It is also helpful to be able to calculate the average speed for each of the journeys aforementioned. For that purpose, the data required may be the line schedule, which is also a publicly available data in most transport network. Figure 2 shows a sample of this piece of data for a given line in the same network as previously [27]. Bus schedules may be established following the use of these timetables.

81 Le Pharo vers Métro St Just

Départ de : **Le Pharo**

Terminus Libération Réformés

Du lundi au vendredi

Heure	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
minutes	45	15	15	00	00	00	00	00	00	08	08	10	10	08	02	03	15	14
		45	34	10	10	12	12	12	10	20	20	22	22	18	07	11	22	53
			46	20	20	24	24	24	21	32	33	34	34	30	14	25	45	
				30	30	30	36	37	32	44	46	46	46	40	28	45		
				40	40	36	48	50	44	56	58	58	58	50	37			
				50	50	48			56						42			
															56			

81 Métro St Just vers Le Pharo

Départ de : **Métro St Just**

Départ de Vieux Port Crs J. Ballard

Terminus Métro 5 Avenues

Du lundi au vendredi

Heure	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
minutes	35	05	15	04	02	09	09	11	11	00	06	06	06	00	09	00	10	20	
		15	34	05	05	21	21	23	24	10	18	18	18	00	12	20	40		
		33	45	14	15	28	34	35	36	20	30	30	30	11	24	22	53		
		45	58	15	25	33	46	47	48	30	42	42	40	22	28	40			
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				35	45	57				54				44	45				
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				55															

Figure 2 - Marseilles' line 81 bus schedule

2.2 Vehicle Timetable creation

A vehicle timetable will be defined as a sum up of all journeys to be travelled by the bus on a given day. No hypothesis is taken with regards to the necessity for a bus to travel the same journeys everyday: the pool remains the same as a consequence of the line schedule regularity but the bus assigned to the travels may vary on a daily basis. The only constraint in a bus network is that buses will spend the night at a depot. It is assumed that a bus belongs to a given depot in the case of multi-depot networks.

As a consequence, the first journey will always consist in the trip from the depot to the assigned line terminal bus stop. This time is off-exploitation and is not paid for by customers or by the city. Bus network operators will always seek at keeping it minimal. The bus operations are then continued with the commercial use on the assigned line. Once the bus has reached the other terminal station, it is assigned the immediately next journey back on the same line. Waiting time at terminal stations is currently kept minimal to avoid waste of bus commercial operation time. Once the bus has completed all its day journeys, it must go back to its depot. The resulting trip will therefore usually be return trip of the opening journey.

Departure	Arrival	Line
6.08	6.28	Off-Exp
6.28	6.54	1
7.02	7.35	1
7.39	8.11	1
8.2	8.52	1
9.35	10.07	1
10.22	10.54	1
11.05	11.37	1
11.37	12.05	Off-Exp

Figure 3 - Bus specific timetable

Figure 3 displays an example of one bus commercially operated between 6:28am and 11:37am. It must be noted that more than one bus is required to grant all commercial trips proposed by the schedule sheet. To ensure that, it is considered that every time a bus cannot travel one journey, another will need to depart the depot to tour the line to ensure all proposed journeys are guaranteed by the end of the process. This was done on several networks and lines have required up to 16 buses travelling on the same line at the same given moment in the day while some others only required one bus to be driven at once. Knowledge of the bus timetable allows the calculation of the electric vehicle power consumption throughout the day and therefore its energy requirements.

2.3 Location-dependent charging strategy overview

Charging infrastructure choice and location optimization will be carried out with the possibility to settle charging station at three types of locations: bus depots, line terminal stations or regular bus stops. Charge at the depot is named depot charging, terminal line charging is called opportunity charging and charging at regular bus stops is named flash charging.

Depot charging is a relatively low power charging, aiming at charging overnight. The typical charging power should be somewhere between 50 kW and 100 kW, with a battery size around 300 kWh, if not more, based on the consumption conclusions from Gallet [12]. A market analysis shows that most 12-meter bus battery capacities is set around this threshold [31-34]. Depot charging therefore does not trigger premature battery aging when compared to other types of faster charging. Energy plugging-in is usually manual with the use of regular safe plugs.

Opportunity charging aims at providing the battery with a significant energy in a typical maximum duration of a quarter of hour. This charging requires a power usually between 150 kW and 500 kW. This faster charging may damage the battery more quickly if done regularly on the buses. The charging stations are to be located at the terminal bus stops, where the line service ends. Energy plugging may either be fully manual (less expensive) or automatic with the use of pantographs.

Flash charging aims at reducing the need for high battery capacity through the transfer of the same energy as for opportunity charging, with a typical duration under thirty seconds. This duration represents a high average stopping time at bus stops to allow passengers to board or get off the bus. The rated power may be as high as 1 MW depending on the energy needs and the actual time spent at the stop. Such power requires to use battery functioning with a more expensive technology to be able to charge at such a rated power. Taking into account its short duration, it is necessary that the energy plug be connected automatically, triggering higher infrastructure costs.

2.4 Conclusions on general electric transport network organization

As a direct consequence of the previous conclusions, charging infrastructures should be located near the regular bus operation routes. Table 1 proposes an analysis of the number of charging stations to be installed, how many connections to the electrical grid must be established and the battery size to be installed in buses under three scenarios: most buses charge at the depot, charge at terminal stations is always carried out, and flash charging is the preferred solution. Data used comes from the public transport network website, at the scale of one bus depot (100 buses) [27]. Table 1 shows an estimated price for each charging strategy, under the simplifying hypothesis that a charging station is worth \$50,000, an urban connection to the grid is worth \$500,000 and that battery cost has a unit cost of \$200/kWh.

Table 1 – Relative performance of three charging strategies

	Depot	Opportunity	Flash
Nb. Stations	114	42	253
Nb. Grid connections	1	23	234
Battery size (kWh)	400	120	40
Est. Cost (M$)	14	16	130

Opportunity charging chosen as the main charging strategy requires least charging stations but many more connection points to the distribution grid. This significantly raises the price of each charging station. However, the battery capacities to be installed in buses is slightly lower than for overnight depot charging. In the event of the choice of such a charging strategy, a bus must stop for a few minutes at each terminal station. This may modify the charging strategy. Figure 4 shows the probabilistic theoretical time spent at terminal stations in the day. During peak time, shorter stops often occur to compensate for the delay accumulated over the previous trips. Compatible stops are observed at a one to six ratio of all terminal stops.

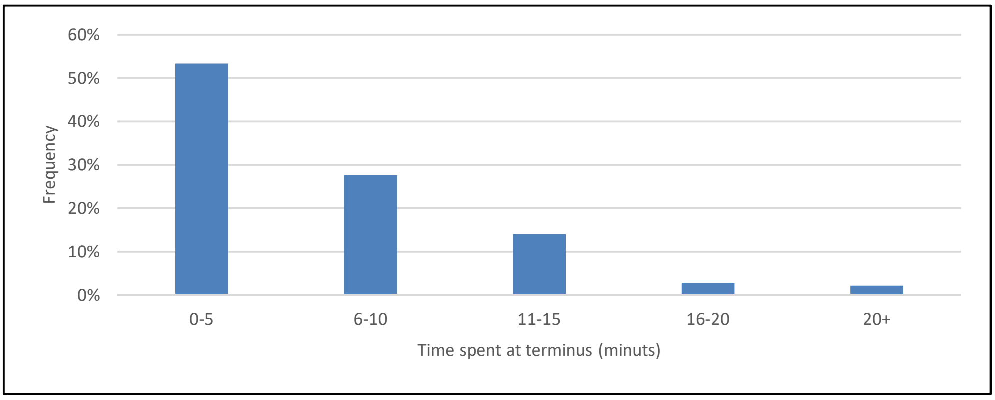

Figure 4 - Time spent at a terminal stations

Flash charging requires extensive infrastructures to be installed and is therefore not financially profitable. It additionally damages the operating conditions since a stop at each station is mandatory to be able to charge enough energy to reach the next one.

This suggests that depot charging should be chosen as the preferred charging strategy as a consequence of better financial and operational performances. The standard taken in the rest of the paper will consist in a charging mainly located at the depot, designed for an overnight charging and minoritary use of charging stations during the day. Occasional charging stations may be added if they improve the charging network’s performance.

3 Charging opportunity and energy consumption calculation

3.1 Presence forecasting at the depot

In a depot-focused system, it is crucial to understand when the bus is parked and whether its battery is able to accept relatively low power charging. It is considered that a bus is willing to be charged if, and only if, it is parked and stopped at the depot. The parking process shall therefore require the driver to plug the charging cordon before leaving the bus. It can then successfully be charged.

Departure from - and arrival to - the depot theoretical times can be derived from each bus schedule. It is indeed possible to apply the methodology in paragraph 2.2 to the commercial public line schedule to estimate the time spent at the depots. Each bus arrival and departure time is independent from other vehicles in the depot and no noticeable external factor influence was noticed on the bus depot availability for charging.

Public data therefore led to the chart on figure 5. It displays the number of buses parked at one depot as a function of time. A peak can be noticed from early evening to early morning, corresponding to when nearly all buses are parked at the depot and are able to charge. An approximate 30 % buses are able to get back to the depot during the day – between morning and evening peak periods – leading to a smaller presence during the day. This presence may be used as an opportunity to charge additional energy at the depot during the day, hence reducing overnight charging.

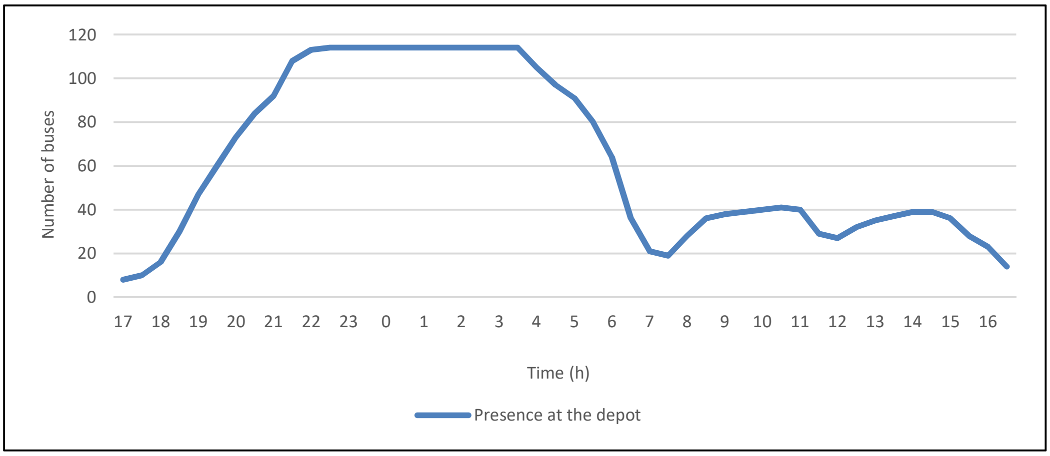

Figure 5 - Bus presence at the depot

3.2 Energy consumption estimation

In order to establish the battery size requirement, it was necessary to estimate the power consumption throughout the bus route. For that purpose, the transport line analysis established in paragraph 2.1 was used. The aim is to take into account the route altitude and travel conditions to estimate average consumption values on the route as well as its significant statistical variations around the average value.

It was decided to set the consumption of an empty vehicle to an approximate 1,200 Wh/km. This corresponds to a value corresponding to a market analysis of bus manufacturers [31-34]. Furthermore, the bus route altitude variations needed to be taken into account. For that purpose, it was estimated that the conversion engines have an efficiency of 80 %, both when gaining and losing potential energy.

As a direct consequence, it means that climbing 1 kWh of potential energy will cost 1.25 kWh in chemical energy in the battery. The battery will recharge 0.80 kWh when the bus will lower its altitude by the equivalent of 1 kWh in potential power. Overall, the complete cycle will have discharged the battery by 0.45 kWh, so an equivalent to 45 % of the positive potential energy variation.

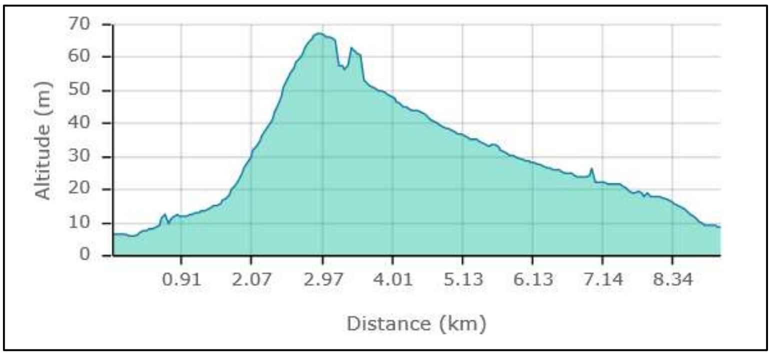

Figure 6 - Altitude profile on a bus line

Figure 6 shows the example of a given bus line in the bus network. Significant altitude variations include a continuous climb from 8 meters to 68 meters, followed by an altitude decrease down to 9 meters high. Assuming that the vehicle mass is 18 metric tons, altitude's impact on the vehicle consumption may be estimated to 1.4 kWh, translating to an average additional consumption value near 150 Wh/km (12.5 % of the empty vehicle consumption).

Last step consisted in considering external driving conditions. A corrective consumption coefficient was attributed to each journey based on its travel speed. It was considered that a lower travel velocity is the consequence of heavy traffic. The corrective coefficient was considered following a normal distribution (mean: 200 Wh/km, standard deviation: 400 Wh/km) to increase the consumption in 67 % of the cases, subsequently to heavy-traffic conditions.

Overall vehicle consumption is defined as the sum of the empty vehicle consumption, the altitude and the external corrective coefficients. It may then be calculated over all the journeys and a consumption is known for the whole bus day operation. Battery size must provide for this consumption under all possible operation conditions. Delays or service cancellations may indeed have a strong negative impact on the technology acceptance by the urban transportation's customers [8].

3.3 Effect of terminal station charging point addition on the network

Vehicle consumption was defined as a mean to set the minimum battery size necessary to operate each of the planned commercial journeys. The dominant charging strategy chosen is off-opperation depot charging, allowing a relatively low power charging at the bus park location.

As a consequence, it is important that batteries be able to provide energy for the whole duration of the journeys. However, it is possible to reduce the energy requirement of most energy intensive services by adding charging stations at terminal stations. Each of the bus line has two – or more – terminal stops. This charging strategy only requires the use of one station amongst the two available. As a consequence, it is recommended to choose the station to exploit according to both a power availability criteria and a possibility to carry out road works.

Charging station rated power will be comprised between 100 kW and 200 kW, to ensure that a single charging station may not require a very high voltage connection to the distribution network. This would indeed be a serious challenge in the city center. In France, the low voltage upper limit is 250 kW, inclusive of all yields.

The use of charging stations at terminal line stops may therefore have two consequences. If the battery dimensioning is free of constraints, it is possible to reduce the size of the embedded battery to the extent of the energy charged during the exploitation of terminal stop stations. The battery reduction can be calculated using formula (1), where ΔE stands for the battery size reduction, P_{rated} represents the rated power and t_{stop} represents the time spent at the bus stop.

$$\Delta E = P_{rated} \cdot \sum_{\substack{charging \\ opportunities}} t_{stop} \quad (1)$$

For instance, the use of a 200 kW complementary charging station on top of a main depot charging may help reduce the battery size by 100 kWh to 150 kWh for a given bus, thanks to one hour safely available at the terminal stop during off-peak time. On a $200/kWh battery price hypothesis, it is therefore possible to reduce the price of a given bus by $30,000.

Alternatively, additional battery autonomy can be used to cater for uncertainties in the overuse energy consumption. This means that opportunity charging could be used in the event of an energy overconsumption in the beginning of the operation day. This strengthens the safety of the bus' ability to complete the trip in spite of all external events occurring on the network.

Other effects include the possibility to travel journeys which could not be completed with a given vehicle due to the battery not being able to handle enough capacity. Indeed, the market analysis showed that buses manufacturers only offer a limited range of batteries associated to the buses design [31-34]. Therefore, it may sometimes not be possible to use an as big as required battery in some of the most energy consumption intensive journeys delivered by the network.

4 Depot charging analysis and optimization

4.1 Natural/Empirical charging

Under the hypothesis that depot charging is the preferred charging strategy, this section focuses on how the charging is done in practice. The aim is to establish an individual charging control at a bus level to ensure the depot safely charges the buses with minimal impact on the grid and therefore on the fleet operator's carging costs.

The first step consists in the analysis of the natural charging. This depot charging strategy consists in plugging-in the bus upon its arrival to the depot and unplugging it at the end of its stay at the depot. This charging strategy only involves charging power management by the Battery Management System (BMS). The charging indeed begins when the BMS delivers the order to accept power from the charging station and stops either when the battery is full or when the bus needs to leave and is unplugged.

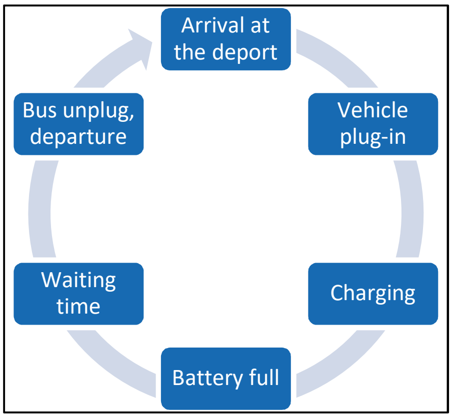

Figure 7 - Empirical charging process

Empirical charging was simulated on a full depot using the process shown on figure 7. This charging requires the use of 50 kW charging stations in most cases. In some cases, it was decided to install 100 kW charging stations. This usually occurred for buses driven a lot over a day without opportunity for mid-day charging. It was also decided to charge the buses at a 100 kW rated power during any mid-day charging opportunity.

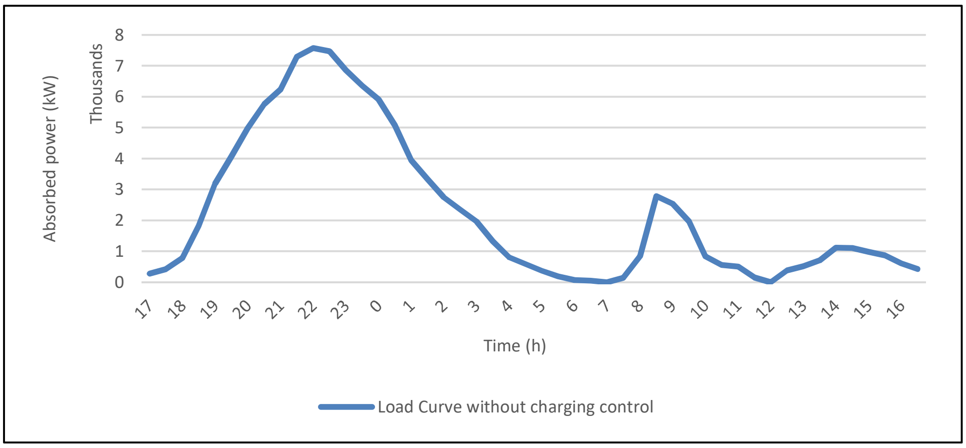

Figure 8 - Natural charging load curve at a depot

This charging shows evidence of a peak load occurring at 10.30pm. This peak is worth 7,572 kW, requiring to install 8 MW at the depot. This value is inclusive of efficiency in the energy conversion value chain. The example depot charged 114 buses at the peak time, including all emergency and maintenance buses (8) parked at the depot at all time. This means the power to be installed per bus is 66.42 kW, inclusive of all yields and of all emergency buses. One functional bus equivalent power is 71.43 kW inclusive of all yields and 59.53 kW actually delivered into the battery chemistry. This corresponds to a 50 kW power delivered to the most buses and an additional 50 kW delivered to 20 % of the busses in the depot.

As a consequence, this charging method required the use of both 100 kW rated-power and 50 kW rated-power charging units. There will be 20 high-power charging units and 100 low-power charging units at the depot. The bus shall be parked at the right charging station depending on its next journeys to complete. To avoid operational constraints on the depot operator, it is therefore suggested to make sure all charging stations may charge all buses, regardless of the next journeys to be driven.

Creation of high peak load requires high power grid connection power, hence increasing initial connection costs. An optimized charging strategy is therefore proposed in the next paragraph, aiming at reducing the peak power required at the depot. Introduction of peak power reduction strategy will need a charging control to ensure that batteries are successfully charged when the bus leaves the depot. Charge management also includes the creation of opportunities to cater for any type of operational emergencies, e.g. when a bus needs to complete an exceptional one-off service for whatever reason.

4.2 Smart-Charging proposal

This section establishes a charging strategy to ensure that the buses are safely charged at the depot while keeping the maximal absorbed power minimal. This is done through different energy allocation at an individual bus level. When compared to the empirical charging method, it is possible to either delay the charging or to end it prematurely to diminish the peak absorbed power.

It is also suggested to set the maximal power to 100 kW for all buses. When the maximum individual charging power is increased, it is possible to increase the overall system flexibility and therefore to further reduce the grid connection power. However, when the maximal power is set to a minimum, it is not possible to defer or stop charging prematurely since later charging will fail to compensate this effect due to low available power.

100 kW as a maximal uniform rated-power was chosen following simulations using various maximal powers, ranging from 50 kW to 1 MW. No significant difference was noticed above a maximal charging power near 100 kW, which is therefore considered an optimal value based on the energy requirements and charging time available.

Input data consists in a certain need for energy availability at certain times throughout the day, typically when the bus departs from the depot and starts operation. The corresponding amount of energy consists in the starting journey consumption. All operational constraints at a depot can be expressed following equation (2), where $SOC_i(t)$ represents the amount of energy available in bus i at moment t, $\underline{SOC_i(t_0)}$ represents the consumption estimate for the journey completed by bus i at moment t_0.

$$\underline{SOC_i(t_0)} < SOC_i(t_0) \quad (2)$$

The problem then consists in an optimization problem in which the bus is able to receive energy at given times, when it is parked at the depot. A given State of Charge (SOC) must be granted in each bus at given times to guarantee they can complete their service regardless of external conditions and uncertainties. The cost function corresponding to the problem is defined by equation (3), where $P_i(t)$ represents the power absorbed by bus i at time t and C stands for cost.

$$C = \max_{t \in \mathbb{R}} \sum_{bus} P_{bus}(t) \quad (3)$$

This methodology successfully provided the result shown on figure 9 for the same depot as before. This chart shows evidence of better energy management and removal of peak effects when buses enter the depot all at once in the early evening. Maximum load during the day is now equal to 3,178 kW for the same total energy (54.5 MWh for 106 operational buses). This translate into a 29.98 kW per operational bus at peak time, inclusive of all efficiencies. This must be compared to the previous 71.43 kW per operational bus at peak time, putting into evidence a 58 % peak power consumption.

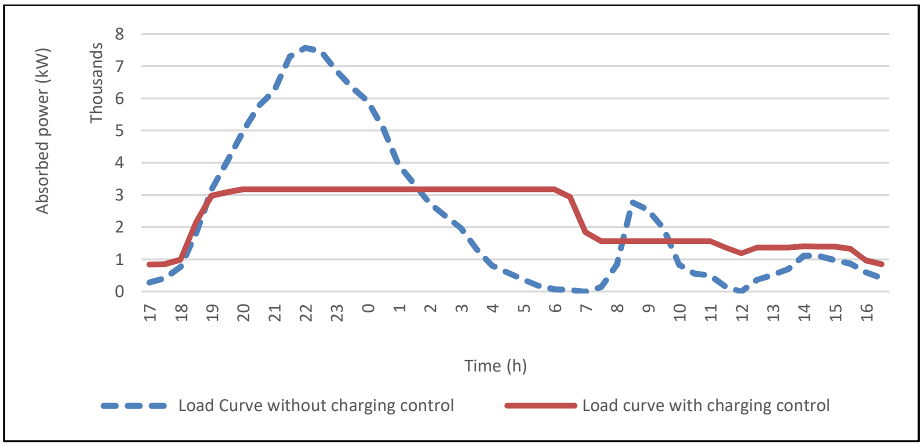

Figure 9 - Effect of charging control on the load curve

5 Conclusions

This study analyzes data publicly made available by public transport network to conclude on the possibilities to help operators transit from combustion engines to full electric motors. The main data used are the route sheet (map) and the bus schedules.

The study consists in the establishment of bus timetables and consumption estimate for each of the journeys taken. It is therefore possible to conclude with regards to a bus' energy requirements throughout a given service day. This energy requirement estimate directly leads to an approximate battery size and charging needs for each of the services.

It was then necessary to establish where and how the bus may be charged during the service and off-exploitation. It was chosen to privilege depot charging where possible, to grant better operational performance as well as lower operational expenditures. Terminal bus stop opportunity charging will be reserved to buses with exceptionally high energy requirements or to buses facing an operational emergency such as power shortage due to exceptional external conditions.

A methodology was created to make an estimate of the driving conditions and consumption as a function of the pathway taken by the bus route, especially its altitude. It is therefore possible to estimate precisely the energy need throughout the day. Operational constraints could be derived for each bus based on the amount of energy required at given moments. This gives the minimal energy present in the batteries when the bus departs the depot.

Based on that, two charging methods were derived and compared. The first one consists in a passive charging, where no charger control is operated. This leads to a significant power peak early in the evening, potentially requiring higher depot to electric distribution grid connection power as well as potential needs for expensive distribution network reinforcements. This natural charging showed evidence of a 71.43 kW peak per bus in operation during peak time. Over a 108 bus depot, this represents a 7,572 kW peak.

This should be compared to a charging method consisting in a better power management aiming at minimizing the peak power at the depot. The charging strategy showed a significant peak shaving, reducing it by 58 %, stabilized at 29.98 kW per operational bus during peak time. This translates to a 3,178 kW power consumption peak at the depot during peak time at the studied depot. In this configuration, the peak period is extended in time and better use of day charging opportunities is made.

This process was replicated over 7 depots using the same methodology. Similar results were obtained for all of them. Results shown on the paper represent the median depot in terms of Smart-Charging success, with results ranging from 28 % to 63 % power reduction thanks to charging control.

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