ARTICLE

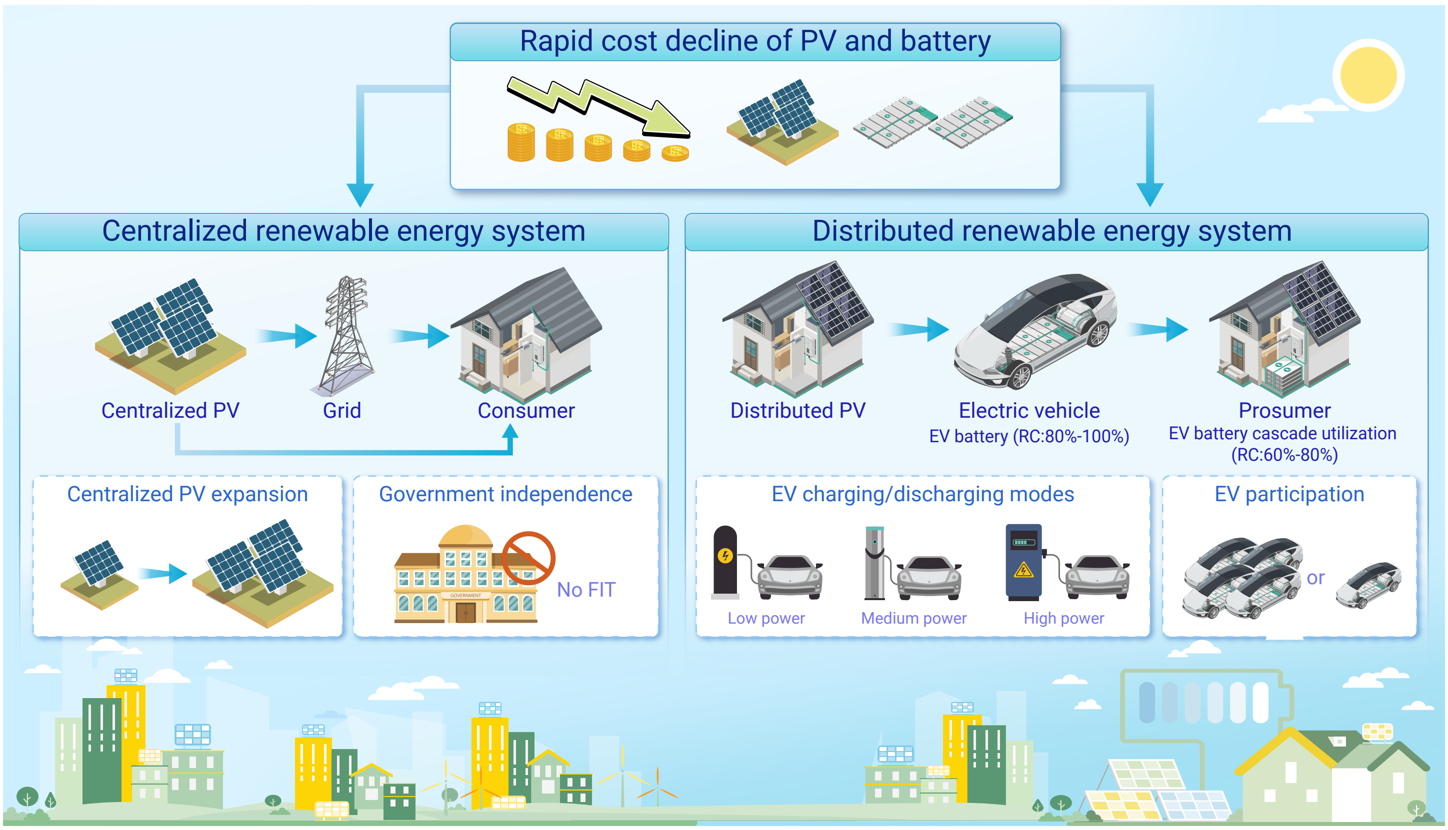
Free autonomy renewable trade markets for government independence and carbon neutrality transitions with grid-demand-storage synergies

Xiaojun Yu[1] and Yuekuan Zhou[1,2,3,4,*]

*Correspondence: Email: yuekuanzhou@hkust-gz.edu.cn; yuekuan.zhou@outlook.com; yuekuanzhou@ust.hk (Zhou Y.)

Received: August 28, 2024; Accepted: December 27, 2024; Published Online: January 11, 2025; https://doi.org/10.59717/j.xinn-energy.2024.100062

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Free trading markets with spontaneous renewable system installations among stakeholders to mitigate investment pressure of government.
- Distributed renewable system in free trading market for energy trading between EV owners and prosumers with flexible energy management strategies.
- Vehicle-to-everything (V2X) with different charging/discharging modes with the trade-off between additional expenditures on EV battery cycling aging costs and additional economic profits.
- The trade-off between profit margin and carbon emission with levelized electricity cost, levelized cost of charging and levelized carbon mitigation subsidy.

Free autonomy renewable trade markets for government independence and carbon neutrality transitions with grid-demand-storage synergies

Xiaojun Yu[1] and Yuekuan Zhou[1,2,3,4,*]

[1]Sustainable Energy and Environment Thrust, Function Hub, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, 511400, Guangdong, China
[2]Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China
[3]HKUST Shenzhen-Hong Kong Collaborative Innovation Research Institute, Shenzhen, China
[4]Division of Emerging Interdisciplinary Areas, The Hong Kong University of Science and Technology, Hong Kong SAR, China
*Correspondence: Email: yuekuanzhou@hkust-gz.edu.cn; yuekuan.zhou@outlook.com; yuekuanzhou@ust.hk (Zhou Y.)

Received: August 28, 2024; Accepted: December 27, 2024; Published Online: January 11, 2025; https://doi.org/10.59717/j.xinn-energy.2024.100062

Citation: Yu X. and Zhou Y. (2025). Free autonomy renewable trade markets for government independence and carbon neutrality transitions with grid-demand-storage synergies. *The Innovation Energy* **2**:100062.

Along with the gradual phase-out of fossil-fuels, technology readiness and cost decline of renewable energy technologies and battery storages can bring new prospects for renewable energy trading market and extensive power-sector decarbonization. Renewable energy trading market has rapidly transformed from traditional grid-based transactions towards future direct free trading with multi-stakeholders. However, the direct free trading market for sustainable development of renewable energy systems is unclear, in terms of establishment conditions, increased profit margin and promotion initiatives. In this study, free trading markets with spontaneous renewable system installations among stakeholders instead of government are proposed for spatiotemporal energy and economic balances with different types of buildings and electric vehicles (EVs). For the centralized renewable energy system, it is proposed based on energy transmission and energy trading between centralized PV farms and consumers. Besides, free trading market in the distributed renewable energy system is also established between EV owners and prosumers with flexible energy management strategies (i.e. EV energy sharing, and EV battery cascade utilization). Roles of EVs under vehicle-to-everything (V2X) with different charging/discharging modes are analysed considering the trade-off between additional expenditures on EV battery cycling aging costs and additional economic profits for economic feasibility and carbon emission reduction for environmental sustainability based on dynamic energy trading mechanism and associated cost decline. The results suggest that, due to the rapid decline in the costs of both renewables and batteries, along with the increased penetration of renewable energy in centralized systems, the free-market trading model could become widely accepted by 2060. Due to the rapid decrease of battery cost and increase in grid price, the EV owners will transit from cost payers to economic earners, along with the levelized cost of charging (LCOC) with EV energy sharing decreases from 2.24 CNY/kWh in 2020 to -1.27 CNY/kWh in 2060. Furthermore, retired EV battery cascade utilization in building energy storages can reduce the levelized electricity cost (LEC) of residential building owners. Overall, this study provides valuable insights into dynamic evolutions of free trading markets on renewable energy which significantly encourages spontaneous renewable investments and trading behaviours for the sustainable renewable energy deployment.

INTRODUCTION

With climate change issues becoming increasingly severe, Paris Agreement in 2015 proposed the objective of pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial level.[1] During the 75th United Nations General Assembly, Chinese government announced that China aimed to reach peak carbon emissions before 2030 and achieve carbon neutrality by 2060 (the so-called "3060" target.[2] Power, building and transport sectors in China accounted for almost 61% of carbon emissions by 2020.[3] Rapid adoption and alternative transformation towards low-carbon living and mobility become crucial and imperative. However, main challenges for widely adoption of renewables and alternative low-carbon sources include: 1) instability and intermittence for difficulty in high-efficient utilisation;[4–6] 2) high costs for limiting economic benefits of investors and user;[7–10] 3) limited spaces for renewables installation and quantities of alternative low-carbon sources.[11,12]

Although difficulties for the instability and intermittency impede the high-efficient utilisation of renewable energies, researchers have already explored a lot of strategies to improve the performance, like direct renewable consumption (PV-driven air-conditioning,[13–15] renewable-driven heat pumps,[16–18] etc), and energy storage systems (renewable-to-thermal conversions and storages, electrochemical battery storages, etc). Energy storage systems are considered as one of the most efficient solutions to maintain the balance between electricity supply and demand, especially for power systems with high penetration of variable renewable sources.[19,20] For electrochemical battery storage, it can balance both electricity supply and demand, while providing load shifting to fill gaps during peak demand and improving grid stability with consistent current supply. Dowling et al.[21] found that long-duration electrochemical storage can effectively improve the energy efficiency and affordability of renewable electricity. Kittner et al.[22] found that optimal combinations of solar, wind, and storage can directly solve the intermittency of renewable energy and compete with fossil-based electricity options. Moreover, photovoltaic thermal (PVT) panels can simultaneously generate thermal and electrical energy, making them appropriate for applications in buildings.[23,24] Han et al.[25] compared techno-environmental indicators of PV and PVT-driven building energy systems under various climates. They reported that PVT-based systems were more efficient with higher air temperature and solar intensity by extracting the waste heat through water. An innovative thermal energy storage unit equipped with PV and PVT panels was proposed and compared by Carmona et al.[26] They indicated that 7.5 % higher electrical efficiency was achieved when PVT was applied as the primary mover.

Moreover, rapid cost decline of renewables and battery storage under fast development and technology maturity provides the great profit margin to compensate the renewable energy with high investment costs. The chain effect of cost decline can not only enhance the economic viability of transitioning away from fossil fuels towards the low-carbon and sustainability, but also open up substantial profit margins for the wide installation of renewable energy and electric vehicle (EV) deployment.[7,9,22,27-28] This dual benefit of cost savings and decarbonization forms the core prerequisite for exploring the economic market and power decarbonization for renewable-grid-demand-storage in China. He et al.[7] explored the impact of cost decline on the deployment of China's power sector. They found that under such rapid cost decline on renewable energies, 62% of China's electricity demand can be supplied by non-fossil sources by 2030 at a cost that is 11% lower compared to slow rapid cost decline conditions. Considering the location, scale and timing, Peng et al.[28] explored the impact of cost decline and battery deployment strategies on the uncertainty of system costs and $CO_{2,e}$ emission. They showed that system costs of the demand-side battery strategy are 13% higher than grid-connected or renewable energy-connected battery strategies in year 2050. Meanwhile, carbon emission of renewable-connected batteries is decreased by 9% compared with grid-connected batteries.

Although rapid cost decline has been proved with considerable profit margin for renewable energy systems, limited spaces for renewables installation and quantities of alternative low-carbon sources still need to be addressed.[11,12] Both centralized renewables (including PV farms[29,30] and onshore/offshore wind turbine farms[30,31]) and distributed renewables (like building integrated photovoltaics (BIPVs)[32,33]) have been widely used to decarbonize building sectors. However, investors, profit margins and decarbonization ability are quite different between centralized and distributed renewable energy systems. In China, traditional trading model of centralized PV system heavily depends on the government-supported feed-in tariff (FiT). Otherwise, the PV system has no market due to its levelized cost of energy much higher than the fossil fuel-powered plant.[34] However, high reliance on grid feed-in tariff (FiT) places a significant financial strain and economic pressure on the government. Considering future economic cost decline factors and market dynamics, whether direct market-to-consumer trading without government-supported FiT can survive and be widely accepted with economic feasibility has not been studied. Furthermore, whether renewable-grid-demand-storage can be widely accepted in the market in the absence of government subsidies is still questionable.[35,36]

Under the distributed energy market, spontaneous multi-stakeholders' participations in investment, trading, recycling activities in energy markets play critical roles in national carbon neutrality targets. Economic benefits and decarbonization performance of multi-stakeholders need to be investigated, like EV owners in vehicle-to-everything (V2X) participations. Prior studies have fully explored the economics of EV charging. Zhou[37] analysed the advanced energy pricing policy and energy interaction mode, which increased the internal trading cost from 0 to 1.78×10^5 HK$ and overwhelmed its battery depreciation cost at 6.88×10^5 HK$. Song and Zhou[38] developed a building-EV energy sharing model and a battery circular economy model to simulate the process of reusing retired EV batteries. They found that the decrease of battery carbon intensity from 1284.57 kg $CO_{2,e}$/kWh to −720.79 kg $CO_{2,e}$/kWh with renewable and secondary-life battery. Huang et al.[39] proposed a coordinated control of building prosumers for improving the cluster-level performance, by making use of energy sharing and storage capability of electricity batteries in both buildings and EVs. They found that, compared with the conventional controls. the developed control can increase the cluster-level daily renewable self-consumption rate by 19% and meanwhile reduce the daily electricity bills by 36%. Based on previous studies, levelized cost of charging (LCOC) of light-duty EVs in the United States has been determined by considering the purchase and installation costs of charging equipment and grid prices from real-world utility tariffs.[40] In European cities, LCOC has been developed to model charging costs under a systematic classification of charging options, gathering extensive market data on equipment costs.[41] However, under the V2X mode with distributed energy markets, LCOC with EV energy sharing is unclear, especially considering additional capital cost from accelerated EV degradation and potential profit from flexible EV energy sharing under smart charging/discharging modes.

Based on the above literature review, scientific gaps can be noticed, as summarised below:

1) Traditional energy trading of the renewable energy system with high reliance on government (like subsidy on renewable projects, grid feed-in tariff policy and etc) imposed extremely heavy economic burden for local government, which is not suitable globally and not sustainable all the time. Instead of relying on local government, direct free trade market with multi-stakeholder's participation and decision-making processes has not been properly explored. Frontier standardizations, regulations and guidelines design on free trading market need to be well studied with proactive stakeholders' participation willingness and market feasibility.

2) Impact of rapid cost decline from renewable systems on the free trading market has not been specifically quantified. Furthermore, unlike the traditional levelized cost of charging (LCOC) without considering building-to-vehicle (B2V) and vehicle-to-building (V2B) processes through EV energy sharing, under the smart mobility within B2V/V2B EV energy sharing framework, the impact of energy trading between EV owners and prosumers on the LCOC is still unclear. Current studies have focused on static assessments of profitability under current market conditions, which overlook the dynamic nature of technological advancements, market mechanisms, and policy changes in the future. Adaptive renewable energy trading market under rapid cost decline is significantly required for stakeholders to maintain economic viability in changing market dynamics. Failure to account for these uncertainties in renewable energy trading market may lead to inappropriate decision-making and uneven resource allocation within the free trading market.

3) Thirdly, evolving trade-off between economic feasibility and environmental sustainability in the free trading market has not been investigated in the academia. Specifically, there's a need to explore whether economic investments in renewables and environmental benefits (like carbon emission reduction) can be balanced and how the profitability affects the environmental performance of renewable energy systems.

Based on the scientific gaps above, contributions of this study can be summarised below:

1) This study provides a standard to evaluate the establishment conditions of the frontier free trading market for both centralized and distributed renewable energy systems. Based on the standard, transition from the current government-dependent market towards the future free trade autonomy market has been discussed, in terms of multi-stakeholders' participation, pricing mechanisms, energy trading mechanisms and flexible energy management strategies.

2) With the technical maturity and market requirement, impact of rapid cost declines from renewable energies and battery storages on trading dynamics in the free trading market has been studied. Furthermore, impact of energy trading between EV owners and buildings in B2V/V2B interactions on the LCOC has been studied. Variation of the stakeholders' profit margin under the rapid cost declines is quantified to determine the economic benefits of participators in the trading market.

3) Under the confliction between global carbon neutrality and considerable economic investment, the trade-off between economic profitability and carbon emission reduction has been proposed to reveal the inherent complexities evolved in balancing economic feasibility and environmental sustainability in the framework of a free trade market.

MATERIALS AND METHODS

In this research, development of energy systems can be broadly classified into centralized and distributed renewable energy systems. In the centralized mode (as shown in Scenario 2), the traditional setup starts with electricity generation from thermal power plants (Scenario 1), which is then distributed to consumers through a local power grid. Conversely, in the distributed renewable energy system (as shown in Scenario 3), BIPV installations facilitate the on-site energy generation and reduce dependency on the central power grid. Compared with the centralized renewable energy system, more flexible energy strategies can be applied in the distributed renewable energy system. In Scenario 4, EVs serve as mobile energy storage devices, supporting dynamic energy sharing and management among prosumers. Scenario 5 shows the distributed renewable energy system by adding EV battery cascade utilization, which further extends the use of EV batteries beyond their initial automotive application by repurposing them for stationary energy storage in consumer settings after the end of their vehicular lifespan.

Trading mechanism and assessment criteria for the centralized renewable energy system

Figure 1 illustrates the mechanism of a free trading market within a centralized renewable energy system, focusing on the interactions between market prices and consumer costs. In this market structure, consumers purchase energy directly from renewable sources. Generated renewable energy is transmitted through the provincial grid, adhering to the existing transmission price. Consumers assume the cost of the transmission price, which compensates for the use of the grid infrastructure to deliver renewable energy from its generation point to the point of consumption. On the market side, the renewable energy (RE) trading price is influenced by several factors. The minimum price level is set by the levelized cost of energy (LCOE), which is the average cost per unit of energy produced. The maximum trading price for renewable energy is capped by the average grid price, excluding transmission costs. On the consumer side, the minimum LEC occurs when the RE trading price equals the LCOE, while the maximum LEC occurs when the RE trading price is at parity with the average cost of electricity from the grid excluding transmission costs. Under this balanced state, the profit of the market and the cost savings to the consumer are supposed to be aligned, which shows the potential economic efficiency of a free trading market within a centralized renewable energy framework.

Assessment criteria for the centralized renewable energy system

1) Average grid price

The average grid price ($\bar{Pr}_{grid}$) refers to the mean cost of electricity provided by the local power grid, typically factored by the time-of-use grid price ($Pr_{grid}(t)$) and dynamic required electricity from the local power grid ($P_{grid}(t)$).

The average grid price is formulated as:

$$\overline{Pr_{grid}}=\frac{\text{Total cost for grid import energy}}{\text{Total grid import energy}}=\frac{\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times P_{grid}(t)\,dt}{\int_{t=0}^{t=lifetime}P_{grid}(t)\,dt} \quad (1)$$

where $Pr_{grid}(t)$ and $P_{grid}(t)$ refer to the time-of-use grid price and required electricity from the local power grid at time t, respectively.

2) Levelized cost of energy (LCOE)

The levelized cost of energy (LCOE) is a commonly used indicator for comparing electricity costs from different energy technologies. It is a measure of the average costs to build and operate a power-generating asset over its lifetime divided by the total electricity output of the asset over its lifetime. LCOE can also be regarded as the minimum cost of selling electricity so as to achieve the payback of the investment cost even over the lifetime of the project. The costs of solar PV projects include power generation, predevelopment, construction, operation and maintenance costs, as well as the discount rate of fixed-term considerations, the depreciation of fixed assets, and/or the residual value of assets. In this research, the lifetime of the solar PV system is assumed to be 20 years. Moreover, the depreciation and residual value of the PV is not considered. Therefore, LCOE is expressed as:

$$LCOE_{centralized\ PV}=\frac{\text{Total lifetime cost of the centralized PV system}}{\text{Total lifetime renewable energy generated by the centralized PV system}}=\frac{C_{initial\ capital,PV}+\sum_{i=1}^{i=N}\frac{C_{o\&M\ PV,i}}{(1+dr)^{i}}}{\sum_{i=1}^{i=N}\int_{t=1}^{t=lifetime}\frac{P_{generated\ RE}(t)\,dt}{(1+dr)^{i}}} \quad (2)$$

where $C_{initial\ capital,\ PV}$ refers to the initial capital cost of the centralized PV and operation and $\sum_{i=1}^{N}$ year $\frac{C_{o\&MPV,i}}{(1+dr)^{i}}$ refers to the operation and maintenance cost considering the discount rate (dr) of 8% during the lifetime of the PV system. $\int_{t=1}^{t=lifetime}P_{generated\ RE}(t)dt$ refers to the total electricity production generated by the centralized PV over the entire lifetime.

3) Renewable energy trading price

Range of the renewable energy trading price needs to be regulated to guarantee the profit for both consumer and the centralized PV market. Maximum renewable energy trading price is limited by the average grid price (excluding the transmission cost afforded by consumers).

If the renewable energy trading price is much higher, consumers cannot obtain profits from the trading. Moreover, the minimum renewable energy trading price is restricted by the LCOE of PV. If the renewable energy trading price is even lower than LCOE, centralized PV market cannot obtain profits from trading.

The balance state is defined as the special condition in which the cost savings of consumers are equal to the profit of the centralized PV market. Profit of the centralized PV market is obtained from the difference between the revenue of selling the renewable energy to the consumer (Re_{PV}) and the total investment cost of the centralized PV market (C_{PV}), which is expressed as:

$$\text{Profit of the centralized PV market}=Re_{PV}-C_{PV}=Pr_{RE}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt-LCOE_{centralized\ PV}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt \quad (3)$$

where Pr_{RE} is the renewable energy trading price; $P_{generated\ RE}(t)$ is the power of renewable energy generated by centralized PV, and LCOE is the levelized cost of energy of centralized PV. Moreover, the cost savings of consumer is defined as the difference between the cost of grid-imported energy for total electricity demand ($C_{grid\ for\ total\ ED}$) and the sum of the cost of buying renewable energy from centralized PV (C_{RE}), the cost of grid-imported energy for the shortage electricity demand ($C_{short\ grid}$), and the transmission cost for renewable energy (C_{trans}). Therefore, cost saving of the consumer is expressed:

$$\begin{aligned}&\text{Cost saving of the consumer}=C_{grid\ for\ total\ ED}-(C_{RE}+C_{short\ grid}+C_{trans})=\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times P_{ED}(t)\,dt-\\&[Pr_{RE}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt+\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times(P_{ED}(t)-P_{generated\ RE}(t))dt+Pr_{transmission}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt]\end{aligned} \quad (4)$$

Based on the principle of the balance state in which the profit of the centralized PV market equals the cost saving of the consumer, the renewable trading price under the balance state is defined as:

$$\begin{aligned}Pr_{RE\ under\ balance\ state}&=\frac{[\text{Total investment cost of the centralized PV market}+\text{Cost for total electricity demand from local power grid}-(\text{Cost for grid - imported energy for the shortage electricity demand}+\text{Cost for renewable energy transmission})]}{2\times\text{Total lifetime renewable energy generated by the centralized PV system}}\\&=\frac{C_{PV}+C_{grid\ for\ total\ ED}-(C_{short\ grid}+C_{trans})}{2\times\int_{t=0}^{t=lifetime}P_{generatedRE}(t)dt}\\&=\frac{LCOE_{centralizedPV}\times\int_{t=0}^{t=lifetime}P_{generatedRE}(t)dt+\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times P_{generatedRE}(t)dt-\left[\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times(P_{ED}(t)-PgeneratedRE(t))\,dt+Pr_{transmission}\times\int_{t=0}^{t=lifetime}P_{generatedRE}(t)dt\right]}{2\times\int_{t=0}^{t=lifetime}P_{generatedRE}(t)dt}\end{aligned} \quad (5)$$

where $LCOE_{centralized\ PV}$ refers to the levelized cost of energy of the centralized PV; $P_{generated\ RE}(t)$ refers to the power generated by the centralized PV at time t $Pr_{grid}(t)$ refers to the time-of-use grid price; refers to the electricity demand of the building, and $Pr_{transmission}(t)$ refers to the transmission cost afforded by consumers following the provincial grid transmission and distribution tariffs at time t.

4) Levelized electricity cost (LEC) of consumer

The levelized electricity cost (LEC) of building consumers is defined as the levelized cost per kWh of building electricity demand for building consumers.

$$\begin{aligned}LEC_{building\ with\ centralized\ PV\ and\ grid}&=\frac{\text{Total operational cost}_{building\ from\ centralized\ PV\ and\ grid}}{\text{Total electricity demand of the building}}\\&=\frac{Pr_{RE}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt+\int_{t=0}^{t=lifetime}P_{grid}(t)\times[P_{ED}(t)-P_{generated\ RE}(t)]\,dt+P_{transmission}\times\int_{t=0}^{t=lifetime}P_{generated\ RE}(t)\,dt}{\int_{t=0}^{t=lifetime}P_{ED}(t)\,dt}\end{aligned} \quad (6)$$

where Pr_{RE} refers to the renewable energy trading price; $P_{generated\ RE}(t)$ refers to the power generated by the centralized PV market at time t; $Pr_{grid}(t)$ refers to the grid price considering the escalation rate at 1.4% per year; $P_{ED}(t)$ refers to the electricity demand of the building at time t and $Pr_{transmission}$ refers to the transmission price defined by the government.

Levelized electricity cost with the grid only is expressed below, which is in fact the special expression of the previous formula that equals to zero.

$$\begin{aligned}LEC_{building\ with\ grid\ only}&=\frac{\text{Total operational cost}_{building\ from\ grid\ only}}{\text{Total electricity demand of the building}}\\&=\frac{\int_{t=0}^{t=lifetime}Pr_{grid}(t)\times P_{ED}(t)\,dt}{\int_{t=0}^{t=lifetime}P_{ED}(t)\,dt}\end{aligned} \quad (7)$$

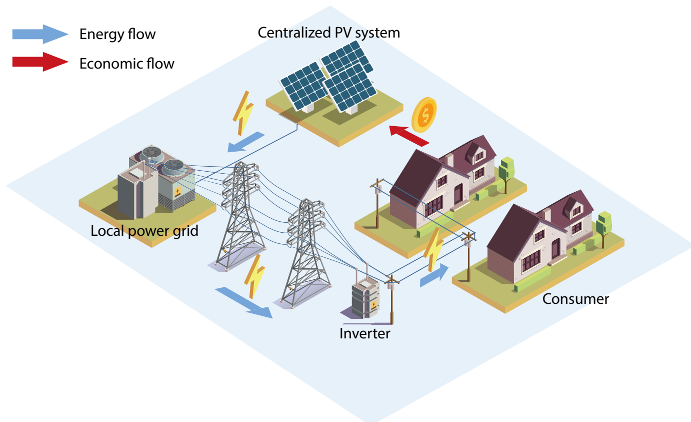


Figure 1. Schematic diagram of the centralized renewable energy trading market.

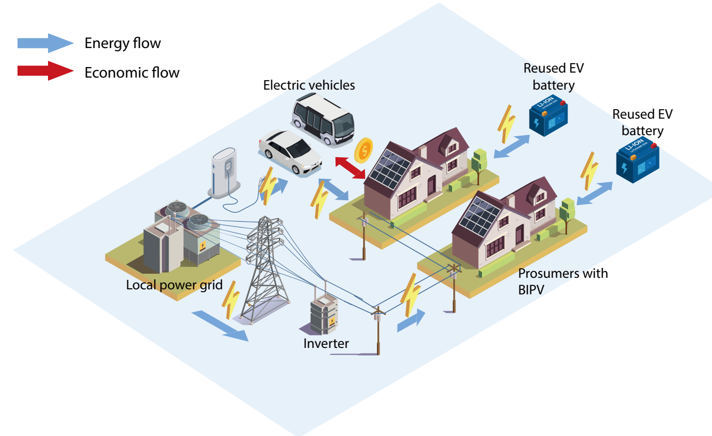


Figure 2. Schematic diagram of the distributed renewable energy trading market.

where $Pr_{grid}(t)$ refers to the grid price and $P_{ED}(t)$ refers to the electricity demand of consumer at time t.

Trading mechanism and assessment criteria for the distributed renewable energy system

In the centralized renewable energy system, PV market predominantly burdens the investment responsibilities. Conversely, as shown in Figure 2, distributed renewable energy system disperses investment obligations across prosumers, allocating the financial burden and operational management at a more localized level. Although this may exacerbate the fiscal burden for prosumers, more flexible strategies can be potentially implemented to mitigate these burdens and concurrently enhance profitability.

When an EV is used, under what conditions and by whom dictates whether or not these EVs can deliver economic benefits. Therefore, behavioural characteristics of EVs are divided into three different charging/discharging modes to explore the economic performance of the EV sharing process.

1) Behavioural characteristics of EVs

Three charging/discharging modes for EV are considered in this research: slow charging/discharging mode offers 3.5 kW power for EV charging and discharging, which can provide long battery lifespan and low initial cost but relatively slow charging and low EV energy efficiency. Medium and high charging/discharging mode provides 15 kW power and 50 kW power, respectively. However, fast charging and high energy efficiency provided by the medium and high charging/discharging mode leads to shorter battery life and higher initial cost compared with the low charging/discharging mode. Under different modes, trade-off between the arbitrage potential from peak and off-peak price differences and the additional EV cost associated with various battery degradation process can be clearly quantified.

2) Number of retired EV through the B2V/V2B process

Number of the retired EV battery is defined based on the relative capacity (RC). When the RC of the EV battery decreases to 80%, EV battery should be replaced and retired EV battery can be utilized as the static battery for energy storage. At the end of the lifespan, last EV battery is converted to a proportion of the expected value.

$$\begin{aligned}&\text{Total number of retired EV battery}\\&=\text{Number of fully degraded EV battery} + \text{Proportion of the expectancy of the last EV battery}\\&=\text{Number of fully degraded EV battery}+\frac{T_{\text{end of life}}-T_{\text{start of the last cycle}}}{T_{\text{end of the last cycle}}-T_{\text{start of the last cycle}}}\end{aligned} \tag{8}$$

Number of fully degraded EV battery refers to number of EV battery with relative capacity degraded to 80%, and number of the last replaced EV battery is defined as the counterparts of the proportional degraded section.

3) Levelized cost of charging (LCOC) of EV

As shown in Figure 2, LCOC can be assumed as the unit cost per kWh for EV charging that is required to be paid by EV owners. It depends on the initial capital cost of EV battery ($C_{\text{initial capital}}$), the cost of operating and maintaining the EV battery ($C_{O\&M}$), cost for G2V (C_{G2V}), cost for B2V (C_{B2V}), profit for V2B ($Profit_{V2B}$), and the total charging energy from both the grid and the building.

$$\begin{aligned}&LCOC_{\text{with EV energy sharing}}=\text{Battery cycling aging cost}+\text{Total electricity cost}\\&=\frac{\text{EV capital cost}}{\text{Total EV charging energy}}+\frac{\text{Cost for G2V}+\text{Cost for B2V}-\text{Profit for V2B}}{\text{Total EV charging energy}}\\&=\frac{\left(C_{\text{initial capital, EV}}+\sum_{i=1}^{N_{\text{th year}}}\frac{C_{o\&M\,EV_i}}{(1+dr)^i}\right)}{\int_{t=1}^{t=\text{lifetime}}P_{\text{EV charging}}(t)\,dt}+\frac{C_{G2V}+C_{B2V}-Profit_{V2B}}{\int_{t=1}^{t=\text{lifetime}}P_{\text{EV charging}}(t)\,dt}\\&=\frac{\left[C_{\text{initial capital, EV}}+\sum_{i=1}^{N_{\text{th year}}}\frac{C_{o\&M,i}}{(1+dr)^i}\right]+\int_{t=1}^{t=\text{lifetime}}[Pr_{grid}(t)\times P_{G2V}(t)]\,dt+Pr_{B2V}\times\int_{t=1}^{t=\text{lifetime}}P_{B2V}(t)\,dt-Pr_{V2B}\times\int_{t=1}^{t=\text{lifetime}}P_{V2B}(t)\,dt}{\int_{t=1}^{t=\text{lifetime}}(P_{G2V}(t)+P_{B2V}(t))\,dt}\end{aligned} \tag{9}$$

Under the traditional operational mode (EV for transportation only), LCOC without EV energy sharing is defined as the special form of the above equation, expressed as:

$$\begin{aligned}&LCOC_{\text{without EV energy sharing}}=\frac{\text{EV capital cost}+\text{Cost for G2V}}{\text{Total EV charging energy from grid}}\\&=\frac{C_{\text{capital EV}}+\sum_{i=1}^{\text{Nth year}}\frac{C_{o\&M\,EV_i}}{(1+dr)^i}+\int_{t=1}^{t=\text{lifetime}}[P_{grid}(t)\times P_{G2V}(t)]dt}{\int_{t=1}^{t=\text{lifetime}}P_{G2V}(t)dt}\end{aligned} \tag{10}$$

where $P_{V2B}(t)$ and $P_{B2V}(t)$ equals to zero under this particular condition.

4) Levelized electricity cost (LEC) of prosumers

Figure 2 presents a detailed approach to calculating the levelized electricity cost (LEC) for prosumers in a distributed renewable energy system. The LEC accounts for the capital and operational maintenance costs of PV panels, including expenses arising from both the inherent battery degradation due to daily use and the additional degradation from engaging in EV energy sharing. It also includes the costs associated with the integration of secondary batteries, specifically retired EV batteries repurposed as static storage, which contributes to the prosumer's capital expenses. The calculation further incorporates the variable costs and profits from EV energy sharing arrangements, such as B2V and V2B transactions, where pricing is contingent upon the LCOE of BIPV and the time-of-use grid price. These components collectively determine the economic feasibility of a prosumer's engagement in this sustainable energy framework.

When electricity demand of prosumer is only supported by the renewable energy and local power grid, total cost of prosumer only includes the capital ($C_{capital\ BIPV}$), operational and maintenance ($C_{o\&M\ BIPV}$) costs for BIPV and electricity cost for grid (C_{grid}) from local power grid.

Levelized electricity cost (LEC) with BIPV and grid only is defined as:

$$LEC_{prosumer\ with\ BIPV\ \&\ grid} = \frac{BIPV capital\ cost + Cost for\ grid}{Total\ electricity\ demand\ of\ prosumer} = \frac{C_{capital\ BIPV} + \sum_{i=1}^{Nth\ year} \frac{C_{o\&M;\ BIPV,i}}{(1+dr)^i} + \int_{t=1}^{t=lifetime} (Pr_{grid}(t) \times ED_{with\ grid}(t))dt}{\int_{t=1}^{t=lifetime} ED(t)\,dt} \tag{11}$$

When EV involves in the energy sharing among prosumers, electricity demand of prosumer is supported by the renewable energy, local power grid, as well as EV energy sharing, total cost of prosumer includes the capital ($C_{capital\ BIPV}$), operational and maintenance ($C_{o\&M\ BIPV}$) costs for BIPV and electricity cost (C_{grid}) for local power grid, but also includes the cost for V2B process (C_{V2B}) and revenue from B2V process ($Revenue_{B2V}$).

$$LEC_{prosumer\ with\ BIPV\&grid\&EV\&SLB} = \frac{C_{Capital\ BIPV} + C_{o\&M\ BIPV} + C_{SLB} + C_{grid} + C_{V2B} - Revenue_{B2V}}{Total\ electricity\ demand\ of\ prosumer}$$
$$= \frac{C_{Capital\ BIPV} + \sum_{i=1}^{Nth\ year} \frac{C_{o\&M\ BIPV,i}}{(1+r)^i} + \int_{t=1}^{t=lifetime} (P_{rgrid}(t) \times ED_{with\ grid}(t))\ dt - LCOE_{BIPV} \times \int_{t=1}^{t=lifetime} ED_{with\ RE}(t)\,dt}{\int_{t=1}^{t=lifetime} ED(t)\,dt} \tag{12}$$

With the participation of EV energy sharing (B2V&V2B processes), previously dumped renewable energy can be reused, generating additional revenue for prosumers to reduce LEC.

Levelized electricity cost (LEC) of prosumer with BIPV, grid, EV energy sharing and EV battery cascade utilization

With the EV battery cascade utilization, total cost of prosumer additionally includes the cost of the retired EV battery (C_{SLB}) besides total cost with EV energy sharing. In addition to B2V&V2B processes, dumped renewable energy can be stored in secondary-life EV batteries (SLB) to further reduce the cost.

$$LEC_{prosumer\ with\ BIPV\&grid\&EV} = \frac{C_{Capital\ BIPV} + C_{o\&M\ BIPV} + C_{grid} + C_{V2B} - Revenue_{B2V}}{Total\ electricity\ demand\ of\ prosumer}$$
$$= \frac{C_{Capital\ BIPV} + \sum_{i=1}^{Nth\ year} \frac{C_{o\&M\ BIPV,i}}{(1+dr)^i} + \int_{t=1}^{t=lifetime} (P_{grid}(t) \times ED_{with\ grid}(t))\,dt - LCOE_{BIPV} \times \int_{t=1}^{t=lifetime} ED_{with\ RE}(t)\,dt}{\int_{t=1}^{t=lifetime} ED(t)\,dt} \tag{13}$$

Levelized carbon mitigation subsidy (LCMS) for economic feasibility and environmental sustainability

Levelized carbon mitigation subsidy (LCMS) is defined as the subsidy for the carbon mitigation when the net EV cost is greater than zero.

$$LCMS = \frac{Net\ \ EV\ \ cost}{Carbon\ \ reduction\ \ with\ \ EV} \tag{14}$$

(Note: Net EV cost represents difference between total cost of EV with energy sharing and total EV cost without EV energy sharing.)

RESULTS

Centralized energy transition and market acceptance

For the energy transmission in the centralized renewable energy system, it follows the traditional transmission line that solar energy generated by the centralized PV market can be supplied to consumers via the traditional grid infrastructure. However, in the centralized renewable energy system, free trading market between centralized PV markets and consumers significantly differs from the traditional trading market between centralized PV market and government. Traditionally, centralized PV markets profit through the feed-in tariff (FiT) from government, resulting in limited profits for centralized PV markets and financial burden on the government. However, itis operated with the negotiated renewable energy trading price between centralized PV markets and consumers. This significantly alleviates the financial burden on the government and enhances the participation willingness of centralized PV markets and consumers by offering higher profit margins.

Figure 3 shows the dynamic acceptance process of the free trading market in the centralized renewable energy system. Without FiT from government, standard for the establishment of the trading in the centralized renewable energy system is that the levelized cost of energy (LCOE) of centralized PV requires to be lower than the regional average grid price, while renewable energy trading price in the trading requires to be set between the LCOE and average grid price. In this study, range of the renewable energy trading price has been quantified (as indicated in blue marked regions in Figure 3). This price range serves as the standard for assessing whether it can be established in the centralized renewable energy system. When the renewable energy trading price surpasses the upper limit of the identified price range (shown as Max RE trading price (average grid price) in Figure 3), it loses the market competitiveness against local power grid (as building consumers will choose the local power grid for electricity supply, instead of renewable energy). On the other hand, when renewable energy trading price is even less than the lower limit of the identified price range (shown as Min RE trading price (LCOE) in Figure 3), centralized renewable energy market cannot realize any profit (as the renewable energy trading income is lower than initial investment cost of renewable systems).

Based on this standard above, although free trading market in 2020 cannot be universally achieved in all regions, it can be achieved by 2060 for both office and residential buildings in all regions. For example, for residential buildings in Kunming in 2020, LCOE at 0.32 CNY/kWh is higher than the average grid price at 0.3 CNY/kWh, resulting in the untenability of the trading. However, in 2060, LCOE in all regions is much lower than the average grid price, resulting in the establishment of the trading. This is due to the rapid cost declines and increased grid price and solar energy penetration that results in higher profit margin until 2060. Overall, this analysis highlights the role of free trading markets in boosting renewable energy adoption, which ensures economic competitiveness and the feasibility of centralized PV markets over traditional local power grids.

Distributed energy transition with electric vehicles and market acceptance

Compared to the centralized energy transition, distributed energy transition is more flexible, controllable, and accessible, like BIPVs, electric vehicles (EVs), fuel cell, combined heat and power generators, and so on. The integration of these technologies enhances connections among multiple stakeholders, particularly for EV owners and prosumers involved in B2V/V2B energy sharing in the distributed renewable energy system. Unlike the traditional levelized cost of charging (LCOC) of EV without considering B2V/V2B EV energy sharing,[40] the LCOC under the B2V/V2B energy sharing needs to consider the net cost during the energy trading between EV owners and buildings. As shown in Figure 4, EV energy sharing and EV battery cascade utilization can be deployed in the distributed renewable energy system to improve the renewable energy penetration and energy efficiency, leading to higher economic benefits for both EV owners and prosumers to compensate the economic burden for additional cycling aging costs on EVs and capital investment costs on BIPVs. Therefore, economic performance of EVs and prosumers needs to be analysed, simultaneously considering additional EV energy sharing process and EV battery cascade utilization.

Based on the free market trading in the distributed renewable energy system, LCOC of EV determines whether the business model of EV-based

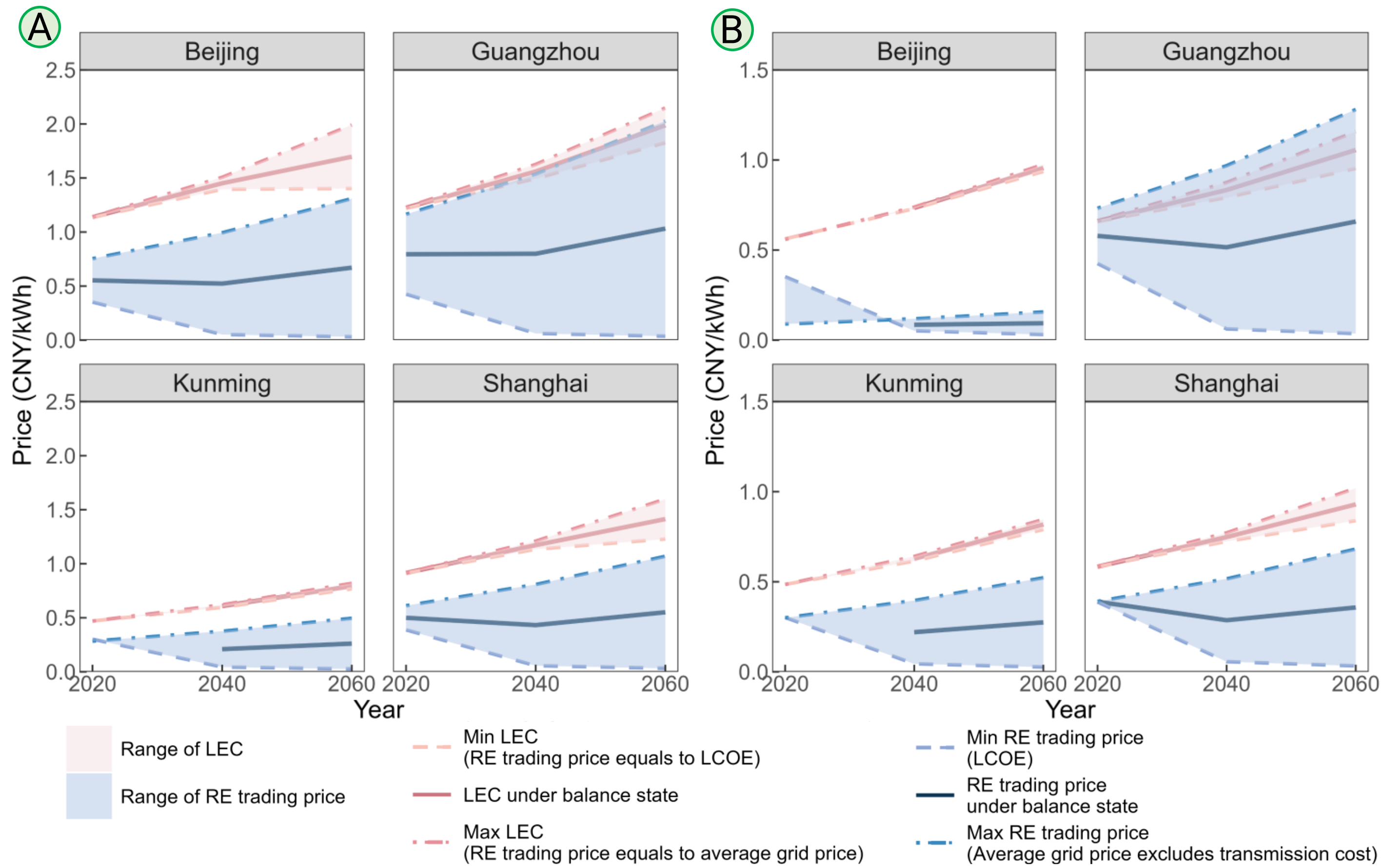


Figure 3. Economic metrics in the centralized renewable energy trading market (A) Office building, (B) Residential building.

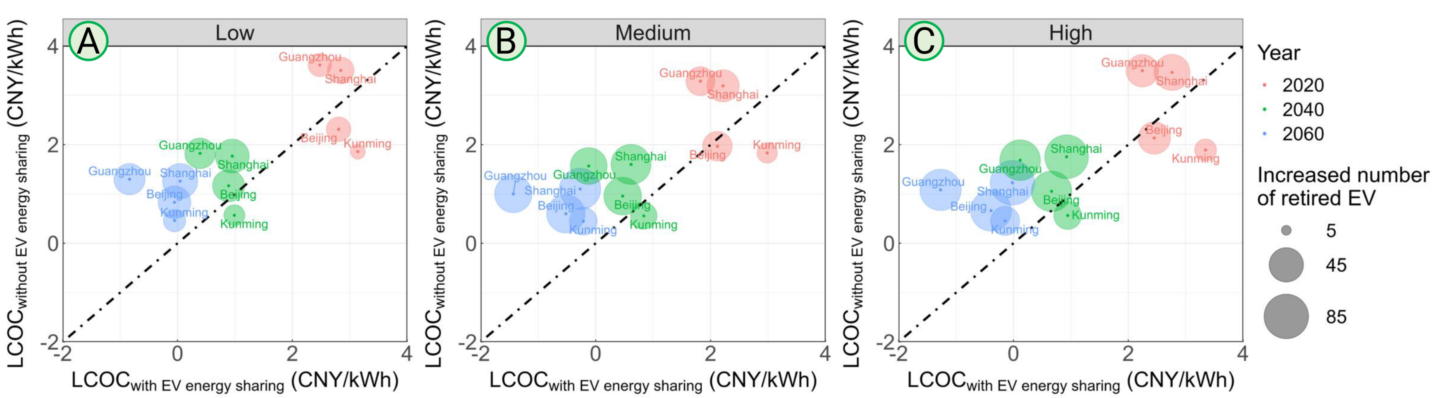


Figure 4. Impact of EV energy sharing on the levelized cost of charging (LCOC) in the distributed renewable energy trading market (A) Low EV charging/discharging mode, (B) Medium EV charging/discharging mode, (C) High EV charging/discharging mode. Low, medium, and high charging/discharging mode refers to the maximum EV charging/discharging power at 5 kW, 15 kW and 50 kW, respectively. The black dashed line represents the scenario where there is no impact of EV energy sharing on LCOC. The upper part of the dashed line indicates a decrease in LCOC through EV energy sharing, while the lower part indicates an increase in LCOC through EV energy sharing. The size of the bubble represents the number of retired EVs by participating in EV energy sharing subtracting the number of retired EVs by not participating in EV energy sharing (i.e., EV for daily transportation only).

spatiotemporal renewable energy sharing can be widely accepted or not. Figure 4 depicts the impact of EV energy sharing on LCOC under different EV charging/discharging modes (i.e., low, medium, and high charging/discharging modes at 5 kW, 15 kW and 50 kW, respectively), considering the trade-off between additional capital cost (i.e., battery degradation and replacement costs due to accelerated EV battery degradation) and additional profits (i.e., profits from B2V/V2B energy sharing process) in EV energy sharing. Economic feasibility of EV energy sharing cannot be achieved in Beijing and Kunming in 2020. For example, as shown in Figure 4C, in Beijing in 2020 under high charging/discharging mode, LCOC without EV energy sharing at 2.13 CNY/kWh is even lower than LCOC with EV energy sharing at 2.45 CNY/kWh. This indicates that additional profit through EV energy sharing cannot compensate the additional capital cost, especially when capital cost of battery is relatively high and grid price for profit is relatively low in 2020.

However, a considerable decrease of LCOC with EV energy sharing can be observed from 2020 to 2060, resulting in the economic feasibility of EV energy sharing compared with the traditional EV mode (i.e., EV for daily transportation only) until 2060. For example, as shown in Figure 4C, in Guangzhou under the high charging mode, the LCOC without EV energy sharing decreases from 3.50 CNY/kWh in 2020 to 1.08 CNY/kWh in 2060, and the LCOC with EV energy sharing decreases from 2.24 CNY/kWh in 2020 to -1.27 CNY/kWh in 2060. The gradual decrease in LCOC from 2020 to 2060 is

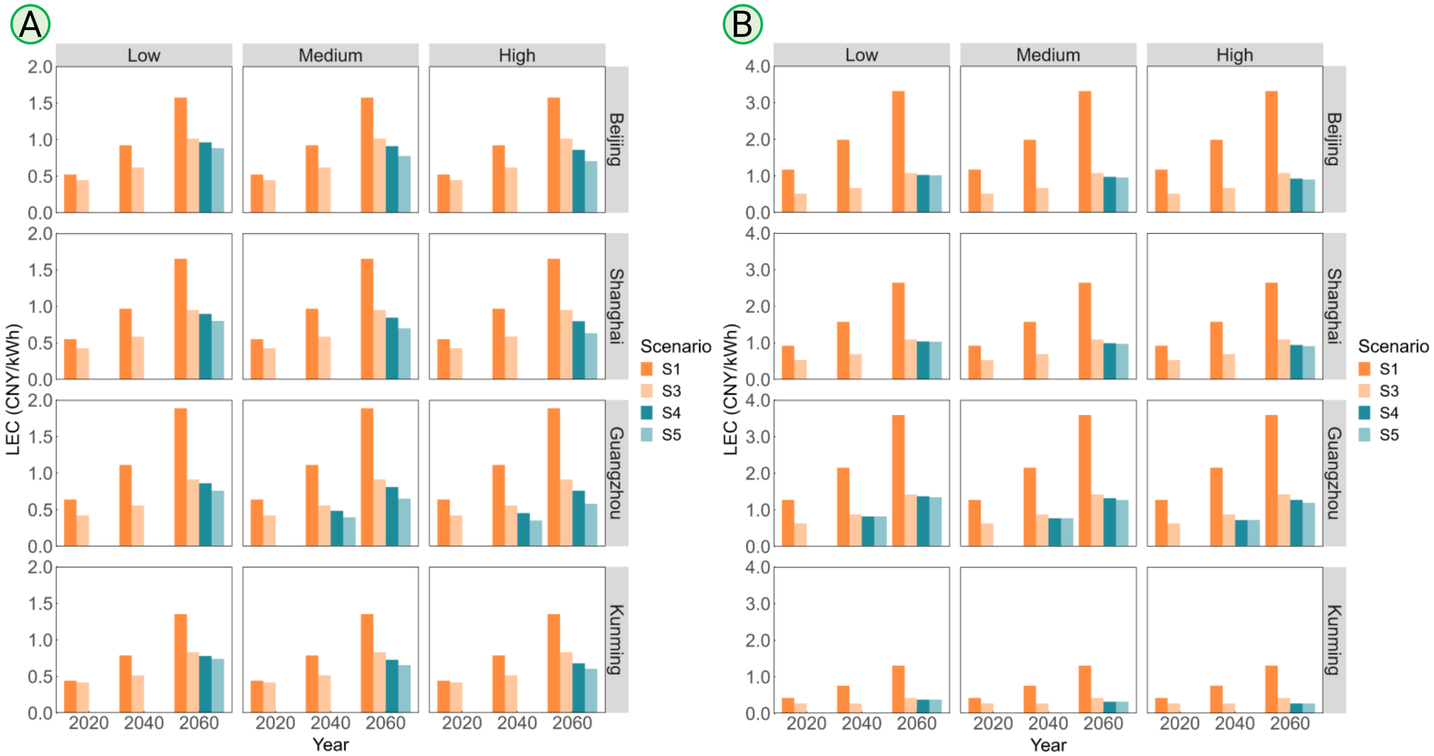


Figure 5. Impact of EV energy sharing on the levelized electricity cost (LEC) in the distributed renewable energy trading market (A) Office building, (B) Residential building. Specifically, S1 refers to the traditional energy system where consumers only depend on the electricity from local power grid. S3 refers to the distributed renewable energy system with BIPV and without EV energy sharing. S4 refers to the distributed renewable energy system with the advanced integration of BIPV and EV energy sharing. S5 refers to the distributed renewable energy system with the integration of BIPV, EV energy sharing and EV battery cascade utilization. S2 refers to the centralized renewable energy system.

mainly attributed to the rapid decrease in the EV battery cost and the increase in grid price, which results in lower cost investment and higher profit margins for EV owners. Moreover, high profit margin for EV owners can be achieved to promote the EV energy sharing until 2060. The negative value of LCOC with EV energy sharing in Guangzhou under the high charging mode is -1.27 CNY/kWh, which is the sum of battery cost at 1.09 CNY/kWh, G2V cost at 1.03 CNY/kWh, B2V cost at 0.03 CNY/kWh, and V2B cost at -3.42 CNY/kWh. This indicates that, by adopting the EV energy sharing, the EV owner can additionally earn 1.27 CNY/kWh when being charged by renewables and spatial heterogeneity in grid prices of local power grids, instead of paying back to the power grid under the traditional EV charging mode. This high profit margin is due to the low initial investment cost in battery and high grid price with higher profit margin for EV energy sharing until 2060.

Furthermore, LCOC with EV energy sharing also highly depends on different EV charging/discharging modes. On the one hand, EV charging/discharging mode affects the battery cycling aging cost (i.e., a faster battery cycling aging under a higher EV charging/discharging mode). On the other hand, EV charging/discharging mode determines the amount of energy transmitted through EV energy sharing, as well as the following profit from EV energy sharing (i.e., more energy can be transmitted under high EV charging/discharging mode with higher profit). However, depending on the relative correlation between increased capital cost (e.g., battery degradation and replacement costs due to accelerated EV battery degradation) and additional economic profits (i.e., profits from B2V/V2B energy sharing process), the medium charging/discharging mode leads to the lowest LCOC compared to the low and high charging/discharging modes. For example, as shown in Figure 4C, in Guangzhou in 2020, the LCOC under the medium charging/discharging mode at 1.82 CNY/kWh is lower than the LCOC under the low charging/discharging mode at 2.48 CNY/kWh and high charging/discharging mode at 2.24 CNY/kWh. This indicates that the medium charging/discharging mode shows superiorities than both the low and high charging/discharging modes, in terms of compensating for the additional EV battery cycling aging cost through the economic profit of EV energy sharing. Therefore, with the comprehensive consideration on economic profits and additional EV battery cycling aging costs, the recommended EV charging/discharging mode for EV energy sharing is the medium charging/discharging mode with the minimum LCOC with EV energy sharing.

Although economic impact of EV energy sharing has been evaluated through LCOC, participation of EV owners with EV energy sharing also significantly affects the economic performance of prosumers in the distributed renewable energy trading market. Figure 5 demonstrates the impact of BIPV installation, EV energy sharing and EV battery cascade utilization on the levelized electricity cost (LEC) in residential and office buildings, respectively. For both residential and office buildings, BIPV is the primary driving force for the LEC reduction, while the reduction magnitude of LEC gradually increases from 2020 to 2060. For example, as shown in Figure 5B, for the office building in Guangzhou, the LEC in 2020 decreases from 1.37 CNY/kWh (in S1 without BIPV) to 0.73 CNY/kWh (in S3 with BIPV) by 0.64 CNY/kWh, while it reduces from 3.69 CNY/kWh (in S1 without BIPV) to 1.52 CNY/kWh (in S3 with BIPV) by 2.17 CNY/kWh in 2060. This is due to the rapid decrease of PV cost (from 1.34×10^4 CNY/kW in 2020 to 4.6×10^3 CNY/kW in 2060) and the increase of grid price (from 1.23 CNY/kWh in 2020 to 2.15 CNY/kWh in 2060) from 2020 to 2060.

Moreover, although EV energy sharing can reduce the LEC, reduction magnitude of LEC under different charging/discharging modes is not obvious. For instance, as shown in Figure 5B, in Guangzhou in 2060, LEC in office building under the high charging/discharging mode at 1.37 CNY/kWh (in S4 with EV energy sharing) is only slightly smaller than that under the low charging/discharging mode at 1.47 CNY/kWh (in S4 with EV energy sharing). This slight decrease in LEC through EV energy sharing is restricted by the fixed EV schedule, which limits the flexible interactions between EV owners and prosumers and further constrains cost-savings from the curtailed renewable energy.

Furthermore, EV battery cascade utilization can help reduce the LEC. Compared to the office building, impact of EV battery cascade utilization on the LEC reduction in the residential building is more obvious. For instance, in Guangzhou in 2060, LEC for office building reduces from 1.37 CNY/kWh with EV energy sharing (in S4) to 1.29 CNY/kWh with EV cascade utilization (in S5)

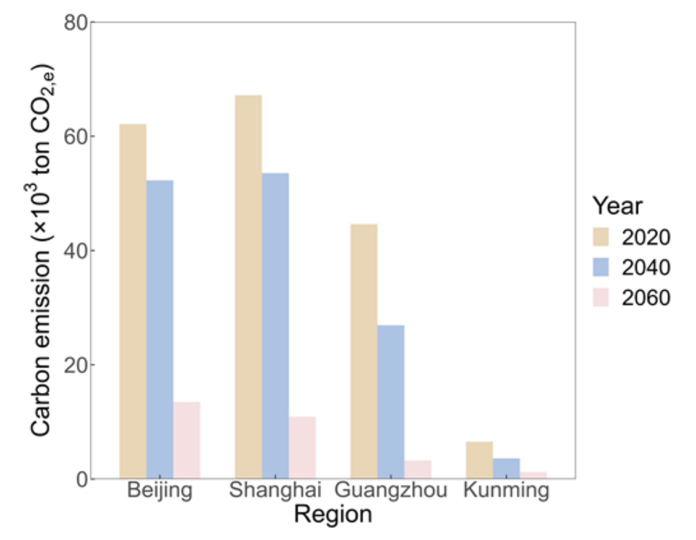


Figure 6. Operational carbon emissions of the centralized renewable energy trading market.

(as shown in Figure 5B), while LEC in residential building reduces from 0.91 CNY/kWh with EV energy sharing (in S4) to 0.75 CNY/kWh with EV battery cascade utilization (in S5). The more obvious reduction on LEC in residential building with EV battery cascade utilization is due to the higher mismatch between electricity demand and renewable energy generation, which allows the retired EV battery to store more excess energy to enhance renewable energy utilization and reduce the LEC.

Overall, EV energy sharing and EV battery cascade utilization can not only promote the adoption and sustainability of the distributed renewable energy system, but also contribute to the economic benefit for EV owners and prosumers in the distributed renewable energy system. Integration of the economic performance of EV energy sharing and EV battery cascade utilization into LCOC and LEC assessments is crucial for EV owners and prosumers to actively participate in the distributed renewable energy system. This integration further highlights the importance of the rapid cost decline of renewables and EV batteries for the economic feasibility of EV sharing and EV battery cascade utilization in the distributed renewable energy system.

Carbon emissions of future advanced power systems

Based on above analysis, advanced technologies (like PV installation, B2V/V2B, EV energy sharing, EV battery cascade utilization and so on) with technical readiness and cost decline on renewable systems can contribute to sustainability transformation with renewable-grid-demand-storage synergies and direct free trading market with considerable economic performance. However, the environmental performance of the advanced energy paradigm and the direct free trading market transformations is critical as well for national carbon neutrality transformation. This section aims to demonstrate the carbon emission evolution based on the transition towards advanced energy paradigm and direct free trade market from the environmental perspective.

Along with the technology readiness and cost decline, participators in advanced energy paradigm and direct free trade market greatly increase, together with system decarbonization. Trade-off between the environmental and economic performance of the renewable energy system needs to be considered. Figure 6 demonstrates the operational carbon emission of the centralized renewable system with the cleaner power grid upgrade (from 68.9% thermal power generation in 2020 to 2.5% in 2060 in Guangzhou). Carbon emission of the centralized renewable energy system is greatly reduced from 2020 to 2060 among all regions. For example, carbon emission in Guangzhou is reduced from 4.5×10^4 ton $CO_{2,e}$ in 2020 to 3.3×10^3 ton $CO_{2,e}$ in 2060. Substantial reduction in carbon emission for the centralized renewable energy system is mainly due to the upgrade of the cleaner grid with increased penetration of renewable energy.

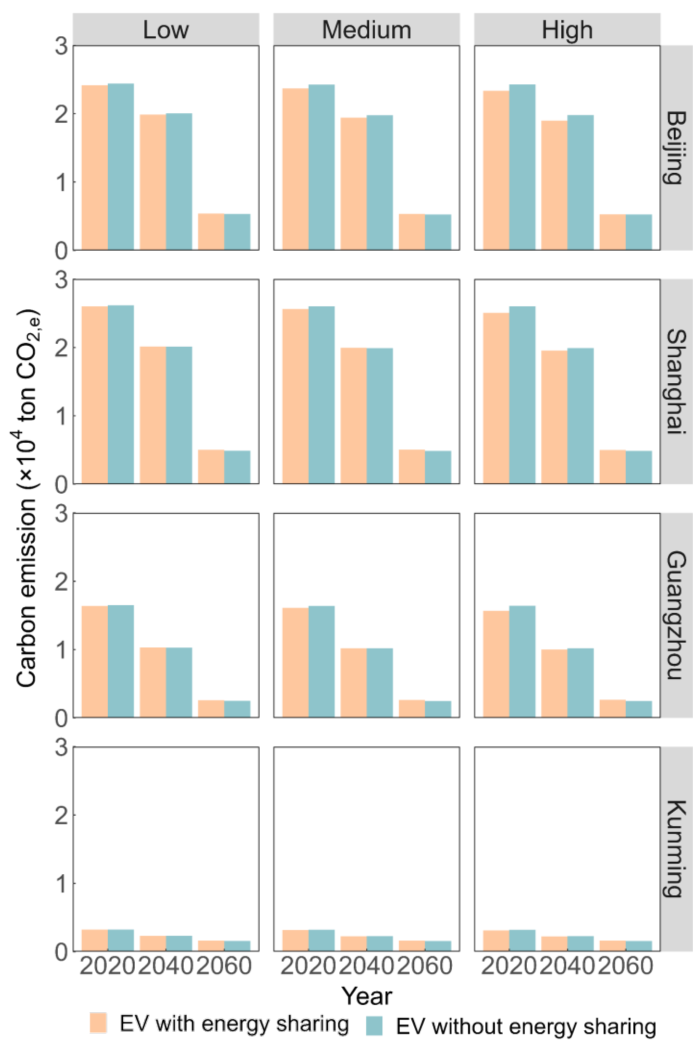


Figure 7. Impact of EV energy sharing on the operational carbon emissions in the distributed renewable energy trading market Low, medium, and high charging/discharging mode refers to the maximum EV charging/discharging power at 5 kW, 15 kW and 50 kW, respectively.

Compared to the decarbonization of the centralized renewable energy system with gradually increasing solar penetration, environmental performance of the distributed renewable energy system needs to be assessed, especially considering the additional carbon emission associated with the increased number of EV batteries in EV energy sharing. Figure 7 compares the operational carbon emission with and without EV energy sharing in the distributed renewable energy system. EV energy sharing can reduce carbon emission in the distributed renewable energy system. However, until 2060, decarbonization magnitude by EV energy sharing becomes less significant. For instance, in Guangzhou under the high charging/discharging mode, compared to carbon emission at 1.64×10^4 ton $CO_{2,e}$ without energy sharing in 2020, carbon emission with EV energy sharing decreases to 1.57×10^4 ton $CO_{2,e}$, leading to 700 ton carbon emission reduction. However, in 2060, compared to carbon emission at 2.66×10^3 ton $CO_{2,e}$ without energy sharing, carbon emission with EV energy sharing decreases to 2.47×10^3 ton $CO_{2,e}$, leading to only 190 ton carbon emission reduction. This is mainly due to the upgrade of the cleaner grid, which greatly reduces the impact of EV on decarbonization.

Based on above analysis, although free trading market between the EV and prosumers in the distributed renewable energy system cannot be established until 2060, decarbonization of the distributed renewable energy system with EV and prosumers has been demonstrated. Therefore, in order to promote the decarbonization of the distributed renewable energy system before the establishment of the free trading market, carbon subsidy needs to be applied for EV owners to compensate their economic investment. As shown in Figure 8, levelized carbon mitigation subsidy (LCMS) serves as the reward for the decarbonization of EV energy sharing to offset the increased total cost for EV owners and ensure the economic feasibility of the free trading market in the distributed renewable energy system. EV energy sharing under the high charging mode is more suitable before the establishment of the free trading market in the distributed renewable energy system. For example, in Guangzhou in 2020, LCMS under high charging/discharging mode at 76 CNY/ton $CO_{2,e}$ is much lower than LCMS under low and medium charging/discharging mode at 273 CNY/ton $CO_{2,e}$ and 130 CNY/ton $CO_{2,e}$, respectively.

Moreover, compared with the suggested carbon price range from 76 to 152 CNY/ton $CO_{2,e}$ in China[42], LCMS for EV owners maximally reaches to 273 CNY/ton $CO_{2,e}$, which is over twice of the suggested carbon price. High cost of EV battery with high capital cost on EV batteries and small EV scale with limited decarbonization ability in 2020 are still the most fundamental issues. Additionally, the ability of decarbonization and cost-saving of EV is also restricted by a fixed EV schedule that lacks flexible interaction between EV owners and prosumer for the utilization of the curtailed renewable energy. Therefore, in the distributed renewable energy system, although the LCMS for EV owner is currently higher than the proposed carbon price in China, this subsidy can be applied for the temporary transition to promote the EV decarbonization (like smart EV scheduling, reduced costs of renewables and batteries, etc) before the establishment of the free trading market. Such an interim measure is critical since it continuously promotes the decarbonization of EVs in the distributed renewable energy system and bridges the gap before the establishment of the free trading market with cost declines and increasing EV scale in the future.

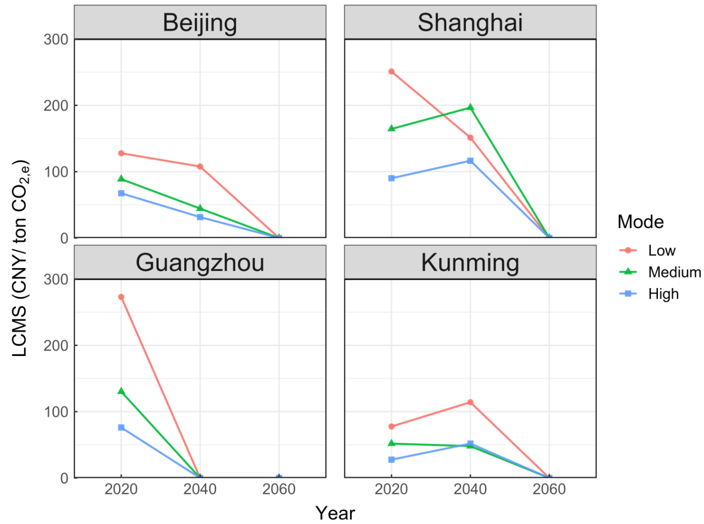


Figure 8. Levelized carbon mitigation subsidy (LCMS) for EV owners.

DISCUSSION

Considering considerable heavy economic burdens of local government from subsidy or grid feed-in tariffs, the fully government-supported decarbonization strategies currently face critical challenges in sustainability and worldwide scalability. In order to radically replace the current government dominated renewable market by free trading market with spontaneous participations of various stakeholders in investment, trading, recycling activities, this study explores establishment conditions, economic viability and feasibility on direct market-to-consumer trading without any subsidy from local government. Impact of rapid cost decline and technical readiness of renewables and storages on direct trading has been studied for both centralized and distributed renewable energy systems, considering both regional energy and economic balances among stakeholders. For the centralized renewable energy system, it has been developed based on the energy trading between centralized PV market and consumers. Furthermore, considering the flexible, controllable, and accessible of distributed renewable energy system, it has also been proposed in the distributed renewable energy system with EV energy trading between EV owners and prosumers. Trade-off between the economic profits from EV energy sharing and additional battery cycling aging cost has been identified and analysed under the rapid cost decline of both renewables and battery. To incentivise multi-stakeholders' proactivity and market vitality, free energy trading market with advanced energy pricing policy has been therefore proposed with the objective to increase the economic benefits and promote participation willingness of each stakeholder. Moreover, trade-off between the profit margin and carbon emission in the free trading market has been explored to balance the economic feasibility and environmental sustainability based on dynamic energy trading and associated cost decline. Key results are summarised below:

1) Establishment conditions on free trading market without economic pressure of local government via subsidy or grid feed-in tariffs have been clearly identified, so as to judge and promote the future renewable free market with spontaneous renewable installations and trading among stakeholders. Compared to the levelized cost of energy (LCOE) and profit of PV in China before 2018[43], profit of PV energy trading after 2020 under the shift in policy and economic context is influenced by self-negotiated PV trading price and LCOE, instead of feed-in tariff supported by the government. This research provides the economic feasibility of renewable energy under the rapid cost decline of PV and the absence of a feed-in tariff.

For the centralized renewable energy system, free trading market of the centralized renewable energy system is established when levelized cost of energy (LCOE) of PV is less than the average grid price. For the distributed renewable energy system with EV-based energy sharing, trading between EV owners and prosumers is established only when the total cost for EV owners and levelized cost of charging (LCOC) with EV energy sharing is lower than those under traditional EV mode (i.e., EV for daily transportation only). This establishment condition ensures that EV owners can benefit from free trading in the distributed renewable energy system, leading to cost saving from EV energy sharing compared to the traditional EV mode without EV energy sharing. Based on the above establishment condition, free trading market in centralized renewable energy system can be completely achieved after 2040, while free trading market in distributed renewable energy trading market between EV owners and prosumers cannot be established until 2060. In other words, for the centralized renewable energy system, both the centralized PV market and consumers can benefit after 2040. For the distributed renewable energy trading market, prosumers are willing to install PV since 2020, while EV owners are not willing to participate in the EV energy sharing until 2060.

In practical applications, conditions for establishing a free trading market proposed in this research can be used to evaluate whether a future renewable energy market can operate autonomously without government subsidies. This allows energy producers to assess profitability without relying on subsidies, enables consumers to purchase energy directly from producers at potentially lower costs, and facilitates energy trading among EV owners and prosumers for economic benefits. These conditions collectively provide a quantitative measurement for the self-sustaining, economically viable renewable energy market.

2) Technology readiness and rapid cost declines of renewables and battery storages can contribute to the free trading market with EV owners' role transition from cost payers to economic owners. Previous research has primarily defined EV as consumers, focusing on the levelized cost of charging (LCOC) in terms of various electricity prices for EVs charging at different locations and under various charging modes.[40,41] However, the participation of EV owners in EV energy sharing transforms the role of EV from merely consuming electricity to actively participating in flexible energy interactions, leading to new LCOC models and represents an emerging trend in the future of energy sharing.

The smart energy management can further promote participators and stakeholders to win economic benefits under the rapid cost declines, enabling multi-stakeholders' proactivity and market vitality. Due to the rapid decrease of battery cost and increase of grid price, EV owners will transit from cost payers to economic earners, along with the levelized cost of charging (LCOC) with EV energy sharing in Guangzhou under the high charging mode decreases from 2.24 CNY/kWh in 2020 to -1.27 CNY/kWh in 2060. Regarding prosumers in the distributed renewable energy system, the levelized electricity cost (LEC) for office building in 2060 reduces from 3.69 CNY/kWh with local power grid to 1.37 CNY/kWh with BIPV installation and EV energy sharing, and further decreases to 1.29 CNY/kWh with EV cascade utilization. Consequently, levelized cost in this research is proposed considering the impact of the rapid technology development on the rapid cost declines of renewables and battery storages. In practical applications, it can be served as a reference to guide the formulation of trading prices, taking into account the significant impact of technological advancements and cost reductions in renewables and battery storage systems. This ensures that the pricing mechanism remains economically viable and reflective of current market conditions.

3) The promotion of free trading market can enable decarbonizations and contribute to the global carbon neutrality target worldwide. By economically incentivising multi-stakeholders' proactivity in participating, market vitality for renewable installation and spatiotemporal energy sharing with high renewable penetration can be activated microgrids. Although economic feasibility for the EV energy sharing in the distributed renewable energy system cannot be achieved until 2060, carbon emission is greatly reduced among all regions due to the upgrade of the cleaner grid with incremental penetration of renewable energy. Based on the above condition, levelized carbon mitigation subsidy (LCMS) is proposed as the subsidy for EV decarbonization to compensate the additional cost for EV energy sharing compared to the traditional EV mode (i.e., EV for daily transportation only). LCMS, ranging from 28 CNY/ton $CO_{2,e}$ to 273 CNY/ton $CO_{2,e}$, can be considered as the temporary economic subsidy to keep the role of carbon reduction of EV energy sharing before the establishment of the distributed free trading market. Compared with the predicted carbon price ranging from 194 to 283 CNY/ton $CO_{2,e}$ in 2040 and from 359 to 1614 CNY/ton $CO_{2,e}$ in 2060,[44] carbon mitigation subsidy in this research is significantly lower than the prevailing carbon prices in the broader market. Therefore, carbon emission mitigation subsidy proposed in this research can be assumed as a reasonable and temporary transitional solution to incentivize early adoption of free trading market.

Accordingly, carbon emission mitigation subsidy proposed in this research can be assumed as a temporary transitional solution to support the establishment of a free trading market. This subsidy can be applied in practice to offset additional costs associated with renewable energy adoption and EV energy sharing. By providing financial support during the transition period, this approach helps maintain stakeholder engagement and promotes gradual market development until trading can operate independently and sustainably.

This study explores the establishment of frontier free trading market under the increasing technology maturity and economic viability in the centralized and distributed renewable energy system, which can be widely applied to promote the free market in reality. In order to achieve this goal, concerted efforts are essentially required to integrate energy interaction and foster collaboration among multi-stakeholders. Government and policymakers are encouraged to set ambitious renewable energy targets and remove regulatory barriers to accelerate the implementation of renewable energy projects and encourage investment in related technologies and infrastructure. Additionally, government should provide financial risk mitigation to create a stable and long-term regulatory economic environment for the investment of the renewable energy trading. Moreover, multiple stakeholders, including EV owners, prosumers, and renewable energy developers, are economically incentivised in the free trading market based on the proposed energy sharing framework, with advanced energy pricing policy, flexible energy interaction and sustainable carbon emission. It can also be integrated with smart grids and advanced energy management technologies to further enhance grid stability and efficiency. Dynamic pricing models and real-time energy trading platforms can be combined with the proposed free trading market to maximize economic benefits while ensuring flexible and stable energy interactions. Overall, this research offers essential guidance for policymakers and stakeholders striving to promote the sustainable development of the renewable energy trading market. Future studies can focus on economic benefits analysis with bioenergy production supply chain[45] and free trading market with battery safety through internal short circuit diagnosis.[46]

REFERENCES

1. IPCC. Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, IPCC - Sr15 (2018).
2. United Nations News. Chinese President Pledges Carbon Neutrality by 2060. (2020). https://news.un.org/en/story/2020/09/1073052.
3. Chen X., Shuai C., Wu Y. et al. (2020). Analysis on the carbon emission peaks of China' s industrial, building, transport, and agricultural sectors. *Sci. Total Environ.* **709**:135768. DOI:10.1016/j.scitotenv.2019.135768
4. Wang J., Chen L., Tan Z., et al. (2023). Inherent spatiotemporal uncertainty of renewable power in China. *Nat. Commun.* **14**:5379. DOI:10.1038/s41467-023-40670-7
5. Zakaria A., Ismail F. B., Lipu M. S. H. et al. (2020). Uncertainty models for stochastic optimization in renewable energy applications. *Renew. Energy* **145**:1543–1571. DOI:10.1016/j.renene.2019.07.081
6. Zhou Y. (2023). Climate change adaptation with energy resilience in energy districts—A state-of-the-art review. *Energy Build.* **279**:112649. DOI:10.1016/j.enbuild.2022.112649
7. He G., Lin J., Sifuentes F., et al. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. *Nat. Commun.* **11**:2486. DOI:10.1038/s41467-020-16184-x
8. Braff W. A., Mueller J. M. and Trancik, J. E. (2016). Value of storage technologies for wind and solar energy. *Nat. Clim. Change* **6**:964–969. DOI:10.1038/nclimate3045
9. Zhuo Z., Du E., Zhang N., et al. (2022). Cost increase in the electricity supply to achieve carbon neutrality in China. *Nat. Commun.* **13**:3172. DOI:10.1038/s41467-022-30747-0.
10. Dong, Q., Liang S., Li J., et al. (2023). Cost, energy, and carbon footprint benefits of second-life electric vehicle battery use. *iScience* **26**:107195. DOI:10.1016/j.isci.2023.107195.
11. Kim C. (2021). A review of the deployment programs, impact, and barriers of renewable energy policies in Korea. *Renew. Sustain. Energy Rev.* **144**:110870. DOI:10.1016/j.rser.2021.110870
12. Atsu D., Seres I. and Farkas I. (2021). The state of solar PV and performance analysis of different PV technologies grid-connected installations in Hungary. *Renew. Sustain. Energy Rev.* **141**:110808. DOI:10.1016/j.rser.2021.110808
13. Li S., Peng J., Li H., et al. (2022). Zero energy potential of PV direct-driven air conditioners coupled with phase change materials and load flexibility. *Renew. Energy* **200**:419–432. DOI:10.1016/j.renene.2022.09.088
14. Nobuyoshi Y. J. R., Ochoa A. A. V., Leite G. N. P., et al. (2023). Real-time energy and economic performance of the multi-zone photovoltaic-drive air conditioning system for an office building in a tropical climate. *Energy Convers. Manag.* **297**:117713. DOI:10.1016/j.enconman.2023.117713
15. Ozcan H. G., Varga S., Gunerhan H. A., et al. (2021). Numerical simulation and parametric study of various operational factors affecting a PV-battery-air conditioner system under prevailing European weather conditions. *Sustain. Cities Soc.* **67**:102754. DOI:10.1016/j.scs.2021.102754
16. Reda F., Paiho S., Pasonen R., et al. (2020). Comparison of solar assisted heat pump solutions for office building applications in Northern climate. *Renew. Energy* **147**:1392–1417. DOI:10.1016/j.renene.2019.09.044
17. Zhao P., Xu W., Liu A., et al. (2022). Performance evaluation of a renewable driven standalone combined power and water supply system with cascade electricity and heat storage. *Renew. Energy* **199**:1283–1299. DOI:10.1016/j.renene.2022.09.089
18. Abedrabboh O., Ko M. and Bier Y. (2024). Comparative thermoeconomic assessment of renewable-driven hybrid-cooled sustainable greenhouses for subtropical regions. *Energy Convers. Manag.* **300**:117990. DOI:10.1016/j.enconman.2023.117990
19. Makolo P., Zamora R. and Lie T. T. (2021). The role of inertia for grid flexibility under high penetration of variable renewables - A review of challenges and solutions. *Renew. Sustain. Energy Rev.* **147**:111223. DOI:10.1016/j.rser.2021.111223
20. Cole W. J., Greer D., Denholm P., et al. (2021). Quantifying the challenge of reaching a 100% renewable energy power system for the United States. *Joule* **5**:1732–1748. DOI:10.1016/j.joule.2021.05.011
21. Dowling J. A., Renaldi K. Z., Ruggles T. H., et al. (2020). Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule* **4**:1907–1928. DOI:10.1016/j.joule.2020.07.007
22. Kittner N., Castellanos S., Hidalgo-Gonzalez P., et al. (2021). Cross-sector storage and modeling needed for deep decarbonization. *Joule* **5**:2529–2534. DOI:10.1016/j.joule.2021.09.003
23. Faraj K., Khaled M., Faraj J., et al. (2020). Phase change material thermal energy storage systems for cooling applications in buildings: A review. *Renew. Sustain. Energy Rev.* **119**:109579. DOI:10.1016/j.rser.2019.109579
24. Khalaf A. E., Eleiwi M. A. and Yassen T. A. et al. (2023). Enhancing the overall performance of the hybrid solar photovoltaic collector by open water cycle jet-cooling. *Renew. Energy* **208**:492–503. DOI:10.1016/j.renene.2023.02.122
25. Han Z., Liu K., Li G., et al. (2021). Electrical and thermal performance comparison between PVT-ST and PV-ST systems. *Energy* **237**:121589. DOI:10.1016/j.energy.2021.121589
26. Carmona M., Palacio Bastos A. and García J. D. (2021). Experimental evaluation of a

hybrid photovoltaic and thermal solar energy collector with integrated phase change material (PVT-PCM) in comparison with a traditional photovoltaic (PV) module. *Renew. Energy* **172**:680–696. DOI:10.1016/j.renene.2021.03.098
27. Wolfram P., Weber S., Gillingham K., et al. (2021). Pricing indirect emissions accelerates low-carbon transition of US light vehicle sector. *Nat. Commun.* **12**:7121. DOI:10.1038/s41467-021-27247-y
28. Peng L., Mauzerall D. L. and Zhong Y. D. (2023). Heterogeneous effects of battery storage deployment strategies on decarbonization of provincial power systems in China. *Nat. Commun.* **14**, 4858 (2023). DOI:10.1038/s41467-023-40337-3.
29. Minoofar A., Mohtasebi S. S., Hashemianzadeh S., et al. (2023). Renewable energy system opportunities: A sustainable solution toward cleaner production and reducing carbon footprint of large-scale dairy farms. *Energy Convers. Manag.* **293**:117554. DOI:10.1016/j.enconman.2023.117554
30. Zhao W. (2022). China's goal of achieving carbon neutrality before 2060: experts explain how. *Natl. Sci. Rev.* **9**:nwac115. DOI:10.1093/nsr/nwac115
31. Liu P., Zhang C., Wang Y., et al. (2021). Carbon footprint and carbon emission intensity of grassland wind farms in Inner Mongolia. *J. Clean. Prod.* **313**:127878. DOI:10.1016/j.jclepro.2021.127878
32. Ballif C., Perret-Aebi L.-E., Lufkin S., et al. (2018). Integrated thinking for photovoltaics in buildings. *Nat. Energy* **3**. DOI:10.1038/s41560-018-0176-2.
33. Liu Z., Jiang Y., Li F., et al. (2021). A comprehensive study of feasibility and applicability of building integrated photovoltaic (BIPV) systems in regions with high solar irradiance. *J. Clean. Prod.* **307**:127240. DOI:10.1016/j.jclepro.2021.127240
34. Alves M., Segurado R. and Costa M. (2020). On the road to 100% renewable energy systems in isolated islands. *Energy* **198**:117321. DOI:10.1016/j.energy.2020.117321
35. Zhang W., Chiu Y.-B. and Hsiao C. Y.-L. (2022). Effects of country risks and government subsidies on renewable energy firms' performance: Evidence from China. *Renew. Sustain. Energy Rev.* **158**:112164. DOI:10.1016/j.rser.2022.112164
36. Lee C.-C., Hussain J. and Chen, Y. (2022). The optimal behavior of renewable energy resources and government's energy consumption subsidy design from the perspective of green technology implementation. *Renew. Energy* **195**:670–680. DOI:10.1016/j.renene.2022.05.093
37. Zhou Y. (2022). Energy sharing and trading on a novel spatiotemporal energy network in Guangdong-Hong Kong-Macao Greater Bay Area. *Appl. Energy* **318**:119131. DOI:10.1016/j.apenergy.2022.119131
38. Song A. and Zhou Y. (2023). Advanced cycling ageing-driven circular economy with E-mobility-based energy sharing and lithium battery cascade utilisation in a district community. *J. Clean. Prod.* **415**:137797. DOI:10.1016/j.jclepro.2023.137797
39. Zhou Y. (2022). Incentivising multi-stakeholders' proactivity and market vitality for spatiotemporal microgrids in Guangzhou-Shenzhen-Hong Kong Bay Area. *Appl. Energy* **328**:120196. DOI:10.1016/j.apenergy.2022.120196
40. Borlaug B., Salisbury S. and Gerdes M., et al. (2020). Levelized Cost of Charging Electric Vehicles in the United States. *Joule* **4**:1470–1485. DOI:10.1016/j.joule.2020.05.013
41. Lanz L., Noll B. and Schmidt T. S. (2022). Comparing the levelized cost of electric vehicle charging options in Europe. *Nat. Commun.* **13**:5277. DOI:10.1038/s41467-022-32835-7
42. Lin, B. and Jia, Z. (2019). Impacts of carbon price level in carbon emission trading market. *Appl. Energy* **239**:157–170. DOI:10.1016/j.apenergy.2019.01.194
43. Yan J., Yang Y., Elia Campana P., et al. (2019). City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China. *Nat. Energy* **4**:709–717. DOI:10.1038/s41560-019-0441-z
44. Qi S., Cheng S., Tan X., et al. (2022). Predicting China's carbon price based on a multi-scale integrated model. *Appl. Energy* **324**:119784. DOI:10.1016/j.apenergy.2022.119784
45. Jiang D., Peng T., Bu Z., et al., (2024). Optimization and benefit analysis of the supply chain for sweet sorghum bioenergy production in China. *Innov. Energy* **1**:100038. DOI:10.59717/j.xinn-energy.2024.100038.
46. Cai H., Liu X., Sun L., et al., (2024). Battery internal short circuit diagnosis based on vision transformer without real data. *Innov. Energy* **1**:100041. DOI:10.59717/j.xinn-energy.2024.100041.

FUNDING AND ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation (NSFC) project (52408137). This research is supported by The Hong Kong University of Science and Technology (Guangzhou) startup grant (G0101000059). This work was also supported in part by the Project of Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone (HZQB-KCZYB-2020083). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

Xiaojun Yu: Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation. Yuekuan Zhou: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data is shown in https://zenodo.org/records/11084794. Original code is available upon request to the Lead Contact.

SUPPLEMENTAL INFORMATION

Supplementary material is available at: https://doi.org/10.59717/j.xinn-energy.2024.100062

LEAD CONTACT WEBSITE

Please contact the Lead Contact, Yuekuan Zhou (yuekuanzhou@ust.hk; yuekuan.zhou@outlook.com) for information related to the data and code described in the following Experimental Procedures section.