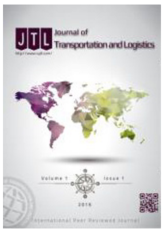

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RESEARCH ARTICLE

Assessment of the municipal bus fleet electrification in Istanbul

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ABSTRACT

The purpose of the study is to provide a holistic view of possible bus fleet replacement with an electrical one for the biggest city in Turkey - Istanbul. More specifically, the research looks at the compatibility of bus charging vs. schedule, and power requirements assess the impact of different battery capacity and provides financial analysis and estimation of the CO_2 impact.

The research focuses on the municipal bus fleet and takes as a base Kadıköy district of Istanbul. The data then is extrapolated proportionally to have an estimation for Istanbul.

The result shows that available technology can be compatible with the busy schedule of the bus fleet. To reduce requirements for day charging batteries with different capacities ha been evaluated.

From a financial perspective, analysis shows that while the electric bus fleet requires a high initial investment, the return on investment is between 6-8 years. The research also shows that while short-distance and not frequent trips should have an easier implementation from the technological perspective, it is the routes with a high daily distance that have the most financial potential.

CO_2 impact is taken from a tank-to-wheel perspective. It shows that even with today's Turkey energy mix bus electrification would have a positive effect on CO_2 reduction thus supporting Net Zero targets.

Keywords: Decarbonization, Clean energy vehicles, Life-cycle cost

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1. Introduction

Based on the International Energy Agency, Transportation is responsible for 25% of global carbon dioxide emissions, three-quarters of which are coming from road transport. With global targets to become carbon neutral, countries are introducing various initiatives to support transport decarbonization. To name a few, Innovation initiatives, government incentives, and targets for the sales of electric vehicles are expected to make difference. Emerging countries such as Turkey have a double challenge as they are still focusing on fast growth while having to cope with their main partners' carbon reduction policies and, of course, their own.

Within the frames of the Green Deal, European Union (EU) is putting a target of 90% reduction of carbon emissions from transportation. Having the EU as the main trade partner, Turkey will be affected by the decisions and two major investments have been done to support this transition. Back in 2018, Turkey's Automobile Joint Venture Group (TOGG) was founded, and the first vehicle is expected to leave the factory in 2022 (Turkey makes strides in producing electric automobiles, 2021). An investment of another 2 billion EUR was announced in March 2021 by the Ford Otosan group. New investment is expected to expand battery production capacity and boost the production of electric vehicles.

Growing local productions of Battery Electric Vehicles (BEV) and Net Zero targets should support the transition on the roads.

Today, Istanbul is the most populated city in Turkey and Europe, counting more than 16 million habitants. Transportation plays a vital role in the city's life and development. At the same time, high pollution levels as well as ambitious Net Zero targets motivate big cities to electrify transportation as soon as possible. The private sector can be stimulated by tax refund schemes and subsidies; however, the transition will depend on the choice and financial ability of final users. Public transport, owned by the municipality, can, potentially, have a faster transition and thus serve as an example to the private sector. Various cities across the globe started the transition of their bus fleets from Conventional Vehicles (CV) to BEV fleets showing that not only it is beneficial to CO_2 emissions, but it is also cost-effective due to lower cost of maintenance and decreasing battery prices.

Two of the most interesting implementations are project ZeEUS, Zero Emission Urban Bus System, in the EU and Shenzhen in China. Project ZeEUS took place between 2013 and 2017 in the EU and follows the small-scale implementation of BEV in various cities in the EU (ZeEUS eBus Report #2. European Commission). The city of Shenzhen in China is a pioneer of bus fleet electrification – so far it is the first and the only city worldwide that succeeded in the entire bus fleet electrification. Today Shenzhen is accounting for 16,000 electrical buses. The change to the electrical buses has proven to be successful and it has moved to the next stage of transport electrification – taxis. Planning of the following steps that would include other modes of transportation (cargo, tractors, etc.) is ongoing (Shenzhen's silent revolution: world's first fully electric bus fleet quietens Chinese megacity, December 2018. The Guardian).

In Turkey, Izmir is the first city that started the introduction of an electrical bus fleet and the usage of Photovoltaic rooftops to meet part of the electricity demand (ESHOT project).

This study aims to find a potential solution for sustainable carbon reduction in a major Turkish city via the exploration of the possibility of municipal bus fleet electrification. Such a development would serve both countries' objectives as well as big cities' ambitions for pollution reduction.

The subject of bus fleet electrification is not new and has been explored by different projects and research. Results and discussions of available literature supported to shape this project.

The study "Electric bus fleet size and mix problem with optimization of charging infrastructure" (Rogge M. et al., 2018) highlights that one of the main challenges of the transition to the BEV bus fleet is the adaptation of the schedule to include charging and impact on the fleet size.

Another example of addressing the battery charging is the study "An Electric Bus with a Battery Exchange System" (Kim J., Inho S. & Woongchul C., 2015) conducted in 2015 in Korea. For this study, the bus has been modified to allow battery pack exchange through the roof by a specially designed robot. The battery exchange operation was completed by the fully automated robot within 60 seconds. Apart from addressing the long recharging time, this approach provides some other benefits such as the possibility to charge batteries outside the pick hours and instead, potentially, provide energy to the grid when needed.

In 2020 a Polish company, Autosan together with National Centre for Research and Development and Łukasiewicz-PIMOT announced an investment of over 1 million EUR to the development of a bus with a removable battery (Autosan aims to build an electric bus with removable battery to cut stopover time, 2020). This investment is partially covered by European Union, which is targeting to become carbon neutral by 2030.

Apart from research back in 2015 and the announcement by Autosan, there is little news about the actual implementation and the technical and commercial impact are difficult to assess. Therefore, this option has not been considered in this project.

The study "Total Cost of Ownership Based Economic Analysis of Diesel, CNG and Electric Bus Concepts for the Public Transport in Istanbul City" (Topal, O. & Nakir, İ., 2018) is particularly interesting for this project as it is focusing on the same geographic area. The study is exploring three different technologies to be used in Istanbul: diesel, Compressed natural gas (GHG), and electric buses. Within the scope of the project, field performance tests have been conducted confirming that electric buses can be operated under the traffic conditions in Istanbul. The conducted financial study confirms that despite the high initial cost of electrical buses operational cost is lower and the total cost of ownership is more beneficial over time. The current project is also looking at the cost of ownership over time (lifetime cost) of CV and BEV buses, however, taking a different perspective – of different bus routes and time of charging. Overall, the conclusions from this project are aligned with the study "Total Cost of Ownership Based Economic

Analysis of Diesel, CNG and Electric Bus Concepts for the Public Transport in Istanbul City" (Topal, O. & Nakir, İ., 2018) on the cost of ownership benefits of the electrical buses vs. diesel ones.

The study "Accelerating Bus Electrification: A Mixed Methods Analysis of Barriers and Drivers to Scaling Transit Fleet Electrification" (Blynn, K. & Attanucci, J., 2019) provides a comprehensive and detailed financial analysis of the buses. It highlights the importance of such parameters as annual distance, fuel, and electricity costs. Differences between CV and BEV technologies result in different requirements of maintenance that also have an impact on cost. The study is also providing results of qualitative research on factors that impact a decision to the switch to BEV bus fleet. The high initial cost of the bus as well as investment in the infrastructure were highlighted as the main barriers of the 'go' decision, stressing the importance of the proper financial analysis that is also looking forward.

The project aims to provide a holistic view of the BEV bus fleet implementation, from technology, financial, and CO_2 emissions perspectives. The project provides insights into the correlation between daily distance, charging requirements, and financial impact.

2. Methodology and Results

The main goal of the project is to assess the feasibility of the replacement of the conventional vehicle bus (CV) with a battery-cell electric vehicle bus (BEV). The project is intended to cover an assessment of the municipality bus fleet electrification from various perspectives:

- Schedule compatibility
- Charging requirements
- Financial assessment
- Impact on the CO_2 emissions

The constraint of the project is to keep the bus fleet size constant, i.e., managing the schedule requirements with additional charges or batteries with higher capacity rather than enlarging the bus fleet.

The scope of the project is described in the table 1.

Table 1: Scope of the project

In scope	Out of scope
Municipality bus fleet, İETT	Private mini-bus, metro-bus, employee shuttle bus
Approach of replacing CV bus fleet with BEV bus fleet	Hydrogen, Hybrid
Full replacement of the current CV bus fleet with BEV bus fleet	Stages of the EV bus fleet implementation
Current technologies for BEV and charging	New development technologies
One type of bus (12m, 3 doors)	Various bus configurations
Technological assessment	Impact on human resources
	Assessment of the distribution infrastructure
	Impact on the grid
	Impact of traffic conditions

The project is divided into five main steps shown in figure 1. The first step has been realized based on the analysis of the Kadıköy district in Istanbul. Assuming that Kadıköy's bus routes schedule can be applied to the whole city, the initial learnings are used to make a further assessment for Istanbul.

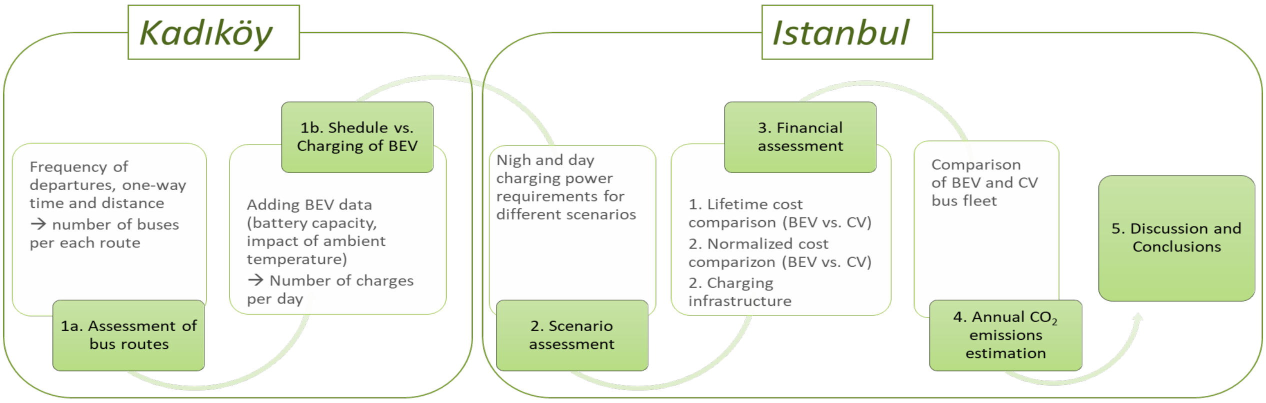

Figure 1. Steps of the project

2.1. Kadıköy: assessment of bus routes

The initial analysis is based on the İETT routes assessment for the Kadıköy district of Istanbul (İETT – Timetable). All routes that indicated Kadıköy as one of the stations were considered (80 in total). Out of 80 routes, the majority (67 routes) connect Kadıköy to other Istanbul districts on the Anatolian side.

As the İETT website did not contain sufficient information on route length, distances were estimated based on route duration and Google maps. Potential deviation based on this method is expected to be negligible.

Characteristics of routes vary significantly, as shown in Table 2. At the same time, all routes have at least four hours between the last and first departures thus allowing the night charging.

Table 2: Characteristics of bus routes in Kadıköy district

Characteristic	min	max
One-way time, min	11,5	102
One-way distance, km	4,3	41
Frequency of departures, week-day, counts	1	207
Stops count	7	79

The following data is used to estimate the number of buses required for each route for one day: time of first and last departures, frequency of departures, and one-way time. This method is estimating the number of buses that are assumed equal for both technologies (CV and BEV) along the analysis. The calculation is done as follows:

$$t_{opsn} = t_{firstn} - t_{lastn}$$

$$t_{in} = \frac{t_{opsn}}{f_n}$$

$$N_n = 2 * \frac{t_n}{t_{in}}$$

t_{opsn} – operating time of the route n

$t_{fisrstn}$ – time of first departure of the route n

t_{lastn} – time of last departure of the route n

f_n – frequency of departures

t_{in} – average interval between departures per route n

N_n – number of buses per route n

t_n – one-way time per route n

Based on the above calculation, approximately 400 buses are required to complete the daily schedule in the Kadıköy district. As a next step, Kadıköy results were extrapolated to the whole city of Istanbul considering Istanbul's total number of bus routes (819 bus routes). Around 13% of buses are serving the Kadıköy district exclusively while 86% are serving two and more districts. Therefore, for extrapolation, a reduction of 30% for routes connecting to other districts was introduced to avoid double counts. The result, 3'087 buses is close to the total data of İETT (3'060), therefore it has been considered as a correct approach.

2.2. Kadıköy: schedule vs. charging of BEV

To make a further analysis of the number of charges needed to complete the daily schedule, it is important to consider the impact of climate conditions. Based on the study "Effects of ambient temperature on the route planning of electric freight vehicles" (Rastani S., Yüksel T. & Çatay B., 2019), the optimal operating temperature for the BEV is between 10°C and 25°C: when neither air conditioning (AC) nor heating is used. Contrary to CVs that partially use heating from the engine to heat the vehicle, BEVs use battery energy thus increasing total energy use per kilometer. In the case of AC use, BEVs use energy from the battery, and CVs have a higher consumption of fuel. Depending on the temperature difference that needs to be achieved by heating or cooling, the energy requirement will differ. To simplify the analysis, the following assumptions were applied to calculate the required number of chargers per each route:

1. Battery capacity 230KWh (ESHOT project):

   AC Off, max distance 348 km

   AC On, max distance 210 km – during calculation, this range was applied for cases when AC or heating is on

2. Based on the Istanbul climate, the worst case scenario is being applied – 8 months per year either heating or AC is accounted to be switched on. This climate assumption is an extreme case and is expected to be more favorable. However, as today electricity cannot be stored, the objective is to analyze the power requirements in extreme case.

The number of charges per each bus to complete daily schedule is calculated as follows:

$$D_n = 2 * d_n * f_n$$

$$D_{bn} = \frac{D_n}{N_n}$$

$$Q_n = \frac{D_{bn}}{D_{max}}$$

D_n – total distance

d_n – one-way distance

f_n – frequency of departures

D_{bn} – one bus distance per day

N_n – number of buses per route n

Q_n - Number of chargers per day

D_{max} – maximum distance as per assumptions

The results of the calculations are presented in Figure 2. When using a battery 240kWh we can conclude that routes can be divided into 3 groups:

- Feasible with one charge with AC On
- Feasibility of 1 charge is changing with season
- Not feasible with one charge with AC Off

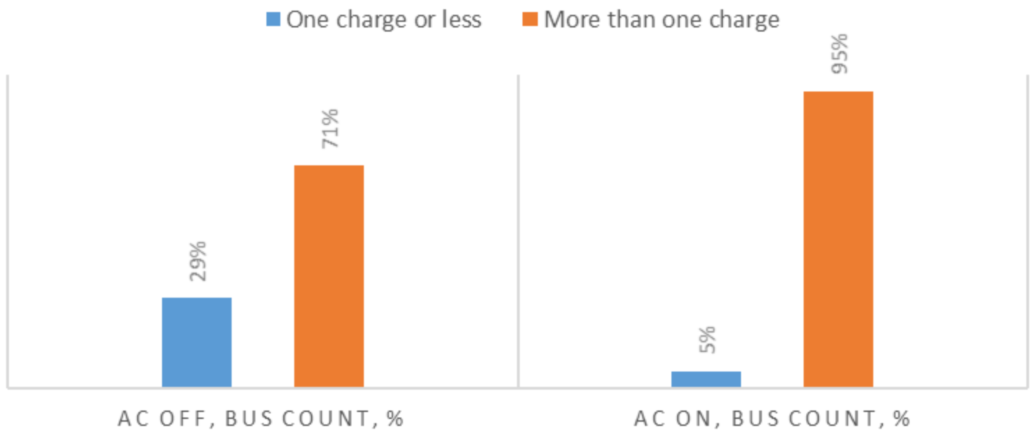

Figure 2. Bus groups in Kadıköy district based on charging requirements (battery capacity 230KWh)

Overall, it can be concluded that the driver behind the charge requirement is the daily distance of one bus which is the result of a combination between the route length and frequency of departures as summarized in table 3.

Table 3: Bus groups characteristics

Group	Routes count	Share of total buses	Frequency of departures (average)	Route length (average)	One bus distance per day (average)
1	20	5%	8	12 km	126 km
2	30	24%	20	21 km	293 km
3	30	71%	91	23 km	394 km

2.3. Istanbul: scenario assessment

While looking at the number of buses, it shows that when AC is on, in case of usage of the 230KWh battery, most buses require additional charge during the day. That might prove to be a challenge due to several factors:

- Possible conflict with bus schedule
- Additional load on the grid during high demand hours
- Difference of electricity prices

To address this situation, three scenarios were analyzed using different battery capacities: 230KWh, 280KWh, and 350KWh. The following assumptions have been applied to the analysis:

- The number of buses and, therefore, power demand is estimated for the complete İETT bus fleet
- In case the bus is completing the daily schedule using less than 50% of the charge, it is assumed that charging for this bus is done every second night. This approach is decreasing the number of buses to be charged during the night and thus decreases the demand for chargers. However, based on the data, the impact is insignificant
- Night charging (23:00 – 06:00) – standard charging for 4 hours. Two options were assessed: 50% and 75% of buses to be charged simultaneously. Quantity of buses to be charged simultaneously depends on the planning that is driven by the daily schedule of each route.
- Day charging (10:00 – 22:00) – fast charging, 2 hours for a full battery. Only the demand to complete the schedule is considered. To assess power demand, it is assumed 50% of buses to be charged simultaneously

Results of different scenario assessment are presented in the table 4.

Table 4: Power demand per each scenario

Power demand depending on the Charging time of the day	Scenario 1: 230KWh		Scenario 2: 280KWh		Scenario 3: 350KWh	
	AC Off	AC ON	AC Off	AC ON	AC Off	AC ON
Night charging (75%), MW	130	132	158	160	194	199
Night charging (50%), MW	87	88	105	107	129	133
Day charging, MW	17	107	2	79	0	41

In cases when AC or heating is off, power demand during the day is insignificant and does not vary much between scenarios. In case when AC or heating is on, the day charging demand grows significantly, which is challenging during July and August when electricity demand is the highest during the year.

Based on the result, it can be concluded that higher battery capacity is allowing a shift in power demand from day to night charging. The best result is achieved with a battery capacity of 350KWh.

Additional advantages of the battery with higher capacity can be reduced battery degradation and reduced number of additional charging stations along the routes.

2.4. Financial assessment

2.4.1. Bus lifetime cost

The lifetime cost assessment is based on the 3 bus groups identified in the previous section:

Group 1: Feasible to complete the daily schedule with one charge with AC On

Group 2: The feasibility to complete the daily schedule with one charge is changing with the season

Group 3: Additional day charging is required to complete the daily schedule with AC Off

The assessment was done over the period of fifteen years using four main criteria:

a. *Capital investment*

Based on the Otokar price list, buses with a similar configuration (CV – Kent LF and BEV – Kent Electra, 12 meters, 3-doors), the price of the BEV bus is almost 2-times higher. The main drivers behind this could be the battery cost which usually composes 50% of the total cost of the BEV and low production volumes. Capital investment is a one-time cost that occurs during the first year and is therefore reflected in the first year for each bus.

b. *Maintenance cost*

Based on the study "Accelerating Bus Electrification: A Mixed Methods Analysis of Barriers and Drivers to Scaling Transit Fleet Electrification" (Blynn, K. & Attanucci, J., 2019), due to fewer rotating parts, regenerative brake system, and less complex drive train, the maintenance cost of BEV bus is around 40% less versus CV bus. The assumption is taken for calculation that maintenance cost occurs after one year of exploitation.

c. *Fuel/electricity cost*

Fuel (diesel) price is taken as the yearly average. Diesel consumption (AC off) is taken as an average of 40L/100km as per the study "Real-world fuel consumption and CO2 emissions of urban public buses in Beijing" (Zhang S. et al., 2014). Consumption from June-September, based on the US department of energy is accounted for a 25% increase due to the use of AC.

Electricity price for calculations is taken from EPİAŞ as an average by the charging time. Thus, 1KWh of day charging would lead to higher costs versus night charging. Climate impact (use of AC or heating) is considered by a difference in the percentage of buses that require additional day charging. The cost is calculated based on the outcome from the previous section (2.3 Istanbul: scenario assessment) to account for the difference between night and day charging.

d. *Midlife cost:* battery exchange for BEV and engine maintenance for CV

- The battery price is still a barrier that drives significant differences in the initial purchase cost. Looking at the EV prices, news announced that in 2020 the price reached 137 $/KWh and expectations are that it will reach 101 $/KWh in 2023 (Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, 2010). However, the study "Learning only buys you so much: Practical limits on battery price reduction" (Hsieh I-Y. L. et al., 2019) is not so optimistic highlighting that there is a limit to the price reduction due to material cost. Depending on the material price development, the EV battery pricing might have different predictions as well. The EV bus battery is also following the trend and based on Bloomberg New Energy Finance predictions, the price per 250KWh battery in 2030 can reach $38 thousand (Electric buses and Tco, a matter of (short) time, 2018). The learning curve, the economy of scale, and process automatization would be the main drivers for the price reduction. Generally, a battery of the BEV represents around half of the total BEV cost. Following this logic, looking at the Otokar price for KENT Electra, the price of the 210KWh battery is around $250 thousand, leading to a cost per 1KWh of 1'200 $/KWh. This number is almost ten times higher than the world average, of 137 $/KWh (Electric buses and Tco, a matter of (short) time, 2018). The reasons behind this might be the low production volumes and the import of the components. With the growing trend of transport decarbonization, it is safe to assume that production volumes will increase thus bringing the battery price closer to the world average. There are also some discussions ongoing that recent developments in the battery sector would ensure the battery lifecycle and probably would lead to the avoidance of the battery exchange. Those discussions, however, have not yet been confirmed in practice. Should that be the case, the lifetime cost of the BEV buses would decrease further leading to a higher gap with CV buses. For the calculations, the expected market average cost for the battery replacement was used.

Lifetime cost is then calculated as an accumulation over the years of the sum of the above-listed criteria. The result of the calculations is presented in Figure 3.

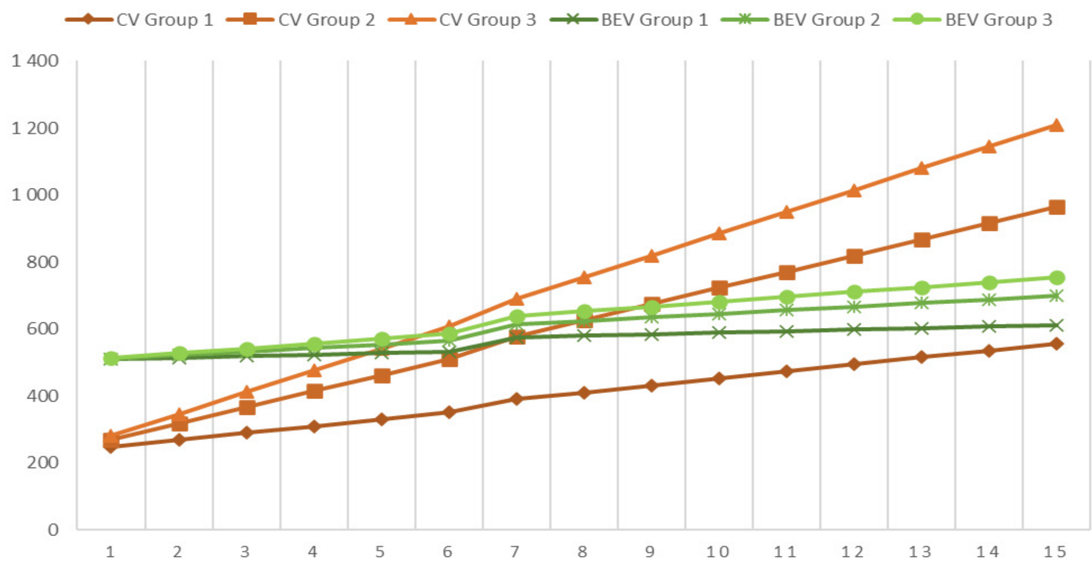

Figure 3. CV and BEV lifetime cost comparison, Scenario 1, thousand dollars

Based on the results, it is safe to conclude that, despite the high initial capital investment, in case of frequent use (high distance during the day) BEV buses are more cost-effective compared to CV buses. This difference is mainly driven by lower cost of fuel and maintenance costs.

The Pay-back period for Group 3 (i.e., 70% of buses) is estimated in 5-6 years. Payback for 95% of buses would come in 8 years (Group 2 and 3). Group 1 of BEV buses has a higher lifetime cost versus Group 1 of CV buses, however, representing 5% of the total number of buses their contribution to the total lifetime cost of the bus fleet is insignificant.

Overall, potential cost savings over the course of 15 years in case of a switch from CV to BEV bus fleet can be expected around $1,5 billion.

2.4.2. Normalized cost per one kilometer

The normalized cost was calculated using the data from the previous section (2.4.1 Bus lifetime cost) divided by the number of years and total distance per year. The normalized cost is calculated for each group of buses and all scenarios (Table 5).

Table 5: Normalized cost per one kilometer

Normalized cost, $/km	BEV Scenario 2	BEV Scenario 2	BEV Scenario 3	CV	Average daily distance of 1 bus
Group 1	0,96	0,87	1,00	0,87	126 km
Group 2	0,47	0,44	0,50	0,65	293 km
Group 3	0,38	0,36	0,34	0,61	394 km

Looking at the normalized cost per kilometer confirms the previous conclusion that in case of frequent use BEV buses are more cost-effective compared to CV buses. In addition, there is no significant difference between scenarios 1 and 3. Given the fact that from the time of the charging scenario 3 is providing the least power demand during the day, it is recommended to opt for the higher capacity battery.

2.4.3. Charging infrastructure

Charging infrastructure is an important aspect of the success of transport electrification. Well-planned and distributed chargers are the guarantee for the seamless completion of the route schedule as well as optimal use of electricity. And while savings are expected from the lifetime of the bus, additional investment for the charging infrastructure is inevitable. Battery capacity as well as daily planning of charging would be essential elements driving the requirements of the charging infrastructure.

Assuming that night charging would take place at bus depots, two capacity options were assessed: 50% and 75% of total busses to be charged simultaneously. The final capacity requirement depends on the daily planning of charging. Based on the charging industry standards, investment for two options would be:

- 50%: $30 – $40 million
- 75%: $50 – $60 million

Some options of chargers on the market today allow to choose between standard and fast charging. In this case, a portion of the chargers installed for the night charging at depo might also be used for fast charging during the day. If day charging is done only in case of schedule requirement (to complete schedule, i.e., groups 2 and 3), chargers at depo would cover 40-50% of the requirement for the daytime fast charging. Additional chargers would need to be installed along the bus routes. For better utilization of chargers along the bus routes, a strategic alliance might be a more cost-effective option.

Regardless of the options chosen for the charging infrastructure, the required investment would not offset the potential cost saving. Therefore overall, switching to BEV buses might prove to be an economically viable option in the long term.

2.5. Annual CO_2 emission estimation

The BEV buses are claimed to be zero emission. While there is no emission from the operation itself, compare to the emissions due to the burning of fuel in the CV engine, there are lifetime emissions and emissions from electricity generation (tank-to-wheel). In this study, the focus is on the comparison of tank-to-wheel emissions between CV and BEV buses.

According to the data by Carbon Independent (Emissions from bus travel, n.d.), on average diesel bus emits 1.3 kilograms of CO_2 per 1 kilometer. Considering the average (per bus fleet) distance per year, one CV bus emits around 127 tons of CO_2, while the total CV bus fleet emits 391 kilotons of CO_2 per year.

The BEV tank-to-wheel emissions depend on the type of the country's energy mix for electricity generation. For the calculation, the assumption was taken that additional electricity requirements for charging will be met using today's Turkey energy mix. The data for the calculation of emissions from electricity generation is based on the US Energy Information Administration (How much carbon dioxide is produced when different fuels are burned, 2021) and presented in table 6.

Table 6: Electricity generation type per time of charging and emissions

Share of power generation, %	**Natural Gas %**	**Dammed Hydro %**	**Lignite %**	**River %**	**Import Coal %**	**Wind %**	**Solar %**	**Fuel Oil %**	**Geothermal %**	**Asphaltite Coal %**	**Black Coal %**	**Biomass %**	**CO_2 Emissions, tonnes/Mbtu**
8months*, NIGHT charging	33,0	10,0	13,0	3,0	25,0	9,0	0,0	0,0	3,0	1,0	2,0	1,0	0,057
4months**, NIGHT charging	31,0	10,0	16,0	6,5	20,0	9,0	0,0	0,0	3,5	1,0	1,5	1,5	0,049
8months*, DAY charging	29,0	23,0	11,0	3,0	21,0	8,0	0,0	0,0	2,0	1,0	1,0	1,0	0,043
4months**, DAY charging	29,0	18,5	14,0	6,5	17,0	8,0	1,0	0,0	2,5	1,0	1,0	1,5	0,042

** AC or heating on: January, February, March, June, July, August, September, December*
*** AC or heating off: April, May, October, November*

Calculated emissions for CV are comparable to emissions documented in the study "Total Cost of Ownership Based Economic Analysis of Diesel, CNG and Electric Bus Concepts for the Public Transport in Istanbul City" (Topal, O. & Nakir, İ., 2018).

As a result, comparing annual CV and BV bus fleet CO_2 emissions, switching to the BEV bus fleet would decrease annual emissions six times which is in line with the global decarbonization objective (figure 4). In addition, in the event of the carbon tax introduction, such change would also bring financial benefits. Some adjustments may be needed to show the real value of the tank-to-wheel emissions from Turkish power plants, however, the fact of the significant difference between CV and BEV emissions remains.

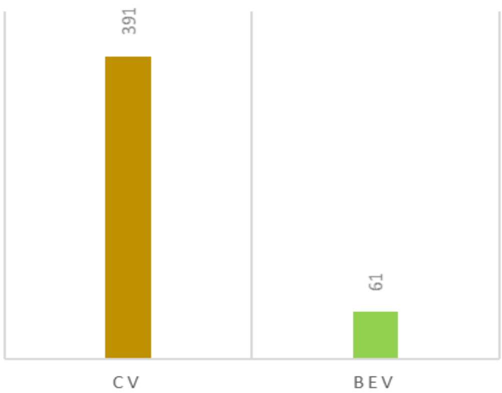

Figure 4. Annual tank-to-wheel CO_2 emissions, KT

4. Discussion and Conclusion

The results are expected to provide value for the mobility state agencies to facilitate discussions on public transport electrifications. It can also serve as a reference for private transportation companies to give a further detailed assessment to their needs.

Based on the conducted analysis, it is possible to conclude that IETT bus fleet electrification in Istanbul, even with today's energy mix for electricity generation in Turkey, would lead to significant CO_2 reduction. Therefore, the switch to the BEV bus fleet goes in line with the global decarbonization objective.

Switching from CV to BEV bus fleet is a change management process that requires careful research and planning: bus fleet requirement, planning of charging, location of charging station, etc.

Bus routes with less daily distance (a combination of bus route length and frequency of departures) might be easier to implement from the planning perspective assuming only night charging. However, as I have shown in the analysis, from financial perspective routes with higher daily distance are more cost-effective and would have 5-6 years of return on investments. At the same time, as most of the bus routes in Istanbul have high daily distances, the right combination of technology (battery type, charger type) and planning (charging schedule and distribution of chargers) must be accounted for at the very beginning of the project.

Planning is also essential for managing the additional electricity load to avoid charging during pick hours and to ensure rational electricity prices. One of the examples is batteries with higher capacity would allow shifting part of the day charging demand to the nighttime. The higher initial cost can be compensated by the difference in electricity prices. In addition, lower wearing-out of battery might be more cost-effective on the long run.

From the operational perspective, a detailed analysis of bus routes is required to build a charging plan in synchronization with the daily schedule. The creation of charging infrastructure, on the other hand, is a paramount milestone in BEV bus fleet implementation. It would require additional investment, however, lifetime cost savings from the BEV bus fleet operation would offset them during the operation. Even with a limited BEV fleet, infrastructure should be sufficient to ensure that operation is not disturbed by a lack of charging points. This would mean that investment in the infrastructure should come first.

While night charging, most probably, would be done at depo, at least part of day charging would be done along the routes. Careful planning of the positioning of charging stations is required to ensure an acceptable balance between the number of chargers and their utilization to reach the seamless operation of the bus fleet. Potentially, strategic alliances might be an interesting option: while outsourcing this part of charging, a higher number of chargers might be installed thus increasing flexibility. The downside of such operations might be the increased complexity of the charging schedule planning as it would need to incorporate charging for other customers as well.

The project was completed by using one bus model, reality would require different options following the required passenger capacity and bus route characteristics. Today the range of the BEV buses is limited compared to the CV propositions, however, based on the current fleet composition, the existing models from local producers are in line with most used buses.

Other options such as the battery exchange systems or the hybrid buses might be considered to manage the bus routes with a tight schedule. A rational balance between different technologies might prove to be the best option.

Storage options and solar PV should be considered when planning such projects. Turkey has significant potential for solar energy. Meeting part of the energy demand by solar PV installed at the charging stations/ depo would not only manage the requirement for additional electricity production but will also help to manage the impact on the distribution systems. Similarly, to the investment in the BEV, storage and solar PV investments would pay off over time from the financial perspective and provide flexibility and, at least partially, independence.

Considering that Istanbul's electricity consumption is 16,5% of total Turkey's electricity consumption (Electricity market 2020 sector report, 2021), additional load from the fully electric IETT bus fleet would represent 2-5% of the consumption in Istanbul. While this number might not be significant, distribution capacity should be created by accounting for light-duty vehicles electrification as well as other commercial transportation.

Looking at the example of Shenzhen in China, electric buses can be a starting point for mobility decarbonization. The acquired experience can afterward be used for the electrification of other modes of transportation. Considering that a large portion of the transportation in Istanbul is privatized, awareness and government support would play a crucial role in driving decarbonization.

Government subsidies have not been discussed in this project. However, they have proven to be an effective booster for transport decarbonization. Indeed, the electrification of the bus fleet in Shenzhen has been supported by subsidies.

Impact on human resources is one of the most sensitive topics when coming to the change management process. Many studies highlight that training would be required to ensure correct operation and adherence to the charging schedule. A simplified maintenance process should be expected to drive a reduction in the maintenance personnel, at the same time additional workplaces might be created to support the operation. Again, Shenzhen's example need to be studied to bring in the best practices.

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