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Editorial

Driving under the sun: Future of solar buses in Hong Kong, China

1. Introduction

The transportation sector, as the second-largest contributor to global carbon emissions, is crucial for achieving carbon neutrality. Successful bus electrification can reduce emissions and promote public transit over private vehicles. Currently, battery electric buses (EBs) dominate the zero-emission bus (ZEB) market but face challenges such as shorter driving ranges and longer charging times than diesel buses (DBs), leading to subsequent issues such as frequent charging, increased fleet size, and more charging stations. These issues vary locally. Shenzhen, China, which has achieved 100% bus electrification since 2017, has opted for large-battery EBs that meet daily operations with one overnight charge supported by its ample facility space (Shenzhen bus report, 2021). However, this experience is unlikely applicable to its neighbor, Hong Kong, China, where double-decker buses constitute 95% of the fleet. Current double-decker EBs usually fall short of Hong Kong buses' daily mileage without extra daytime charging, and this shortfall is exacerbated by the city's hilly terrain and hot weather, which increase energy consumption. Trials of double-decker hydrogen buses (HBs) show promise with driving ranges and refueling times similar to DBs, but high costs and a lack of refueling infrastructures remain barriers. The trade-off between EBs and HBs complicates Hong Kong's ZEB transition, prompting academia and industry to seek compromise solutions. Solar energy, as a clean and renewable resource, shows great potential in transportation systems through solar panels installed on charging stations, buildings, and vehicles (Liu et al., 2024). In this editorial, we consider installing solar panels on bus rooftops to improve bus performance, which has been used worldwide, such as in USA, Australia, China, Singapore, and Denmark (Table 1). Technically speaking, solar panels can be applied to any bus type, leading to solar diesel buses (SDBs), solar electric buses (SEBs), and solar hydrogen buses (SHBs). However, the key questions are as follows: Is it worthwhile to implement solar buses in Hong Kong, China? If so, which bus type is most suitable? These questions need a cost–benefit analysis and could provide further insights for decision-makers (e.g., government agencies and bus operators) to make informed decisions regarding Hong Kong's ZEB transition.

2. Solar bus specification

2.1. How do solar buses work?

Buses typically have large, flat roofs that are ideal for installing photovoltaic (PV) modules. These PV modules can continuously generate electricity from sunlight whenever the bus is moving or stationary (i.e., parking and charging). This continuous energy supply directly powers the bus's auxiliary systems, such as air conditioning and ventilation. As a result, more energy from onsite refueling stations can be reserved for the primary motor systems of buses, such as moving and braking (Chen et al., 2022). As shown in Fig. 1a, a typical rooftop PV module on Hong Kong, China buses consists of 20 solar panels, each 0.8 m × 1.0 m and weighing approximately 70 kg in total (Citybus news, 2020; KMB news, 2024). Given Hong Kong's solar radiation levels and shading conditions for buses, a reasonable estimation is that solar panels on each bus could generate approximately 5 kWh/day of additional power[1]. This additional power can extend the driving range of DBs, EBs, and HBs by 4, 3, and 4 km, respectively[2] (please refer to the Appendix for detailed calculations).

2.2. What are the benefits?

Installing rooftop solar panels on buses has direct and indirect benefits in terms of the bus's environmental and technical performance.

- Lower carbon emissions. Solar panels generate clean, renewable electricity, supporting carbon neutrality goals. SDBs can reduce tailpipe emissions by decreasing diesel fuel use. Although SEBs and SHBs have no tailpipe emissions, solar panels can reduce lifecycle emissions in fuel-cycle processes, especially if the energy sources for hydrogen or electricity are not carbon free.
- Extended driving range. Solar-generated electricity powers auxiliary systems, conserving energy storage for motor systems. This extends the driving range and reduces the reliance on an onsite energy supply, potentially prolonging the lifetime of energy storage systems, espe-

[1] Monocrystalline silicon solar panels generate electric energy at approximately 200 Wp/m^2 based on standard test conditions. In Hong Kong, with approximately 3–4 peak-sun hours of daily sunlight, the daily energy yield is approximately 3.2 Wh/Wp per day. Considering a 50% power generation reduction due to shading effects during bus operations, the additional power generated by solar panels is: 200 Wp/m^2 × (0.8 m × 1 m × 20) × 3.2 Wh/Wp/day × 50% = 5000 Wh/day.

[2] Note that our estimate is based on energy consumption status, which is more conservative than public news. According to Hong Kong 2050 news (2023), this additional power can reduce a DB's fuel consumption by 5% (i.e., equating to 30 km) or extend an EB's driving range up to 10 km. The news represents a more optimistic scenario.

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Table 1
Solar bus application examples around the world (Source: collected by the authors).

Area	Bus type	Figure	Area	Bus type	Figure
Australia	Single-decker		Japan	Single-decker	
China's mainland	Single-decker		Singapore	Single-decker	
Democratic People's Republic of Korea	Single-decker		Uganda	Single-decker	
Denmark	Single-decker		USA	Single-decker	
Germany	Single-decker		Hong Kong, China	Double-decker	

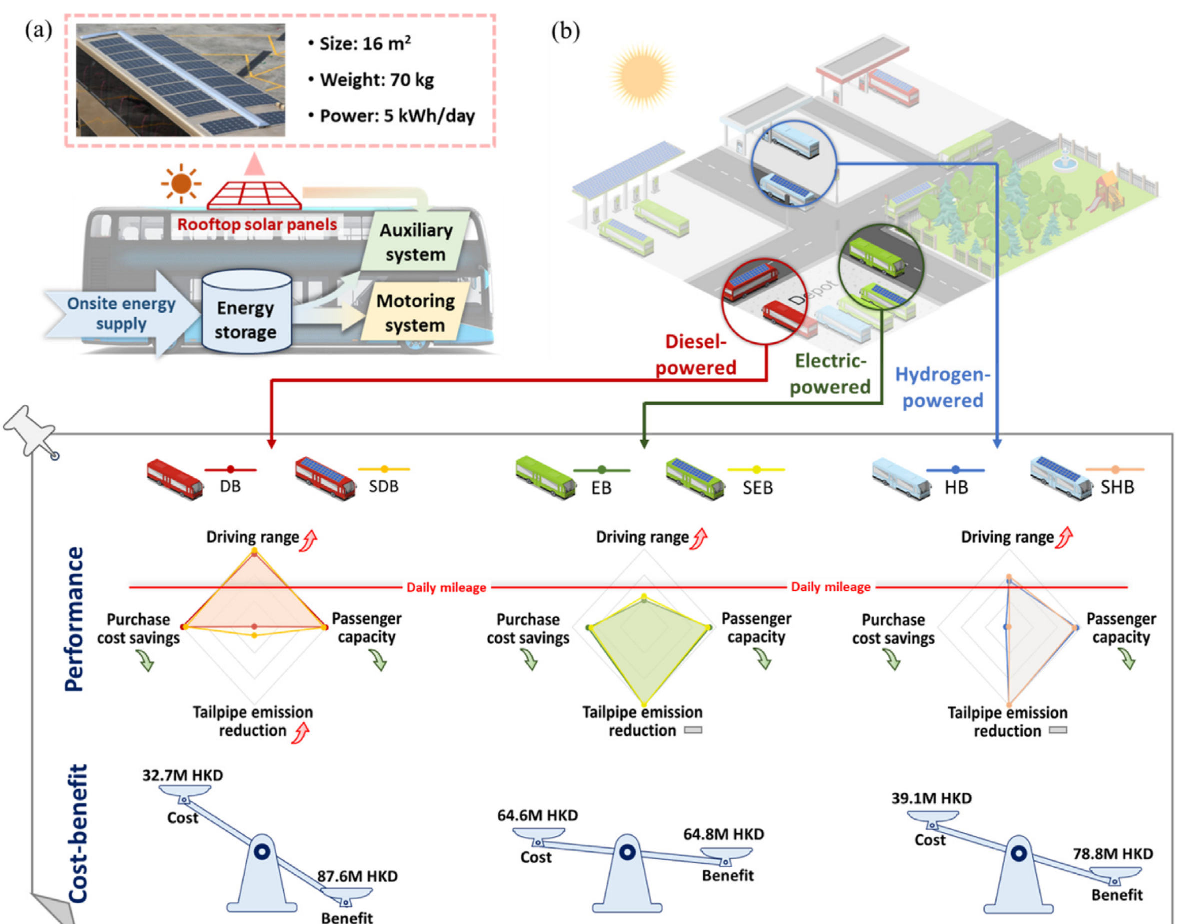

Fig. 1. Specification and applications of solar buses: (a) solar bus specifications; (b) comparison of DBs and SDBs, EBs and SEBs, and HBs and SHBs.

cially Li-ion batteries in SEBs, by reducing the number of charging cycles.

- Reduced refueling demand. An extended range decreases the refueling frequency, thus saving fuel costs. This particularly benefits SDBs and SHBs in Hong Kong, China, where diesel and hydrogen are more expensive than electricity.
- A smaller fleet size and fewer refueling stations. Driving range extension allows the current fleet to meet more operational needs, reducing the fleet size and purchase costs. Consequently, fewer refueling stations are needed, benefiting SEBs and SHBs by lowering the costs associated with new or upgraded energy infrastructures. This is particularly important for SHBs, as Hong Kong lacks existing hydrogen infrastructure, requiring large investments for production, transmission, distribution, and storage.
- Continuous cooling system. PV panels can continuously power the air conditioning system even when the bus is parking, maintaining a cooler temperature in summer. This reduces the time needed to reach comfortable temperatures upon starting, minimizing emissions and energy waste (KMB news, 2024).

2.3. What are the costs?

In addition to the benefits, there are also costs to consider from both technical and monetary perspectives to achieve them.

- Reduced passenger capacity. Additional solar panels increase the overall weight of the bus, potentially reducing the passenger capacity to maintain the originally designed technical performance (e.g., driving speed and range, starting speed, and braking speed). However, the increased weight is minimal for heavy buses, especially double-decker buses, which might be a unique advantage in the Hong Kong context.
- Increased purchase and maintenance costs. Installing solar panels requires significant initial technical investment and installation costs. Additionally, maintaining these panels incurs extra expenses, adding to the overall bus operation costs. Nevertheless, economies of scale could reduce investment over time when this technology is widely adopted.

3. Potential of SDBs, SEBs, and SHBs

The installation costs of solar panels on bus rooftops are relatively uniform across different bus types, but the benefits vary significantly. When selecting bus types for solar panel installation in Hong Kong, it is essential to consider both bus features and local conditions. Fig. 1b presents four key performance metrics—driving range, purchase cost savings, passenger capacity, and tailpipe emission reduction—as well as cost–benefit tradeoffs to explore the potential of SDBs, SEBs, and SHBs. We focus on direct costs (fleet purchase and fare loss) and direct benefits (fleet size and fuel costs), assuming that the replacement meets the current fleet size of 6,000 buses (Hong Kong 2050 news, 2023). The costs are calculated annually and averaged over the bus lifetime. For detailed calculations, please refer to the Appendix.

- SDBs: economical solutions in ZEB transition

DBs in Hong Kong, China perform the best in terms of driving range, purchasing cost, and passenger capacity, making SDBs similarly advantageous. However, neither achieves zero emissions, necessitating eventual replacement for carbon neutrality. Nevertheless, SDBs appear to be an economically interim solution when they transit to ZEB fleets. The solar panels save approximately 1.6 L of diesel per bus per day, equating to 40 Hong Kong Dollar (HKD). This benefit leads to 87.6 million HKD per year of the whole fleet size, which is particularly advantageous in Hong Kong, China which has high diesel prices.

- SEBs: cost-effective improvement in technical performance

EBs themselves often struggle to meet daily mileage requirements, especially with air conditioning and uphill routes. In this case, the extended driving range from solar panels on SEBs significantly improves their performance, reducing the fleet size and facility needs while extending the battery lifetime. Our estimate shows that the fleet reduction can be 2.8%, or 166 buses, contributing to 66% of the total benefit, equating to 42.7 million HKD annually. Indirect benefits, including lower operating costs, reduced land acquisition for parking and charging, and decreased charging facility expenses, are also promising. The remaining 34% of the benefit comes from electricity cost savings, which are expected to grow as electricity prices rise in Hong Kong.

- SHBs: promising potential at the initial stage

HBs have the desired performance in terms of range, emission, and passenger capacity but are the most expensive. Since HBs can meet daily mileage needs, solar panels help reduce hydrogen costs, especially when hydrogen prices are high at the initial stage. With the current hydrogen price in Hong Kong at 108 HKD/kg, the cost savings can reach 0.33 kg hydrogen per bus per day, leading to 78.8 million HKD annually for the whole fleet. In addition, the indirect benefits of SHBs could be significant, as they can decrease the need for costly hydrogen infrastructure (although not included in the present cost–benefit analysis).

4. Discussion

Solar energy, as a clean and renewable resource, holds significant potential in the future. In the transportation field, people are harnessing this energy by installing PV modules on charging stations, buildings, and vehicles. On the basis of energy estimation and cost–benefit analysis, this editorial demonstrates that installing rooftop solar panels on buses has great potential for Hong Kong's future across all bus types. SDBs achieve the greatest cost savings, making them an ideal interim solution during the ZEB transition. SEBs benefit greatly from extended driving ranges and are a cost-effective solar ZEB option. SHBs are advantageous when hydrogen-related costs are high, especially at the initial stage. The substantial monetary benefits yielded by minimal investment in solar panels are particularly advantageous in Hong Kong, China, where bus companies are profit driven rather than reliant on government subsidies. Transitioning to ZEB fleets requires additional budgets, and solar buses present an affordable and cost-effective solution. Note that bus companies in Hong Kong, China are already equipped with relatively mature bus rooftop PV technology. They tried this technology on DBs and are planning further expansion (Hong Kong 2050 news, 2023). Our analysis shows that the expansion of EBs and HBs has a promising future as well. Beyond direct benefits, there are wider advantages, such as reduced depot land acquisition, lower labor and maintenance costs, and lower investments for upstream energy supply facilities (particularly for the hydrogen infrastructure).

Nevertheless, there are some limitations in the present editorial, which call for further exploration. First, the environmental benefits currently focus on tailpipe emissions during bus operations, whereas considering lifecycle emissions across fuel-cycle processes would provide a more comprehensive evaluation. Our findings indicate that solar panels can save 1.6 L of diesel per SDB, 5 kWh of electricity per SEB, and 0.33 kg of hydrogen per SHB daily in a carbon-free manner. These contributions to sustainability should be factored into the assessment analysis, since current energy generation methods in Hong Kong, China are not entirely carbon free. Second, our assumption of generating 5 kWh of electricity per bus per day is based on average sunlight conditions in Hong Kong, China and accounts for a 50% power generation reduction during bus operations. However, the generated electricity may vary due to time of day, weather conditions, sunlight intensity, shading along bus routes, etc. These uncertainties may significantly affect electricity generation efficiency as well as the associated maintenance and operational costs. Future studies may explore route design and daily operational scheduling to optimize solar bus benefits by considering these uncertainties. Third, the cost–benefit analysis presented in the editorial does not account for long-term market dynamics or potential technological advancements and their impacts on costs and environmental considerations. Further studies could delve deeper into these aspects for a more comprehensive analysis.

CRediT authorship contribution statement

Zhuowei Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Yiyang Peng:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Hongxing Yang:** Writing – review & editing, Validation, Funding acquisition, Formal analysis. **Anthony Chen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used GPT-4o in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The calculation assumes that rooftop solar panels weigh 70 kg and generate 5 kWh of extra energy per day. The additional energy can extend the driving range and reduce fuel costs. Diesel can generate electricity through diesel engines at approximately 3.1 kWh/L, and hydrogen can generate electricity through fuel cells at approximately 15 kWh/kg. Table A1 shows the basic information and calculation of key indices, and additional costs and benefits are shown in Fig. 1b.

Table A1
Calculation details of installing solar panels on buses.

Category	Item	Unit	DB	SDB	EB	SEB	HB	SHB
Performance analysis (on vehicle basis)								
Basic information[a]	Weight	kg/bus	18,000	18,070	24,000	24,070	23,200	23,270
	Purchase cost[b]	1000 HKD/bus	1200	1264	3000	3064	8000	8064
	Tailpipe emission	kg CO_2/km	1918	1822	0	0	0	0
	Diesel tank	L	275	275	—	—	—	—
	Battery capacity	kWh	—	—	355	355	—	—
	Hydrogen tank	kg	—	—	—	—	36	36
	Lifetime	year	12	12	8	8.2	10	10
	Fleet size estimation	bus	6000	6000	8182	8000	6000	6000
Performance metrics	Driving range	km	600	604[b]	220	223	400	404[c]
	Passenger capacity	people/bus	130	129	117	116	119	118
	Tailpipe emission reduction	kg CO_2/km	0	96	1918	1918	1918	1918
	Purchase cost savings	1000 HKD/bus	6864	6800	5064	5000	64	0
Cost–benefit analysis (on fleet basis)								
Additional cost	Solar panel cost	1000 HKD/yr	—	+32,000	—	+63,620	—	+38,400
	Fleet fare loss[d]	1000 HKD/yr	—	+720	—	+968	—	+720
	Additional cost sum	1000 HKD/yr	—	+32,720	—	+64,588	—	+39,120
Additional benefit	Fleet size benefit[e]	1000 HKD/yr	—	0	—	+42,699	—	0
	Fuel price benefit[f]	1000 HKD/yr	—	+87,600	—	+22,082	—	+78,840
	Additional benefit sum	1000 HKD/yr	—	+87,600	—	+64,781	—	+78,840

Note:
[a] Bus specifications are sourced from Hong Kong Encyclopedia (https://hongkongbuses.fandom.com/wiki/Hong_Kong_Buses_Wiki). For EB, we select the B12D model from the BYD company as an example (https://cv.byd.com/cv/carShow.html-param=B12D). For the HB, we select the WSD6121BR3FCEV model from the Weisheit company as an example (https://hongkongbuses.fandom.com/wiki/Weisheit_WSD6121BR3FCEV). Technical standards can be found in the above sources, and cost-related data can be found in the documents provided by the Hong Kong Transport Department (https://www.td.gov.hk/en/transport_in_hong_kong/public_transport/buses/index.html).
[b] The solar bus cost includes bus purchase and solar panel installation costs. Monocrystalline silicon solar panels typically have an energy capacity of 200 Wp/m^2 (p is the peak power rate), and the installation cost (including materials) is approximately 20 HKD/Wp in Hong Kong, China. Hence, the solar panel installation cost for one bus is 200 Wp/m^2 × 16 m^2 × 20 HKD/Wp = 64,000 HKD.
[c] Solar panels on SDBs can save (5 kWh)/(3.1 kWh/L) = 1.6 L diesel, and those on SHBs can save (5 kWh)/(15 kWh/kg) = 0.33 kg hydrogen.
[d] Assume one passenger loss per trip, with 10 HKD fare, and that each bus serves 12 daily trips.
[e] EBs and SEBs cannot fulfill the daily bus mileage of Hong Kong, China (i.e., 300 km). We estimate the fleet size as follows: daily mileage/driving range × base fleet size. Hence, the fleet size benefit of SEBs is as follows: (300 km/220 km × 6000 buses) – (300 km/223 km × 6000 buses) = 166 buses.
[f] In Hong Kong, China, diesel costs 25 HKD/L, electricity costs 1.5 HKD/kWh, and hydrogen costs 108 HKD/kg.

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