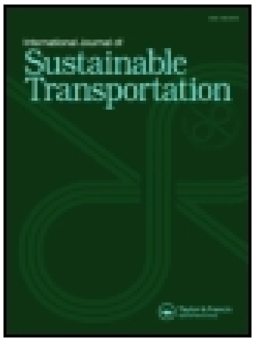

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The role of alternative fuel buses in the transition period of public transport electrification in Europe: a lifecycle perspective

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ABSTRACT

In alignment with climate change, the European Union endeavors to accelerate the electrification progress of the public transit system. In particular, Copenhagen in Denmark and Oslo in Norway develop a blueprint to have 100% public transit electrification by 2030 and 2028, respectively. In this study, the lifecycle approach is applied to explore the role of electric buses in the electrification progress of the public transport system in different European countries. To better model the energy/fuel consumption, we integrate the theoretical model of human thermal comfortable temperature into our proposed framework. We take into account the effects of weather, the daily operation characteristics, and the energy mix of different European counties, and evaluate the lifecycle environmental and economic performance of electric buses. The result shows that the public transportation system with both hybrid and electric buses can be good compensation between financial and environmental needs instead of using electric buses to replace all the conventional buses. Moreover, the operational plan of the public transportation system mixed with electric and hybrid buses may be adjusted according to the seasonal temperature variation so as to maximize the environmental benefits. Considering the different economic and environmental scenarios of energy sources, some EU countries would be able to reduce or remove the incentives for electric buses.

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Alternative-fueled buses; lifecycle cost; public transportation system

1. Introduction

The transportation sector creates approximately 22% of total greenhouse gas (GHG) emissions in European Union states (European Environment Agency, 2019). Considering the advantages of alternatively fueled buses in urban areas, several European cities and regions endeavor to accelerate the electrification progress of the public transportation system. For example, before 2025, several cities (e.g., Athens, Paris, Copenhagen, Berlin, and Madrid) and government (e.g., Norway) have the plan to abandon diesel vehicles or stop purchasing conventional buses. In 2016, to achieve zero-emission transportation, European countries have proposed the Clean Bus Deployment Initiative to cut carbon emissions from the public transportation system. Over 80 cities, regions, manufacturers, and other organizations have signed the Clean Bus Declaration. In particular, Copenhagen in Denmark and Oslo in Norway develop a blueprint to have 100% public transit electrification by 2030 and 2028, respectively. Therefore, the governmental policymakers and transit operators in European countries are facing challenges in the transition period to purely electrified public transportation systems. In order to support their decision-making, lifecycle analysis has been widely applied to understand the overall and long-term worth of public transport electrification. The energy mix determines the environmental performance of electric vehicles (Faria et al., 2013). Moreover, with the maturing of electric vehicle technologies, it is important to determine when or how to achieve purely electrified public transportation systems. Therefore, it is important to investigate the lifecycle cost of battery-electric buses considering the existing energy mix and possible future conditions. The results can help policymakers and operators to design proper strategies to maximize the benefit and minimize the side effect of transportation electrification.

Lifecycle analysis associated with passenger cars and buses, which are powered by alternative powertrains, has gained worldwide attention. Mahmoud et al. conduct a comprehensive review of buses with detailed alternative powertrains considering the economic, operational, energy, and environmental characteristics (Mahmoud et al., 2016). The review pointed out that the lifecycle cost-benefit of the battery-electric bus highly depends on operational characteristics and energy resources.

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In the United States, by assessing the value of lifecycle emissions and oil consumption for different vehicle types power by alternative fuel technologies, Michalek et al. indicated that the external costs of plug-in vehicles are largely dependent on GHG and SO_2 emissions from battery manufacturing and vehicle charging (Michalek et al., 2011). Mckenzie and Durango-Cohen applied a hybrid input–output model to analyze the life-cycle economic and environmental performance of alternative fuel transit buses (Mckenzie & Durango-Cohen, 2012). The results showed that buses powered by alternative fuel have lower operating costs and emissions. However, the lifecycle cost of alternative fuel buses is higher than diesel buses. By comparing lifecycle environmental impact from convention buses and battery-electric buses, Cooney et al. indicated that energy resources dominate most impact categories in the operation phase (Cooney et al., 2013). Moreover, battery production can significantly affect global warming, carcinogens, ozone depletion, and eco-toxicity. Bi et al. compared the impact of different charging technologies on the lifecycle performance of battery-electric buses in terms of energy consumption and GHG emissions (Bi et al., 2015). The results show that the wireless charging system outperforms the plug-in charging system in terms of lifecycle energy consumption and GHG emission. Bi et al. investigated the lifecycle performance of the battery-electric bus system with different charging methods and compared the cost to both conventional diesel and hybrid bus systems (Bi et al., 2017). Tong et al. conduct a lifecycle cost analysis for transit buses powered by different sources, such as diesel, diesel hybrid-electric, compressed natural gas, liquefied natural gas, and electricity (Tong et al., 2017). The study considered GHGs and criteria air pollutants together with ownership costs to estimate total costs. The results showed that diesel buses have lower lifecycle ownership costs than alternative fuel-powered buses. Moreover, the battery-electric bus can significantly reduce city-level air pollutants.

In Europe, Brand et al. introduced the U.K. transport carbon model which covers the transport-energy-environmental issues from energy demand reduction to lifecycle carbon emission and external costs (Brand et al., 2012). Antonio García Sánchez et al. investigated the impact of the Spanish electric mix on different powertrain technologies in terms of lifecycle energy consumption and GHG emissions (Antonio García Sánchez et al., 2013). Among all powertrain technologies, battery-electric buses generate the lowest GHG emissions. By extensively simulating different bus routes, Lajunen investigated the cost-benefit of hybrid and electric buses and pointed out that electric bus is one of the best choices to decrease energy consumption and emissions (Lajunen, 2014). Ribau et al. indicated the importance of driving profile and the tradeoff between investment cost, efficiency, and LCA in the powertrain design of hybrid electric vehicles (Ribau et al., 2014). The results show that fuel-cell powered hybrid vehicles lead to a lower lifecycle cost and higher financial savings potential than plug-in electric hybrid vehicles. Lajunen investigated the lifecycle cost and energy consumption of different charging power and battery requirements considering electric buses on different operating routes (Lajunen, 2018). The results show battery size has a limited impact on the lifecycle performance of fast charging buses. Harris et al. developed a framework to access the lifecycle of alternative bus technologies considering the uncertainty of these technologies (Harris et al., 2018). By comparing to the diesel bus, the results showed that the electric bus can significantly reduce GHG emissions. However, the lifecycle cost of electric buses is 129–247% higher than the conventional buses. By considering emissions associated with fuels and batteries producing process of alternative bus powertrains, Xylia et al. proposed a model to optimize the location of bus chargers using a life cycle perspective (Xylia et al., 2019). The results show that electric buses with larger battery sizes may not lead to a significant drop in total emissions. Nordelöf et al. point out that impacts related to emission decreases with the degree of electrification which is based on renewable energy resources (Nordelöf et al., 2019). Recently, Zhang et al. uncovered the impact of battery degradation on electric bus fleet operation (Zhang et al., 2020). The result shows that maintaining proper depth of discharge during the operation would able to extend battery lifespan up to three years. Moreover, they also point out that battery degradation would significantly affect the lifecycle cost of electric bus fleets.

Moreover, Sharma et al. investigated the economic and greenhouse performance of passenger vehicles with alternative powertrains in Australia (Sharma et al., 2013, 2012). The simulation results show that Class-B electric vehicle has worse performance than an equivalent conventional vehicle in terms of ownership cost and lifecycle emissions. The major reason is that electric vehicle has significantly higher embedded emissions where battery contributes about 50% of the electric vehicle embedded emissions. Bases on on-road tests in Macau, China, Zhou et al. compared the lifetime carbon dioxide emission of battery-electric buses and conventional buses (Zhou et al., 2016). They pointed out that the impact of air-conditioning usage on energy consumption is larger than passenger load. Moreover, Song et al. conduct a lifecycle assessment to compare the traditional diesel public buses and electric buses in terms of GHG emission by using real-world data in Macau (Song et al., 2018). The result shows that electric buses can hardly reduce GHG emissions from traditional diesel public buses based on current electricity distribution. Enrique et al. investigate the life cycle environmental impact of manufacturing BEV and BEB in Brazil considering geographic characteristics (Enrique et al., 2019). As a result, manufacturing BEB and BEV in Brazil is not environmentally competitive unless the impact of metal extraction and metal use can be reduced.

According to the results from the existing works, the lifecycle cost of electric vehicles varies with the analysis methods, data resources, geographic locations, and other impacts. However, to the best of the authors' knowledge, limited work explored the performances of alternative fuel buses in different countries by partially considering local climate, battery degradation, and operation characteristics. By addressing the existing limitations, we explored the lifecycle

Table 1. Drive cycles characteristics.

Cycle	E11 (Lajunen & Lipman, 2016)	H550 (Lajunen & Lipman, 2016)	Braunschweight	MLTB
Duration (s)	1548	3384	1740	2281
Distance (km)	10.2	28.7	10.9	9
Average speed (km/h)	27.9	36	30.1	14.2
Maximum speed (km/h)	74.9	58.4	58.2	48.7
Maximum acceleration (m/s^2)	1.6	2	2.4	1.5
Maximum deceleration (m/s^2)	−1.9	−2.9	−3.6	−2.2
Percent of idle time	11.8%	15.5%	25.7%	33.8%

economic and environmental performance of buses with different powertrains in European countries. Based on the results, we provide insight into the tradeoff between economic and environmental benefits during public transport electrification progress. And several suggestions are proposed to speed up the electrification progress of the public transportation system.

2. Methodology

An evaluation framework was developed to compare the performance of conventional, hybrid, and electric vehicles considering the influence of ambient temperature, daily operation, battery characteristics, and local energy mix. Based on the vehicle power models used in this study have been widely used in the existing works (Gao et al., 2017; Lajunen, 2018; Lajunen & Lipman, 2016), we integrated the theoretical model of cabin comfort temperature into the models to provide detailed and comprehensive energy evaluation of buses. As described in Table 1, the simulations were based on four different European drive-cycles, which are Braunschweig, E11, H550, and Millbrook London Transport Bus (MLTB) drive-cycles. Meanwhile, the yearly operation hours and mileage from different European countries are based on the ZeEUS reports (International Association of Public Transport, 2017, 2016). Additionally, battery operation and degradation models are integrated into the life-cycle assessment framework.

2.1. Vehicle power models

Recently, Luin et al. indicated that the power-based energy consumption model is easy to apply and/or modify to model different vehicle types (Luin et al., 2019). Considering the widely applied vehicle power models develop by Lajunen (2018), Gao et al. (2017), and Wang and Rakha (2017, 2016a, 2016b), the total instantaneous bus tractive power (P_{out}) of conventional buses, BEB and Euro VI hybrid bus is formulated as follows:

$$P_{out} = \frac{0.5\rho_a C_D A_f v^3 + vMgC_{rr}\cos\alpha + vMg\sin\alpha + vM\frac{dv}{dt} + \omega v}{\eta_{fd}} + P_{AUX}, \tag{1}$$

$$\omega = \begin{cases} T_{m0} i_{fd}, & \text{For } BEB, \\ (\lambda + 0.0324\xi v^2) M \dfrac{dv}{dt}, & \text{For diesel or hybrid bus.} \end{cases} \tag{2}$$

where ρ_a is the air density; C_D is the coefficient of drag; C_{rr} is the coefficient of rolling resistance; A_f is the frontal area of the bus; M is the total mass of bus; g is the gravitational acceleration; η_{fd} is the driveline efficiency (Wang & Rakha, 2016a); v is the speed; t is operating time; α is the road grade; T_{m0} is the inertial torque for the electric engine (Lajunen, 2018); i_{fd} is the gear ratio of the final drive (Lajunen, 2018); λ is the mass factor accounting for rotational masses, a value of 0.1 is used for heavy-duty vehicles (Feng et al., 2007); ξ is the term related to the gear ratio, which is assumed to be zero due to the lack of gear data (Wang & Rakha, 2017, 2016a, 2016b); and, P_{AUX} is the auxiliary power demand.

Liu et al. pointed out that the ambient temperature significantly affects the electric vehicle auxiliary loads and energy efficiency (Liu et al., 2018). However, only a few works are conducted to modeling the effect of ambient temperature on the auxiliary loads of buses. Recently, Vepsäläinen et al. develop a computationally efficient model for electric buses, which takes the impact of ambient temperature on auxiliary loads into consideration (Vepsäläinen et al., 2019). However, the model is a black-box model that does not provide the mathematical formulation to describe the relationship between ambient temperature and auxiliary loads. Therefore, by searching the existing works, we derived a model to describe the relationship between ambient temperature and auxiliary loads. Moreover, the proposed model is compared with the model described in the work conducted by Vepsäläinen et al. (2019). Moreover, based on hybrid buses, Bottiglione et al. (2014) formulated the auxiliary load as follows

$$P_{AUX}(t) = P_{constant} + \gamma(A_{sun}|T_{sun} - T_{desired}| + A_{shad}|T_{shad} - T_{desired}|) \tag{3}$$

where $T_{desired}(t)$ is the desired cabin temperature in the cabin; T_{sun} is the temperatures at the area exposed to sunlight; T_{shad} is the temperature at the shadow area; A_{sun} is the area of the bus external surface exposed to sunlight; A_{shad} is the shadowed bus external surface; γ is the average thermal resistance of the cabin walls, which is 7.09 W/(m^2 · °C); and $P_{constant}$ includes power other than AC, which is 6 kW (Lajunen & Kalttonen, 2015).

The exposition area of the bus varies with the location, time of day, direction, and seasons. Moreover, there is no existing model to describe the temperature difference between the area exposed to sunlight and the shadow area of the bus. Results from existing works proposed the U-shaped relationship between auxiliary load and ambient temperature (Liu et al., 2018; Lu et al., 2019; Wang et al., 2017; Yuksel & Michalek, 2015). Therefore, Equation (3) is simplified as follows:

$$P_{AUX}(t) = P_{constant} + \gamma A_{bus}|T_a - T_{desired}|, \tag{4}$$

where A_{bus} is the bus external surface, which is 116 m^2 (Bottiglione et al., 2014); T_a is the ambient temperature (°C).

Human thermal comfort is highly dependent on the thermal insulation in clothing (Oğulata, 2007). Pala and Oz and Velt and Daanen propose the HVAC design methods considered human thermal comfort (Pala & Oz, 2015; Velt & Daanen, 2017). In this study, we assume that the desired temperature in the bus cabin satisfied the human thermal comfort of passengers. Therefore, based on the theoretical work developed by Huang (2007) and Oğulata Oğulata (2007), the thermal comfortable temperature of passengers and the desired temperature in the bus cabin is formulated as follows:

$$T_{desired} = \frac{T_{cl}}{I_{cl} e^{\frac{|T_a|}{60}}} + 1, \tag{5}$$

$$T_{cl} = \frac{T_{sk} + (0.155 I_{cl} + 0.4805 {I_{cl}}^2) h_c T_a}{[1 + (0.155 I_{cl} + 0.4805 {I_{cl}}^2) h_c]} - \frac{0.155 I_{cl} \times \sigma \times 0.75 \times \left[(T_{sk} + 273)^4 - (0.94 T_a + 271.62)^4\right]}{[1 + (0.155 I_{cl} + 0.4805 {I_{cl}}^2) h_c]\left[(h_c + h_r) \times I_{cl} \times 0.155 + 1/(1 + 0.31 \times I_{cl})\right]}, \tag{6}$$

$$h_r = \sigma \times 0.75 \times \frac{(T_{sk} + 273)^4 - (0.94 T_a + 271.62)^4}{T_{sk} - (0.94 T_a + 271.62)}, \tag{7}$$

$$T_{sk} = 35.7 - 0.00285 \times \text{Metabolic rate}, \tag{8}$$

where h_r is the coefficient of radiative heat transfer; σ is Stefan–Boltzmann constant, which is 5.67×10^{-8} W/m^2 K^4(Huang, 2007); T_{sk} is the mean skin temperature (°C); h_c is the coefficient of convective heat transfer; and I_{cl} is the the intrinsic insulation value.

According to the work conducted by Pala and Oz (2015), the convective heat transfer coefficient can be calculated as follows:

$$h_c = 8.3 V_{air}^{0.6}, \tag{9}$$

where V_{air} is the air velocity inside the bus, which is 0.35 m/s (Pala & Oz, 2015).

Based on the reference data, Havenith et al. (2012) proposed a regression model to recover the relationship between intrinsic clothing insulation and ambient temperature.

$$I_{cl} = 1.372 - 0.01866 T_a - 0.0004849 T_a^2 - 0.000009333 T_a^3. \tag{10}$$

Considering the human acceptable temperature range in the existing studies (Cheung & Jim, 2019; Pala & Oz, 2015; Yang et al., 2016), the desired temperature in the bus should not exceed 20°C. As shown in Figure 1, the modeled relationship between auxiliary power and ambient temperature is compared with the reference curve from the study conducted by Vepsäläinen et al. (2019). The proposed model well captured the pattern of the existing relationship developed from the existing black-box model. The major reason for the difference between the proposed model and the reference curve is that the desired temperature would be impacted by different factors, such as lifestyle, residence length, and climate (Cheung & Jim, 2019; Yang et al., 2016).

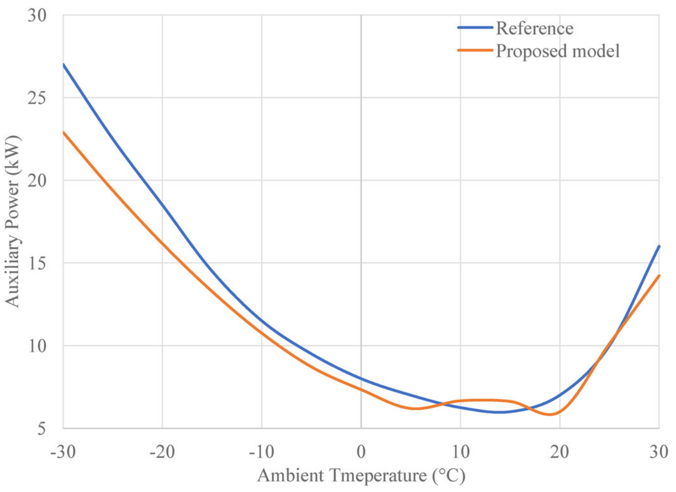


Figure 1. Comparison of the proposed model and the curve proposed in Vepsäläinen et al. (2019).

2.1.1. Modeling energy consumption of electric bus

Despite the tractive power (P_{out}), the internal losses of the battery system must be considered in the energy consumption model of the electric bus. Therefore, the power consumption of electric buses contains tractive power (P_{out}) and battery internal losses ($P_{loss_{BEB}}$), as described in Equation (11).

$$P_{BEB} = P_{out} + P_{loss_{BEB}} = P_{out} + R_b {I_b}^2, \tag{11}$$

$$I_b = \frac{OCV - \sqrt{OCV^2 - 4 R_b P_{out}}}{2 R_b}, \tag{12}$$

where I_b is the battery current; R_b is the battery internal resistance; and, OCV is the battery open-circuit voltage.

Among different battery technologies, Li-ion batteries are widely implemented in electric buses (Mahmoud et al., 2016). Therefore, Li-ion battery models are applied in this study as the energy storage of electric buses. The generalized OCV model proposed by Zhang et al. (2016) is formulated as follows:

$$OCV = K_0 + K_1(-lnSoC)^{K_2} + K_3 SoC + K_4 e^{K_5(SoC-1)}, \tag{13}$$

where SoC is the state-of-charge.

Moreover, Stroe et al. (2016) proposed an internal resistance (IR) model as follows:

$$R_b = (K_0 \cdot e^{K_1 \cdot T})(K_2 \cdot e^{K_3 \cdot SoC}) A^{K_4}, \tag{14}$$

where A is calendar age, in month; T is battery temperature.

In the existing work conducted by Lashway and Mohammed (2016), the relationship between SoC at time t is calculated as follows:

$$SoC_t = SoC_0 + \frac{\eta}{3600C_n}\int_0^t I_b(\tau)V(\tau)d\tau \times 100\%. \tag{15}$$

The Coulombic efficiency η is 1.0 and 0.98 during the discharge and charging, respectively (Zou et al., 2015).

In the existing works, the battery retires when it reaches 20% capacity loss (Guena & Leblanc, 2006). Therefore, Hoke et al. (2011) proposed a battery cycle life models as follows:

$$Cycle\ \ life = \left(\frac{DOD}{145.71}\right)^{-1/0.6844} \tag{16}$$

where DOD is the depth of the discharge cycle in percent.

Additionally, the general form of the battery cycle life model is

$$Cycle\ \ life = 5\Delta C_{EOL}\left(\frac{DOD}{145.71}\right)^{-1/0.6844} \tag{17}$$

where ΔC_{EOL} is a relative variation of battery total capacity necessary to reach the End-Of-Life criterion.

Therefore, the actual capacity of the Nth cycle (C_n) can be calculated as follows:

$$C_n = C_0\left(1 - \frac{N \cdot \Delta C_{EOL}}{Cycle\ \ life}\right) \tag{18}$$

where C_0 is the original capacity of the electric bus battery.

Data collected from the electric bus operated in the urban area is used to validate the proposed energy consumption model. Figure 2 shows good agreement between the estimated energy consumption and the ground truth energy consumption of real-world operated buses.

Table 2. Parameters of the OCV model and IR model for lithium iron phosphate battery (Stroe et al., 2016; Zhang et al., 2016).

Model parameters	K_0	K_1	K_2	K_3	K_4	K_5
OCV model	3.135	−0.685	0.478	1.734	−1.342	0.4
IR model	6.9656E-10	0.05022	2.897	0.006614	0.8	NA

2.1.2. Modeling fuel consumption and emission of conventional and hybrid buses

Based on the tractive power (P_{out}), Wang and Rakha (2017, 2016a, 2016b) proposed a group of models to calculate the instantaneous fuel consumption (FC) of diesel and diesel-hybrid buses.

$$FC = \begin{cases} \alpha_0 + \alpha_1 P_{out} + \alpha_2 {P_{out}}^2, & \forall P \geq 0, \\ \alpha_0, & \forall P < 0. \end{cases} \tag{19}$$

Moreover, the instantaneous basic emission of diesel and diesel-hybrid buses is calculated as follows:

$$ER_x = EF_x \ \times max(P_{out}, 0) \tag{20}$$

where EF_x is the emission factor for pollutant x).

2.2. Simulation parameters

For the simulations, the parameters applied in this study are consistent with the existing works which are widely used to describe general technical specifications of the existing bus powertrains (Lajunen, 2018; Wang & Rakha, 2017, 2016a, 2016b). Table 5 summarized the technical characteristics of the simulated bus powertrains. Recently, point out that the battery in electric vehicle contributes a significant weight penalty compared to conventional vehicles (Gao et al., 2017). Therefore, the weight penalty of an electric bus is estimated as

$$M_{penalty} = 6.67 \times C_0 - 170. \tag{21}$$

In this work, we assume that the original battery capacity of electric buses is 300 kWh. Moreover, the passenger load was 50 passengers in simulations with average weight vary between and 75 kg according to the literature (Ally & Pryor, 2007; Lajunen, 2018; Rogge et al., 2018). Four different drive-cycles, which are E11, H550, Braunschweig, and (MLTB) drive-cycles, are used to simulate the bus operation routes. The daily operation hours and mileage of buses in

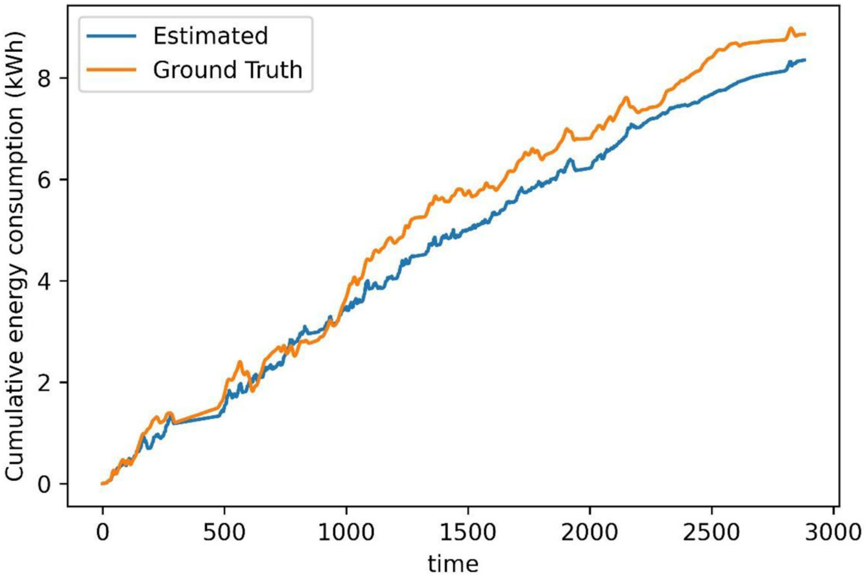


Figure 2. Electric bus energy consumption model validation.

Table 3. Parameters of the fuel consumption models (Wang & Rakha, 2017, 2016a, 2016b).

Vehicle type	α_0	α_1	α_2
Diesel	1.66 E–03	8.68 E–05	1.00 E–08
Diesel-hybrid	1.00 E–03	5.18 E–05	1.00 E–08

Table 4. Emission factors of diesel and diesel-hybrid buses.

Vehicle type	CO2 (kg/L)	PM (g/kwh)	NOx (g/kwh)	CO (g/kwh)	THC[c] (g/kwh)
Diesel	2.7[a]	0.03[b]	2[b]	4[b]	0.55[b]
Diesel-hybrid	2.7[a]	0.01[b]	0.46[b]	4[b]	0.16[b]

[a] Emission Factors for Greenhouse Gas Inventories (U.S Environmental Protection Agency, 2018).
[b] Keramydas et al. (2018).
[c] THC is the total hydrocarbons.

Table 5. Technical characteristics of bus powertrains (Lajunen, 2018; Wang & Rakha, 2017, 2016a, 2016b).

	Abbrv.	Electric	Diesel	Hybrid
Gross weight (kg)	M_g	12837	12837	14125
Penalty weight (kg)	$M_{penalty}$	2171	N/A	N/A
Vehicle frontal area (m^2)	A_f	6.2	6.2	6.2
Drag coefficient	C_D	0.7	0.8	0.8
Rolling resistance coefficient	C_{rr}	0.008	0.008	0.008
Rolling radius (m)	r_d	0.412	0.412	0.412
Final drive ratio	i_{fd}	4.88	N/A	N/A
Driveline efficiency	η_{fd}	0.97	0.95	0.95
Nominal torque (Nm)	T_{mot}	1000	N/A	N/A
Mass factor	λ	N/A	0.1	0.1

different countries are according to the ZeEUS reports (International Association of Public Transport, 2017, 2016). The ambient temperature fluctuation in each country is based on the data from the National Oceanic and Atmospheric Administration. Since the battery thermal management system has been widely used in the electric vehicle to ensure battery life (Huang et al., 2019; Jiang & Qu, 2019), the battery temperature is kept in the range of 15–30 °C according to the data from real-world electric buses (Vepsäläinen et al., 2019). Recently, Zhang et al. pointed out that maintain the SoC of the electric bus fleet at a reasonable level and within proper charging depth can lead to longer battery service life and lower lifecycle cost (Zhang et al., 2020). Therefore, in this work, the electric buses are assumed to charge the battery when SoC is between 30% and 40%. During the daytime, the bus would stop charging when SoC reaches 80%. The overnight charging will charge to full.

2.3. Lifecycle ownership costs

The lifecycle cost model is based on the existing works (Lajunen, 2018; Tong et al., 2017). The model contains four major cost areas: capital costs, operation costs, emission costs, and replacement costs. These annualize costs are calculated according to the formulas as follows:

$$Annulized\ Cost_{lifecycle} = \frac{Cost_{capital}}{Annuity\ factor} + Cost_{operation} + Cost_{emission} + \frac{Cost_{replacement}}{Service\ Life_{Bus}}, \tag{22}$$

$$Annuity\ factor = \frac{1-(1+R_{discount})^{-Service\ \ Life_{Bus}}}{R_{discount}}, \tag{23}$$

$$Cost_{operation} = Cost_{Energy} + Cost_{Maintenance}, \tag{24}$$

$$Cost_{emission} = Emissions_x \times Social\ \ cost_x. \tag{25}$$

The capital costs considered the bus purchase costs, infrastructure costs, and the bus salvage value.

With the maturing of battery technology, the battery price is continuously decreasing. In this study, the battery cost follows the result of the study conducted by Cole and Frazier (2019). Based on the existing study conducted by Guena and Leblanc (2006), the battery will be replaced when it lost 20% of the original capacity. In other words, 80% of the original capacity is still usable, which makes it possible to repurpose the disposed batteries. The second life use of the disposed battery of electric vehicles has been widely considered as a potential solution to cut electric vehicle costs (Martinez-Laserna et al., 2018). According to the existing studies (Martinez-Laserna et al., 2018; Neubauer et al., 2015), the battery replacement cost is described as follows:

$$Cost_{replacement} = \sum [Cost_{battery}(j) \times C_0 - Salvaje\ \ Value_{battery}(j) \times C_0 \times (1-\Delta C_{EOL})] \tag{26}$$

$$Salvage\ \ Value_{battery}(j) = K_h \cdot \mathrm{K}_u \cdot Cost_{battery}(j) \tag{27}$$

where j is the year of battery replacement; K_h and K_u are the health factor and the used product discount factor, respectively.

Based on the values suggested in the existing literature, the chosen cost parameters in this study are shown in Table 6. Diesel prices and electricity prices vary a lot between countries. Moreover, the emissions of electricity are determined by the energy mix of each country. In this study, the diesel price of each country is obtained from Statista (Statista Research Department, 2019). Moreover, the electricity price of each country is obtained Eurostat ("Electricity price statistics - Statistics Explained," n.d.). The carbon intensities of electricity for each country are based on the study conducted by Moro and Lonza (2018).

With the proposed framework, the energy consumption of electric buses is modeled based on Equations (1)–(18). And the fuel consumption of conventional and hybrid buses is modeled based on Equations (1)–(10), and (19) and (20). Therefore, the energy/fuel consumption, GHG emissions, and battery life of different European countries are simulated by considering different vehicle characteristics, daily operation patterns, temperatures, and drive-cycles. By using results from the simulation as inputs of the lifecycle cost model (Equations (22)–(27)), the annualized life-cycle cost can be estimated by using the parameters from Table 6.

3. Results and discussion

In this section, the energy consumption and emissions are calculated from the simulation results considering the

Table 6. Cost parameters.

Cost parameter	Value	Source
Diesel bus purchase cost (€)	225,000	(Lajunen & Lipman, 2016; Schroten et al., 2019)
Hybrid bus purchase cost (€)	315,000	(Lajunen & Lipman, 2016)
Electric bus purchase cost (€)	425,000	(Schroten et al., 2019)
Discount rate	3.5	(Harris et al., 2018)
Service life (yrs)	12	(Harris et al., 2018)
THC (€/kg)	4.3	(Borén, 2020)
NOx (€/kg)	7.07	(Birchby et al., 2019)
PM2.5 (€/kg)	120.65	(Birchby et al., 2019)
CO2 (€/ton)	39.4	(Tong et al., 2017)
Electric bus maintenance cost (€/km)	0.16	(Mahmoud et al., 2016)
Diesel bus maintenance cost (€/km)	0.31	(Mahmoud et al., 2016)
Electric bus infrastructure cost (€/km)	0.12	(Mahmoud et al., 2016)
Diesel bus infrastructure cost (€/km)	0.03	(Mahmoud et al., 2016)

characteristics of different European countries. The results are summarized and compared in the following subsections.

3.1. Lifecycle emission performance

Considering the range limitation and charging time of the electric bus, it may need more electric buses to replace the existing conventional buses in the public transport system to guarantee the existing service quality. According to the research conducted by Lajunen (2014), the replacement ratio of the number of electric buses to the number of conventional buses in the system is shown as follows:

$$R_{replace} = \frac{N_{EB}}{N_{CB}}, \tag{28}$$

where N_{EB} is the number of required electric buses; and N_{CB} is the number of existing conventional buses.

Considering the ideal case where replace ratio is 1 ($R_{replace} = 1$), the GHG emission performance is shown in Figure 3. Both of electric buses and hybrid buses outperformed diesel buses in terms of GHG emission, which supports the policy of abandoning diesel buses. The results indicated that electric buses outperformed hybrid buses in GHG emission in most of the European countries. However, the average improvements in GHG emissions caused by electric buses and hybrid buses are very close in Latvia. Moreover, in several countries, the worst case of the GHG emission improvement indicated that the electric bus may not lead to fewer emissions compare to the hybrid bus. Moreover, the GHG emissions caused by electric buses vary across European countries. The results are consistent with the research conducted by Moro and Lonza (2018).

The GHG emission saving of the electric bus in different months is shown in Figure 4. According to Figure 4, the performance of electric buses in terms of GHG emission varies with month and country. The electric buses could reduce more overall GHG emissions during the summer than winter in Estonia (EE) and Poland (PL). However, the electric buses could reduce more overall GHG emissions during the winter than summer in Malta (MT) and Cyprus (CY). The major reason for this difference is the difference in the weather. In EE and PL, they have relatively cool summer and cold winter, which makes electric buses use more energy during the winter than summer. However, in MT and CY, they have hot summer and warm winter, which makes electric buses use less energy during the winter than summer.

As shown in Equation (29), the electric bus (EB) performance index is introduced to clearly show how electric buses outperform hybrid buses in terms of GHG emissions. When HB outperforms EB in terms of GHG emission, the EB performance index reaches 0. Alternatively, when the GHG emission of EB reaches 0, the EB performance index reaches 1.

$$EB\ GHG\ Performance\ Index = \\ max\left(\frac{GHG\ Emission_{HB} - GHG\ Emission_{EB}}{GHG\ Emission_{HB}}, 0\right) \tag{29}$$

Generally, one hybrid bus can replace one conventional bus in the public transport system and maintaining the same service quality. Therefore, only the different replacement ratio of electric buses is considered in this study. Considering different replacement ratios, the EB performance in terms of GHG emission of different European countries is shown in Figure 5. The performance of EB varies with the country and replacement ratio. In some countries, hybrid buses lead to better or the same system-level GHG emission performance as electric buses. According to Figures 4 and 5, considering the existing constraints of electric buses, the public transportation system mixed with hybrid buses and electric buses can reduce more GHG emissions than a purely electrified system since the mixed system can have a lower replacement ratio to maximize the environmental benefit of introducing electric buses.

3.2. Lifecycle cost performance

Other than GHG emissions, the lifecycle total ownership cost is also very crucial for public transport electrification. In this subsection, the lifecycle total ownership of electric buses and hybrid buses are compared with conventional buses.

According to most of the existing lifecycle analyses, battery cost is one of the most important components of the lifecycle total ownership cost of an electric bus. Bloomberg New Energy Finance (2018) indicated that the battery warranty is between 5 and 10 years. Moreover, Yang et al. indicated that battery life in the different states of the United State is varying from 5.2 years to 13.3 years (Yang et al., 2018). Annual

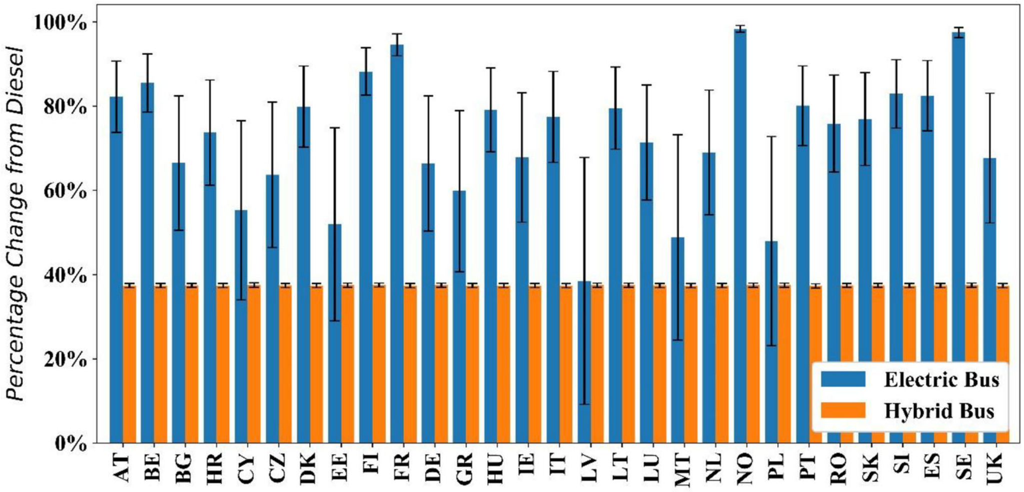


Figure 3. GHG emissions improvement of electric bus and hybrid bus. The percentage is calculated as the difference between alternative powertrains and diesel powertrain.

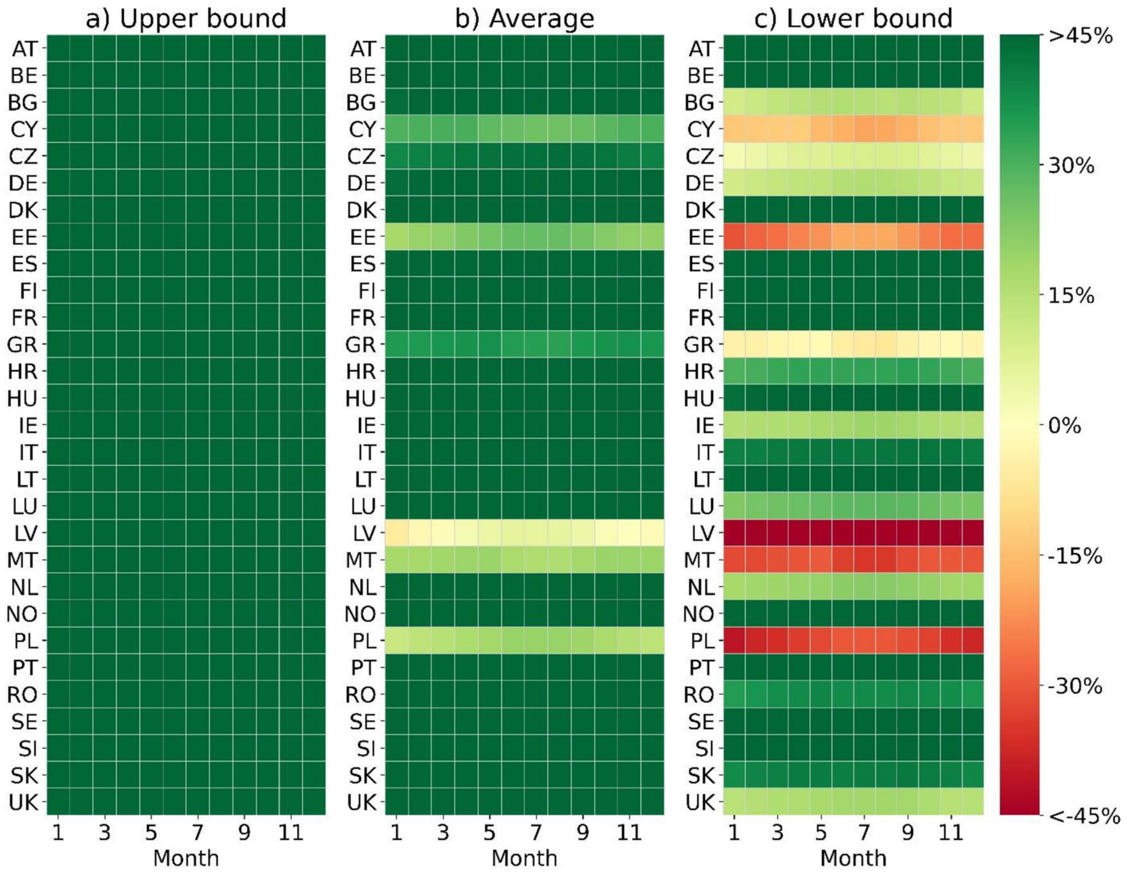
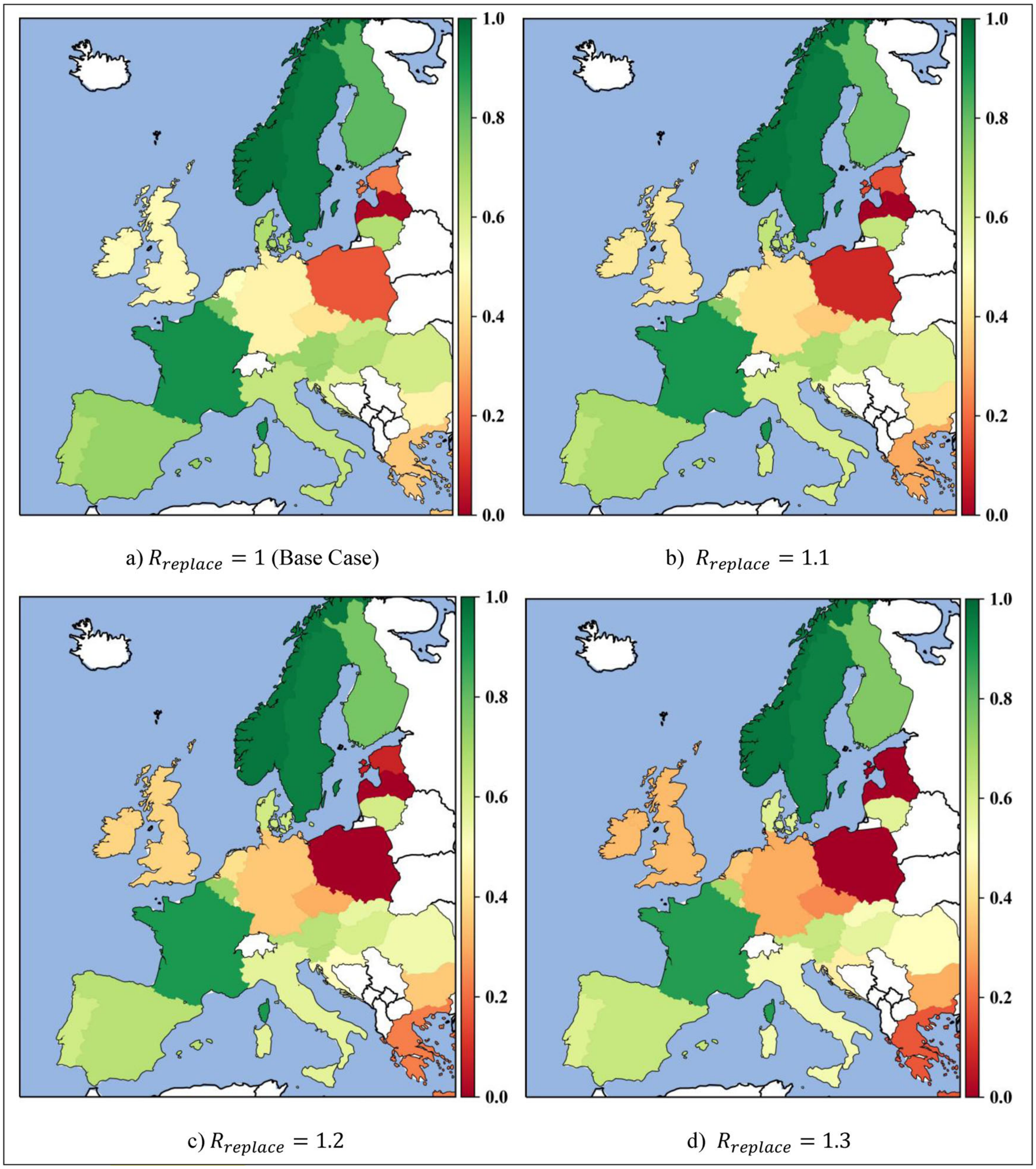


Figure 4. GHG emissions improvement of the electric bus during different months.

travel demand and ambient temperature are the major reasons for battery degradation. The simulated battery lifespans of electric buses in EU countries are shown in Figure 6. Similar to the case in the United States, the battery life of electric buses varies from 5 to 12 years in different European countries. Moreover, the simulated battery lives in Figure 6 are in-line with the results from the existing study and the battery warranty from existing manufacturers.

Considering the operation characteristics, battery life, and environmental benefit of the buses in different European countries, the lifecycle total ownership cost (LCC) of hybrid buses and electric buses are compared with conventional buses to indicate if the electrification of the public transport system will be beneficial, as shown in Figure 7. Overall, hybrid buses lead to a significantly less lifecycle total ownership cost compared to diesel buses and electric buses. Moreover, the electric buses in several countries have the potential to outperform diesel buses in terms of lifecycle total ownership cost under specific conditions, such as large price differences between diesel and electricity, long battery



a) $R_{replace} = 1$ (Base Case)

b) $R_{replace} = 1.1$

c) $R_{replace} = 1.2$

d) $R_{replace} = 1.3$

Figure 5. GHG emission performance of electric buses in EU countries with different replacement ratios.

life, and green electricity. Since the hybrid buses outperformed diesel buses in terms of emission and lifecycle cost, this work supported the plans made by several EU cities (e.g., Athens, Paris, Copenhagen, Berlin, and Madrid) and government (e.g., Norway) to abandon diesel vehicles or stop purchase conventional buses before 2025. According to the lessons from Germany (Buehler & Pucher, 2011), public transport services should be financially sustainable while satisfying social needs. Therefore, a public transport system with both battery-electric buses and hybrid buses is a potential approach to make the system both financially and environmentally sustainable.

In order to investigate the potential of reducing or removing incentives for the electrification progress of the public transport system, different energy scenarios are simulated and compared. Table 7 shows the details of the scenarios. Based on the average lifecycle cost, Figure 8 shows the lifecycle economic performance of electric buses in different EU countries under different conditions. We find out that some countries have the potential to achieve a purely electrified public transport system by reducing or removing incentives, such as tax benefits, interest-free or low-interest loans, and subsidies. Without further financial support from the government, hybrid buses would be the best solution for most countries considering both the economy and environmental benefits. In the real world, the government always introduces incentives to support the local application of new technologies which may lead to further change in business mode, lifestyle, policy, and so on. Since renewable energy generation and battery technologies are maturing fast, adjusting the pace of replacing the buses the public transport system with battery-electric buses according to the local condition can maximize the benefits of transport electrification without sacrificing the economic performance.

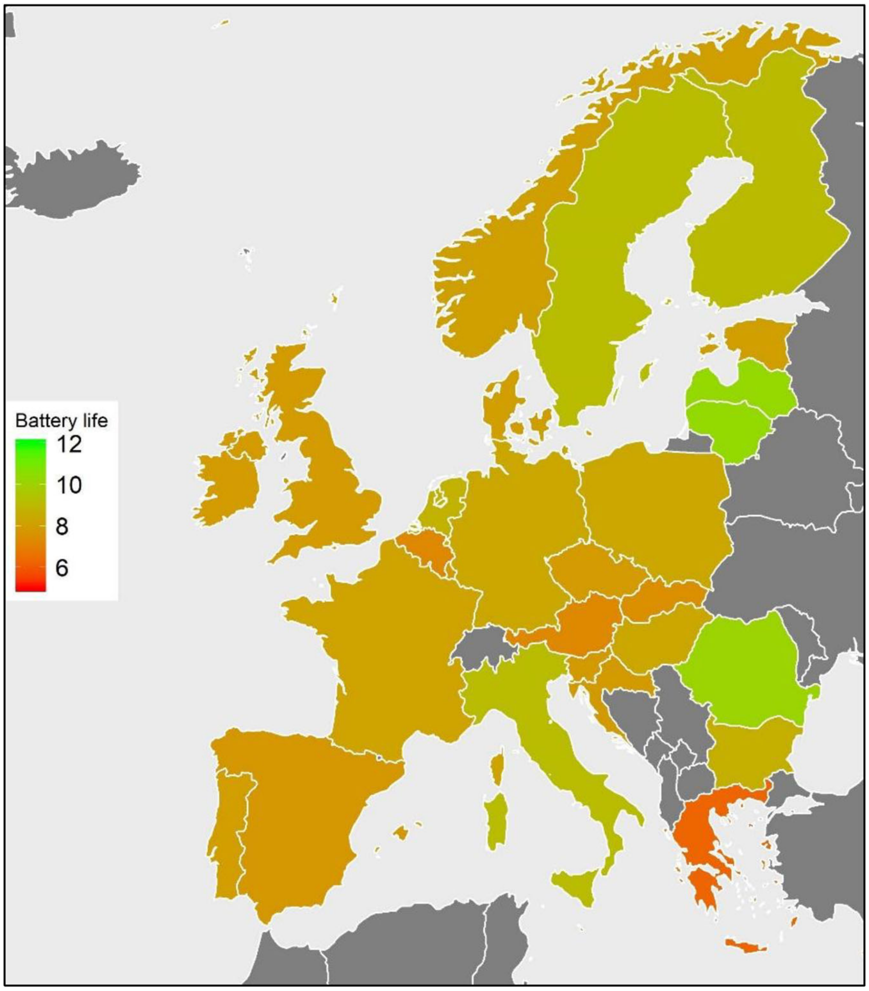


Figure 6. The battery life of electric buses in EU countries.

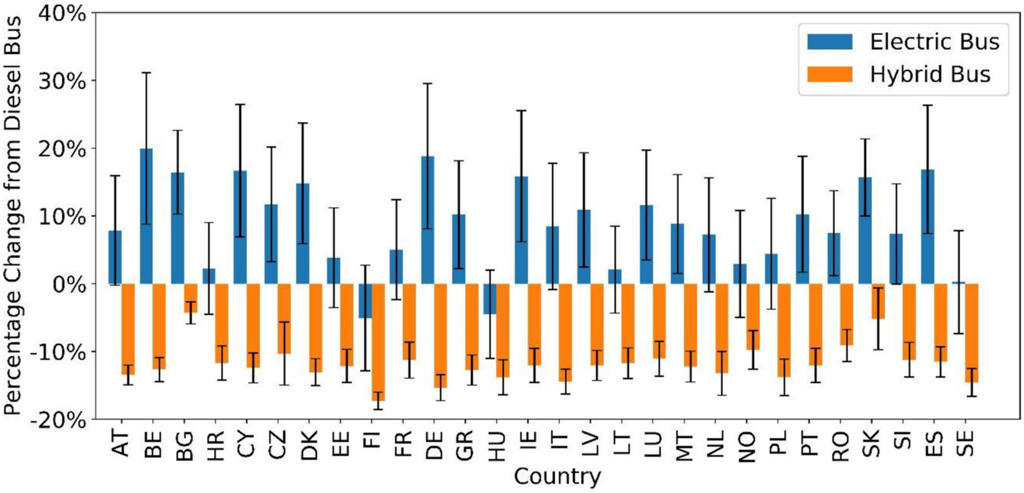


Figure 7. Lifecycle cost performance of electric bus and hybrid bus. The percentage is calculated as the difference between alternative powertrains and diesel powertrain.

Table 7. Scenario descriptions.

			Diesel price increment (Euro/L)			
	Emission reduction	Price reduction	0	0.25	0.5	1
Electricity	0%	0%	Base Case	Scenario 1.1	Scenario 1.2	Scenario 1.3
	7.5%	5%	Scenario 2.1	Scenario 3.1	Scenario 3.2	Scenario 3.3
	15%	10%	Scenario 2.2	Scenario 3.4	Scenario 3.5	Scenario 3.6
	30%	20%	Scenario 2.3	Scenario 3.7	Scenario 3.8	Scenario 3.9

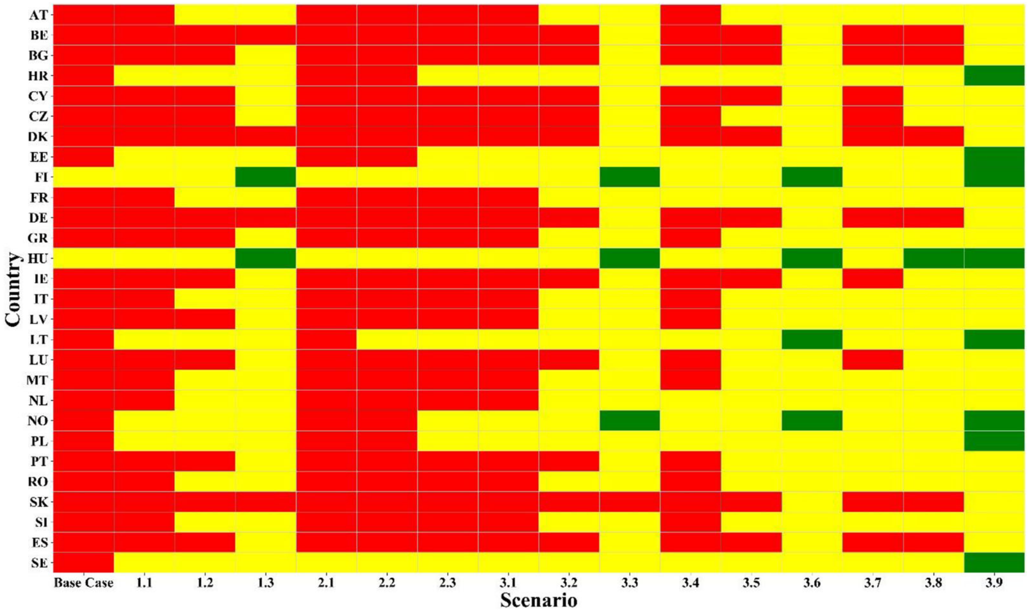


Figure 8. Lifecycle cost performance of electric buses. Yellow indicates the LCC of EB is between DB and HB, Green indicates the EB has the lowest LCC, Red indicates EB has the highest LCC.

Therefore, the public transport system mixed with electric and hybrid buses will be the most common situation in most of the European countries until the best compensation points of technologies and incentive policies are reached considering local situations.

4. Conclusions and future works

In this article, we estimated lifecycle cost and GHG emissions for electric, hybrid, and diesel buses in different European countries to gain deeper insight into the role of electric buses in the electrification progress of the public transport system. To better model the energy/fuel consumption, we integrated the theoretical model of human thermal comfortable temperature into the framework. Considering the weather, the daily operation characteristic, and the energy mix of different European counties, the lifecycle environmental and economic performance of electric buses are evaluated. The result shows that the public transportation system with both hybrid and electric buses can be good compensation between financial and environmental needs instead of using electric buses to replace all the conventional buses. Moreover, the operation plan of the public transportation system mixed with electric and hybrid buses may be adjusted according to seasonal temperature variation to maximize the environmental benefit. Considering the different economic and environmental scenarios of energy sources, some EU countries would able to reduce or remove the incentives for electric buses. Moreover, public transport operators and policymakers are suggested to adjust the electrification pace and incentive policies by considering the local situation and technology development.

The results and findings of this work are limited by the assumptions made in this work. In the methodology section, we applied four driving cycles to represent the real-world energy/fuel consumption of buses in different countries. Using real-world bus operation data from different countries and/or cities may yield different results because of the difference in travel demand, terrain, and traffic conditions (Bingham et al., 2012; Liu et al., 2017). Additionally, the policies (such as tax rate, discount rate, incentives, and so on) of different countries should be further considered in future works. In future studies, more real-world data should be collected and applied in the model development. Moreover, the parameters of the battery models are based on laboratory results and not calibrated based on the data collected from the real-world operated electric buses. With more realistic battery models developed in the future, a more precise life cycle cost and detailed bus composition plan will be provided. Meanwhile, the potential benefits of electric buses, such as noise reduction and renewable energy fluctuation mitigation, are not considered in this work.

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