ISSN 2959-6149

How we deal with transition planning as we approach the e-bus era

Junxiao Yu[1], Yuhan Xia[2], Yuan Huang[3], Zixian Lv[4]

[1] Chengdu Shude High School, Chengdu, 610066, China;
[2] Hangzhou Foreign Languages School, Hangzhou, 310018, China;
[3] Shenzhen College of International Education, Shenzhen, 518033, China;
[4] Wuxi Dipont School of Arts and Science, Wuxi, 201206, China;
1536236781@qq.com [a], yuhan2006.xia@outlook.com[b], s22404.huang@stu.scie.com.cn [c], Sophia_Lv1227@outlook.com[d]

Abstract:

With the rapid development of new energy, the widespread adoption of electric buses is significant. This paper delves into the environmental impact, economic implications, and strategic planning solutions associated with the proliferation of electric buses. We initiate this process by using bus data from Qingdao, China. Subsequently, using the fuel life cycle method, we carefully examined CO and the pollutant emission characteristics of Qingdao bus fleet before and after electrification. The research results reveal that CO, nitrogen oxides, and VOC emissions have all increased. An economic analysis of electric vehicle adoption in public transportation was conducted in response to the second question. Considering government subsidies, a cost-saving model for electric vehicles per 100 kilometers was constructed.

Furthermore, the study found that as the electrification rate increases, the operating costs of electric buses in Qingdao gradually decrease. We developed a comprehensive linear integer programming model to address the third question. The model, aimed at achieving the lowest comprehensive cost while considering various constraints, was solved through the branch and bound method. We applied this model to analyze the optimal plans for completing the conversion of electric buses in Qingdao, Zhengzhou, and Xi'an within a 10-year timeframe. For the fourth question, we have put forward policy recommendations.

Keywords: WTW; GREET Model; Economic analysis; Integer Linear Programming; Branch and Bound.

1. Problem Restatement and Problem Analysis

1.1 Problem Restatement

In recent years, new energy vehicle technology development has led to the widespread adoption and implementation of electric buses. Electric buses have been proven to effectively reduce greenhouse gas emissions. However, the start-up and continuous operation of the electric bus fleet requires a significant amount of investment and experience, which poses some risks to the deployment of electric buses. Therefore, establishing economic cost prediction models for the electrification of public transportation in different cities is of great significance.

1) Choose a metropolis with a population of over 500000 and in the early stages of adopting electric buses. Construct an integer programming model using mathematical models to explore the ecological impact of the transition from cities to fully electric bus fleets.

2) Build a model to analyze the financial impact of the transition from traditional fuel buses to electric buses on the city, including cost, revenue, and funding sources. This model can account for up to 50% of the conversion cost.

3) Assisting the city‘s transportation management department in planning the electric bus fleet renewal. Utilize the previously constructed model to formulate a ten-year road map, aiming for a fully electric bus fleet by 2033. Evaluate the feasibility of this road map and assess progress toward achieving the goal in the chosen city and two additional metropolitan areas.

4) Outlined the environmental, economic, social, and other advantages of transitioning to electric buses and provided recommendations based on survey results.

1.2 Problem Analysis

Environmental considerations remain at the forefront of this effort, particularly in addressing issues related to carbon dioxide emissions. In terms of economic evaluation, we have introduced two evaluation criteria from the perspectives of direct cost and additional cost: the cost of bus travel per mile and the cost of bus travel per hour. Using linear programming models has improved our ability to generate results and alternative strategies at different substitution rates. The version takes Qingdao as the case city.

2. Assumptions and Annotations

2.1 Assumptions

- Following installation, the charging infrastructure for pure electric buses is available for continuous use throughout the planning period.
- The bus service schedule remains unaltered.
- The fleet's total annual operating mileage remains consistent.
- Passenger traffic demand remains constant.

2.2 Annotations

Because there are too many math symbols in this paper, we only list the math symbols in Section 5 in this section; the rest of the symbols are explained in the original text.

Table 1 Annotations

Symbol	Description
Ck	Charger Types Required for Recharging an Electric Bus of Type k
CT	Types of Chargers
DC	Types of Chargers Available at Depots
J^k	Permissible Age Range for a Bus of Type k
K	Types of Buses
K_e	Types of Electric Buses
R	Types of Runs
T	Set of Time-Flexibility Periods in the Planning Horizon
a_j^k	Initial Fleet Count of Buses of Type K and Age J at the Beginning of the Planning Horizon
b_t	Budget for Purchases Initiated at the Beginning of Period T
e^c	Quantity of Chargers (Type C) Owned at the Commencement of the Planning Horizon
F	Periodic Demand Charges (Per Kilowatt)
f_t^k	Cost of Procuring Buses of Type K at the Onset of Period T
G	Aggregate Depot Grid Restriction (in Kilowatts)
g^c	Power Consumption (in Kilowatts) of Charger Type C
H	Overall Depot Space Limitations
h_{jtr}^k	Binary parameter set to 1 if and only if a bus of type k and age j is compatible with assignment run type r during period t
mc_t^k	Costs incurred at midlife when a bus of type k reaches its midlife age α^k during period t
o_{jtr}^k	Cumulative periodic operating cost when a bus of type k is of age j at the beginning of period t and performs a run of type r during that period
P	Minimum proportion of the fleet that must be comprised of Electric Buses (EBs) by the target period tG ∈ T
p^c	Cost of Procuring Charger Type C
q_{tr}	Number of Buses to be Assigned to Run Type R in Period T
s_{jt}^k	Residual value of abus of type k and age j retired at the beginning of period t
β	Discount factor for a single period

Γ	Maximum average age of buses in the final period tF
θ^c	Minimum proportion of chargers (type c) relative to the total number of Electric Buses (EBs) of types {k ∈ KE ∣ c ∈ Ck } in the fleet
k^k+1	Age at which buses of type k are required to be retired
u_t^c	Quantity of chargers procured and installed at the commencement of period t
v_t^c	Count of available chargers (type c) during period t
w_{jtr}^k	Number of buses of type k and age j assigned to run type r in period t
x_t^k	Quantity of buses of type k acquired at the start of period t
y_{jt}^k	Number of buses of type k and age j retired at the beginning of period t
z_{jt}^k	Count of accessible buses of type k and age j in period t

3 CO2 and pollutants reduction analysis model for electric bus fleet transition

This paper assesses the environmental impact of bus fleet electrification by calculating CO2 and tailpipe emissions of four conventional pollutants (CO, NOx, VOC, and PM2.5) using the fuel life-cycle approach, known as well to wheels (WTW).

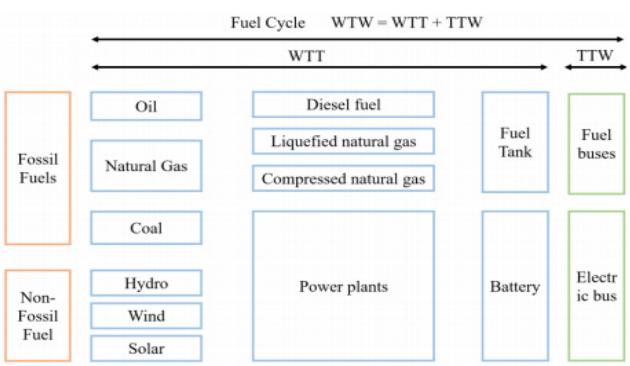

Fig. 1 WTW research boundary of internal combustion engine bus and electric bus

3.1 WTW phase Co2 and pollutant emission calculations

The WTW phase emissions can be split into two phases, WTT and TTW, and the total emissions of the WTW phase can be calculated as shown in Eq. (1).

$$E_{c,p}^{WTW} = E_{c,p}^{WTT} + E_{c,p}^{TTW}, \quad (1)$$

where $E_{c,p}^{WTW}$, $E_{c,p}^{WTT}$ and $E_{c,p}^{TTW}$ are the emissions of pollutant p (CO, NOx, VOC, and PM2.5) in t.

for the two types of c (internal combustion engine buses, electric buses) in the WTW, WTT and TTW phases, respectively [1].

3.1.1 WTT phase

The CO2 and pollutant emissions in the WTT phase are calculated based on fuel consumption, and the WTT phase emissions are calculated as shown in Eq. (2).

$$E_{c,p}^{WTW} = D_c \times FC_c \times EF_{c,p}^{WTT} \quad (2)$$

where D_c is the distance traveled by model c (internal combustion engine bus and electric bus) inkm; FCC is the average energy consumption per unit mile; and $E_{c,p}^{WTW}$ is the emission factor ofpollutants p in the WTT stage.

3.1.2 TTW phase

The TTW phase is generally considered to have only CO2 and pollutant emissions from internal combustion engine public transportation, as shown in Eq. (3).

$$E_{c,p}^{TTW} = D_c \times FC_c \times EF_{c,p}^{TTW} \quad (3)$$

where c is the internal combustion engine bus, p is CO2, D_c is the distance traveled by the internal combustion engine bus in km, FCc is the average energy consumption per unit mile, which is

obtained from Table 1, and $E_{c,p}^{TTW}$ are the CO2 emission factors of pollutants in the TTW stage.

For other pollutant emissions, calculations were made using a method based on trajectory mileage versus trajectory speed, see Eq. (4).

$$E_{c,p}^{TTW} = \sum_{m=1}^{m} \sum_{N_m=1}^{N_m} D_{c,m,n} \times EEF\left(v_{m,n}\right)_{c,p,m,n_i^-}^{TTW} \quad (4)$$

where c is the internal combustion engine bus, p is other pollutants, m is the number of buses participating in the calculation, N_m is the number of trajectory segments for them. $D_{c,m,n}$ is the mileage traveled by the n-th vehicle on the n-th trajectory segment, and $EEF\left(v_{m,n}\right)_{c,p,m,n_i^-}^{TTW}$ is the emission factor of pollutant p calculated based on the average speed of the m-vehicle on the nth trajectory segment $v_{m,n}$ is the emission factor of pollutant p calculated for them-vehicle in the nth trajectory based on the average speed $v_{m,n}$.

3.2 Emission factor acquisition

We adjusted the proportion of thermal power generation based on the predicted power supply situation in the modern energy system planning of Qingdao city. Please refer to Table 2 for details.

Table 2 Power generation structure and optimized power generation structure of Qingdao/%

Year		Generation structure		
	Fired power generation	Hydroelectricity	Wind power	Solar power
2023	86.99	3.75	6.94	2.32
2028	76.00	15.00	6.20	2.80
2033	60.00	31.40	5.20	3.40

The results show that the power emission factor significantly decreases after structural optimization. The emission factors, based on energy consumption for vehicles with different fuel types in the well-to-tank (WTT) and tank-to-wheels (TTW) stages, are presented in Table 3.

Table 3 Emission factors for various fuel types based on energy consumption

Fuel type	WTT				TTW	
	CO2 /kg Unit−1	VOC /g. Unit −1	CO /g Unit−1	NOx /g Unit−1	PM2.5 /mg Unit−1	CO2 /kg Unit−1
Diesel fuel	0.44	0.25	0.40	0.66	41.14	1.15
CNG	0.32	0.38	1.20	1.42	19.48	1.25
HEV-Diesel	0.44	0.25	0.40	0.66	41.14	1.15
HEV-LNG	0.52	0.36	0.87	1.09	38.05	1.25
HEV-CNG	0.32	0.38	1.20	1.42	19.48	1.25
PHEV-LNG	0.52	0.36	0.87	1.09	38.05	1.25
PHEV-CNG	0.32	0.38	1.20	1.42	19.48	1.25
Hydrogen	0.97	0.12	0.27	0.45	44.57	1.25
Electric-2023	0.92	0.08	0.29	0.74	66.85	0.00
Electric-2028	0.80	0.07	0.24	0.61	55.49	0.00
Electric-2033	0.63	0.05	0.19	0.48	43.80	0.00

4. Economic cost analysis model for electric bus fleet transition

In this section, we evaluated the cost savings within a distance of 100 kilometers before and after the replacement. We also describe the operating costs of traditional fuel vehicles. The comprehensive operating cost of a 100-kilometer fuel vehicle includes energy, depreciation, operation, maintenance, and other related expenses. As shown in Eq. (5).

$$C_o = P_o \times Q_o + \frac{P_o}{D_o} \times 100 + C_{om} + \sum_{i=1}^{n} C_{oi} \tag{5}$$

where C_o is the total operating cost for 100 kilometers; Q_o is the fuel consumption for 100 kilometers; P_o is the purchase price of the vehicle; D_o is the total mileage of the vehicle during its lifetime; com is the maintenance cost for 100 kilometers; $\sum_{i=1}^{n} C_{oi}$ is the cost of other items for the vehicle.

After using electric buses instead of fuel buses, the model for calculating the 100-kilometer, operating cost of the ware can be expressed by Eq. (6).

$$C_e = P_e \times Q_e + \frac{P_e}{D_e} \times 100 + C_{em} + \sum_{i=1}^{n} C_{ei} \tag{6}$$

where C_e is the total operating cost for 100 kilometers of Electric Vehicles (EVs); P_e is the charging tariff for EVs; Q_e is the power consumption for 100 kilometers of EVs; D_e is the total mileage of the EV during its lifetime; C_{em} is the maintenance cost for 100 kilometers of EVs; $\sum_{i=1}^{n} C_{ei}$ is the cost of other items for EVs. The cost savings resulting from replacing traditional fuel vehicles with EVs can be expressed by Eq. (7).

$$?C = C_o - C_e + C_E \tag{7}$$

$?C$ is the 100-kilometer operating cost saved by replacing conventional vehicles with electric vehicles.

5. Integer linear programming model for electric bus fleet transition

5.1 Analysis of the issue

5.1.1 Electric bus tasking

The task assignment methodology utilizes the aggregation method proposed in [3], which breaks down the planning cycle into runs and ensures that each bus completes a task within its assigned cycle. In the decision-making process for task, a binary parameter h_{jtr}^{k} is introduced, indicating whether buses of a specific type and age can perform a particular task within a specific cycle.

5.1.2 Vehicle configuration

Vehicle allocation for electric buses encompasses decisions regarding the acquisition, operation, and retirement of buses with different types and ages throughout the planning cycle.

Fleets must establish budgets at the commencement of each planning cycle based on vehicle acquisitions and charging infrastructure requirements. Revenues derived from scrapping are considered in this process.

5.1.3 Charging infrastructure

Initially, the available charger types (CT) and a subset of charger types (C^k) were defined. The decision-making process needs to determine the number of chargers to be purchased, ensuring the proportion of each type of charger(θ^c). Over time, it remains above the predetermined level. In addition, the purchase cost of the charger type, the power provided (kW), and the initial number of chargers already in place were also considered. Finally, in order to ensure the reasonable utilization of charging infrastructure, a limit has been set on the number of specific types of chargers, and their total power cannot exceed the limits of the power grid at the same time.

5.1.4 Budget considerations

The budget factors include the acquisition cost of the vehicle, operating costs, mid-life costs, and the impact of charging infrastructure acquisition costs, including the number and type of chargers. Ultimately, the budget allocation must balance the needs for vehicle acquisition and charging infrastructure to ensure the sustainable operation of electric buses [4].

5.2 Integer Linear Programming Model

The mathematical formulation of the Electric Bus Fleet Planning (EBFTP) involves decision variables that are all integer and non-negative. These variables are defined as follows:

- x_t^k represents the number of buses of type k purchased at the beginning of period t.
- y_{jt}^k represents the number of buses of type k and age salvaged at the beginning of period t.
- z_{jt}^k represents the number of available buses of type k and age j in period t.

The electric bus fleet conversion problem can be described as a linear integer programming model [5].

$$\sum_{t\in T} \beta^{t-1} \sum_{k?k} \left(f_t^k x_t^k - \sum_{j=1}^{k^k+1} s_{jt}^k y_{jt}^k + \sum_{r?R} \sum_{j=0}^{k^k} O_{jtr}^k w_{jtr}^k + mc_t^k z_{\alpha^k t}^k \right) + \sum_{t?T} \beta^{t-1} \sum_{c?CT} \left(P^C u_t^c + Fg^c v_t^c \right) \tag{8}$$

$$\text{minimize} \qquad + \sum_{k\in K} \sum_{r?R} \sum_{j=0}^{k^k-1} \sum_{i=1}^{k^k-j} \beta^{t_F+i-1} O^k_{j+i,t_F,r^{W^k_{jt_F}r}} \tag{9}$$

$$-\sum_{k\in K} \sum_{j=0}^{k^k} \beta^{t_F+k^k-js^k_{k^k+1,t_F} z^k_{jt_F} + \sum_{k\in K} \sum_{j=0}^{\alpha^k-1} \beta^{t_F} + \alpha^{k-j-1} mc^k_{t_F} z^k_{jt_F}} \tag{10}$$

subject to
$$\sum_{k\in K_E}\sum_{j=0}^{k^k} z_{jt}^k \geqslant P\left(\sum_{k\in K}\sum_{j=0}^{k^k} z_{jt}^k\right) t\in T \mid t\geqslant t_G \tag{11}$$

$$\sum_{k\in K_E}\sum_{j=0}^{k^k} w_{jt}^k = q_{tr} r\in R, t\in T \tag{12}$$

$$w_{jtr}^k \leqslant h_{jtr}^k z_{jt}^k k\in K, r\in R, t\in T, j\in j^k \setminus \left\{k^k+1\right\} \tag{13}$$

$$\sum\nolimits_{r\in R} w_{jtr}^k = z_{jt}^k k\in K, t\in T, j\in j^k \setminus \left\{k^k+1\right\} \tag{14}$$

$$x_t^k = z_{0t}^k k\in K, t\in T\setminus\{1\} \tag{15}$$

$$x_1^k + \alpha_0^k = z_{0,1}^k k\in K \tag{16}$$

$$z_{jt}^k = z_{j-1,t-1}^k - y_{jt}^k k\in K, t\in T\setminus\{1\}, j\in j^k \setminus \left\{0, k^k+1\right\} \tag{17}$$

$$y_{k^k+1,t}^k = z_{k^k,t-1}^k k\in K, t\in T\setminus\{1\} \tag{18}$$

$$y_{k^k+1,t}^k = \alpha_{k^k+1}^k k\in K \tag{19}$$

$$z_{j1}^k = \alpha_j^k - y_{j1}^k k\in K, j ? j^k \setminus \left\{0, k^k+1\right\} \tag{20}$$

$$\sum_{k\in K}\left(f_t^k x_t^k - \sum_{j=1}^{k^k+1} s_{jt}^k y_{jt}^k\right) + \sum_{c\in CT} p^c u_t^c \leqslant b_t t\in T \tag{21}$$

$$v_t^c \geqslant \theta^c \sum_{k\in K_E \mid c\in c^k}\sum_{j=0}^{k^k} z_{jt}^k c\in CT, t\in T \tag{22}$$

$$\sum\nolimits_{c\in DC} g^c v_t^c \leqslant G t\in T \tag{23}$$

$$\sum\nolimits_{c\in DC} v_t^c \leqslant H t\in T \tag{24}$$

$$v_1^c = e^c + u_1^c, c\in CT \tag{25}$$

$$v_t^c = v_{t-1}^c + u_t^c t\in T\setminus\{1\} c\in CT \tag{26}$$

$$\sum_{k\in K}\sum_{j=0}^{k^k} j z_{jt_F}^k \leqslant \ulcorner \sum_{k\in K}\sum_{j=0}^{k^k} z_{jt_F}^k \tag{27}$$

$$y_{jt}^k, z_{j-1,t}^k \in Z^+ k\in K, t\in T, j\in j^k\setminus\{0\} \tag{28}$$

$$x_t^k \in Z^+ k\in K, t\in T \tag{29}$$

$$u_t^c, v_t^c \in Z^+ c\in CT, t\in T \tag{30}$$

$$w_{jtr}^k \in Z^+ k \in ? K, r\in R, t\in T, j\in j^k \setminus \left\{k^k+1\right\} \tag{31}$$

Constraints (2) ensure the achievement of the electrification target. Constraint (3) ensures adherence to the required quantity of buses for each journey. Constraints (4) dictate that run assignments must comply with bus type and age compatibility during each period. Constraints (5) mandate that runs should be assigned to all available buses of a specific age and type during a particular period. Constraints (6) and (7) ascertain that the number of new buses available for each type in each period corresponds to the number of buses procured at the commencement of that period. Constraints (8) specify that the quantity of buses of a specific type and age available in a given period t>1 equals the number of buses of that type that was one period younger in t- 1, reduced by the number scrapped at the beginning of t. Constraints (9) and (10) mandate that buses of age κ^k+1 are scrapped. Constraints (11) dictate that the quantity of buses of a particular type and age available during the initial period should be the same as the existing amount, subtracted by the number salvaged at the commencement of the planning period. Constraints (12) specify that the purchasing funds available at the start of a period comprise the sum of the budget and the revenue obtained from salvage. Constraints (13) guarantee that the proportion between EBs and chargers for every type of charger is adhered to. Constraints (14) and (15) ensure that both power and space constraints at the depot(s) are adhered to during each period. Additionally, Constraints (16) and (17) keep track of the quantity of each type of EB charger present. Finally, we impose Constraints (18) to mitigate end-of-horizon effects by setting the maximum average vehicle age to Γ in the final period tF . Constraints (19)-(22) specify the decision variable domain.

6. Results and analysis

6.1 Case study of problem 1

6.1.1 Qingdao bus operation status

We find that in Qingdao, since 2010, the number of public vehicles in Qingdao has skyrocketed from 6067 to 10759. The cumulative driving distance has also increased from 320 million to 530 million kilometers. Qingdao's urban area currently boasts 8,553 regular buses, serving 655 operating routes with a combined length of 1,631 kilometers. The annual passenger volume reaches 65,014 million people, with a daily average of 1.78 million passengers.

In summary, while Qingdao has made progress in introducing pure electric buses, the proportion remains relatively low, with a significant number of fuel and hybrid vehicles still operating.

6.1.2 Scenario setting of Qingdao bus fleet electrification environmental benefits

We have established five emission calculation schemes to evaluate the benefits of emission reduction (as outlined in Table 4). The fleet and activity level distinctions are follows:

F1: Represents the vehicle trajectory obtained from data between December 1 and 7, 2017, aligning with the fleet structure in 2017 (per-electrification).

F2: Represents the vehicle trajectory obtained from data between December 2 and 8, 2019, matching the fleet structure in 2019 (post-electrification).

F3: Represents vehicle trajectories based on data from December 2 to 8, 2019, aligning with the fleet structure corresponding to full electrification replacement in 2019 (full electrification).

Generation mix: E1, E2, and E3 represent the 2023, 2028, and 2033 generation mix, respectively.

Table 4 Scenario setting of bus fleet electrification

Scenario	Vehicle fleet and activity level	Generation structure	description
S1	F1	E1	Pre-electrification scenario
S2	F2	E1	Post-electrification fleet mix and activity levels, 2023 generation mix
S3	F2	E2	Fleet Structure and Activity Levels after Electrification, 2028 Generation Structure
S4	F3	E2	Fully electrified fleet, 2025 generation mix
S5	F3	E3	Full electrification of the fleet power generation mix by 2033

6.1.3 Results and Discussion

In Table 5, data for different types of buses are presented. The calculation of pollutant emissions reduction in Qingdao after the complete implementation of bus electrification is illustrated in Table 2. The results indicate that the electrification of the bus fleet leads to a substantial reduction in emissions of NOx and SO2. Furthermore, emissions of pollutants like CO can be directly reduced to 0.

Table 5 The parameters of different e-buses

Type	HEB	BEB	CDB
Urban energy consumption(/100km)	28L diesel	100kWh electrical energy	35L diesel

WTP	Carbon dioxide emission rate	0.579kg/L diesel	0.85kg/kWh electrical energy(China)	0.31kg/kWh electrical energy(Europe)	0.579kg/L diesel
	100km CO2 emissions	16.21kg	85kg	31kg	20.27kg
PTV	Oxygen emission rate	2.677kg/L diesel	0	0	2.677kg/L diesel
	100km CO2 emissions	74.96kg	0	0	93.69kg
WTW	100km CO2 emissions	91.17kg	85kg	31kg	113.96kg
	CO2 emission during life-cycle	455,850kg	425,00kg	155,00kg	569,800kg
	Carbon dioxide emission reduction rate	20.0%	25.4%	72.8%	0

Table 6 Emission reduction after bus electrification of different pollutant

Pollutant	Diesel bus	Electric bus	Emission reduction after bus electrification
CO	116.80	/	116.80
N0x	568.00	10.81	557.19
VOC	5.80	/	5.80
PM2.5	11.00	/	11.00
PM10	17.64	/	17.64
S02	2.50	11.38	-8.88

6.2 Case study of problem 2

6.2.1 Economic analysis of electric buses BYD K9

The main parameters of both conventional fuel vehicles and the K9 pure electric vehicle models are detailed in Table 7.

Table 7 Main parameters of regular fuel and K9 pure electric car models

Parameters	Regular fuel buses	K9 Pure Electric Bus
Price / 10,000 RMB	50	200
New energy subsidy / 10,000 RMB	0	100
Fuel consumption per 100 km / L	30	/
100km power consumption / kw · *h*	/	120
Diesel oil price / (RMB · L−1)	5. 52	/
Electricity tariff / (RMB · (kw · *h*)−1)	/	0. 73
Daily mileage / km	250	250
O&M cost / (RMB · (100 km)−1)	7	5
Annual operating days	353	353

Years of operation /year	8	8

In Table 7, the market price of the BYDK9 pure electric bus is approximately RMB 2 million. Considering the 50% government allowance, the cost of the car would be RMB 1 million. The electricity price is determined by the full-day peak and valley average price of industrial electricity in Qingdao, amounting to RMB 0.73/kW · h.
The primary pollutants emitted by medium and heavy-duty commercial fuel oil vehicles over 100 kilometers under clean energy power supply are outlined in Table 8.

Table 8 Emission comparison between medium and heavy-duty diesel vehicles and electric vehicles kg/100 km

Items	CO2	CO	Nx Oy	Sx Oy	Cx Hy
Diesel vehicle	84. 9	0. 06	0. 05	0. 21	0. 006
E-buses	0	0	0	0	0
Emission reductions	84. 9	0. 06	0. 05	0. 21	0. 006

Utilizing the parameters mentioned and the 100-kilometer operating cost model, the 100-kilometer operating costs for electric and fuel vehicles are computed, as presented in Table 9.

Table 9 Calculation results of 100-kilometer operating costs for electric buses/RMB

Items	Fuel bus	K9 pure e-bus
Environmental costs	0. 33	-
Operating costs (unsubsidized)	243. 75	374. 89
Operating costs (subsidized)	243. 75	233. 24
Cost savings (unsubsidized)	131. 14	- 131. 14
Total cost savings (subsidized)	- 10. 51	10. 51

The calculations in Table 9 indicate that, without factoring in the subsidies provided by national and local governments for new energy vehicles, the 100-kilometer operating cost of the K9 electric bus is considerably higher than that of conventional fuel buses. However, when considering the national subsidies for new energy vehicles, the 100-kilometer operating cost of the electric bus becomes lower. Given the current subsidy policy and market fuel price level, replacing traditional fuel buses with BYD K9 pure electric buses appears economically feasible in terms of the 100-kilometer operating cost.

6.2.2 Analysis of the specific situation in Qingdao

We further simulated the effect of the electrification rate of the urban bus fleet on the number of different models purchased, and the results are shown in Figure 2. It can be seen that the purchase volume of small pure electric buses (Model 3) exceeds that of large pure electric buses. This phenomenon is due to the high proportion of purchase cost in the total cost, significantly affecting the optimal alternative decision plan. Large pure electric buses are no longer selected when the electrification rate target is below 70%.

The electrification rate target for the bus fleet has a substantial impact on the cost of fleet replacement, as depicted in Figure 3. With the increasing electrification rate of the fleet, the social cost of carbon emissions and fleet energy consumption costs consistently decrease. Meanwhile, operating and maintenance costs experience a slight increase. However, the costs associated with purchasing vehicles and charging infrastructure are significantly rising, whereas the congestion cost in passenger cars remains almost unchanged.

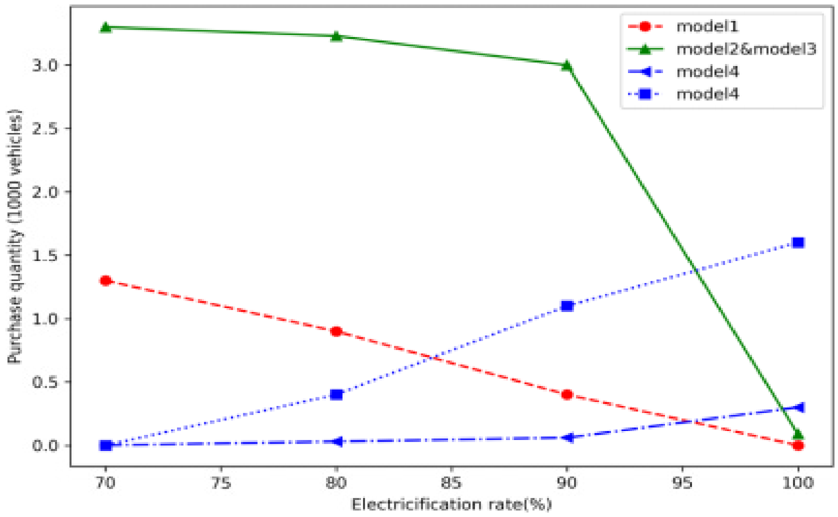

Fig. 2 The impact of the bus fleet electrification rate on the type and quantity of vehicles purchased.

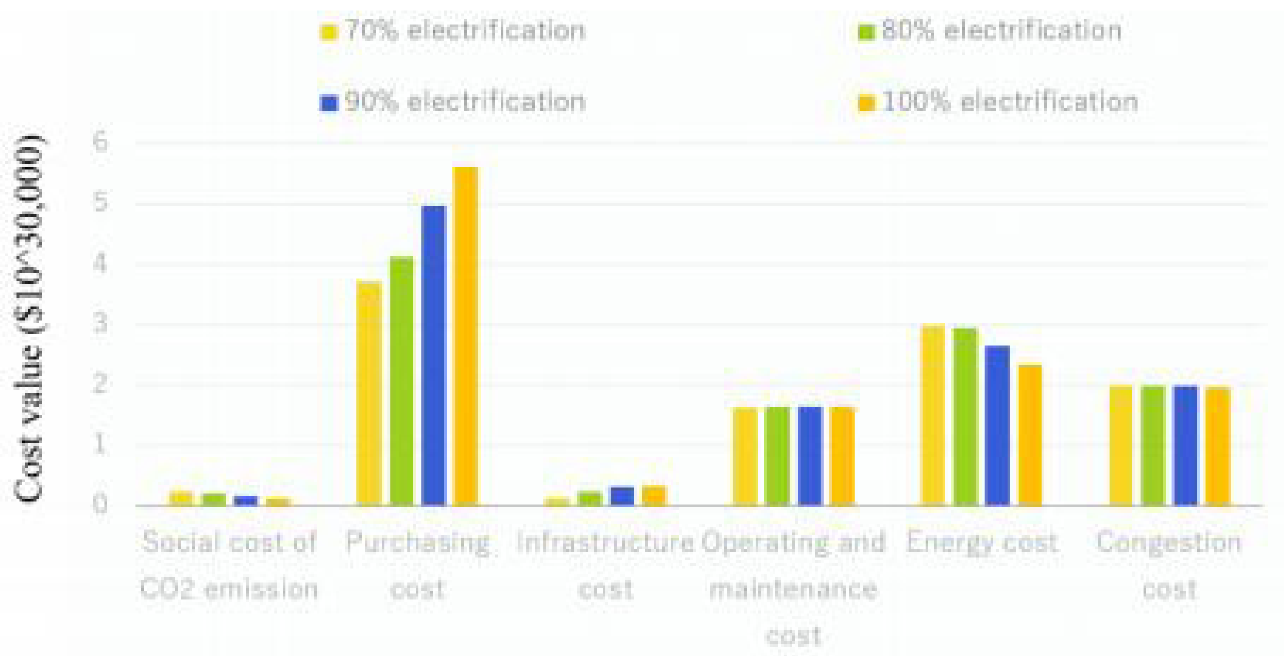

Fig. 3 Costs of different transit electrification rates

6.3 Case study of problem 3

We gathered data from Qingdao City and employed the linear integer programming model established in this article to calculate the optimal arrangement for an all-electric bus fleet within a 10-year time frame. We have set 2033 as the target year for electrification, aiming to transition 100% of the initial diesel buses to electric buses. All amounts are converted to 2023 U.S. dollars, applying an annual discount rate of 3%. We then applied the model to Zhengzhou and Xi'an and obtained similar results.

Table 10 Optimal Transition Plan for Qingdao

Year:	2024	2028	2033
Bus types:			
Diesel 40 ft	58	0	0

Diesel 60 ft	38	0	0
Hybrid 40 ft	0	0	0
Hybrid 60 ft	0	0	0
CNG 40 ft	0	0	0
CNG 60 ft	0	26	6
Electric 350 kWh 40 ft DC	0	0	0
Electric 650 kWh 60 ft DC	0	12	32
Electric 250 kWh 40 ft DC	0	3	4
Electric 250 kWh 40 ft DC + FC	4	59	58
Electric 110 kWh 40 ft DC + PC	0	0	0
Charger types:			
Depot plug-in charger (DC)	2	22	47
Fast plug-in charger at line terminal (FC)	1	2	3
Pantograph charger at three bus stops (PC) Costs:	0	0	0
Bus purchase cost (M$):	92.80		
Charger purchase cost (M$):	2.02		
Operating cost (M$):	95.24		
Demand charge (M$):	4.90		
End-of-horizon cost (M$):	6.78		
Total cost (M$):	201.74		
Solution time (s):	354.31		

7. Conclusion

Our article specifically focuses on the models developed to assess the potential environmental and economic benefits.

The long-term operation of electric bus fleets provides a promising way to reduce the basic operating costs of urban public transportation systems, ultimately resulting in sustained benefits. However, the start-up and continuous operation of electric bus fleets require significant initial investment and operational expertise, posing inherent risks to their deployment.

As a case, Qingdao provides an analysis of the development status, basic data, and results obtained from calculating different substitution rates, including government subsidies and car purchase costs.

Economically, a hybrid fleet consisting of fuel and pure electric buses has been proven more economical, especially in terms of total costs. As passenger demand increases, people's preference for large, fast-charging pure electric buses will also increase.

Our recommendation for Qingdao City involves adopting a diversified fleet layout, harnessing multiple vehicle models' cost reduction potential and enhanced environmental benefits. Reinforcing subsidies in this domain can further support this initiative, ultimately contributing to reduced future costs. However, resource settings, including charging infrastructure and staffing arrangement, necessitate further exploration based on the city's specific conditions.

Reference

[1] Zou, C., Wang, Y., Wu, L., He, J., Ni, J., & Mao, H. (2023). Environmental Benefits of Electrification in Zhengzhou Bus Fleet: Pollution Reduction and Carbon Mitigation. Environmental Science, 1- 13. doi: 10.13227/j.hjkx.202304156.

[2] Hao, X., Wang, H., Li, W., & Ouyang, M. (2019). Analysis of CO2 Emissions from PHEVs Based on the Structure of the Chinese Power Grid and Travel Characteristics of Vehicles in Typical Cities. Environmental Science, 40(4), 1705- 1714. doi: 10.13227/j.hjkx.201806058.

[3] Stasko, T. H., & Gao, H. O. (2010). Reducing Transit Fleet Emissions through Vehicle Retrofits, Replacements, and Usage Changes over Multiple Time Periods. Transportation Research Part D: Transport and Environment, 15(5), 254-262. doi: 10.1016/j.trd.2010.03.004.

[4] Chen, Z., Yin, Y., & Song, Z. (2018). A Cost-Competitiveness Analysis of Charging Infrastructure for Electric Bus Operations. Transportation Research Part C: Emerging Technologies, 93, 351-366. doi: 10.1016/j.trc.2018.06.006.

[5] Pelletier, S., Jabali, O., Mendoza, J. E., & Laporte, G. (2019). The Electric Bus Fleet Transition Problem. Transportation Research Part C: Emerging Technologies, 109, 174- 193. doi: 10.1016/j.trc.2019.10.012.

[6] Lin, Y., Zhang, K., Shen, Z.-J. M., Ye, B., & Miao, L. (2019). Multistage Large-Scale Charging Station Planning for Electric Buses Considering Transportation Network and Power Grid. Transportation Research Part C: Emerging Technologies, 107, 423-443. doi: 10.1016/j.trc.2019.08.009.