An energy paradigm transition framework from negative towards positive district energy sharing networks

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An energy paradigm transition framework from negative towards positive district energy sharing networks—Battery cycling aging, advanced battery management strategies, flexible vehicles-to-buildings interactions, uncertainty and sensitivity analysis

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HIGHLIGHTS

- Solar-wind energy paradigm transition from negative to positive district community.
- Distributed renewable sharing for renewable penetration and grid independence.
- Qualitative battery replacement times for various static and vehicle batteries.
- Flexible management strategy with battery cycling aging in various energy paradigms.
- Techno-economic incentives for promoting building and vehicle owners' participation.

GRAPHICAL ABSTRACT

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ABSTRACT

In response to the clean power production with large-scale deployment of renewable systems, technical challenges are proposed, including the resilient and smart building system design, cycling aging of battery storages, energy congestion between renewable and flexible grid energy, the flexible micro-grids to energy supply fluctuations in multi-energy systems, and so on. In this study, a series of technical solutions, including the integration of plug-in vehicles (under multi-directional energy interaction paradigms), the Vehicles-to-Buildings interaction levels, and the grid-responsive control, were proposed, studied, and discussed to promote the resilient and smart energy systems from district levels in subtropical regions. Dynamic battery cycling aging and advanced modelling tool in this study outperforms traditional rough battery cycling aging approaches, and correct conclusions on battery and vehicle-to-building interaction, to avoid the battery performance overestimation. Novel energy management strategies advance traditional power flow strategy, in terms of the off-peak grid electricity shifting, the enhancement of renewable penetration, and the deceleration of battery cycling aging. Techno-economic performances have been investigated, including net present value (NPV), the discounted payback

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time (DPT), and the net direct energy consumption (DEC). Furthermore, the energy paradigm transition from negative to positive building-vehicle systems outperforms single case study in academia for carbon-neutral transition. The research results showed that, with the energy paradigm transition from the negative to the positive system, the net present value increases from -7.182×10^7 to 5.164×10^8 HK\$, and the average annual net DEC decreased from 249.1 to -343.3 kWh/m².a. Furthermore, compared to Control Strategy 2 (grid-responsive control strategy), the proposed Control Strategy 3 (battery-protective control strategy) can improve the net present value, and the increasing magnitude is dependent on the specific energy paradigm. Furthermore, compared to the positive buildings-vehicle system, the impact of the vehicle-to-building interaction on the decreasing magnitude of the net present value is more prominent for the negative system. The uncertainty and sensitivity analyses indicate that the net present value of the positive energy paradigm as compared to the negative energy paradigm is more sensitive to the battery cost. This study demonstrates the techno-economic performance of district building-vehicle systems with the energy paradigm transition from the negative to the positive, together with a series of effective solutions. The research results can provide multi-dimensional effective approaches for district energy sharing systems in subtropical regions.

Nomenclature		BIPVs	building-integrated photovoltaics
<i>Symbols</i>		B2V	building-to-vehicle
C	cost [HK\$]	B2G	building-to-grid
L	load [kW]	DPT	discounted payback time
P	power [kW]	EV	electric vehicle
<i>Subscripts</i>		FSOC	fractional state of charge
exp	export	G2B	grid-to-battery
imp	import	G2B'	grid-to-battery charging
off-peak	off-peak period	G2V	grid-to-vehicle
peak	peak period	NPV	net present value
RE	renewable energy	RC	relative capacity
<i>Acronyms</i>		SB	static battery
AHU	air-handling unit	V2X	vehicle-to-grid/building/home

1. Introduction

1.1. Background

For clean power production, forecasting on carbon emission [12] and mitigation on global warming [3], the deployment of renewable energy systems [4] of various scales in different forms is an effective approach for responding to the energy shortage crisis and increased energy consumption [56]. Instead of only relying on oil [7] and natural gas [7–9], renewable systems are full of promising prospects and can be classified into distributed [10] and centralised renewable systems [11], depending on energy forms. Compared to the centralised renewable systems, the distributed renewable systems have attracted more interest [12], mainly because of their flexible integration with buildings (such as building-integrated photovoltaics) [13,14], the avoidance of energy transmission losses [15], and limited special space for centralised renewable system installation in highly densified metropolises [16]. Depending on the relative difference between the energy demands and the renewable generation [17], district energy systems can be classified as negative, nearly zero, and positive systems for the integration of distributed renewable systems in district energy systems. In order to realise resilient district energy systems with efficient renewable utilisation and reliability of the fluctuation of power supply, the energy paradigm transition from negative to positive requires energy-efficient storage, energy sharing between buildings, and advanced energy management and control strategies.

As promising movable energy storage systems with considerable travelling demands, electric vehicles can provide flexibility to buildings and micro-grids through smart charging/discharging. Through the vehicle-to-building (V2B) integration, the load levelling of building demand profiles

can be realized owing to peak shaving and valley filling [18,19]. Moreover, vehicle-to-grid (V2G) integration can improve the stability of grid power supply [20], fast grid response [21] and frequency regulation [22]. However, the conventional refuelling strategy of electric vehicles through grid-connected vehicle charging piles will impose challenges on micro-grids, such as peak power pressure, grid capacity expansion, and power fluctuation. Smart energy exchange strategies between district buildings and mobile vehicles [23] are effective approaches, in terms of the improvement in renewable penetration, independence of the electric grid, robustness and reliability for power supply, and the stability of micro-grids. However, the cycling aging of vehicle batteries needs to be considered, managed, and well-addressed to improve the performance of the district interactive building-vehicle systems. This can be done through their synergistic functions, flexible energy interaction modes, smart charging for battery protection, and flexible renewable integrations.

1.2. Literature review

With the advanced technology of battery storages, the battery systems have been widely deployed in the renewable supported multi-energy systems [24]. The main functions of battery storages include the mitigation on renewable intermittence [25,26], load leveling through peak shaving and valley filling [27,28], power stability of micro-grid [29,30], economic savings with energy shifting [31,32], together with battery optimisation [33,34] and grid-responsive energy flexibility [35]. Phan et al. [32] optimized the battery storage capacity for the operating cost savings of a grid-connected building energy system. The daily operating cost was reduced by 31% through the generic algorithm, and by 28% through the particle swarm optimisation [32]. An et al. [33] optimised battery storage for wind penetration improvement. Results showed that, the large battery storage can contribute to low monetary cost with high-

level wind penetration [33]. From the perspective of power grid, Zhou and Cao [35] designed static and mobile electric batteries to improve the energy flexibility and grid independence of an office building.

The integration of electric vehicles with district buildings can extend the energy sharing boundary from single building to neighborhoods, through the mobility of vehicles as energy carriers [36] and synergistic energy patterns between buildings and vehicles [37]. In respect to various fuel-based vehicles and different types of buildings, Zhou et al. [18] provided a comprehensive review for energy interactions. Barone et al. [38] quantitatively studied the energy interactions of a building-vehicle-building system, incorporating multi-diversified energy interaction modes, such as buildings-to-vehicles (B2V), vehicles-to-buildings (V2B), and buildings-to-grid (B2G). Results showed that electricity imported from grid was reduced between 45% and 77%. It is noteworthy that, smart battery charging can extend the battery lifetime with the improved battery state of health [39]. Furthermore, vehicles, with mobility and battery storage, are full of potential for home-plug EV charging with renewable energy [40]. Furthermore, Buonomano [41] studied the parametric analysis on a Building-Vehicle-Building system for the decision making. To improve the economic benefits, under the average local price, the capital battery cost should be lower than 150 €/kWh. Heredia et al. [42] adopted an adaptive charging network algorithm for the smart charging on an electric vehicle-to-building integration system. Results showed that, the proposed smart charging strategy can reduce the operation cost and the peak charging load by 37% and 29%, respectively. Huang et al. [43] studied the impact of heat pump, thermal storage and electric vehicle on the renewable sharing. The case study indicates that, through the integrated strategies, the 77% district-level PV electricity self-consumption share rate can be realized.

Depending on the integrated capacity of distributed renewable systems, district energy systems can be classified into the negative, the nearly zero and the positive energy systems, in accordance with the relative difference between demands and renewable generations [44,45]. With the expansion of integrated distributed renewable systems and the energy paradigm transition from the negative to the positive, advanced energy control strategies and flexible V2B integration modes are worthy to be well investigated, considering the dynamic cycling aging of diversified batteries. Moreover, regarding the grid-connected district energy system, the impacts of the smart battery charging and time-of-use grid electricity exploitation on the operational cost savings need to be quantitatively studied. Last but not the least, from the life-cycle perspective, the life-cycle based techno-economic feasibility needs to be analysed,

systematically and comprehensively considering the replacement cost of retired batteries and cost savings from time-of-use grid electricity.

Strategies for district energy systems mainly include demand-side management and grid-responsive controls, as listed in Table 1. Effective solutions for multi-criteria improvement include the demand response, smart battery charging/discharging, grid-responsive strategy and battery-protective strategy.

In the academia, depending on the time-duration for techno-economic analysis of interactive district energy sharing networks, studies can be classified into one-year and life-cycle based analysis, as shown in Table 2. In respect to the one-year performance analysis, multi-criteria include interacted energy [38], economic cost [35], equivalent CO₂ emission [40], energy matching performance [50] and energy flexibility [35]. It is noteworthy that, most of the abovementioned studies were focused on the one-year performance study regarding the techno-economic feasibility assessment on single renewable integrated building energy system, whereas the life-cycle based analysis for the relevant district buildings-vehicles system is quite limited. On the other hand, the authors' former study [51] studied the impact of the battery degradation on the life-cycle performances of the positive building-vehicle energy systems, and the results showed that due to the dynamic battery degradation, the net present value can be reduced by up to 24% while the discounted payback time can be increased by up to 1.25 times [51]. However, the former study [51] did not investigate the following problems: (1) the impact of the energy paradigm transition (from the standard building to positive energy building) on the life-cycle performances of the hybrid building-vehicle systems by taking the battery degradation into account; (2) the impact of the energy paradigm transition (from the standard building to positive energy building) on the life-cycle effects of the battery protective control strategies and different V2B interactions; (3) the impact of the energy paradigm transition and integrated renewable energy types on the techno-economic performances. The abovementioned missing problems will be correspondingly investigated in the current study.

1.3. Scientific gaps and contribution of this paper

From above-mentioned literature review, scientific gaps can be identified, as shown below:

- 1) In academia, V2B and vehicle-to-grid interactions are emerging and promising techniques for renewable penetration, grid-independent systems, fast grid response, and frequent regulation, together with

Table 1

Advanced energy management and control strategies for multi-criteria improvement of the interactive district energy sharing network.

Energy management and control strategies	Studies	Systems	Objectives	Methodology	Results
Demand-side management	Mehrjerdi et al. [46]	Renewable, battery and hydrogen vehicles	Energy cost and CO ₂ emission	Interruptible loads	Optimal strategy can decrease the cost by 7%, CO ₂ emission of electric vehicle by 56.24% and the hydrogen vehicle by 12.5%
	Cheng et al. [47]	A sharing economy of residential community and a plug-in electric vehicle	Electricity cost saving and reduction on peak-to-average ratio	Demand-side management (DSM)	The proposed DSM system and proper rearrangement of electric vehicles' behaviour are economically beneficial.
	Ioakimidis et al. [48]	University building with plug-in electric vehicles	Peak power shaving	Peak shaving and valley filling of the building power demand through the vehicle charging/discharging	Peak power can be decreased between 3% and 20%.
	Khemakhem et al. [49]	Residential building with vehicle	Flattened load profile of the residential power	Charging/discharging strategy on plug-in electric vehicle	Local and a global control can decrease the demand fluctuation.
Grid-responsive controls	Zhou and Cao [35]	Office with vehicles	Import cost saving through off-peak grid electricity shifting	Grid charging strategy	Off-peak grid electricity was shifted to peak period.
	Zhou et al. [39]	Office-vehicles-hotel system	Battery relative capacity, operating cost and emission	Heuristic battery-protective strategy	Relative capacity of batteries can be improved from 0.94 to 0.986.

Table 2

Techno-economic assessment of renewable supported district energy network.

Time-duration for analysis	Research objective	Metrics	Studies	System/scale	Methodology	Results
One-year analysis	Energy sharing	Interacted energy	Barone at al. [38]	An interactive building-vehicle-building system	Case study	Grid electricity consumption was decreased by 77%.
	Economy	Economic cost	Zhou and Cao [35]	High-rise office with vehicles	Case study and parametric analysis	The adoption of the grid-responsive strategy can reduce the import cost from 77.6 to 68.5 HK\$/m ² .a.
	Environmental performance Dimensionless indicators	Equivalent CO ₂ emission	Zhou and Cao [40]	A residential building with an electric vehicle	Parametrical analysis	BIPVs and an 8-kW wind turbine can realise the net-zero energy system.
		Energy matching performance	Keiner et al. [50]	PVs, batteries, heat pumps, and electric vehicles	Case study	The self-consumption ratio will reduce gradually with the increase in simulation period.
		Energy flexibility	Zhou and Cao [35]	High-rise office with vehicles	Case study and parametric analysis	The adoption of grid-responsive strategy can improve the grid electricity shifting.
	Multi-criteria	Energy, economic and environmental performances	Buonomano et al. [52]	buildings with vehicles	Parametrical analysis	The EVs' integration could contribute to a reduction of 51.63% for CO ₂ emissions.
Energy, economic, environmental and energy flexibility		Zhou et al. [53]	High-rise office-vehicles-hotel system	Multi-objective optimisation	Multi-optimal solutions can be provided.	
Life-cycle based analysis	Matching and emission	Life-cycle based load matching and environmental impact	Cusenza et al. [54]	Retired electric vehicle batteries in building applications	Parametrical analysis	A 46-kWh battery can realise the highest load match and environmental sustainability.
	Economy and system payback time	Net present value and discounted payback time	Zhou and Cao [51]	District buildings-vehicles	Case study and parametric analysis	The battery aging cost will reduce the techno-economic feasibility.

reliability and stability improvement on micro-grids for power supply fluctuations. However, the complicated and complex semi-empirical or empirical models are not applicable for the estimation of dynamic battery cycling aging in the centralised energy management system for online battery degradation estimation. A simplified cycling aging model with considerable estimation accuracy is highly necessary for online dynamic aging predictions on hybrid battery storages (both static and mobile batteries) in the district building-vehicle system.

- 2) In response to the energy paradigm transition from negative to positive, there are limited studies on the techno-economic feasibility of different energy control strategies and flexible V2B interactions. Advanced energy control strategies and flexible V2B interactions need to be proposed, discussed, and implemented in the district interactive building-vehicle system, in terms of the techno-economic feasibility in different energy paradigms.
- 3) With respect to district interactive buildings-vehicles systems, the impact of flexible approaches, such as grid charging and V2B interaction, on techno-economic performance with energy paradigm transition from negative to positive systems, has not been quantitatively investigated, with dynamic cycling aging and replacement of retired battery.

The originality of this study can be summarised as follows:

- 1) A district energy-sharing network with different types of high-rise buildings and occupant-centric profile-based vehicles was formulated with multi-diversified energy interaction modes such as B2V/V2B, B2G/G2B, and G2V, together with cycling aging of battery storage systems.
- 2) In terms of lifecycle-based techno-economic analysis, the impact of the energy paradigm transition from negative to positive district energy systems on life-cycle-based performance has been studied.
- 3) The feasibility of combined flexible solutions was studied with respect to different energy paradigms, and the flexible solutions include off-peak electricity shifting, smart grid-to-battery charging, and V2B interaction management.

Compared to research approaches in the academia, this study provides a generic approach on the dialectical analysis of electrochemical

battery storage, especially considering the real-time battery cycling aging and high battery cost. Conclusions in previous studies without or with rough battery cycling aging, will actually lead to overestimation on battery performance. The research methodology in this study can cover this gap and shed lights on conservative and accurate estimation of battery storage systems. Furthermore, instead of only focusing on specific case study (negative, net-zero or positive energy systems), this study provides a comprehensive and holistic overview on energy paradigm transition from negative to net-zero and, then to positive energy systems, highlighting the necessity for carbon-neutral transition with qualitative and quantitative techno-economic viability. Compared to experimental study with high experimental cost, extensive labour cost and rather long-time cost for 20-year lifecycle analysis under different scenarios (i.e., different renewable systems, energy management strategies and diversified vehicles' integration), the advanced simulation modelling and tools can provide possibility with relatively low cost for the lifecycle analysis. The paper structure is: the description on interactive district energy sharing network is shown in Section 2. Research methodology is in Section 3. Results and discussion are given in Section 4. Finally, the conclusion is presented in Section 5.

2. Interactive district energy sharing network with hybrid storages and multi-directional interactions

2.1. Integrated energy system design

The studied buildings included a 30-floor office building and a 30-floor hotel building (a net floor area of 400 m² and a height of 3.2 m for each floor). Cooling systems are designed as listed in Table 3. The HVAC system design is based on the performance-based building energy code [57].

Table 4 lists the basic information of vehicle systems. Battery storage capacities for each electric vehicle (Nissan LEAF lithium-ion battery [59]) and each public shuttle bus (ST Autobus-RD3154K [60]) are 58 and 200 kWh, respectively. The numbers of vehicles are 30 for private cars and 24 for public autonomous mini-buses.

Table 3

Design of AHU cooling and space cooling chillers.

	Buildings	Rated capacity (kW)	Commercial product	Nominal COP	Set point temperature	Type in the TRNSYS	Storages
AHU cooling chiller	High-rise office Building	293	Carrier 30RB302 [55]	2.8	7 °C	Type 655 [58]	AHU/space cooling storage tank 25/15 m ³ , DHW tank (office/hotel) 0.45/4.5 m ³ , and battery 300 kWh
	High-rise hotel Building	93.9	CGAD090 [56]	3.2 ^a			
Space cooling chiller	High-rise office Building	506	Carrier 30RB522 [55]	2.6 ^a	15 °C		
	High-rise hotel Building	293	Carrier 30RB302 [55]	2.8 ^a			

2.2. Hybrid wind-solar renewable systems

Complementary solar wind renewable systems are designed to cover the energy demands. A 3-blade horizontal-axis wind turbine [65] was designed with the rotor diameter, hub height, and rated wind speed at 54 m, 50 m, and 10 m/s. The thickness, conductivity, and emissivity are 0.004 m, 3.6 kJ/(h·m·K), and 0.9, respectively. The reference PV efficiency is 0.1427 under standard testing conditions, that is, the reference radiation was at 1000 W/m², and the reference temperature was at 25 °C. During the 20-year operation, the depreciation rate of renewable generation from building integrated photovoltaics (BIPVs) and wind turbines is 0.5%/year [63] and 1.6%/year [64], respectively.

2.3. The local electric grid information

In this research, the latest bulk tariff was adopted, as shown in Table 5 [66]. The escalation rate of the grid electricity tariff is 1.4% [67].

2.4. District energy demands

Duration curves of the energy demand of the district energy system are shown in Fig. 1. As illustrated in Fig. 1, the peak powers of private cars and public shuttle buses are 41.1 and 146.9 kW. As listed in Table 6, the electricity demands are 145.4 and 135 kWh/m².a for the office and the hotel, respectively.

3. Methodology

Fig. 2 demonstrates the holistic roadmap for the study of energy paradigm transition from the negative to the positive buildings-vehicles system. Four scenarios with different renewable systems have been designed, including the negative buildings-vehicles system (Scenario 1: the BIPVs on the south façade and Scenario 2: BIPVs on four facades), the net-zero buildings-vehicles system (Scenario 3), and the positive buildings-vehicles system (Scenario 4). The previously developed battery cycling aging model [39] was integrated in all scenarios to characterise the real-time battery cycling aging. Subsequently, advanced energy control strategies were used for energy management. As a critical parameter in the interactive building-vehicle system, the impact of V2B

Table 4

Information of the battery-based electric vehicles.

Vehicle groups	Battery capacity (kWh)	Daily travelling distance (km/day)	Electricity consumption (kWh/km)
Mini-bus in each group	200 [62]	31.2	1.2 [60]
Private car Group 1	58 [61]	45.5	0.15 [59]
Private car Group 2		35.5	
Private car Group 3		25.5	

Table 5

Specific import costs of the office building in Hong Kong [66].

E _{imp} (each month, kWh)	C _{grid,imp1} ^a (HK \$/kWh)		P _{peak,max} (each month, kVA)	C _{grid,imp2} ^b (HK \$/kVA)		Fuel surcharge cost, C _{grid,imp3} ^c (HK \$/kWh)
	Off-peak period ^d	Peak period ^e		Off-peak period ^d	Peak period ^e	
<200,000	0.649	0.726	≤650 kVA	0	68.4	0.278
>200,000		0.71	>650 kVA	26.8	65.4	

^a “C_{grid,imp1}” is the energy charge price.^b “C_{grid,imp2}” is the demand charge price.^c “C_{grid,imp3}” is the fuel cost.^d “Off-peak Period” is the daily period between 21:00 h and 09:00 h for working days, and all days for both Sundays and Public Holidays.^e Peak Period” comprises other days. **Fig. 1.** Duration curves of the electric vehicle fleets.**Table 6**

Building energy loads and peak powers.

Building types	High-rise office building Energy (kWh/m ² .a)/Peak power (kW)	High-rise hotel building Energy (kWh/m ² .a)/Peak power (kW)
Space cooling load	67/599.6	68/301.6
AHU cooling load	39/358.6	38.8/95.6
Total heating load	4.1/34.7	40.9/134.5
Basic electricity demand	101.2/271	68.2/237.8
Electricity demand	145.4/428.8	135/408.6

(Note: Electricity demand includes the basic electricity demand and electricity consumption of HVAC systems).

interactions on the multi-criteria performances has been quantitatively studied. Finally, considering the dynamic fluctuation of each component in the commercial market, uncertainty and sensitivity analyses on each scenario have been conducted, to guide the system design and operation.

Fig. 2. A holistic roadmap for the study on energy paradigm transition from the negative towards the positive buildings-vehicles system.

The research tool of this study is based on the TRNSYS simulation environment. All the building energy and vehicle systems with respect to the four scenarios are established and investigated in the TRNSYS 18 simulation environment.

3.1. Systematic configuration and assumptions

There are various energy interfaces, as depicted in Fig. 3(a), including the Vehicles-Grid interface, the Building-Vehicles interface, and so on. Both cooling/heating and electrical energy storage, as shown in Fig. 3(b), are designed to cover the thermal and electrical demands. The energy paradigm transition from negative to positive systems was studied with distributed BIPVs and nearby wind turbine systems of different capacities, as depicted in Fig. 3(c). Scenario 1 indicates the BIPVs that are solely on the south façade; Scenario 2 indicates the BIPVs on four façades; Scenario 3 indicates the net-zero energy system with the BIPVs on full walls and a 0.72-MW wind turbine; Scenario 4 indicates the positive buildings-vehicles system with the BIPVs on full walls, nearby PVs (with the same rated capacity as BIPVs), and a total wind turbine capacity of 1.44 MW (two 0.72-MW wind turbines). It should be noted that Scenario 4 is for the illustrative purposes of extreme cases where the renewable energy capacities are twice to those in Scenario 3.

Some assumptions are made to model the district energy sharing network: 1) deterministic profiles are applied in building occupants' behaviours (as predefined in Performance based building energy code [57]) and vehicle driving behaviours; 2) to dynamically balance the renewable surplus energy and the building demand shortage, the power grid is assumed as a 'virtual' storage system, in which there are no constraints on dynamic grid import and export powers; 3) constant daily

transportation energy demands for each vehicle group are assumed, without considering the deviation and difference on daily transportation demand.

3.2. Energy management systems with energy control strategies

Fig. 4 shows the systematic diagram of Control Strategy 1, in which the surplus energy is to charge the static battery, and then to the vehicle's battery before exporting to the grid. In contrast, the energy demands are covered by static battery, and then by vehicle battery, before importing from the grid. The vehicle-building interaction level ($V2B_{interaction}$) is calculated by Equation (1).

$$V2B_{interaction} = 1 - \frac{FSOC_{V2B} - FSOC_{EV,lower}}{FSOC_{EV,upper} - FSOC_{EV,lower}} \quad (1)$$

where $FSOC_{EV,lower}$, $FSOC_{EV,upper}$ and $FSOC_{V2B}$ are lower limitation, upper limitation of FSOC for transportation, and lower limitation of FSOC for V2Bs interaction, respectively.

Fig. 5 shows the multi-directional energy interaction paradigms. The grid-responsive control strategy (Control Strategy 2) and battery-protective control strategy (Control Strategy 3) are formulated. Advantages for these strategies include: 1) the grid electricity can be shifted to peak period with considerable economic viability by implementing the Control Strategy 2; 2) the off-peak renewable energy can be shifted to the peak period through hybrid electrical storage systems with cost-saving potentials, together with the mitigated pressure on the electric grid.

Fig. 6 shows the energy flow with respect to Control Strategy 1, 2 and 3. The Control Strategy 1 does not follow peak and off-peak grid-responsive control. As shown in Fig. 6(a), during the renewable shortage

Fig. 3. Systematic diagram of the neighbourhood-based energy system: (a) system interfaces; (b) hybrid electrical and thermal storages; (c) the energy paradigm transition from negative to positive systems. (Note: Scenario 1 indicates the BIPVs on the south façade; Scenario 2 indicates the BIPVs on four façades; Scenario 3 indicates the net-zero building-vehicle system with BIPVs on full walls and a 0.72-MW wind turbine; Scenario 4 indicates the positive buildings-vehicles system with BIPVs on full walls, nearby PVs (with the same rated capacity as BIPVs), and total wind turbine capacity of 1.44 MW.)

period, the building energy demand is met by the electricity discharged from batteries. As depicted in Fig. 6(b), unlike the off-peak grid charging occurs during the entire off-peak period in Control Strategy 2, the off-peak grid charging occurs only in the ‘slow degradation zone’ in Control Strategy 3. As defined in our previous study [39], the ‘slow degradation zone’ is the region when the relative capacity is higher than 0.96, in which the cycling aging rate is much slower than that in the ‘acceleration zone’.

3.3. Assessment criteria

In this section, the life-cycle based cost performances have been studied, including the discounted payback time (DPT) and relative net present value (NPV_{rel}).

The import cost, C_{imp} , and the import cost saving of Case X, $C_{imp,sav-Case X}$, are calculated by Equations (2) and (3). The escalation rate of grid electricity is 1.4% [67].

$$C_{imp} = \int_{t_i}^{t_e} P_{imp,office}(t) \cdot C_{eg,imp}(t) dt + \int_{t_i}^{t_e} P_{imp,hotel}(t) \cdot C_{eg,imp}(t) dt + \int_{t_i}^{t_e} P_{imp,vehicles}(t) \cdot C_{eg,imp}(t) dt \quad (2)$$

Fig. 4. The Control Strategy 1: renewable-demand control.

Fig. 5. The Control strategy 2 and 3 [39]. (Note: Unlike the off-peak grid charging occurs during the entire off-peak period in Control Strategy 2, the off-peak grid charging occurs only in the ‘slow degradation zone’ in Control Strategy 3.)

$$C_{imp,sav-CaseX} = C_{imp,Case0} - C_{imp,CaseX} \quad (3)$$

where $P_{imp,office}(t)$, $P_{imp,hotel}(t)$ and $P_{imp,vehicles}(t)$ are the instantaneous imported power (kW). $C_{eg,imp}(t)dt$ is the instantaneous import electric price from the electric grid (HK\$/kWh). $C_{imp,Case0}$ is the import cost of the reference case (no renewable systems). $C_{imp,CaseX}$ is the import cost of the investigated case X.

The discounted payback time (n) is calculated through Equation (4).

$$IC_{RE} + \sum_{j=1}^4 IC_{battery,j} + \sum_{i=1}^n \sum_{j=1}^4 \frac{C_{battery,j,i}}{(1+r)^i} \leq \sum_{i=1}^n \frac{(C_{imp,sav-CaseX,i} + C_{RE,CaseX,i})(1+\eta)^i}{(1+r)^i} \quad (4)$$

where IC , j , and $C_{battery,j,i}$ refer to the initial cost, j^{th} battery group, and battery replacement cost in year i , respectively. The battery in electric vehicles is replaced when the state of health is below 0.8 [68]. The battery cost is assumed to be 3045 HK\$/kWh; r and η refer to the interest rate and escalation rate, respectively. $C_{RE,CaseX,i}$ is the renewable generation income for case X in year i , with grid feed-in income at a value of 3–5 times the import cost [69].

The relative net present value (NPV_{rel}) is calculated by Equation (5) with respect to the reference system without renewable system, static battery and electrical vehicles.

$$NPV_{rel} = \sum_{t=1}^{20} \frac{(C_{RE} + C_{imp,sav,t})(1+\eta)^t - (C_{O\&M,t} + C_{repl,t} + \sum_{j=1}^4 C_{battery,j,t})}{(1+r)^t} + \sum_{t=1}^{20} \frac{C_{subsidy,t}}{(1+r)^t} - (IC_{RE} + \sum_{j=1}^4 IC_{battery,j,t}) \quad (5)$$

where $C_{O\&M,n}$ is the operation and maintenance cost, and $C_{repl,n}$ is the replacement cost of certain devices. $C_{battery,j,t}$ is the battery replacement cost, HK\$. C_{RE} and $C_{imp,sav,t}$ are economic income of renewable systems under the grid feed-in tariff and the import saving, HK\$. IC_{RE} and $IC_{battery,j,t}$ are initial cost of renewable systems and battery systems, HK\$. $C_{subsidy,t}$ is the received subsidy for the invested system. The variable “ r ” is the interest rate between 0% and 10%.

The net direct energy consumption (DEC) as calculated by Equation (6) is adopted as the technical assessment criteria.

$$E_{net} = \int_{t_i}^{t_e} [P_{imp}(t) - P_{exp}(t)]dt/A \quad (6)$$

where $P_{imp}(t)$ and $P_{exp}(t)$ refer to the instantaneous imported power from the grid and exported power to the grid, respectively. “ t_i ” and “ t_{end} ” refer to the beginning and the ending of the simulation time, respectively. It should be noted that, in the follow-up text, the unit “kWh/m²” is used to indicate the overall energy consumption in 20 years per unit floor area.

4. Results and discussions

4.1. Battery replacement times in respect to energy management strategies and vehicle-to-building interaction levels

4.1.1. Battery replacement times in respect to different energy management strategies

By implementing the battery cycling aging model in the district

Fig. 6. The energy flow chart of the Control Strategy 1, 2 and 3 [39]: (a) energy flow charts; (b) charging constraints and charging power. (Note: $RC_{battery}$ is the abbreviation of the relative capacity of battery systems. The red dashed rectangle refers to the energy flow of Control Strategy 1 [35].) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. The battery replacement times for the transition from negative to positive system with different energy control strategies: (a) Static battery in Office; (b) Static battery in Hotel; (c) Private Car Battery; (d) Shuttle Bus Battery.

energy sharing network, the replacement times of battery systems have been investigated. Comparative analysis among the proposed energy management strategies (Control Strategies 1, 2, and 3) was conducted to demonstrate the technical effectiveness. Furthermore, the transition from a negative to a positive building-vehicle system has been studied to demonstrate the techno-economic effectiveness of proposed strategies with different renewable capacities.

The impact of energy paradigm transition and different energy management strategies on battery replacement times (BRT) is shown in Fig. 7 with respect to different renewable-supported building-vehicle systems. With respect to the negative buildings-vehicle system (with

vertical BIPVs on the south wall, Scenario 1) with Control Strategy 1, there is no need to replace the static battery, as shown in Fig. 7(a) and (b), during the 20-year operation. Furthermore, in Scenario 1, the Vehicles-to-Buildings interaction (Control Strategy 1 with $V2B_{interaction}$ at 100%) increases the BRT of private cars (from 2 to 7, as shown in Fig. 7(c)) and shuttle buses (from 3 to 5, as shown in Fig. 7(d)). Compared to private cars, the increasing magnitude of the BRT of shuttle buses is less prominent. This is mainly because of the parking of the shuttle buses in office during the night, when the demand of the office building is quite low owing to the low indoor occupancy. It is noteworthy that, with the energy paradigm transition from negative (Scenario 1) to the positive buildings-vehicle system (Scenario 4), the impact of the Control Strategy 2 and 3 on the BRT is quite different. For instance, compared to Control Strategy 1 (with $V2B_{interaction}$ at 100%), Control Strategy 2 and 3 can reduce the BRT of private cars, as shown in Fig. 7(c), for the negative system from 7 to 6 and from 7 to 5 (Scenario 1), and Control Strategies 2 and 3 keep the BRT of private cars constant for net-zero and positive energy systems, whereas the impact of Control Strategies 2 and 3 on shuttle buses is case-dependent. The main reason is that, during the off-peak period, the shuttle buses are parked in offices with relatively low indoor occupancy and low building demand, whereas private cars are parked in hotels with high building demand. With respect to the private cars, Control Strategies 2 and 3 can compensate for the battery degradation with a decrease in the depth of discharge (DoD) through grid charging. In the negative district energy sharing network, compared to the Control Strategy 1 with $V2B_{interaction}$ at 100%, the Control Strategy 2 increases the BRT of shuttle buses from 5 to 6 in Fig. 7(d). However, in the positive district energy sharing network, compared to the Control Strategy 1 with $V2B_{interaction}$ at 100%, the Control Strategy 2 decreases the BRT of shuttle buses from 5 to 4 in Fig. 7(d). The reason is that, in the negative district energy sharing network, the shuttle bus battery mainly shifts the grid electricity to peak period through grid charging (the battery relative capacity will be decreased much faster due to the increased charging load) because of the relatively low energy charged by renewables. However, in the positive district energy sharing network, the shuttle bus battery mainly stores the surplus energy, and grid charging can reduce the DoD or decelerate the battery depreciation rate with relatively low grid-to-battery charging electricity. For instance, according to the simulation results, the total grid charging electricity in Control Strategy 2 is 46.8, 42.4 (mainly for the shifting of the grid electricity to peak period), 20.6 and 7.4 kWh/m² (mainly for the decrease of the DoD or decelerating battery depreciation rate) for Scenarios 1, 2, 3, and 4, respectively. Moreover, in the Control Strategy 2, the total electricity discharged from batteries are 1222.7, 1215.8, 914.4 and 726.3 kWh/m² for the vertical BIPVs for Scenarios 1, 2, 3 and 4, respectively.

With the transition of the energy paradigm from the negative to the net-zero energy system, a general increasing tendency on BRT can be noticed for each static battery in Control Strategy 1 (without $V2B_{interaction}$). This is due to the increase in on-site renewable generation, resulting in an increase in the charging and discharging times of battery systems. However, the further transition from the net-zero to the positive energy system decreases the BRT for each static battery. This is because of the improvement on DoD in the negative energy system, leading to the deceleration of battery depreciation rate. Contrary to the negative buildings-vehicle systems, the Control Strategy 2 can reduce the BRT of the shuttle bus in the net-zero and positive building-vehicle system. For instance, compared to Control Strategy 1 with a $V2B_{interaction}$ of 100%, the adoption of Control Strategy 2 reduces the BRT of the shuttle bus from 6 to 5 in the Net-Zero energy system (as shown in Fig. 7(c)) and from 5 to 4 in the positive energy system (as shown in Fig. 7(d)). This indicates that the Control Strategy 2 can effectively protect the shuttle bus battery through the flexible management of the DoD in the net-zero and positive building-vehicle systems.

Fig. 8. The BRT for the transition from negative to positive system with different $V2B_{interaction}$: (a) Static battery in Office; (b) Static battery in Hotel; (c) Private Car Battery; (d) Shuttle Bus Battery. (Note: $V2B_{interaction}$ refers to the proportion of energy discharged from batteries to buildings to the available energy in batteries (excluding the energy for transportation purpose). The vehicle-building interaction level at 0% indicates that vehicles cannot be discharged to cover the building energy demand.)

4.1.2. Battery replacement times in respect to Vehicle-to-Building interaction levels

In this section, the impact of the Vehicles-to-Buildings (V2B) interactions on the techno-economic performances of the building-vehicle system has been investigated. Furthermore, the Control Strategy 3 was adopted in this section.

In the energy paradigm with diversified battery storages, Fig. 8 shows the impact of the $V2B_{interaction}$ on the BRT. As shown in Fig. 8, the increase in the $V2B_{interaction}$ increases the BRT of vehicles, whereas the impact of the $V2B_{interaction}$ on the replacement times of static batteries is dependent on the integrated renewable capacity. For instance, in the negative energy system (Scenario 1), with the increase of the $V2B_{interaction}$ from 0% to 100%, the BRT increases from 2 to 5 for private cars (as shown in Fig. 8(c)), and from 3 to 5 for the public shuttle buses (as shown in Fig. 8(d)). In contrast, the increase of the $V2B_{interaction}$ from 0% to 100% reduces the BRT of the static battery in hotels from 9 to 5 (as shown in Fig. 8(b)). The underlying reason is that the increase in the $V2B_{interaction}$ increases the reliance on the vehicle battery for the demand coverage, leading to decreased reliance on static batteries in hotels for load coverage. With respect to the positive system, the increase in the $V2B_{interaction}$ from 0% to 100% increases the BRT from 1 to 3 for private cars (as shown in Fig. 8(c)) and from 2 to 4 for shuttle buses (as shown in Fig. 8(d)). The BRT of static battery in office is independent on the $V2B_{interaction}$. Furthermore, with respect to the public shuttle buses (as shown in Fig. 8(d)), compared to the critical point of the $V2B_{interaction}$ at 75% for Scenario 1 and 3, and 100% for Scenario 2, the critical point of the $V2B_{interaction}$ is 25% for the positive system (Scenario 4). The reason is that the system demand in the negative buildings-vehicles system is more dependent on the battery discharging, owing to the insufficient renewable generation as compared to the positive system. Therefore, the BRT of public shuttle buses are more sensitive to the $V2B_{interaction}$ only when the vehicle-building interaction level is lower than 25% in the positive buildings-vehicles system (Scenario 4). According to the simulation results, with the increase of the $V2B_{interaction}$ from 0% to 75%, the total electricity discharged from public shuttle batteries increased from 453 to 818 kWh/m² by 80.6%, from 423.3 to 809 kWh/m² by 91.1%, from 351.4 to 650 kWh/m² by 85%, and from 322.1 to 556 kWh/m² kWh/m² by 72.6% for Scenarios 1, 2, 3, and 4, respectively. This indicates that the BRT of public shuttle buses in Scenario 4 are less sensitive than Scenarios 1, 2, and 3.

In summary, in the negative building-vehicle system, the $V2B_{interaction}$ can reduce the battery depreciation rate and the BRT of the static battery in the hotel, whereas the static battery performance is independent of the $V2B_{interaction}$ in the positive energy system. Secondly, compared to the positive building-vehicle system, the BRT of public shuttle buses are more sensitive to the $V2B_{interaction}$ in the negative buildings-vehicles system. Therefore, compared to the positive system, more potentials can be exploited in the negative buildings-vehicles system through the development of a battery-protective control strategy and intelligent management of V2Bs interactions.

4.2. The techno-economic performances for different energy management strategies and V2B interaction levels

Tables 7 and 8 lists the lifecycle-based techno-economic performances, in respect to different energy control strategies and different V2B interaction levels. As shown in Table 7, the Control Strategy 1 shows a bit higher net present value with lower average annual net direct energy consumption than other strategies, while the Control Strategy 2 shows a bit longer discounted payback time. In terms of V2B interaction in Table 8, the increase of V2B interaction level will decrease the net present value, prolong the discounted payback time and increase the average annual net direct energy consumption. The detailed comparison analysis will be conducted in the following-up subsections.

Table 7
Impact of energy control strategy on lifecycle-based techno-economic performances.

Control Strategies	Net present value (HK\$)				Discounted payback time (years)				Average annual net direct energy consumption (kWh/m ² .a)			
	Scenario 1				Scenario 2				Scenario 3			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Control Strategy 1 (without V2B interaction)	-71819835.1	-29531197.4	162220004.3	516418698.5	-	-	4.0	2.0	249.1	199.5	20.7	-343.3
Control Strategy 1 (100% V2B interaction)	-111036672.7	-69467608.7	108375860.9	492670812.6	-	-	7.0	2.0	250.3	202.4	21.3	-335.7
Control Strategy 2 (100% V2B interaction)	-182365371.7	-136848900.3	87466377.7	477505916.4	-	-	7.0	3.0	252.3	205.2	21.5	-334.7
Control Strategy 3 (100% V2B interaction)	-115473825.4	-104768301.6	121992844.3	478915115.0	-	-	6.0	3.0	260.1	211.3	23.0	-334.6

Table 8
Impact of vehicle-to-building interaction levels on lifecycle-based techno-economic performances.

V2B interaction level	Net present value (HK\$)				Discounted payback time (years)				Average annual net direct energy consumption (kWh/m ² .a)			
	Scenario 1				Scenario 2				Scenario 3			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
0%	-87683760.5	-53600777.4	169033343.4	500467429.6	-	-	5.0	3.0	252.7	207.3	17.2	-335.7
25%	-108826441.7	-76706846.4	158776786.5	497444006.9	-	-	6.0	2.0	254.9	208.0	19.7	-335.0
50%	-105903774.0	-84359655.1	146249244.1	477418942.2	-	-	6.0	2.0	256.7	210.3	22.2	-334.7
75%	-117031009.1	-83287986.7	134050916.4	477481213.1	-	-	6.0	2.0	258.7	210.8	22.8	-334.7
100%	-115473825.4	-104768301.6	121992844.3	478915115.0	-	-	6.0	2.0	260.1	211.3	23.0	-334.6

(Note: the Control Strategy 3 is adopted.)

Fig. 9. Impact of energy paradigm transition and energy control strategy on techno-economic performances of the buildings-vehicles system: (a) NPV; (b) the DPT; (c) the average annual DEC. (Note: the discounted payback time is not presented when it exceeds 20 years).

4.2.1. Impact of energy management strategies on techno-economic performances

Fig. 9 shows the impact of the energy paradigm transition on system performance with different strategies. As shown in Fig. 9(a), the implementation of the V2B interaction reduces the net present value compared to the case without V2B interaction, and the decreasing magnitude is dependent on the type of the energy paradigm. In Scenario 1 (the BIPVs on the south façade only), the 100% V2B interaction in Control Strategy 1 reduces the net present value from -7.182×10^7 to -1.110×10^8 HK\$ by 35.3%. In Scenario 4 (the positive buildings-vehicles system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW), the 100% V2B interaction in Control Strategy 1 reduces the net present value from 5.164×10^8 to 4.927×10^8 HK\$ by 4.8%. In other words, from the life-cycle-based analysis when

considering the dynamic cycling aging of batteries, the V2B interaction is not economically feasible because of the considerable costs for battery replacement, and the negative economic effect is more prominent for the negative system than for the positive system. With respect to all scenarios, compared to Control Strategy 1 (100% V2B interaction), Control Strategy 2 decreases the NPV, that is, the NPV decreases from -1.110×10^8 to -1.824×10^8 HK\$ in Scenario 1, from -6.947×10^7 to -1.368×10^8 HK\$ in Scenario 2, from 1.084×10^8 to 8.747×10^7 HK\$ in Scenario 3, and from 4.927×10^8 to 4.775×10^8 HK\$ in Scenario 4. The underlying reason is the increase in the battery replacement cost from 1.067×10^8 to 1.773×10^8 HK\$ in Scenario 1, from 1.124×10^8 to 1.731×10^8 HK\$ in Scenario 2, and a decrease in the economic benefit ($C_{RE} + C_{cost,saving}$) from 3.110×10^8 to 2.881×10^8 HK\$ in Scenario 3, and from 6.876×10^8 to 6.543×10^8 HK\$ in Scenario 4. It can also be

noticed that, by adopting the Control Strategy 3, compared to the Control Strategy 2, the net present value can be improved from -1.824×10^8 to -1.155×10^8 HK\$ by 36.7% in the Scenario 1 (the BIPVs on the south façade only), from -1.368×10^8 to -1.048×10^8 HK\$ by 23.4% in the Scenario 2 (the BIPVs on four façades), from 8.747×10^7 to 1.220×10^8 HK\$ by 39.5% in the Scenario 3 (the net-zero energy system with BIPVs on full walls and a 0.72-MW wind turbine), and from 4.775×10^8 to 4.789×10^8 HK\$ by 0.3% in the Scenario 4 (the positive buildings-vehicles system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW).

Furthermore, as shown in Fig. 9(a), Control Strategy 1 is superior to Control Strategy 3, with higher NPV. The underlying mechanism is that, in the Scenario 1, compared to the Control Strategy 1, the Control Strategy 3 shows the higher battery replacement cost with lower economic benefit. For instance, in Scenario 1, Control Strategy 1 (100% V2B interaction) shows the battery replacement cost at 1.067×10^8 HK\$, and the economic benefit ($C_{RE} + C_{cost,saving}$) at 3.171×10^7 HK\$. Meanwhile, Control Strategy 3 shows the battery replacement cost at 1.097×10^8 HK\$, and the economic benefit at 3.022×10^7 HK\$. In Scenario 4, compared to Control Strategy 1, Control Strategy 3 shows lower battery replacement cost but a still decreased economic benefit. For instance, in Scenario 4, Control Strategy 1 (100% V2B interaction) shows the battery replacement cost at 1.062×10^8 HK\$, and the economic benefit ($C_{RE} + C_{cost,saving}$) at 6.876×10^8 HK\$. Meanwhile, Control Strategy 3 shows the battery replacement cost at 8.673×10^7 HK\$, and the economic benefit ($C_{RE} + C_{cost,saving}$) at 6.543×10^8 HK\$. This can be explained further by following. In Scenario 1, Control Strategy 1 (100% V2B interaction) shows the BRT of the static battery in offices, hotels, private car batteries, and shuttle bus batteries at 0, 0, 7, and 5, respectively, with a total import cost of 6.616×10^7 HK\$. Meanwhile, in Scenario 1, Control Strategy 3 shows the BRT of the static battery in offices, hotels, private car batteries, and shuttle bus batteries at 11, 5, 5, and 5 with a total import cost of 6.770×10^7 HK\$. As a result, with the above-mentioned significant increase in the BRT and the slight increase in the import cost (as also mentioned in Section 4.1), Control Strategy 3 essentially worsens both the battery lifetime and the economic performance of the system in Scenario 1. On the other hand, in Scenario 4, Control Strategy 1 (100% V2B interaction) shows the BRT of the static battery in offices, hotels, private car batteries, and shuttle bus batteries at 8, 15, 3, and 5, respectively, with an import cost of 9.553×10^6 HK\$. Meanwhile, in Scenario 4, Control Strategy 3 shows the BRT of the static battery in offices, hotels, private car batteries, and shuttle bus batteries at 5, 9, 3, and 4, respectively, with an import cost of 4.382×10^7 HK\$. As a result, with the abovementioned reduction of the BRT but more than four times of the import cost, the Control Strategy 3 essentially protects the battery lifetime in Scenario 4, but the economic performance is still worsened.

It can be concluded that the underlying mechanism for the economic ineffectiveness of the Control Strategy 2 and 3 is the higher import cost compared to Control Strategy 1. According to the simulation results, in Scenario 2, Control Strategy 1 (with V2B interaction), 2 and 3 show import costs of 5.362×10^7 HK\$, 6.053×10^7 HK\$, and 6.104×10^7 HK\$, respectively. In Scenario 4, Control Strategy 1 (with V2B interaction), 2 and 3 show import costs of 9.553×10^6 HK\$, 4.370×10^7 HK\$, and 4.382×10^7 HK\$, respectively. In the future, the decrease in the electricity grid tariff in the positive energy system may make Control Strategy 2 and 3 more economically competitive than Control Strategy 1, when the low battery replacement cost in Control Strategy 2 and 3 can become the dominant factor of the NPV and become more significant than the inefficient import cost. Furthermore, with the decrease in the off-peak grid electricity tariff or the increase in price difference between peak and off-peak grid electricity, the import cost of Control Strategy 2 and 3 might become much lower than that of Control Strategy 1 because of the off-peak grid electricity shifting mechanism [35,39]. According to the research results, because of the enhancement in off-peak grid electricity shifting and the battery protection effects in Control Strategy 3,

the decrease in the off-peak grid electricity tariff from 0.9 to 0.1 HK\$/kWh will reduce the import cost from 3.97×10^7 to 2.78×10^7 HK\$. Meanwhile, a decrease in the off-peak grid electricity tariff from 0.9 to 0.1 HK\$/kWh will reduce the import cost from 8.68×10^6 to 6.08×10^6 HK\$ in Control Strategy 1. Therefore, the life-cycle-based economic potentials of Control Strategy 2 and 3 might become more prominent than that of Control Strategy 1, as the decrease in the off-peak electricity will improve the economic benefit ($C_{RE} + C_{cost,saving}$) owing to the enhanced economic saving potential through off-peak grid electricity shifting.

In terms of the discounted payback time, as shown in Fig. 9(b), the system cannot be economically recovered, owing to the relatively low renewable generation of Scenario 1. Moreover, as the discounted payback time of Scenario 2 exceeds 20 years (higher than the life-time of analysis), it is not presented for the conservative estimation. With the implementation of Control Strategy 3 compared to Control Strategy 2, the DPT can be reduced from 7 to 6 years in Scenario 3 (BIPVs on four façades with a 0.72-MW wind turbine). Therefore, the enhancement of wind turbine capacity in the complementary solar wind energy system is an effective approach for recovering the economic investment. For instance, without the V2B interaction, the DPT can be reduced from 4 (in net-zero energy system with BIPVs on four façades and a 0.72-MW wind turbine, Scenario 3) to 2 years (in a positive buildings-vehicles system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW, Scenario 4). In addition, the relatively short DPT in Scenarios 3 and 4 is mainly the result of the new competitive feed-in tariff in Hong Kong [69] (three times that of the import tariff, and applying to the total generation rather than the exported amount) as well as the significant proportion of MW-scale wind turbine output among the total generation, which significantly favours the cases with large-scale wind turbine capacities.

For the average annual DEC, as shown in Fig. 9(c), the transition of the energy paradigm from negative to positive will significantly reduce the average annual DEC. In the building-vehicle system without the V2B interaction, the transition from Scenario 1 (the BIPVs on the south façade only) to Scenario 4 (the positive buildings-vehicles system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW) will reduce the average annual DEC from 249.1 to -343.3 kWh/m².a. The reason is the increase in renewable generation from 395.6 to 12911.6 kWh/m² for 20 years. Furthermore, the implementation of Control Strategy 2 and Control Strategy 3 will slightly increase the average annual DEC in all scenarios. For instance, in Scenario 1 (the BIPVs on the south façade only), compared to Control Strategy 1 (with 100% V2B interaction) with the average annual DEC at 250.3 kWh/m².a, Control Strategy 2 and Control Strategy 3 will increase the average DEC to 252.3 kWh/m².a and 260.1 kWh/m².a, respectively. The main reason is that the battery charging loss increased from 86.7 to 120 kWh/m² in Control Strategy 2, and to 285 kWh/m² in Control Strategy 3 during the 20-year operation.

4.2.2. Impact of energy paradigm transitions and V2B interaction levels on techno-economic performances

This section is to quantify the impact of energy paradigm transitions and V2B_{interaction} on techno-economic performances. Based on the above-mentioned discussion results, Control Strategy 3 can enhance the lifetime and reduce the replacement times of the batteries in the net-zero and positive-energy systems. Correspondingly, to specifically study the impact of the V2B_{interaction}, the Control Strategy 3 is adopted in this section to better protect the batteries, especially for the net-zero and positive-energy systems when the V2B interactions are enhanced.

Fig. 10 shows the impact of the V2B_{interaction} on the performances of the system, for different energy paradigms. As shown in Fig. 10(a), an increase in the V2B_{interaction} reduce the net present value, and the decreasing magnitude is dependent on the type of the energy paradigm. In Scenario 1 (the BIPVs on the south façade only), the increase in the V2B_{interaction} from 0% to 75% reduced the net present value from

Fig. 10. The impact of energy paradigm transitions and $V2B_{interaction}$ on techno-economic performances of the system: (a) NPV; (b) the average annual DEC. (Note: Scenario 1 indicates the BIPVs on the south façade; Scenario 2 indicates the BIPVs on four façades; Scenario 3 indicates the net-zero energy system with BIPVs on full walls and a 0.72-MW wind turbine; Scenario 4 indicates the positive buildings-vehicles system with BIPVs on full walls, nearby PVs and total wind turbine capacity of 1.44 MW.)

Fig. 11. Impact of energy paradigm transition and integrated renewable types on the NPV and DPT of the interactive buildings-vehicles system. (Note: Scenario 3' and 4' refer to cases in which the renewable system is BIPVs with the same total annual generation as Scenario 3 and 4, respectively. Scenario 3'' and 4'' refer to cases in which the renewable system is BIPVs with the same rated power as Scenario 3 and 4, respectively. The discounted payback time is not presented when it exceeds 20 years.)

-8.768×10^7 to -1.170×10^8 HK\$, by 33.4%, and then increase the net present value to -1.155×10^8 HK\$ when the $V2B_{interaction}$ is 100%. The former is mainly due to the increase in battery depreciation cost from 7.782×10^7 to 1.116×10^8 HK\$, and the latter is mainly due to the combined effect of the increase in the economic benefits and the comparable battery degradation effect. In Scenario 4 (the positive buildings-vehicles system with 1.44-MW wind turbine), an increase in the $V2B_{interaction}$ from 0% to 75% reduced the net present value from 5.005×10^8 to 4.775×10^8 HK\$ by 4.6%, and then increased the net present value to 4.789×10^8 HK\$. The decrease in the net present value is mainly

because of the increase in the battery depreciation cost from 5.891×10^7 to 8.817×10^7 HK\$, whereas the increase is because of the increase in the economic benefits and the comparable battery degradation effect.

For the average annual DEC, as shown in Fig. 10(b), the increase in the $V2B_{interaction}$ increases the average annual DEC, which depends on the type of the energy paradigm. For instance, in Scenario 1 (the BIPVs on the south façade only), the increase in the $V2B_{interaction}$ from 0% to 100% increases the average annual DEC from 252.7 to 260.1 kWh/m².a. This is mainly because of the increase in the energy loss for battery charging from 140 to 285 kWh/m². In Scenario 4 (the positive building-

vehicle system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW, the increase in the $V2B_{\text{interaction}}$ from 0% to 100% increases the average annual DEC from -335.7 to -334.6 kWh/m².a. This is mainly because of the increase in the energy loss for battery charging from 60 to 72.6 kWh/m².

4.2.3. Discussion of the impact of energy paradigm transition and integrated renewable types on economic performances

To further investigate the impact of integrated renewable types on the economic performances of the interactive building–vehicle system, a case study was conducted with respect to a pure BIPV system (with both the total annual generation and rated power being same), and the hybrid BIPVs and wind turbine system. In order to guarantee the same total annual generation, Scenario 3' and 4' with BIPVs only are designed with the same total annual generation as Scenario 3 and 4, respectively. In order to guarantee the same rated power, Scenario 3'' and 4'' with BIPVs only are designed with the same rated power as Scenario 3 and 4, respectively. The energy management strategy is Control Strategy 3 and the $V2B_{\text{interaction}}$ is 100%, Scenario 4.

As shown in Fig. 11(a), the energy paradigm transition from Scenario 1 (the BIPVs on south façade) to Scenario 2 (BIPVs on four façades) increases the NPV from -1.155×10^8 to -1.048×10^8 HK\$. The underlying reason is the increase in the economic benefits from 3.022×10^7 to 8.509×10^7 HK\$. A sudden increase in NPV to 1.220×10^8 HK\$ can be observed in Scenario 3, together with the DPT at 6 years. The mechanisms include the increase in grid feed-in income, the decrease in import cost, and the relatively lower cost of wind turbines than PVs in terms of per kWh power generation. The further increase of the integrated wind turbine capacity to 1.44 MW in Scenario 4 can further improve the NPV to 4.789×10^8 HK\$.

The comparison among Scenarios 3, 3' and 3'' indicates that the hybrid BIPVs and wind turbines in Scenario 3 show the highest NPV at 1.220×10^8 HK\$ and the lowest DPT at 6 years, whereas Scenario 3'' (the only BIPVs with the same rated power as Scenario 3), shows the lowest NPV at -6.984×10^7 HK\$ and the highest DPT, which exceeds the lifetime of the analysis (20 years). The reason is due to the lower total renewable generation in Scenario 3'' at 2340.3 kWh/m² (refer to the floor area) than that in Scenario 3 at 5373.4 kWh/m² (refer to the floor area). Furthermore, the magnitude differences of NPV among Scenarios 4, 4' and 4'' become more obvious than those among Scenarios 3, 3' and 3''. The hybrid BIPVs and wind turbines in Scenario 4 show the highest NPV at 4.789×10^8 HK\$ and the lowest DPT at 3 years, whereas Scenario 4'' (the only BIPVs with the same rated power as Scenario 4), shows the lowest NPV at 1.551×10^8 HK\$ and the highest DPT at 7 years. The underlying reason is the lower total renewable generation in Scenario 4'' at 7047.6 kWh/m² (refer to the floor area) than that in Scenario 4 at 12911.6 kWh/m² (refer to the floor area). The comparison of the DPTs between the abovementioned scenarios further highlights the significant impact of large-scale wind turbine generation on the reduction of the DPT, as mentioned in Section 4.2.1. With the aid of the competitive new feed-in tariff in Hong Kong [69] (three times to that of the import tariff, and applying to the total generation rather than the exported amount), the DPT for the cases with large-scale wind turbine capacities will be significantly shortened.

Table 9
Uncertainty levels of initial investments.

Uncertainty levels	Initial cost				Benchmark
	−40%	−30%	−20%	−10%	
PV cost (HK\$/kWp)	6190.5	7222.2	8254.0	9285.7	10317.4 [70]
Wind turbine cost (HK\$/kW)	9000	10,500	12,000	13,500	15000.0 [71]
Battery Cost (HK\$/kWh) [73]	1827	2131.5	2436	2740.5	3045.0

4.2.4. Uncertainty and sensitivity analysis

Sensitivity analysis was conducted to demonstrate the economic viability for different energy paradigms. The energy control strategy is the Control Strategy 3, and the $V2B_{\text{interaction}}$ level is 100%. Table 9 lists uncertainty levels of initial investments. The interest rate and escalation rate are from 0% to 10%, with an increasing step at 2%. Cases I, II, III, IV, and V refer to Scenario 1 when BIPVs are only on the south wall. Cases I', II', III', IV', and V' refer to Scenario 4 with BIPVs on full walls, nearby PVs, and a total wind turbine capacity of 1.44 MW.

The uncertainty and sensitivity analysis of the NPV is shown in Fig. 12 with respect to both negative and positive energy paradigms. As shown in Fig. 12(a), the NPV increases with an increase in the interest rate in the negative energy paradigm, whereas the NPV decreases with an increase in the interest rate in the positive energy paradigm. For instance, in Cases V and V', with an increase in the interest rate from 0% to 10%, the NPV increases from -1.294×10^8 to -7.687×10^7 HK\$ in the negative energy paradigm, whereas the NPV decreases from 5.700×10^8 to 2.200×10^8 HK\$ in the positive energy paradigm. The underlying mechanism is that, with an increase in the interest rate from 0% to 10%, the decreasing magnitude of the cost benefits ($C_{\text{BIPVs}} + C_{\text{imp,sav}}$) from 3.022×10^7 to 1.619×10^7 HK\$ is significantly lower in the negative energy paradigm (Case V) than that in the positive energy paradigm (Case V') from 6.543×10^8 to 3.542×10^8 HK\$. As shown in Fig. 12(b), according to the results of Scenario 1 (negative system), the decrease in the battery cost from 3045 to 1827 HK\$/kWh increases the net present value from -1.329×10^8 to -7.230×10^7 HK\$ by 46%. The completely contrary tendency of NPV for the negative and positive energy paradigm can also be noticed on the interest rate, as shown in Fig. 12(b). For instance, when the battery cost is 3045 HK\$/kWh, with an increase in the interest rate from 0% to 10%, the NPV increases from -1.330×10^8 to -7.883×10^7 HK\$ by 41% for the negative system, while the NPV decreases from 5.669×10^8 to 2.186×10^8 HK\$ by 61%. This is attributed to the higher decreasing magnitude of the cost benefits ($C_{\text{BIPVs}} + C_{\text{imp,sav}}$) from 6.543×10^8 to 3.542×10^8 in the positive system as compared to the negative system from 3.022×10^7 to 1.619×10^7 HK\$. The sensitivity analysis of the escalation rate, as shown in Fig. 12(c), shows that, with the increase in the escalation rate, the increasing magnitude of NPV in the positive energy paradigm is more prominent than that in the negative energy paradigm. For instance, with the increase in the escalation rate from 0 to 10%, the NPV increases from -1.222×10^8 to -7.474×10^7 in Case V, and the NPV increases from 3.982×10^8 to 1.408×10^9 in Case V'. The underlying reason is the lower increasing magnitude of cost benefits ($C_{\text{BIPVs}} + C_{\text{imp,sav}}$) in the negative than the positive energy paradigm, that is, 2.655×10^7 to 7.403×10^7 HK\$ for the negative system and 5.760×10^8 to 1.590×10^9 HK\$ for the positive system.

4.3. Research applications, limitations and future studies

4.3.1. Comparison of approaches, results and conclusions

In comparison with studies in the academia, this study shows advantages, in terms of approaches, results and conclusions.

- (1) Compared to the general conclusion in the academia that the $V2B$ interaction and battery storage are techno-economically effective, this study provides a generic approach on the dialectical analysis of electrochemical battery storage, especially considering the real-time battery cycling aging and high battery cost. Conclusions in previous studies without or with rough battery cycling aging, will actually lead to overestimation on battery performance. The research methodology in this study can cover this gap and shed lights on conservative and accurate estimation of battery storage systems.
- (2) Compared to specific case study on negative (such as the reference by Qian et al. [72]), net-zero (such as the reference by Mehrjerdi et al. [10]) or positive energy systems (such as the

Fig. 12. Uncertainty and sensitivity analysis of Net Present Value (NPV) on the negative system with only south BIPVs system and the positive system, in respect to: (a) renewable system cost; (b) battery cost; (c) and escalation rate. (Note: battery cost is 3045 HK \$/kWh and the escalation rate is 1.4% for (a); PV, wind turbine cost and the escalation rate are 10317, 15,000 HK\$/kWp, and 1.4% for (b); and the interest rate is 2% for (c). Case I (I'): PV cost = 6190.5 HK\$/kWp (wind turbine cost = 9000 HK\$/kW); Battery Cost = 1827 HK\$/kWh; Case II (II'): PV cost = 7222.2 HK\$/kWp (wind turbine cost = 10,500 HK\$/kW); battery cost = 2131.5 HK \$/kWh; Case III (III'): PV cost = 8254 HK \$/kWp (wind turbine cost = 12,000 HK \$/kW); Battery Cost = 2436 HK\$/kWh; Case IV (IV'): PV cost = 9285.7 HK\$/kWp (wind turbine cost = 13,500 HK\$/kW); battery cost = 2740.5 HK\$/kWh; Case V (V'): PV cost = 10317.4 HK\$/kWp (wind turbine cost = 15,000 HK\$/kW); Battery Cost = 3045 HK \$/kWh.)

reference by Zhou and Cao [51]) in the academia, this study provides a comprehensive and holistic overview on energy paradigm transition from negative to net-zero and, then to positive energy systems. The carbon-neutral transition roadmap is quite necessary to provide both qualitative and quantitative

techno-economic results, so as to necessitate the renewable system design strategies.

- (3) Compared to experimental research methodology, numerical simulation in this study is more flexible and cost-effective. Moreover, the lifecycle analysis for 20 years with different

scenarios (i.e., different renewable systems, energy management strategies and diversified vehicles' integration) is hardly feasible by experimental study within the normal research project period, whereas the advanced simulation modelling and tools can provide possibility for the theoretical lifecycle analysis.

However, some disadvantages of this study need to be noticed:

- a. In respect to the building occupants' behaviour and vehicle driving behaviour, only deterministic profiles are applied without considering the stochastic behaviours on building occupants and vehicles. Actually, the energy interaction between buildings and vehicles are highly dependent on stochastic behaviours, as the building energy demand is dependent on building occupants' behaviour and the parking/driving schedules will dominate the time-duration for energy interaction between buildings and vehicles.
- b. The building energy modelling is based on performance-based building energy code [57], without considering the uncertainty of thermo-physical parameters. The impact of uncertainty-based building demands on energy interaction in the district energy sharing network is worthy to be studied.

4.3.2. Applicability of research outcome

Research results can be applied in renewable energy planning, system design, operation, together with economic investment activity with business models. The detailed applicability is summarised below.

- a. The integration of battery cycling aging model can provide accurate online performance estimation of electrochemical battery storages, so as to avoid the underestimation and overestimation on techno-economic performance.
- b. The energy paradigm transition from negative to positive district energy sharing network can provide renewable system design guidelines for carbon-neutral district community. The research results in this study can provide system design guidelines and operational strategies on electricity-based district energy sharing network in tropical, subtropical and coastal regions (sufficient solar radiation and wind resources, and cooling dominated regions), such as Hong Kong, Singapore, Guang Dong province (mainland China), Portugal and so on.
- c. During the system operation process, novel energy management strategies, i.e., renewable-demand control (Control Strategy 1), grid-responsive control strategy (Control Strategy 2) and battery-protective control strategy (Control Strategy 3), can provide advanced energy management strategies on dynamic power flow, to improve the techno-economic performance. The underlying mechanisms for techno-economic performance enhancement include off-peak electricity shifting, smart grid-to-battery charging, and flexible V2B interactions.
- d. The lifecycle-based techno-economic analysis can provide clear blueprint to system investors, building owners and system managers, with the comprehensive consideration of depreciation of renewable systems and battery cycling aging. Uncertainty and sensitivity analysis on interest rate and escalation rate can guide the commercial market to promote renewable systems with economic incentives.

4.3.3. Future research direction

The techno-economic feasibility of an interactive energy system has been studied with respect to the energy paradigm transition from negative to positive. Both the cycling aging of battery charging/discharging processes and the degradation of renewable generation have been considered. Novel energy management strategies have been explored to improve the techno-economic performance. Comparative and sensitivity analyses have been conducted, from perspectives of different energy paradigms (following the roadmap of the negative system, the nearly zero energy system and the positive system), different

V2Bs interaction levels, and diversified energy management strategies. It should be noted that the frequent replacement time of battery systems is mainly because of the prompt response for battery charging (in accordance with the surplus renewable or off-peak grid signal) or discharging (in accordance with the demand shortage) without delay. However, in real applications, there will be delays for the battery charging and discharging process. The studied buildings are high-rise buildings in Hong Kong, whereas studies on low-rise buildings are necessary to provide references and guidelines for other regions. From the perspective of the energy demand side, impact of uncertainty-based building demands on energy interaction in the district energy sharing network will be studied. In addition, as the dynamic behaviour on energy interaction is highly dependent on stochastic behaviours of building occupants and vehicles, studies on stochastic behaviours will be conducted to quantify the effects. Furthermore, the strategy does not consider the grid-to-battery charging in the 'acceleration zone' to improve the battery performance. Future studies will focus on the development of a dynamic grid-to-battery charging strategy, throughout both the 'slow degradation zone' and the 'acceleration zone'. Last but not the least, considerations will be given to the optimal design and robust operation of renewable and battery storage systems with respect to the transition of energy paradigms and different energy management strategies.

5. Conclusions

In this study, carbon-neutral transition from negative to net-zero energy system, and then to positive district energy sharing network is one of most promising strategies for cleaner power utilisation, energy crisis shortage and global warming mitigation. A district energy-sharing network has been developed, consisting of high-rise office and hotel buildings, battery storages, occupant-centric profile-based vehicles and grid integrations. A series of technical solutions have been proposed, studied and discussed, including flexible renewable system design, plug-in vehicles' integration (under multi-directional energy interactions such as the building-to-vehicle, B2V, vehicle-to-building, V2B, and so on), the grid-responsive and battery-protective controls. With the consideration on real-time battery cycling aging and the degradation on renewable systems, lifecycle analysis has been conducted to provide techno-economic viability. Novel strategies were implemented and contrasted for off-peak grid electricity shifting, smart grid-to-battery charging, the enhancement of renewable penetration, and the battery relative capacity improvement. Furthermore, given the uncertainty of system prices and interest rate in the commercial market, sensitivity analysis on both negative and positive building-vehicle systems has been conducted with respect to renewable system costs, battery costs, and interest rates. Key conclusions are drawn as follows:

- 1) To realise the sustainable and continuous operation of the district energy sharing network, the retired battery needs to be replaced, considering the cycling aging of battery storages. The energy paradigm transition from negative to positive buildings-vehicles systems and the increase of the $V2B_{interaction}$ will increase the battery replacement times (BRT). In the negative buildings-vehicles system, with the increase of the $V2B_{interaction}$ from 0% to 100%, the BRT increase from 2 to 5 for the private cars, and from 3 to 5 for the public shuttle buses. Meanwhile, effective energy management strategies are critical for reducing the BRT. In the case study, the adoption of the battery-protective control strategy (Control Strategy 3) can decrease the BRT from 8 to 5 and from 16 to 9 for the static battery in the office and hotel, respectively.
- 2) Net present value and average annual net DEC are highly dependent on the designed energy paradigm transition and the implemented energy management strategy. With the energy paradigm transition from the negative system (BIPVs on the south façade) to the positive system (BIPVs on full walls, nearby PVs, and total wind turbine

- capacity of 1.44 MW), the net present value increased from -7.182×10^7 to 5.164×10^8 HK\$, and the average annual net DEC decreased from 249.1 to -343.3 kWh/m².a. Furthermore, compared to Control Strategy 2 (grid-responsive control strategy), Control Strategy 3 (battery-protective control strategy) can improve the net present value from -1.824×10^8 to -1.155×10^8 HK\$ by 36.7% (for the negative system with BIPVs on the south façade only), and from 4.775×10^8 to 4.789×10^8 HK\$ by 0.3% (for the positive system).
- 3) Compared to the positive buildings-vehicles system, the impact of the V2B interaction on the decreasing magnitude of the net present value and the DPT is more prominent for the negative system, and the flexible management of the building and vehicle interaction is more cost-effective for the negative than the positive buildings-vehicles system. In the case study, an increase in the V2B_{interaction} from 0% to 100% reduced the net present value from -8.768×10^7 to -1.155×10^8 HK\$ by 31.7%, and increased the average annual DEC from 252.7 to 260.1 kWh/m².a in Scenario 1 (the negative system with only BIPVs on the south façade). Meanwhile, the increase in the V2B_{interaction} from 0% to 100% reduced the net present value from 5.005×10^8 to 4.789×10^8 HK\$, by 4.3%, and increased the average annual DEC from -335.7 to -334.6 kWh/m².a in Scenario 4 (the positive buildings-vehicles system with BIPVs on full walls, nearby PVs, and total wind turbine capacity of 1.44 MW).
- 4) The sensitivity analysis indicates that technical solutions for life-cycle-based techno-economic performance improvement include the decrease of the renewable systems cost and battery cost, the increase of the interest rate (for the negative energy system), the decrease in the interest rate (for the positive energy system), and so on. According to the results in Scenario 1, a decrease in the battery cost from 3045 to 1827 HK\$/kWh increased the net present value from -1.329×10^8 to -7.230×10^7 HK\$ by 46%, and the increase in the escalation rate from 0% to 10% improved the net present value from -1.222×10^8 to -7.474×10^7 HK\$ by 38.8%. Furthermore, compared to the negative energy paradigm, the net present value of the positive energy paradigm is more sensitive to the battery cost. In other words, compared to the negative energy paradigm, future system designers need to pay more attention to the initial costs of battery storage systems in the commercial market in the positive energy paradigm.

Future studies will study the impact of uncertainty-based building demands and stochastic behaviours of building occupants and vehicles on energy interaction in the district energy sharing network. Furthermore, a dynamic grid-to-battery charging strategy, throughout both the 'slow degradation zone' and the 'acceleration zone', will be developed to improve the battery relative capacity. In addition, the economic performance of the peer-to-peer energy sharing from standpoints of different stakeholders will be studied to quantify their participation willingness.

CRedit authorship contribution statement

Yuekuan Zhou: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Sunliang Cao:** Supervision, Funding acquisition, Project administration, Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Jan L.M. Hensen:** Investigation, Writing - original draft, Writing - review & editing.

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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