Analysis of the potential for electric buses

A study accomplished for the European Copper Institute

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1. Introduction

This report offers an overview of the economic potential for electric powertrains applied in urban bus fleets. Being recognised by an ever-growing number of national and regional authorities, electrified powertrains serve as an essential means to reduce our impact on both climate change and to improve local air quality. Due to a plummeting price for batteries over the last years [1], [2], a tipping point for electric buses to break through is within reach. Therefore, governments need guidance to change course drastically and to go electric today, rather than to postpone the decision and to procure another batch of conventional (or in the best case non-plug-in hybrid/compressed natural gas) vehicles. For this reason, an analysis is made covering the total cost of ownership (TCO) of different urban bus powertrains on a technological level. These are conventional diesel, plug-in hybrid electric (PHEV), compressed natural gas (CNG) and their battery electric variants. For the latter, we distinguish two types of charging, i.e. overnight charging (also: 'depot charging') and opportunity charging over the course of the bus's trajectory. The TCO includes the capital expenditure of the bus and its lifetime operational costs, including the required charging/refuelling infrastructure.

The outcome presented for this exercise results from both interviewing the most prominent bus and infrastructure manufacturers, while occasional gaps in their answers are filled with the available information from the literature. Thus, we present an update of previous TCO analyses and focus on the European market. This report starts with an overview of the main parameters for the TCO study, to be subsequently followed by a sensitivity analysis. Then, an estimation of the required copper content of the combination of an electric bus fleet and its infrastructure is presented. Finally, we compare the current situation to the expected market potential by 2025.

2. TCO parameters and assumptions

When bus operators renew their fleet, the renewal often includes the purchase of a batch of vehicles, which allows for a reduced upfront cost per bus. The size of such a capital expenditure (CAPEX) is important, but not necessarily crucial if a high upfront cost is, for instance, levelled out over the years by lower maintenance costs. Therefore, a TCO proves its worth by offering a multi-year scope on the total investment for running a fleet. For this exercise, we focus on standard 12-meter buses rather than on their articulated (18 m) variants. Buses are assumed to be used actively in a concession of ten years, to be either sold afterwards or used as a substitute for more modern buses that are temporarily out of service. Furthermore, we assume a bus covers 60.000 km per year. Whereas there is no need to discuss range issues for conventional (diesel and CNG) powertrains, it does matter for electrified variants. In case of the PHEV bus, we assume that it operates in an all-electric mode for five percent of the time, while being charged overnight rather than to make use of pantographs stations on its road. The latter has nonetheless been realised in pilot projects. The electric parameters of the different powertrains are shown in Table 1.

TABLE 1: POWERTRAIN CHARACTERISTICS

Powertrain type	Bus length [m]	Battery capacity [kWh]	Electric range [km]	Charger power (kW)	Charging time (minutes/hours)
Diesel Euro VI	12	-	-	-	-
CNG Euro VI	12	-	-	-	-
PHEV Euro VI	12	20	7	50	0,5-1 hours
Electric (depot)	12	300	250	50	4-6 hours
Electric (opportunity)	12	150	160-170	450	3-6 min

The main difference between the depot and opportunity charged buses is their battery capacity and the power they can be charged with. Where the former is typically equipped with a large battery pack that is charged overnight or in between driver work shifts, opportunity charging *en route* allows the operator to tailor the battery capacity needs to the specific requirements of the bus line. This optimisation process requires careful planning and strategic placement of one or more pantograph charging stations on the bus line, for which real-life applications have proven its efficacy. Examples are to be found in Differdange, Luxembourg, where four bus lines share two pantograph chargers (Figure 1)[1]. The PHEV bus could also be charged at pantograph stations, as it happens in Hamburg[2].

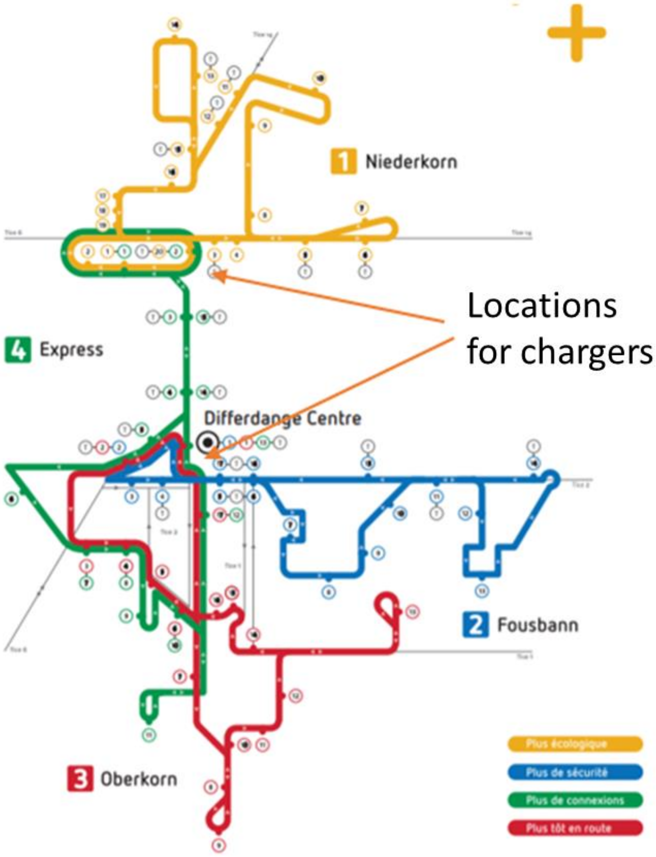

FIGURE 1: EXAMPLE OF ARRANGING BUS LINE OVERLAP TO ALLOW SHARED CHARGING LOCATIONS

a. The present value of recurring costs

Throughout this exercise, investments over ten years are discussed. Therefore, we need to recalculate the value of future costs in today's currency. This is done using the present value methodology and considers a real discount rate of 0,38%, as indicated by the 10-year interest rate for European government bonds published by the European Central Bank[3]. Equation 1 shows how we calculate the present value of recurring costs like fuel expenditure, maintenance, insurance, road tax and battery leasing. The abbreviations used in the equation are PV for the present value, A_0 for the recurring cost, r for the interest rate and t for the period.

EQUATION 1: PRESENT VALUE OF RECURRING COSTS:

$$PV = A_0 \times \frac{(1+r)^t - 1}{r \times (1+r)^t}$$

[1] http://www.differdange.lu/files/8614/9630/8505/Diffbus_plan_horaire_web.pdf
[2] https://www.siemens.com/press/en/feature/2013/infrastructure-cities/rail-systems/2013-07-ebus.php

[3] http://sdw.ecb.europa.eu/quickview.do?SERIES_KEY=165.YC.B.U2.EUR.4F.G_N_A.SV_C_YM.SR_8Y, consulted on March 22, 2018

b. Purchase price

Compared to the conventional diesel powertrain, the alternatives currently come at a higher investment. Notwithstanding, diesel technology itself has become more expensive over the different Euro emission standards as stricter emission limits require better exhaust gas aftertreatment and more catalytic converters to make this possible. Whereas the current Euro VI emission standard dates to 2013, its successor within the heavy-duty sector will focus on system efficiency, for which targets have recently been proposed. Thus, a CO_2 reduction by 15% by 2025 and 30% by 2030 is targeted, relative to the situation in 2019[4]. Such measures will increase the upfront cost for conventional buses, while the operational costs for fuel expenses will decrease.

Following interviews with both bus operators and manufacturers, an update of the upfront cost for buses available anno 2018 is given in Table 2. Notice how the dual technology applied to a PHEV powertrain comes at a price that does not differ substantially from the fully electrified powertrains. The difference in the upfront cost between a depot and opportunity charged electric bus can be related to the installed battery capacity. Each bus is assumed to be depreciated to ten percent of its original purchase cost over the course of ten years.

TABLE 2: UPFRONT COST PER TECHNOLOGY

Technology	CAPEX	Depreciation (years)	Depreciation rate
Diesel Euro VI	€230.000	10	0,85
CNG Euro VI	€270.000	10	0,85
PHEV Euro VI	€445.000	10	0,85
Electric (with battery)	€502.500	10	0,85
Electric (with battery leased)	€475.000	10	0,85

Some of the electric bus models come with the option of leasing the battery packs, rather than buying them. This has the advantage that the manufacturer guarantees a minimal capacity during an agreed number of years under contract. The annual costs for leasing contracts range from €1.500 to €10.000 for eight years. For this exercise, we assume a cost of €8.500 per year. Typically, a battery is considered no longer applicable for mobile applications when the capacity has degraded to 70-80% of its original value. Manufacturers can decide to diagnose batteries for locating degraded cells to be replaced or to replace the entire battery pack when it is at the end of its 'first life'. In a second life, the considerable remaining capacity that can be applied to stationary applications, e.g. for storing renewable energy. Therefore, we assume a residual value of €40 per kWh, which is in line with what paid today for a used Nissan Leaf battery. The lifetime of batteries is expressed in the number of charging cycles. For the currently available battery technologies for BEVs, their expected lifetime is about 1.000 cycles at a depth of discharge of 80%. This is considered a full charging cycle with a residual capacity of 20 percent as a buffer to prevent the battery from degrading too quickly. Depending on the battery size and the chemistry used, lifetimes can differ. One the one hand, Chinese bus manufacturers like BYD focus on sizeable lithium-iron phosphate (LFP) battery packs, which can store up to 350 kWh of energy but cannot handle high charging currents. Therefore, they are charged at e.g. 50-150 kW during several hours overnight. On the other hand, European manufacturers have turned to chemistries based on nickel, cobalt and manganese (NMC), which allow higher currents and thus fast charging with power ratings up to 600 kW. Such batteries can be designed smaller and can last longer if their battery levels are topped up during the day at pantograph stations, rather than being entirely discharged over the course of the day. Typically, a 30% depth-of-discharge is aimed for to prolong the use of the battery maximally. As such, the smaller NMC batteries are assumed to last as long as the vast LFP battery packs. Table 3 shows the relevant parameters for the electrified powertrains, added with the current costs and those projected for the near-term future. Notice how battery prices are expected to drop in the following years, as a target price of € 90/kWh is set according to the 2016 European Commission's SET-Plan Action N° 7 [4]. This price has a significant impact on BEVs as battery replacements for vehicles bought today

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2018:284:FIN

will be available at much lower costs, which further decreases the operational costs of the technology. Considering cycle life, the 2022 objective of 1.000 cycles is already within reach anno 2018, while a doubling is expected by 2030 (or sooner).

TABLE 3: BATTERY SPECIFICATIONS, LIFETIMES AND COST FORECASTS

	PHEV	BEV – Opportunity charged	BEV – Overnight charged
Stored energy (kWh)	20	150	300
Battery lease (€/year)	/	8.000-10.000	1.500-9.000
Assumed leasing cost (€)	/	8.500	8.500
Battery cost (€/kWh)* 2018	180	180	180
Batteryd cost (€/kWh) 2022	90	90	90
Battery replacement cost (€)**	1.960	13.660	27.160
Residual value (€/kWh)	40	40	40
Residual value battery	800	6.000	12.000
Lifetime (#cycles)	3.000-5.000	1.000	1.000
Lifetime (km)	300.000	300.000	300.000
Lifetime (years)	5	5	5

*on pack level, including battery management and packaging, **including ½ day of work at €40/hr

c. Infrastructure cost

When including alternative powertrains in the picture, it makes sense not only to look at the costs for the respective vehicles but to consider their required infrastructure as well. To allow a fair comparison, however, the cost for a diesel and a CNG refilling station consisting of two pumps is included in Table 4. For the PHEV bus, we assume it is charged overnight, although it can be charged by a pantograph station if the interoperability between different providers and manufacturers allows it. The sensitivity of the infrastructural cost consists of the number of buses that could share infrastructure. Where tens of vehicles can share the conventional diesel and CNG stations, this is far less the case for the electric chargers. Thus, the infrastructure cost for an electrified bus becomes considerably higher with the specific charging time. The last column in Table 4 shows the assumed number of buses sharing infrastructure as the highest value of the range, for a batch of 90 procured buses. For the electric buses, the higher the charging current gets, the more buses can share a charging station.

TABLE 4: INFRASTRUCTURAL SPECIFICATIONS

Infrastructure type	**Cost**	**Depreciation (years)**	**Maintenance**	**#buses**
Diesel fuel station	€420.000	20	€1.500	1-90
CNG refilling station	€350.000	20	€1.500	1-90
(Plug-in) Electric charging station 50 kW	€25.000	20	€1.150	1
Pantograph charging station 450 kW	€350.000	20	€5.750	1-3

The annual cost of maintaining the infrastructure was assumed to be €1.500 for diesel and CNG infrastructure. For the depot and opportunity chargers, both the working hours, spare parts and initial start-up of the infrastructure are retrieved from manufacturer data. Where depot chargers can be used for more than one bus, the location of an opportunity charger must be selected so that it can be found at an intersection of bus lines. By doing so, several vehicles could make use of one pantograph station, which could considerably decrease the infrastructural cost for buses relying on them. The costs presented in Table 4 are all-inclusive, i.e. covering for the necessary electrical transformation and cabling as well as for the physical infrastructure on-site. In our TCO model, maintenance on PHEV infrastructure includes both the diesel refuelling station and the 50 kW charger. Likewise, the opportunity charger is charged overnight and at pantograph stations during the daytime. An alternative way to regarding infrastructure is not to consider it as CAPEX, but as a service. In this case, third parties could offer charging opportunities in and around cities while bus operators pay per kWh of energy used. This will be further discussed in the sensitivity analysis. Contrary to the buses, which are depreciated to ten percent of their original purchase price after ten years of service, the infrastructure is entirely depreciated over a period of twenty years.

d. Fuel cost

The fuel cost is determined for an average annual distance of 60.000 km travelled regardless of the powertrain choice. Unit prices per fuel type are based on discounted market prices for large consumers for the first quarter of 2018 and are given in Table 5 together with the powertrain-specific fuel consumption data. Due to its limited battery capacity, the PHEV bus is assumed to drive electrically for five percent of the time, while in reality, the electromotor(s) might only assist in accelerating without having the possibility to drive in an all-electric mode. This percentage could nonetheless be increased substantially if the PHEV bus recharges at pantograph opportunity chargers as well. This, however, requires compatibility with the charging rates that characterise pantograph stations as well as a high degree of interoperability.

TABLE 5: OVERVIEW OF FUEL COSTS PER TECHNOLOGY

	Diesel	CNG	PHEV	BEV
Kilometres/year	60.000 km	60.000 km	60.000 km	60.000 km
Fuel consumption	42,5 L/100 km	48,85 kg/100 km	34 L/100 km; 1 kWh/km	1 kWh/km
Fuel price	€1,01/L	€0,6/kg	€1,01/L; €0,10/kWh	€0,10/kWh
Annual fuel costs	€26.101,64	€17.587,39	€19.952,28	€6.000

e. Vehicle maintenance

The maintenance cost applied in the present TCO addresses both preventive and corrective measures to keep the vehicles in traffic as well as the cost of tyre replacements and lubricants. These costs are obtained by averaging the feedback from European bus operators, for which an overview per powertrain technology is given in Table 6. Considering the tyre lifetime, the added weight of the battery pack for the electrified powertrains results in roughly 10% and 15% higher tyre wear for PHEV and BEV buses, respectively. Tyre cost per unit is €230 while replacing the set of six wheels costs €150 (Belgian prices).

TABLE 6: OVERVIEW OF MAINTENANCE COSTS PER TECHNOLOGY

	Diesel	CNG	PHEV	BEV
Lifetime tyres	60.000 km	60.000 km	54.500 km	52.000 km
Annual tyre cost	€1.530	€1.530	€1.690	€1.760
Lubricant cost per kilometre	€0,011	€0,011	€0,008	€0,007
Annual maintenance cost	€23.514	€30.419	€15.083	€11.724

f. Insurances

In the absence of European averages on the cost for insuring a bus for daily operation, Belgian data for conventional diesel buses are used. The insurance costs presented in Table 7 cover both public liability and a so-called 'omnium' coverage for collision damage, including a waiver of €1.250 per damage case. These two fees are deemed equal regardless of powertrain technology.

TABLE 7: OVERVIEW OF THE ANNUAL INSURANCE COSTS

	Diesel	CNG	PHEV	BEV
Annual insurance public liability	€2.000	€2.000	€2.000	€2.000
Annual insurance omnium coverage	€3.000	€3.000	€3.000	€3.000

g. Taxes

Several taxes are applicable for road vehicles, of which the most common are the registration tax and the circulation tax. Whereas these taxes are country-specific and public bus operators might even be exempt from paying them, we decided to exclude this parameter from the exercise.

h. Subsidies

Subsidies can be implemented in various ways, ranging from fuel tax exemptions to financial incentives relieving the upfront cost of new vehicles. Like taxes, subsidies are determined on a national and/or regional level, which makes it difficult to quantify them on a European level. Therefore, we assume no subsidies are in force. Nonetheless, subsidies can have a substantial impact on the breakthrough of novel technologies for which costs are expected to decrease in short to mid-term.

i. Summary table

Concluding our TCO parameter overview, the total cost for ten years of operation is brought back to a distance-specific expense in euro/km. Take into account that for the operational costs, the present value is shown in summary Table 8. If we include the capital expenses for both buses and their respective infrastructure, we consider their depreciation cost after ten years. Keep in mind the assumptions made in Table 4 concerning the number of buses per infrastructure unit as these return in the calculation of the latter's depreciation cost.

TABLE 8: OVERVIEW OF THE TCO EXERCISE'S PARAMETERS

	Diesel	**CNG**	**PHEV**	**BEV (opport.)**		**BEV (depot)**	
				With batt.	Lease	With batt.	Lease
Fuel cost (€/km)	*€0,43*	*€0,29*	*€0,33*	*€0,10*	*€0,10*	*€0,10*	*€0,10*
Maintenance cost (€/km)	*€0,42*	*€0,53*	*€0,28*	*€0,23*	*€0,23*	*€0,23*	*€0,23*
Battery lease (€/km)	-	-	-	-	*0,14*	-	*€0,14*
Battery replacement (€/km)	-	-	*€0,002*	*€0,013*	-	*€0,025*	-
Insurance cost (€/km)	*€0,09*	*€0,09*	*€0,09*	*€0,09*	*€0,09*	*€0,09*	*€0,09*
Tax cost (€/km)	-	-	-	-	-	-	-
Subsidies	-	-	-	-	-	-	-
OPEX 10 years (€/km)	*€0,93*	*€0,91*	*€0,70*	*€0,42*	*€0,55*	*€0,44*	*€0,55*
CAPEX bus	*€184.719*	*€216.844*	*€357.391*	*€403.571*	*€381.485*	*€403.571*	*€381.485*
Infrastructure + maintenance	*€2.509,37*	*€5.120.48*	*€8.618,18*	*€83.773,96*	*€83.773,96*	*€24.435,24*	*€24.435,24*
TCO 10 years (€/km)	***€1,24***	***€1,27***	***€1,32***	***€1,24***	***€1,33***	***€1,18***	***€1,23***

3. Results

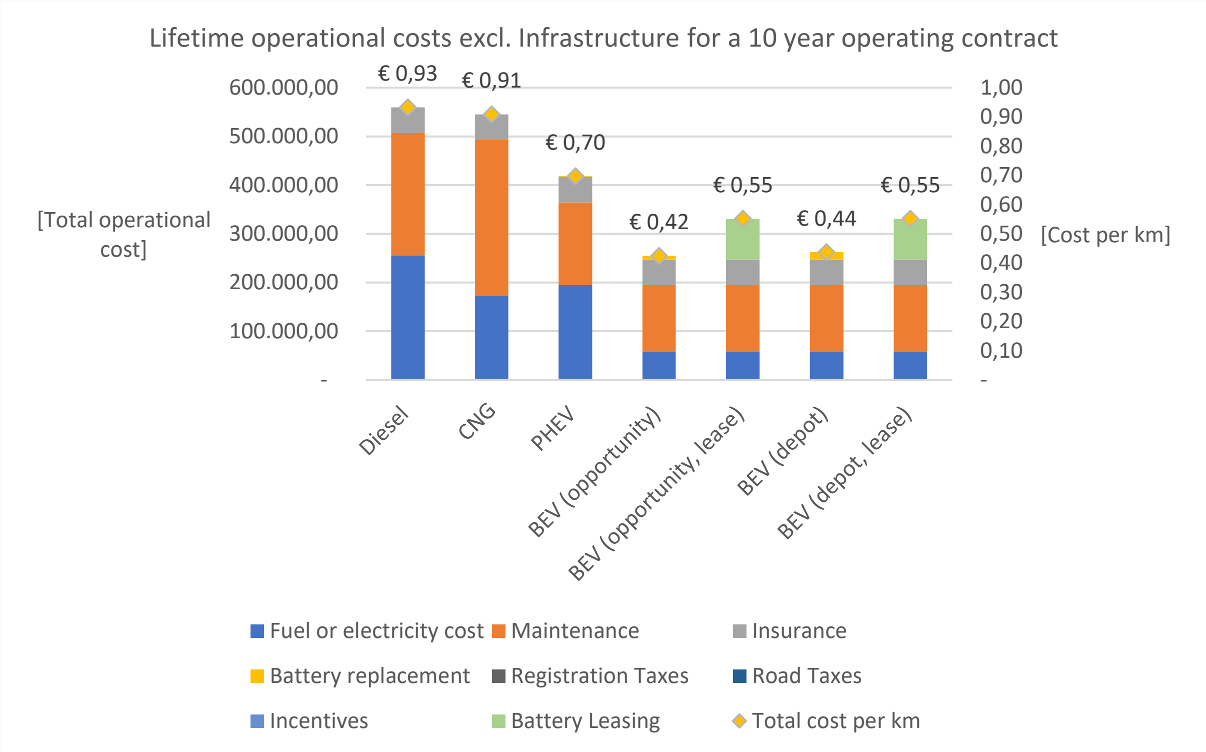

FIGURE 2: OVERVIEW OF THE LIFETIME OPERATION COSTS PER BUS TECHNOLOGY

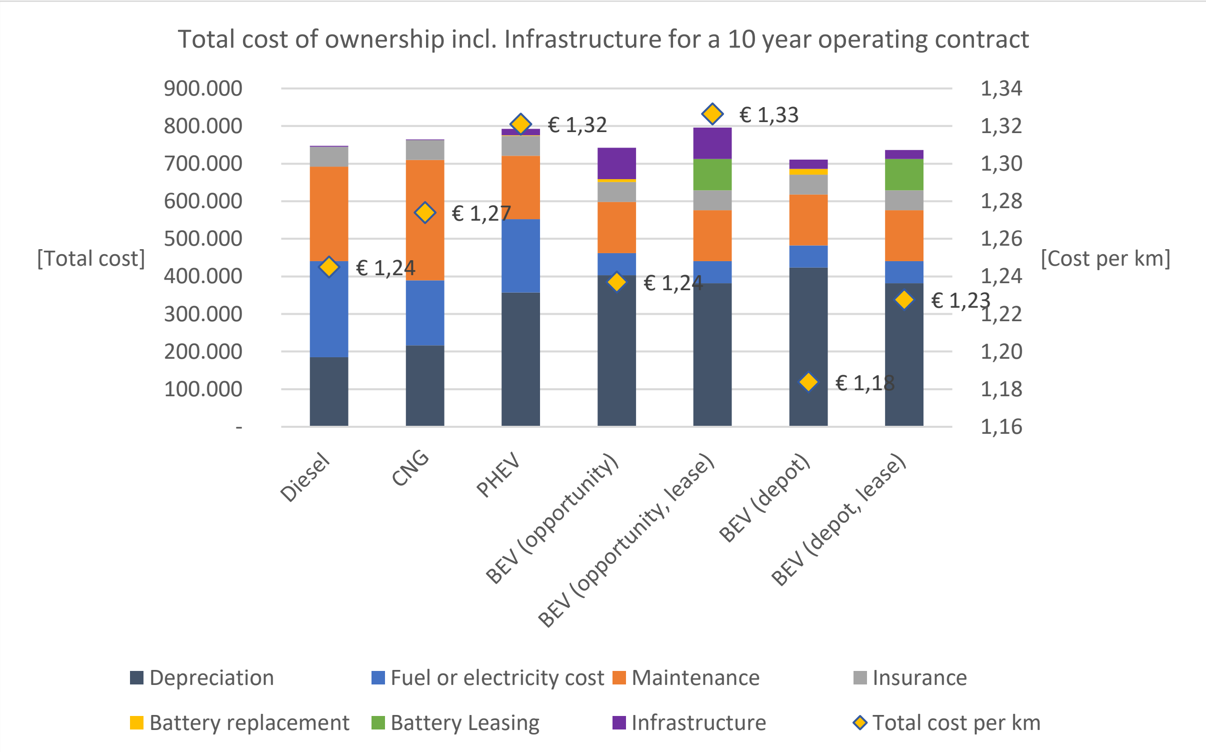

FIGURE 3: OVERVIEW OF THE TOTAL COST OF OWNERSHIP PER TECHNOLOGY

4. Discussion

As it is indicated in Figure 2, the OPEX decreases with an increasing electrification rate as fuel and maintenance costs are substantially lower than for conventional buses. Due to higher maintenance costs for CNG powertrains, they are an economically less attractive option than their diesel variants. Thus, fully electric buses offer the most economical solution when considering the operational costs. For PHEV technology, the better fuel economy leads to an OPEX reduction of nearly one-fourth compared to diesel. For the all-electric options, the influence of leasing the batteries is emphasised as an extra cost per kilometre ranging from 4% to 7%. The difference between the e-buses relying on opportunity and depot charging, respectively, can be related to battery replacement costs. Here, the former's smaller battery pack results in lower costs.

By including the costs of purchasing and maintaining the required infrastructure, as well as the depreciation of the buses over a ten-year period, the total cost of ownership can be calculated. Results in Figure 3 show the depot-charged battery electric bus is already a better solution today when compared to the conventional diesel powertrain. Despite the opportunity-charged electric bus's inherent advantage of allowing smaller battery packs, the current lack of a price difference between the two types of electric buses does not allow for its TCO to become more advantageous. Unmistakably, this is an important sign for bus operators as switching over to e-buses today proves to economically feasible. One important aspect that is not highlighted in our model, however, is the labour cost. The reason for its exclusion is the spread for this cost across the EU. By adding them to the calculation, the ratios between the different power technologies are nonetheless assumed to remain stable.

5. Sensitivity analysis

As our model is built on the interactions between many parameters, a sensitivity analysis becomes useful to assess the impact altering some inputs. In this subchapter, we will investigate the impact of the battery life and the concession contract on the TCO. Also, we will discuss what it takes to reach TCO parity between diesel and electric buses if third parties would offer the charging infrastructure and a price per kWh of energy consumed is paid

a. Battery lifetime

The field of battery development has been one of swift progress since the last decade. Thus, progress has led to both higher energy and power densities, while the cost has been decreasing substantially. Whereas earlier scientific publications forecast a battery cost of $100/kWh by 2025 [5][6][7], the market is evolving to reach this target sooner. To become the market leader in the field of battery development, the European Commission targets €90/kWh by as soon as 2022 [4]. Disregarding whether it will be lithium iron phosphate or nickel manganese cobalt chemistries that will dominate battery sales by 2025, we can safely assume batteries will become smaller and lighter for the same energy density. Where technological improvements are vital in our TCO model as battery packs bought today will have to be replaced when its end-of-life is reached, it is essential to assess the impact of this current lifetime. As indicated earlier, lifetimes up to 1.000 cycles are feasible today if batteries are optimally used. Ideally, the depth-of-discharge is kept low in case of opportunity charging buses' NMC batteries. For overnight charged buses, the applied LFP chemistries can take increased depths of discharge.

Nonetheless, changes in the bus's driving route or failing chargers can put an extra strain on the available stored capacity. Therefore, we assess the impact of reducing the battery lifetime by 20%, 30% and 40%, respectively. Results in Figure 4 show the effect on the TCO for both the PHEV and the e-buses with a bought battery, as replacements are considered to be included in the leasing fee. The impact is found to be the biggest for the depot charged e-bus as its battery pack is the most expensive of the three discussed technologies. As such, a worst-case scenario of a 40% reduced lifetime results in a 4,3% higher TCO.

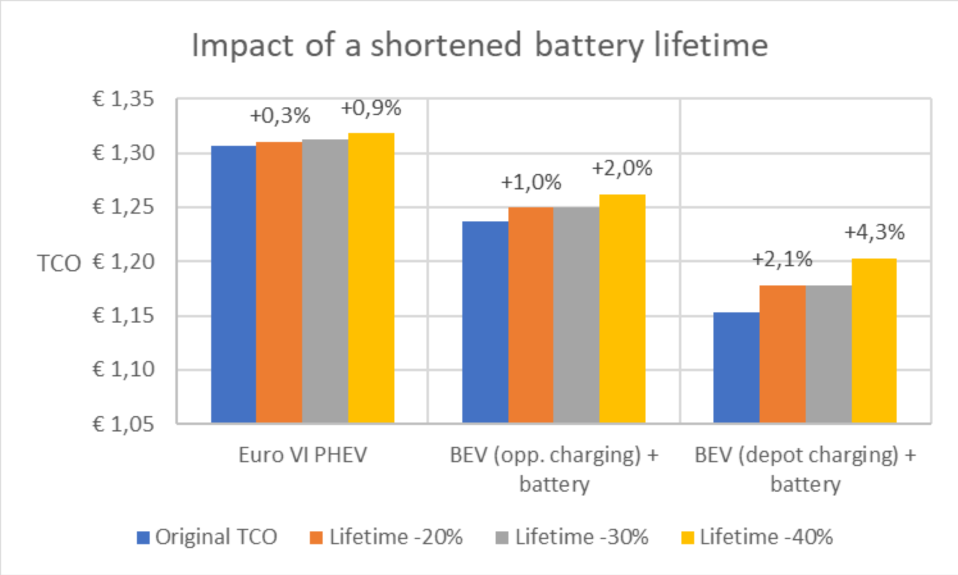

FIGURE 4: OVERVIEW OF THE IMPACT OF A REDUCED BATTERY LIFETIME

b. Concession time

Next, we'll investigate the impact on the total cost of ownership of shortening and extending the concession period of a bus fleet. Where originally, we target a ten-year concession, we'll now look at the effect of reducing this to eight years or prolonging it to twelve years. The results in Figure 5 show a symmetrical impact for the internal combustion engine-based technologies as well as for the overnight charged bus with a leased battery pack. What catches the eye is that the TCO gap between opportunity and overnight charged e-buses decreases with longer concessions as the latter shows a less pronounced TCO decrease for the two-year extension. The other way around, a shortened concession results in higher total costs of ownership for the opportunity charged variants. The bigger impact for e-buses relying on opportunity charging can be explained by the depreciation of the charging infrastructure and its maintenance.

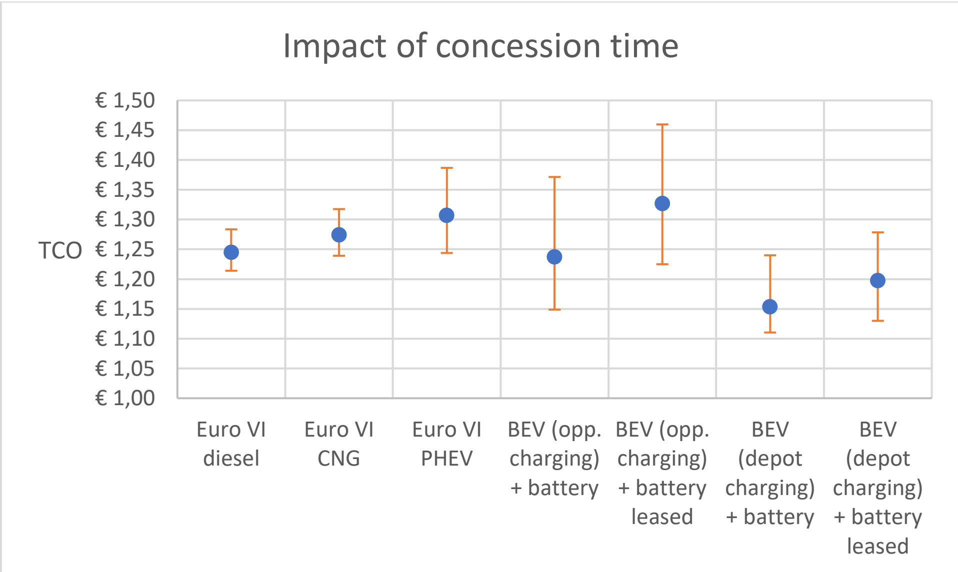

FIGURE 5: OVERVIEW OF THE INFLUENCE OF THE CONCESSION TIME ON THE TCO

c. Roadside charging as a service by third parties

Perhaps the most interesting sensitivity in this exercise is to shift the operator's burden from buying and operating pantograph charging stations to third parties offering this as a service. For this option to become economically feasible for bus operators, we must compare TCO's as a function of the price paid per kilowatt-hour of energy used. If this would be set to equal the price of diesel fuel per kilometre, added with the cost for depreciating and maintaining the technology's infrastructure, the energy price should come at €0,46/kWh. For this exercise, we remove the CAPEX for the pantograph infrastructure for opportunity charged buses, while maintaining the cost for their overnight charging infrastructure. The latter's maintenance is kept as well. Keep in mind that the discussed e-buses are assumed to consume 1 kWh of electricity per kilometre driven. The results in Figure 6 show how a €0,46/kWh price would offset the e-bus's TCO by nearly one-fifth (+18%), which is why this option would not be viable for e-bus operators, as TCO parity with diesel powertrains was originally met (see Figure 3). By stepping down the cost per kWh an equilibrium is reached at a price of €0,23 per unit of energy, indicating that this is the cost at which it will become interesting for e-bus operators to outsource power supply to other players on the market. This concept is a logical step in the market uptake of electric buses, as bus operators do not pay for bus stations or road infrastructure either. Instead taxes are applied for motorists to cover for these expenses, while public transport is typically exempted from such road taxing.

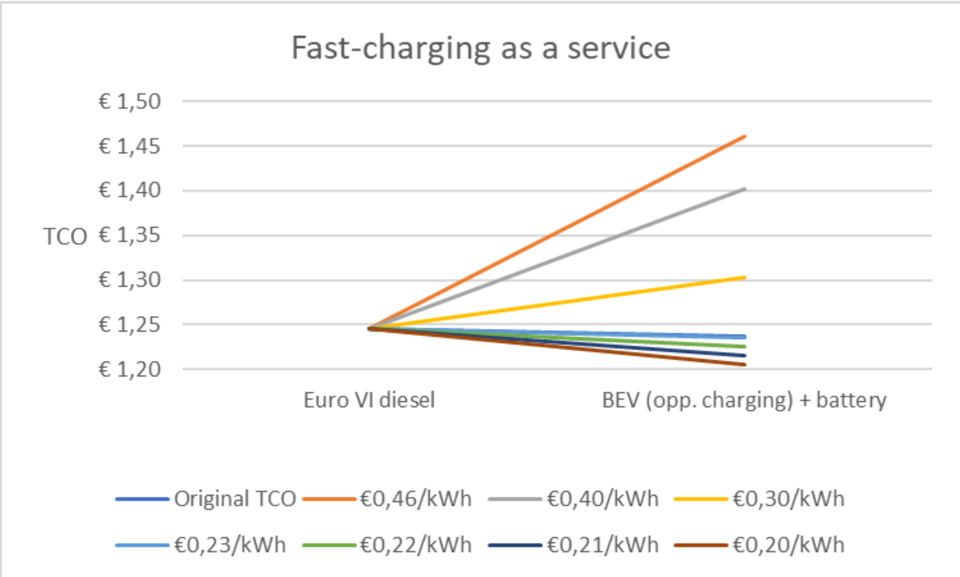

FIGURE 6: EVALUATION OF THE PRICE PER KWH FOR OPPORTUNITY CHARGING OFFERED AS A SERVICE

Nonetheless, a price as low as €0,23/kWh is challenging for third parties to realise, if we compare to the prices that are paid nowadays for fast-charging passenger cars. As it goes with many innovations, it is often up to the early adopters to take this higher initial cost, while subsidies can help to overcome this financial burden. As the market turns towards e-mobility, economies of scale will work as a counterforce to bring down prices for both electrified buses and their infrastructure.

6. Starting from scratch: opportunity vs depot charging

For operators considering to switch to electric buses, a crucial question is whether to opt for depot charging or to include opportunities on the bus routes as well. This exercise is far from straightforward as it included many variables. An overview is given here.

a. Energy demand and charger locations
   i. Operators need to simulate the total energy consumption over a bus route and this for the number of times a bus performs this route per day
   ii. Based on the energy demand and the topology of the city, suitable locations for chargers and/or an overnight depot for charging need to be determined
   iii. Worst-case scenarios should be simulated based on traffic data and the possibility of charger system failures
b. Matchmaking
   i. For each charging solution, timetables must be aligned with charging times, while redundancy must be considered to allow for charger failures without consequences for the buses relying on them
   ii. With this knowledge, batteries can be sized to the specific needs of the different bus routes. Over-dimensioning is an option, although it comes at a higher CAPEX and thus negatively influences the TCO
c. Cost analysis
   i. With the battery size determined, the number of chargers must be determined as well as the charging power they are characterised by
   ii. In case of outsourcing this task, feasible charging rates must be negotiated with service providers
   iii. If the operator manages roadside charging, costs for grid connection should be determined
   iv. Finally, operating costs should be calculated
   v. With these different cost variables, the TCO can be calculated, and a decision can be made whether the investment is worthwhile and competitive with those of other powertrain technologies.

The trade-off between the two possibilities is further highlighted in Figure 7, which shows both charging power and the infrastructure use frequency as a function of battery size. A differentiation is made between depot charging, charging at end stations, while driving (inductive or via catenaries) or at bus stops. The shorter the charging time gets, the higher charging currents become to transfer the same amount of energy in less time.

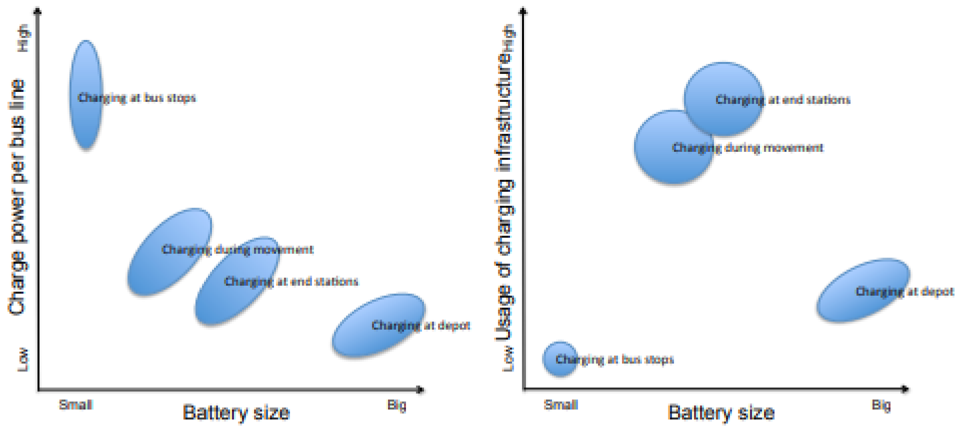

FIGURE 7: COMPROMISING CHARGE POWER AND INFRASTRUCTURE USE WITH BATTERY SIZE [8]

Opting to concentrate all chargers in one depot can have consequences for the grid it is connected to, as the aggregated load can cause either a severe strain on the network or requires a costly connection to a distant medium-voltage network. Figure 8 graphically indicates this.

FIGURE 8: BALANCING THE LOAD ON THE GRID VS CONCENTRATING IT IN ONE LOCATION [9]

For the moment, the European market for electric buses and their needed infrastructure is still up for grabs as there is no pronounced tendency towards one of the two charging solutions. It is nonetheless expected that operators will implement both depending on the possibilities for pantograph stations within a city's borders. In the coming years from now, challenges to grid stability are not yet expected, as operators will only gradually shift to e-buses [10]. Figure 9 shows a practical example of how an electric bus fleet charged at a depot can be implemented. As can be seen, several buses can be charged during off-peak moments, i.e. between 9 a.m. and 3 p.m.

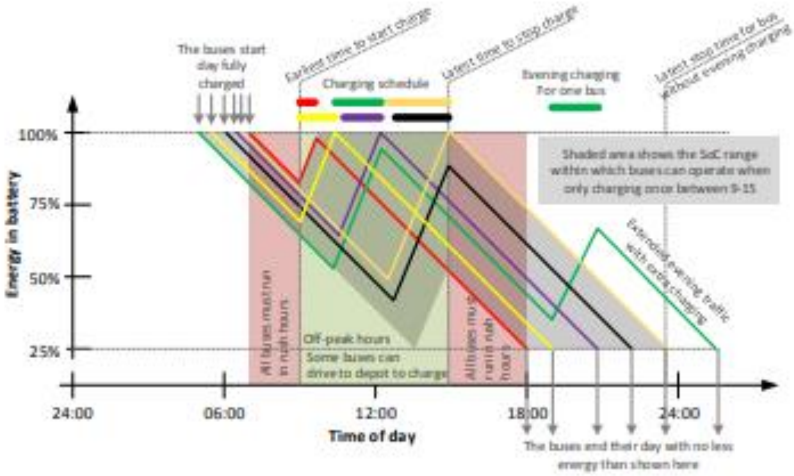

FIGURE 9: A PRACTICAL IMPLEMENTATION OF A DEPOT CHARGED BUS FLEET [8]

7. Market evolution by 2025 and consequences for TCO

Although several city governments around the globe have started to ban non-electric buses from their centres by 2025, it is China that spurs the global e-bus market. Thus, about half the global public bus fleet will be fully electric by 2025, with virtually all (99%) electric buses registered in China [11]. Moreover, price parity is expected to be reached with diesel buses for some e-bus models one year later. Let us assume the latter refers to opportunity charged models, as they typically have a smaller battery pack. Also, let us assume conventional powertrains get more expensive to coop with efficiency improvement targets, for instance by 10% as shown in Table 9. If price parity is to be reached by 2026, the CAPEX for e-buses is bound to drop by 45-50%. In a sensitivity analysis covering only these changes to the original TCO, hence maintaining the current prices for infrastructure, the TCO for electric buses would drop substantially as shown in Figure 10.

TABLE 9: CAPEX ASSUMPTIONS BY 2026

	Diesel	CNG	PHEV	BEV – opp.	BEV - depot
CAPEX 2018 (€)	230.000	270.000	445.000	502.500	527.500
Change (%)	+10%	+10%	-30%	-50%	-45%
CAPEX 2025	253.000	297.000	311.500	251.250	290.125

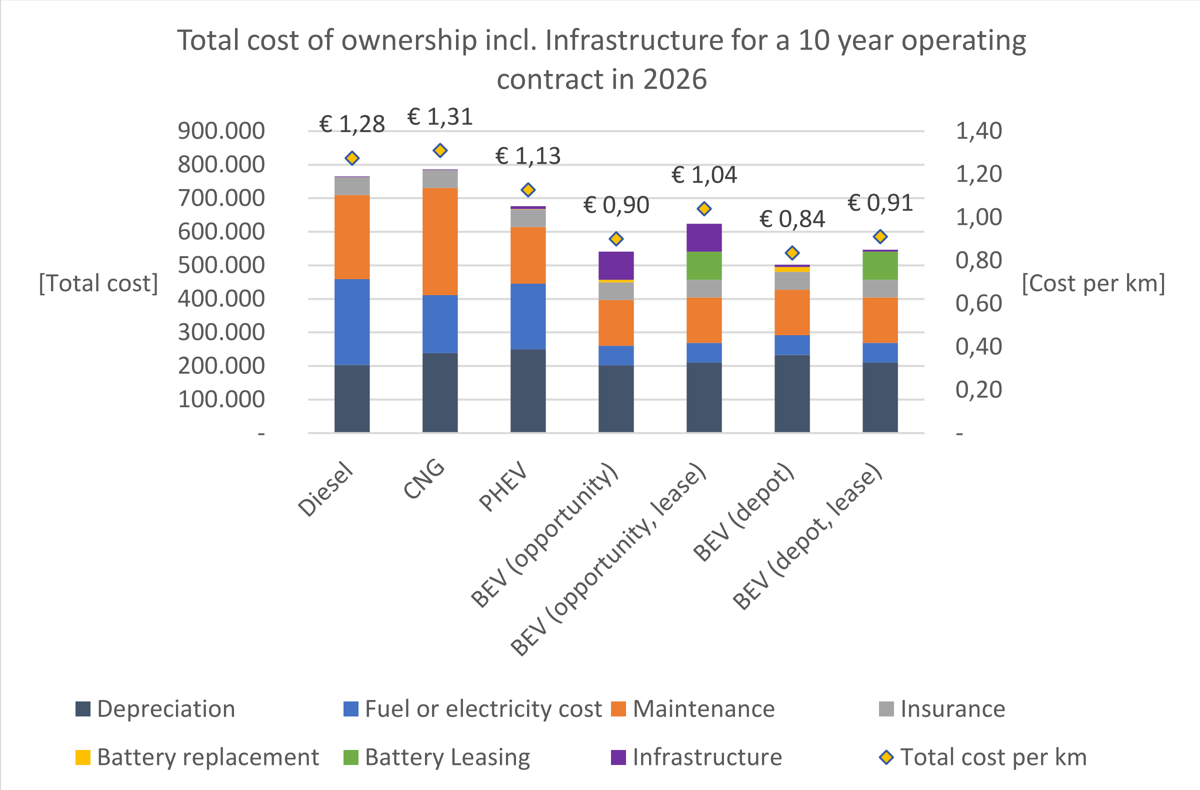

FIGURE 10: TCO FORECAST FOR 2026 WITH SUBSTANTIALLY DECREASED CAPEX FOR ELECTRIFIED POWERTRAINS

Results show how a price parity between diesel and an opportunity charged bus could drastically bring down the TCO in favour for the latter. This is nonetheless a rough estimation of the near-term situation, as no changes were made to fuel nor electricity prices, nor to battery replacement costs. Nevertheless, 2026 battery prices might have decreased further from the assumed €90/kWh since 2022.

8. Conclusions

In short, we can conclude on the following:

a. Operational expenses (OPEX) decrease with increasing degree of electrification. This is mostly due to low fuel costs and lower maintenance costs.
b. By including the depreciation of both vehicle and infrastructure to the OPEX, we can calculate the total cost of ownership TCO. Based on our assumptions:
    i. A lower TCO is found for depot charged buses than for diesel variants when compared on a one-on-one basis and this without subsidies;
    ii. TCO parity is found between the opportunity charged bus with a bought battery and a diesel bus, and;
    iii. Both CNG and PHEV buses have a TCO exceeding the reference diesel TCO.
c. By simulating a decreasing battery cycle life, the buses with the largest battery capacity are affected most as the TCO for depot buses increases from +2,1% to +4,3% for a 20% and 40% cycle life drop, respectively.
d. Extending or shortening operating concessions has the most pronounced effect on opportunity charged e-buses as expensive infrastructure accompanies them. Extending the concession further widens the TCO gap between electric buses and the conventional diesel and CNG options.
e. Having third parties offering opportunity charging as a service is an interesting option for e-bus operators as it allows them to exclude the substantial cost from their CAPEX. In order to reach a TCO parity with the diesel reference, costs per kWh should be capped at €0,23/kWh, indicating the need for competition and a critical number of buses to make this competition possible. Interoperability is key for third parties to offer such charging solutions.
f. Planning implementation of e-buses requires significant analysis of the possibilities within the city's constraints. Trade-offs between battery size, charging time and infrastructure use frequency need to be considered to reach an optimal solution, which is aligned with the existing bus schedules. There is no apparent market tendency for one of the two charging options, as both will be implemented at first without experiencing possible grid stability issues. As the e-bus market starts to grow in numbers, strategic implementation of chargers will become more decisive.
g. CAPEX parity between diesel and some e-bus models is forecast by 2026. Despite an assumed increase of the diesel bus's upfront investment due to efficiency targets, this means the CAPEX for e-buses will come down drastically, namely by 45% to 50%. This will result in obvious TCO benefits for opting for e-buses.

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