CHEMICAL ENGINEERING TRANSACTIONS

VOL. 89, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-87-7; **ISSN** 2283-9216

DOI: 10.3303/CET2189089

Potential of Electric Bus as a Carbon Mitigation Strategies and Energy Modelling: A Review

Lek Keng Lim, Zarina Ab Muis*, Haslenda Hashim, Wai Shin Ho, Muhammad Nurariffudin Mohd Idris

Process Systems Engineering Centre (PROSPECT), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
zarinamuis@utm.my

The transportation sector is one of the main contributors to greenhouse gases. One of the mitigation strategies is to introduce electric buses for public transport. The study has summarized the current status and prospect of different countries in electric buses. Electric buses are proven to reduce carbon emission in life cycle analysis with proper implementation and successfully mitigate carbon emission in urban areas. However, the battery technology is still not mature due to low energy storage compared to conventional vehicles. The state of charge for batteries is vital for low energy storage and limited access to the energy source. A review of energy consumption modeling for electric buses is carried out in this study. Energy consumption rate will vary due to several uncertainties such as traffic congestion, driver behavior, passenger load, weather and topographic condition of the road. Electric bus modeling should be carried out to differentiate electric buses as every electric bus operates under different parameters and conditions.

1. Introduction

Transportation contributes to 24 % of direct CO_2 emissions from fuel combustion, and carbon dioxide is one of the biggest contributors (76 %) to greenhouse gas emissions. Most of the transport system now still requires fuel as the main energy source, uses conventional energy sources and emits tons of CO_2. In 2018, 8.2 Gt of CO_2 emission was contributed by the transportation sector (IEA, 2020). Ritchie (2020) reported that 74.5 % of transport emissions came from road vehicles, and 45.1 % were contributed by the passenger on the road such as cars, motorcycles, buses and taxis, while another 29.4 % were contributed by freight on the road. Electrification of vehicles is one of the solutions to mitigate carbon emissions.
The presence of electric vehicles (EV) is not helping in reducing carbon emission and has positive net carbon emission if the analysis is carried out from a cradle-to-gate perspective. The increase of EV would cause high electric consumption and an increase of pollutants emission by power plants (Lazzeroni et al., 2021). The advance in battery storage, magnet and renewable sources has reduced the carbon emission of the EV. The optimization of electricity structure and increase in battery energy density and EV mileage can further reduce the life cycle environmental impact of the EV (Yu et al., 2018). According to Bloomberg Electric Vehicle Outlook 2020, three percent of oil consumption was reduced due to the implementation of electric vehicles, and three-quarters of the reduction was due to electric buses. Previous review papers have discussed the energy consumption model of the electric bus; however, the data for the journey trip is too specified, and the energy consumption rates of electric buses are different. This review summarizes them for future research purposes. The previous review papers have only discussed the status and prospect of the electric vehicle. This review has a more detailed scope and focuses on the electric bus.

1.1 Benefits of the Electric Bus

Electrification of public transport can mitigate local air polluters such as nitrous oxide (NOx) and particulate matter (PM) emitted by the conventional bus (Xylia et al., 2019). Results have shown that not all cities would experience huge air pollution reduction as pollution is mostly caused by private transport. Usage of electric buses and other forms of public transport in cities should be promoted to the community.

Paper Received: 23 June 2021; Revised: 27 August 2021; Accepted: 9 November 2021
Please cite this article as: Lim L.K., Ab Muis Z., Hashim H., Ho W.S., Mohd Idris M.N., 2021, Potential of Electric Bus as a Carbon Mitigation Strategies and Energy Modelling: A Review, Chemical Engineering Transactions, 89, 529-534 DOI:10.3303/CET2189089

Borén (2019) designed a model to identify the societal cost, the total cost of ownership, the variation of annual energy usage due to seasons and the noise produced by accelerating buses. The case study was conducted in five cities in Sweden, in which the electric bus system was implemented. The study showed a reduction in societal cost and total cost of ownership when the electric bus was used instead of diesel- and biogas-powered buse as it happens due to the reduction of noise, no emission in using phase and energy reduction.
Trondheim Norway has implemented a new bus fleet of 36 electric and 58 hybrid buses. The study has designed a model to carry out a life cycle assessment which included gas emission and energy required to produce the different parts of the electric bus (Lie et al., 2021). The results from the case study showed that implementing biofuel and electrified buses could reduce 37 % carbon footprint, and full electrification could reduce up to 52 % carbon footprint. The study also found that the operation emissions were estimated at 49 CO_2-eq/person-km, below Norway's average for city buses and passenger cars. Lajunen and Lipman (2016) evaluated the life cycle costs and carbon dioxide emissions of different city bus types. The operating environments were Finland and California. The model used in the study was Autonomie. Results indicated that diesel hybrid buses had a better life cycle cost than diesel and natural gas buses. Electric buses can reduce carbon emissions by up to 75 %. Table 1 illustrates the tank-to-wheel greenhouse gas emission (TTW GHG) and well-to-wheel greenhouse gas emission (WTW GHG) of different bus technologies and bus sizes. The data in Table 1 was extracted from Asian Development Bank.

Table 1: Greenhouse Gas Emissions of Different Types of Bus (Asian Development Bank, 2018)

Bus Size	8 m		10-12 m		18 m	
Bus Tech	TTW GHG	WTW GHG	TTW GHG	WTW GHG	TTW GHG	WTW GHG
Diesel	28	35	48	24	80	102
Natural Gas	31	44	46	62	83	119
Diesel-hybrid	23	29	40	66	66	81
Natural gas-hybrid	25	36	38	51	69	98
Electric	0	24	0	55	-	-

All values above are illustrated in tons of CO_2 equivalent

2. Implementation of Electric Buses in Different Countries

According to the ZeEUS eBus Report, the first application of a full-electric bus was during Olympic Games 2008 in Beijing, followed by launching a 12 m full battery-electric bus with a range of 250-300 km in 2010. These incidents have opened up the electric bus market for Chinese manufacturers. China is by far leading the deployment of electric buses in Asia. Currently, China has more than 421,000 electric buses with a rate of circulation of 9,500 buses every 5 weeks. Until 2018, 99 % of electric buses in circulation were located in China, and they successfully reduced the demand for diesel by more than 270,000 barrels by the end of 2019. China's government will provide a subsidy of 500,000 yuan for every electric vehicle purchased by the public transport operator in Shenzhen each year for nine years.
The development of electric buses is lagging in North America as the US does not have more than 500 electric buses, but the countries are making efforts to follow up the pace of electrifying the buses. California aims to have 100 % electric buses, which are around 12,000 city buses by 2040. Other 15 states have also followed the steps of California in electrifying heavy-duty vehicles, including buses, to achieve zero-emission transportation. (O'Kane, 2020). Dominion Energy aims to replace 50 % diesel school buses with electric buses in its Virginia territory by 2025 and 100 % replacement of electric buses by 2030. Replacement of a diesel bus with an electric bus is equivalent to replacing 5.2 cars off the road (Richmond, 2019).
According to the article from IES synergy, in Canada, line 36 was the first fully electric bus transit line by 2020. After two years of testing, the application of electric buses received a high satisfaction rate and proved it can withstand the Canadian winter. Chile is the first country in South America to provide electric buses. In Santiago, 30 % of the community travels by public transport, making the capital determined to replace all its fleets by 2040. Currently, Santiago has 411 electric buses, and they are in circulation for a 6 million population. Guayaquil, Ecuador, had inaugurated a fleet of 20 electric buses in March 2019. Cali, Colombia, is in the stage of commissioning 125 electric buses.
In Europe, the European Union adopted a new rule in February 2019 where a quarter of new buses purchased by public authorities should be "clean" by 2025. Major cities in Europe have announced to ban all diesel buses by 2025. According to the magazine Sustainable Bus, there are 1,000 electric buses in operation in the Netherlands. Dutch public transport buses are targeted to reach 20 % emission-free in five years. Table 2 below summarizes the development and future trend of different cities. The cities were first selected based on regions

such as Asia, Europe, and the US and then selected based on clarified clear target or implementation of electric buses in their system.

Electric buses are a new transportation trend due to their low carbon emission and nearly zero air pollution in the city, but the development of electric buses has constraints. One of the constraints is the limited driving range and low accessibility to the charging station compared to conventional transport. Nakyoung (2021) emphasized that electric vehicles have different energy consumption behavior than conventional vehicles, and electric vehicles were more energy-consuming when climbing hills. Energy management for electric buses should be well studied, starting from the energy consumption model of the electric bus.

Table 2: Current Status and Prospect of Electric Bus in Different City/Country

City/Country	Current Status and Prospect	Reference
Shen Zhen/ China	Achieved full electrification of its bus fleet, which is around 16,000 buses.	Ralston (2020)
Beijing/ China	More than 10,000 electric bus is in service for Bei Jing Beijing Public Transport Corporation targeted to electrify more than 50 % of the public buses. China's clean energy drive had increased from 20 % in 2015 to 60 % in 2020.	Xinhua (2020)
Delhi	Targeted to have 2,000 electric buses in Delhi by the end of 2021.	Goswami (2020)
California/ US	California Air Resources Board has approved a measure for all public transit agencies in the state to transform 100 % of their buses into zero-emission buses by 2040.	-
Virginia/ US	Dominion energy targeted to have 50 % of diesel school buses replaced with electric buses and 100 % electrification by 2030.	Richmond (2019)
Montreal/ Canada	All the buses in line 36 are electric, and they are proven applicable even under Canadian winter after testing for two years. The bus fleet consists of 30 slow-charging electric buses and four fast-charging electric buses.	IES synergy (2020)
Santiago/ Chile	Chile is the first country in South America to provide electric buses. By 2020, 411 electric buses had been put into the public transport service in Santiago.	Sustainable Bus (2020)
Guayaquil/ Ecuador	Applied for a fleet of 20 electric buses in March 2019.	IES synergy (2020)
Dutch/ Netherlands	The Netherlands currently has 1,000 electric buses in operation. 9 % of public transport buses in the Netherlands are electric. Dutch public transport aims to have 20 % of buses converted into electric buses in five years.	Sustainable Bus (2020)
Malaysia	Malaysia launched several electric buses pilot programs such as the Putra NEDO EV bus project in Putrajaya (4 EB) and BRT Sunway by Rapid KL (15EV Buses).	Azman (2021)
Singapore	In March 2020, Singapore decided only to procure electric and hybrid buses and targeted to electrify its bus fleet of around 5400 vehicles by 2040.	Tan (2020)

3. Energy Modelling of Electric Buses

3.1 Overview Energy Model of the Electric Bus

Electric buses can be differentiated into different types, including hybrid-electric buses, fuel cell buses, and battery electric buses (BEB). Wu et al. (2015) first developed the energy consumption model for the BEB based on a longitudinal dynamic model.

The electric bus can be separated into several parts for energy estimation. Basma et al. (2020) prepared a detailed model to determine the travelling mileage of electric buses. The model was separated into three major parts: the powertrain, cabin model/HVAC system, and auxiliaries. Figure 1 lists several components that include the propulsion system, cabin-HVAC and auxiliaries to estimate the energy consumption of the powertrain model. Several parts are to be discussed, including battery model, electric machine model, wheels and braking system model and torque control strategy. Apart from that, buses require HVAC systems to maintain optimum temperature for the passenger, and the heat required to maintain the optimum temperature in a bus should be determined as it will vary according to the passenger load and the number of bus door openings. The detailed description is presented in (Brèque and Nemer, 2017). The HVAC model includes a reversible heat pump, an air circulation system, a battery thermal management system and a control scheme. In the auxiliaries model, there are electric auxiliaries, hydraulic auxiliaries and pneumatic auxiliaries. Table 3 illustrates the energy consumption of different auxiliaries.

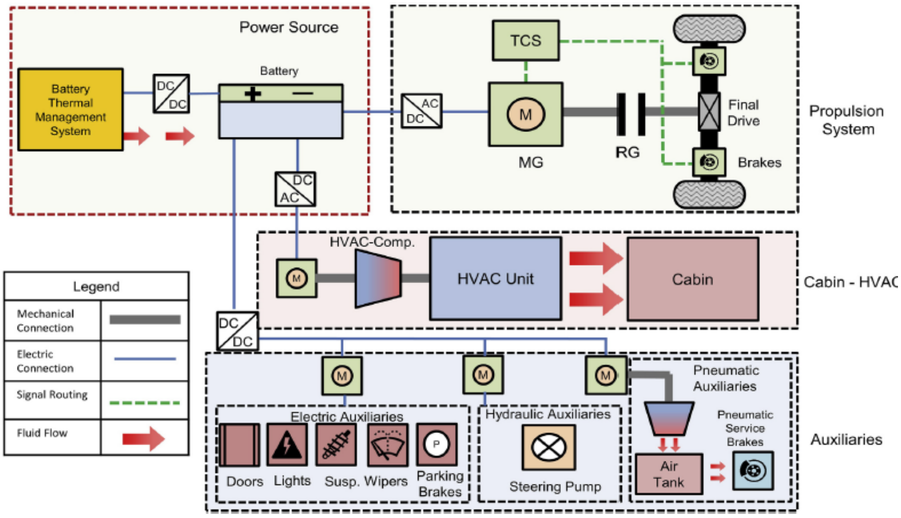

Figure 1: Overview Energy Model of the Electric Bus (Basma et al., 2020)

Table 3: Energy Consumption of Auxiliaries in the Electric Bus (Basma et al., 2020)

	Power (W)	Duration (s)
Door operation	90	3
Activation of Parking Brakes	560	1
Lighting System	500	-
Wipers	110	-

3.2 Energy Consumption Model of the Electric Bus

Several studies have discussed the energy consumption model of the electric bus. Table 4 summarizes the energy consumption per km for the electric bus of different models, and Table 5 summarizes several driving cycles used in the models below.

Table 4: Energy Consumption per km for Electric Bus

Ref	Energy consumption per km	Research Gap
Gao et al. (2017)	1.35 kWh/km	Detailed economic analysis is not conducted
Teoh et al. (2018)	6.1 kWh/km	Energy usage distribution is not carried out
Saadon Al-Ogaili et al. (2020)	2.486 kWh/km	The model does not include random charging and early departure.
Zhou et al. (2016)	12 m-buses –1.38-1.75 kWh/km 8 m- buses – 0.79 kWh/km	The model uses battery data and does not forecast the energy needed.
Lajunen and Lipman (2016)	PAR – 3.6 kWh/km (parallel battery arrangement) SER – 3.3.kwh/km (series battery arrangement)	The model does not include detailed auxiliary.

Gao et al. (2017) created a comprehensive framework to determine city transit electric buses' energy consumption and battery performance based on a real day to day route. The model examined the feasibility of bus electrification with real-world vehicle performance, city transit bus service's reliability, battery sizing and charging infrastructure. The average battery energy consumption of the electric bus was 1.35 kWh/km, while the average mechanical energy consumption of the engine for the conventional vehicle case was 1.80 kWh/km. The corresponding diesel fuel energy consumption was 5.52 kWh/km (engine efficiency 35 %). The average braking energy recovered was nearly 0.39 kWh/km.
Saadon et al. (2020) developed an integrated model that consisted of a digital elevation and longitudinal dynamics model to determine the energy consumption of electric buses using real system-wide data. The real-world data was obtained from the Bus-Rapid KL, Malaysian Innovation of Electric Bus (EBIM), the Space Shuttle

Radar Topography Mission (SRTM), and the Malaysia Representative Network (MRN). The integrated model included a digital elevation model (DEM) for topographical geodatabase, PIS (Passenger Information System) for acceleration and deceleration driving nodes and MRN (Malaysia Representative Network) for bus route charging. The simulation was then carried out for different scenarios: actual, empty load, elevation neglected, and elevation neglected while empty load. Real data for the simulation averaged 2.486 kWh/km for the different routes.

Zhou et al. (2016) studied the effect of load and air-conditioning usage on energy consumption. The study used the operational results, which contained vehicle speed and battery power with respect to time per second from 3 different BEB. The study also determined the speed-dependent function for 3 BEB under different scenarios. The two 12 m-buses consumed 138-175 kWh/100 km, and the 8-m bus consumed 79 kWh/100 km. 21~ 27 % of increments were shown when the bus travelled under full load and maximum AC usage.

Table 5: Driving Cycle

Cycle Name	Duration (s)	Distance (km)	Average Speed (km/h)	Max Acceleration(m/s2)	Max Deceleration (m/s2)	Deceleration (m/s2)	Idle Time (s)	Number of Stops	Reference
New York Bus	600	1.113	5.93	6.1	4.3	0.163	404	12	Gao et al. (2017)
Manhattan Bus	1,089	3.32	10.98	2	2.5	0.188	395	21	Lajunen and Lipman (2016)
New York Composite	1,023	4.5	14.1	-	-	0.19	341	19	Basma et al. (2020)
Orange County Transit Authority	1,909	11.845	19.84	4.06	5.13	0.237	407	31	Gao et al. (2017)
Central Business District	569	3.64	20.43	-	-	0.2478	122	14	Basma et al. (2020)
City Suburban Heavy Vehicle	1,780	12.1	21.86	-	-	0.167	385	19	Basma et al. (2020)
Braunschweig	1,740	12.23	22.4	2.4	3.6	0.241	442	29	Lajunen and Lipman (2016)
Espoo11 (Finland)	1,548	10.2	23.8	1.6	1.9	-	183	17	Basma et al. (2020)
Helsinki	3,384	28.7	23.8	2	2.9	-	525	37	Basma et al. (2020)
Washington Metropolitan Area	1,839	6.86	76.48	3	4.5	-	805	-	Basma et al. (2020)

4. Conclusions

In this paper, the potential of electric buses is discussed, and most of the countries are targeting to replace diesel buses with electric buses to achieve zero carbon emission from public transportation. The data collected have further proven that the installation of electric buses may help mitigate carbon emissions. Compared to the conventional bus, the electric bus faces some constraints such as limited driving range and low accessibility to the charging station. The energy consumption model of the bus is very important to assist in designing a bus network and ensure sufficient energy for the electric bus to complete its driving cycle. The energy consumption model for the electric bus will vary based on the size of the electric bus, traffic condition, driving pattern and the weather. The energy consumption model should be specialized for different electric buses and drivers based on their specifications to enhance the model's accuracy.

Acknowledgments

The authors would like to acknowledge Universiti Teknologi Malaysia for the research grant with cost center number of FRGS/1/2019/TK10/UTM/03/1 (R.J130000.7851.5F184) and Q.J130000.2446.04G33 that were provided for this research study.

References

Basma H., Mansour C., Haddad M., Nemer M., Stabat P., 2020, Comprehensive energy modelling methodology for battery electric buses. Energy, 207,118241.

Borén S., 2019, Electric buses' sustainability effects, noise, energy use, and costs. International Journal of Sustainable Transportation, 14(12), 956-971.

Brèque F., Nemer M., 2017, Cabin Thermal Needs: Modeling and Assumption Analysis. Paper presented at the Proceedings of the 12 th International Modelica Conference, Prague, Czech Republic, May 15-17, 2017.

Gao Z., Lin Z., LaClair T. J., Liu C., Li J.-M., Birky A.K., Ward J., 2017, Battery capacity and recharging needs for electric buses in city transit service. Energy, 122, 588-600.
Goswami S., 2020, 2,000 electric buses in Delhi by end-2021: Govt. < hindustantimes.com/delhi-news/2-000-electric-buses-in-delhi-by-end-2021-govt/story-UNUbjbowri3qPJJQbEI6JJ.html> accessed 4.05.2021.
IEA., 2020, Transport sector direct CO2 emissions in the Sustainable Development Scenario, 2000-2030. < iea.org/data-and-statistics/charts/transport-sector-direct-co2-emissions-in-the-sustainable-development-scenario-2000-2030> accessed 25.03.2021.
Jürg Grütter A., Frecon A. F., Gong L.., Song L., Wang J., Li L., Yang X., Gao, Huanan. ,2018, Sustainable Transport Solution Low-carbon Buses in the People's Republic of China, Mandaluyong, Philippines.
Lajunen A., Lipman T., 2016, Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy, 106, 329-342.
Lazzeroni P., Cirimele V., Canova, A. ,2021, Economic and environmental sustainability of Dynamic Wireless Power Transfer for electric vehicles supporting reduction of local air pollutant emissions. Renewable and Sustainable Energy Reviews, 138, 110537.
Lie K.W., Synnevåg T.A., Lamb J.J., Lien K.M., 2021, The Carbon Footprint of Electrified City Buses: A Case Study in Trondheim, Norway. Energies, 14(3), 770.
Azman N.H., 2021, MGCC aims 100 electrical buses in M'sia., 2020, <themalaysianreserve.com/2020/03/11/mgcc-aims-100-electrical-buses-in-msia> accessed 6.05.2021
Nakyoung Y, Donggyun K., Minje C, Seungjae L., 2021, An Eco-friendly Path Guidance Algorithm for Electric Vehicle. Chemical Engineering Transactions, 83, 217-222.
The Netherlands have more than 1,000 electric buses in operation, 2020, Sustainable Bus <sustainable-bus.com/news/the-netherlands-have-more-than-1000-electric-buses-in-operation/> accessed 3.06.2021
O'Kane S., 2020, 15 states will follow California's push to electrify trucks and buses <theverge.com/2020/7/14/21324552/electric-trucks-buses-clean-air-zero-emissions-states> accessed 7.06.2021
Ralston W., 2020, How Shenzhen turned all its 16,000 buses fully electric <wired.co.uk/article/shenzhen-electric-buses-public-transport> accessed 5.06.2021
Richmond Va., 2019, Dominion Energy Proposes Largest Electric School Bus Initiative in the Country <news.dominionenergy.com/2019-08-29-Dominion-Energy-Proposes-Largest-Electric-School-Bus-Initiative-in-the-Country> accessed 5.06.2021
Ritchie H., 2020, Cars, planes, trains: where do CO2 emissions from transport come from? <ourworldindata.org/co2-emissions-fromtransport#:~:text=Transport%20accounts%20for %20around%20one, CO2%20emissions%20from%20energy%5D> accessed 25.03.2021
Saadon Al-Ogaili A., Ramasamy A., Juhana Tengku Hashim T., Al-Masri A.N., Hoon Y., Neamah J.M., Marsadek M., 2020, Estimation of the energy consumption of battery driven electric buses by integrating digital elevation and longitudinal dynamic models: Malaysia as a case study. Applied Energy, 280, 115873.
Tan C, 2020, All new public buses will be electric or hybrid <straitstimes.com/politics/all-new-public-buses-will-be-electric-or-hybrid> accessed 10.05.2021
Teoh L.E., Khoo H.L., Goh S.Y., Chong, L.M., 2018, Scenario-based electric bus operation: A case study of Putrajaya, Malaysia. International Journal of Transportation Science and Technology, 7(1), 10-25.
Wu X., Freese D., Cabrera A., Kitch W.A., 2015, Electric vehicles' energy consumption measurement and estimation. Transportation Research Part D: Transport and Environment, 34, 52-67.
Wu X., He X., Yu G., Harmandayan A., Wang Y., 2015, Energy-Optimal Speed Control for Electric Vehicles on Signalized Arterials. IEEE Transactions on Intelligent Transportation Systems, 16(5), 2786-2796.
Xinhua. ,2020, 60 percent of China's buses go electric amid clean energy push, <chinadaily.com.cn/a/202010/26/WS5f9631b1a31024ad0ba80e19.html> accessed 8.05.2021
Xylia M., Leduc S., Laurent A.-B., Patrizio P., van der Meer Y., Kraxner F., Silveira S., 2019, Impact of bus electrification on carbon emissions: The case of Stockholm. Journal of Cleaner Production, 209, 74-87.
Yu A., Wei Y., Chen W., Peng N., Peng L., 2018, Life cycle environmental impacts and carbon emissions: A case study of electric and gasoline vehicles in China. Transportation Research Part D: Transport and Environment, 65, 409-420.
Zhou B., Wu Y., Zhou B., Wang R., Ke W., Zhang S., Hao J., 2016, Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. Energy, 96, 603-613.