Article


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Abstract: As the building industry increasingly adopts various photovoltaic (PV) and energy storage systems (ESSs) to save energy and reduce carbon emissions, it is important to evaluate the comprehensive effectiveness of these technologies to ensure their smooth implementation. In this study, a building project in Shenzhen was taken as a case study and energy–environment–economy (3E) analysis was performed to evaluate four strategies for employing PVs and ESSs. In addition, a sensitivity analysis was carried out to further compare the effect of the capacity of each strategy. Although the integration of PV and battery systems leads to the highest reduction in energy consumption and life cycle carbon emissions (reaching up to 44%), it has a long payback period (of up to 6.8 years) and a high carbon cost ratio. The integration of PV and ice storage systems is economically viable, with promising energy and environmental performance, indicating a potential reduction of $30 \pm 5\%$ in life cycle carbon emissions. As far as electric vehicles (EV) go, adopting two-way charging between the building and the EV can offset the additional power load that the EV requires. The comprehensive evaluation of low-carbon strategies in this study is crucial for sustainable building design and policy-making.

Keywords: energy–environment–economy analysis; rooftop PVs; energy storage systems; residential building

1. Introduction

In the context of global warming, many countries are implementing net zero policies to indicate their determination and efforts in terms of reducing carbon emissions in various sectors. The Paris Agreement established a target for countries to achieve net zero greenhouse gas emissions by the second half of this century [1]. The building sector is a major energy-consuming sector, responsible for more than one-third of the total final energy consumption worldwide [2]. For example, in the United States, residential buildings and commercial buildings are responsible for 21% and 19% of the total energy use, respectively [3]. In the EU, greenhouse gas emissions by buildings make up approximately 40% of the overall emissions [4]. In China, the building sector accounts for approximately half of the total carbon dioxide emissions and 45% of the total energy end use [5]. If no measures are taken, the energy consumption and carbon emissions by buildings will continue to rise due to the increasing population and accelerated urbanization, leading to a rise in the total building stock and consequently the total energy consumption by buildings [6]. Furthermore, global warming is increasing the demand for thermal comfort, leading to a corresponding increase in the energy consumed by HVAC systems [7]. Excessive energy consumption by and carbon emissions from buildings can have negative impacts on the environment, influencing human health and impeding social development [8–10]. Thus,
low-carbon energy transition in the building sector is important for achieving the goals of net zero emissions and ensuring a sustainably built environment.

Currently, renewable energy system (RES) technologies are regarded as the most widely accepted solutions for reducing energy consumption and carbon emissions in the building sector [11]. Photovoltaic (PV) and wind systems are regarded as the most viable RES solutions for urban areas [12]. PV systems have experienced the fastest growth in recent years, becoming more widely accepted due to the decreasing cost of PV panels [13]. Technologies such as building-integrated photovoltaics (BIPVs) and rooftop PVs are becoming increasingly common in urban areas [14,15]. However, the major challenge of PV power generation is its variability and unpredictability, which may destabilize power grids [16]. The integration of a PV system with energy storage systems (ESSs) can overcome these problems, as energy storage can increase the flexibility of the grids and reduce daily demand fluctuations by charging the battery during valley demand and discharging it during peak demand [17–19]. The common applications of ESSs include building envelope (thermal mass) and independent units (battery storage, HVAC thermal storage, and electric vehicles (EVs)) [20,21].

Researchers have conducted extensive studies on the integration of PVs and ESSs, demonstrated as a key solution for zero-energy buildings [22]. Syed et al. investigated the actual on-site data of a residential building in Australia fitted with PV and battery energy storage systems, and their findings demonstrated 75% self-sufficiency of the building system overall [23]. Sehar et al. studied the integrated automation of PV and ice storage integrated with packaged air-conditioning (AC) units, which maximizes economic benefits while maintaining the thermal and visual comfort of occupants [24]. Fachrizal et al. presented a study on PV–EV integration in a residential grid. This integration resulted in a significantly higher EV hosting capacity and a slightly higher PV hosting capacity [25]. Some researchers have also studied the combination of the PV system and multiple ESSs [26,27]. Li et al. found that the energy usage of a gymnasium building can be easily covered by adopting PV installation of an appropriate size and battery capacity, while the EV charging strategy can decrease the peak grid power [28]. These studies have demonstrated the feasibility and effectiveness of integrated PVs and ESSs in building design.

PVs and ESSs can help to reduce building energy consumption, while also positively impacting the environment. Several researchers have investigated the environmental performance of these technologies [29,30]. Life cycle assessment (LCA) is commonly used to evaluate the environmental impacts of products and services across their lifespans [21]. Rossi et al. conducted an LCA of user-scale electric systems involving PV panels and batteries and their environmental optimal design via a comparative cross-analysis [31]. Toosi et al. proposed a new comprehensive LCA model to investigate the optimal sizing of thermal and electrical ESSs in residential buildings integrated with PV systems [32].

Although PVs and ESSs have the potential to positively impact building energy and the environment, their economic viability must also be considered for practical implementation and widespread adoption [33–35]. Several studies have focused on the potential economic benefits of integrating PVs and ESSs with various economic models. O’Shaughnessy et al. reviewed the economic benefits of integrating PV systems with storage and load control in residential buildings and suggested that it could increase the value of residential PV systems and result in cost savings for end-users [36]. Chadly et al. proposed a techno-economic model to compare three ESSs technologies linked to a PV system in commercial buildings and found that along with providing maximum efficiency, Li-ion batteries are a more economical solution than fuel cells [37]. Al-Aali and Modi examined the economic viability of using PV generation combined with centralized battery energy storage for electric load shifting and decentralized ice storage for cooling load shifting, finding a 20% reduction in annual system costs [38]. Economic and technological analysis also allows researchers to identify the optimal solutions for combining PVs and ESSs to maximize benefits [39,40].
There have also been a few studies on the energy–environment–economy (3E) performance of PVs and ESSs. For instance, Li et al. reviewed and summarized the economic, technical, and environmental evaluation indicators of PVs and ESSs [41], while Mazzeo conducted a 3E feasibility study on nocturnal EV charging in a residential setting by comparing three different EV charging scenarios [42]. Interactive relationships exist among energy, environment, and economy due to the potential conflicts among different performance variables, such as energy consumption, environmental impact, and initial investment [43,44].

However, previous studies on the integration of PV systems and various types of EESs in buildings have two main limitations. First, while the combination of PVs and EESs is common in practical applications, the differences in the energy efficiency and density, embodied carbon, and cost of different types of EESs, as well as their capacity configurations, can result in varying performance in terms of energy consumption, environmental impact, and economic impact [45]. A system-level study that thoroughly investigates these differences is still lacking. Second, although there is ample research demonstrating the usefulness of PVs and EESs in building systems, most studies only consider their operational benefits [46]. However, in reality, people tend to be more concerned with the return on investment. Therefore, the specific quantification of the 3E performance across the entire life cycle is lacking. Thus, it is necessary to establish appropriate 3E evaluation models for the integration of PVs and ESSs so as to assist decision-makers in selecting the optimal setting in terms of low energy consumption, low investment, and low emissions.

In this study, an in-depth 3E analysis is developed regarding the energy reliability, economic cost savings, and emission reductions associated with different ESS options combined with PV systems. The main contributions of this study are as follows:

- A comprehensive energy–environment–economy (3E) assessment methodology has been developed to evaluate the performance of PVs and ESSs in specific building systems. This assessment methodology takes into account the entire life cycle of the systems, incorporating the life cycle assessment method into the environmental analysis. The economic performance is evaluated using various quantifiable indicators, such as payback year, levelized cost of electricity, and carbon cost ratio, which help to assess the low-carbon and sustainable development potential of these systems.
- Four typical strategies of integrating the PV system and different ESS techniques are set up based on a real case study of a building to analyze its 3E performance. These four strategies consider the arrangement of standalone PV systems and PV systems combined with different types of ESSs, selecting three common energy storage methods, batteries, ice storage, and EV batteries, which are currently favored in the southern region of China.
- Sensitivity analyses are conducted to further identify the optimized parameter setting of each strategy. Due to the distinct characteristics and operational rules of different ESS technologies, the study explores the effects of varying ESS capacity on the overall system performance. This provides valuable insights into the optimal configuration of PVs and ESSs in building systems with different energy demands and environmental requirements.

Thus, in this study, the goal is to provide a comprehensive and reliable evaluation for combining the PV system and different ESS options to assist building stakeholders in selecting the most efficient and cost-effective energy storage solutions for their projects. This study also provides a practical framework for social planners and government agencies to evaluate and optimize the economic and environmental benefits of PVs and ESSs in building systems, thereby promoting their widespread implementation in real-world applications.

This paper is organized as follows. Section 2 introduces the system layout of PVs and ESSs and the energy–environment–economy analysis modeling. Section 3 provides information on the building in Shenzhen that is part of the case study. Section 4 contains the 3E analysis results of the case study. Section 5 includes a discussion of the limitations and further developments of this study. Section 6 reports the conclusions of this case study.
2. Methods

2.1. Research Framework

Figure 1 presents the research framework of this study. First, a building assessment framework will be established to evaluate the baseline performance of the building in terms of energy consumption, life cycle carbon emissions, and electricity cost. Then, four different strategies and their operational rules will be set up and a 3E analysis will be conducted to evaluate the energy, environmental, and economic performance of the building project under the four strategies. Furthermore, a sensitivity analysis will be used to investigate the impact of capacity changes under each strategy based on the 3E factors.

![Research framework](image)

**Figure 1.** Research framework.

2.2. Schematic Layout of the System

The following section introduces the operational principles of PVs and ESSs integrated with building systems.

2.2.1. PV System

A PV system is often used in on-site renewable energy generation. A typical implementation method is rooftop PV installation that can use unoccupied space on the rooftop and receive greater sunlight [47–49]. In the case of high-rise buildings, while the rooftop PV system is not able to provide enough energy [50,51], building owners can purchase rooftop areas of surrounding buildings to install PV systems or invest in PV fields to increase the renewable energy supply rate and achieve a net zero building.

PV energy can provide a direct source of electricity for buildings. When the electricity generated by the PV is insufficient, buildings can obtain additional power from the grid.

Equation (1) shows the power of each part of the system according to the energy balance [52]:

\[ P_{\text{building}} = P_{\text{PV}} + P_{\text{grid}} + P_{\text{PV,curtailed}} \]  

where \( P_{\text{building}} \) is the building load, in kW, which is always positive; \( P_{\text{PV}} \) is the power generated by the PV system, in kW, which is always positive; \( P_{\text{grid}} \) is the grid power supply to the building, in kW, which is always positive; and \( P_{\text{PV,curtailed}} \) is the curtailed power of the PV system, in kW, which is always negative.

PV energy is curtailed when the grid cannot handle additional PV generation due to a mismatch between energy supply and demand [53]. The curtailment is viewed as an economic and environmental loss. ESSs are introduced to improve the flexibility of PV systems and minimize curtailment.
2.2.2. Battery Storage System

A battery storage system is widely used to make building energy systems flexible by shifting the energy load to match renewable energy production [54,55]. During the daytime, the PV system first powers the building and then charges the battery system. When the SOC of the battery reaches its maximum, the surplus PV power returns to the grid. At night, the building is first powered by the battery and then the grid, that is, the remaining part is provided by the grid [56].

Equation (2) shows the power of each part of the system according to the energy balance [28]:

\[
P_{\text{building}} = P_{\text{PV}} + P_{\text{battery}} + P_{\text{grid}} + P_{\text{PV,curtailed}}
\]  

(2)

where \(P_{\text{battery}}\) is the interactive battery power between the building and the battery systems, in kW. When \(P_{\text{battery}}\) is positive, the battery powers the buildings, and when \(P_{\text{battery}}\) is negative, the battery is charged by the PV system.

2.2.3. Ice Storage System

The ice storage system is a suitable thermal storage system for Shenzhen, where cooling is the main part of the HVAC system and the cooling period is long. Using ice as thermal storage, the surplus PV energy is used to make the ice mass during the daytime, while the stored ice is used for cooling during the night [57].

Equation (3) shows the power of each part of the system according to the energy balance:

\[
P_{\text{building}} = P_{\text{PV}} + P_{\text{ice}} + P_{\text{grid}} + P_{\text{PV,curtailed}}
\]  

(3)

where \(P_{\text{ice}}\) is the interactive battery power between the building and the ice storage system, in kW. When \(P_{\text{ice}}\) is positive, the stored ice cools the buildings, and when \(P_{\text{ice}}\) is negative, the surplus PV energy is stored as ice.

2.2.4. EV

EV brings an extra charging load to the building system. The batteries of EVs can store energy and improve the flexibility of building systems [58–60]. In this study, the EV batteries are split into two parts, the load \((E_{\text{EV,load}})\) and the storage system \((E_{\text{EV,battery}})\), to regulate the energy curve of the entire system, which is calculated as shown in Equations (4) and (5):

\[
E_{\text{EV,load}} = \sum_i (SOC_{i,\text{exp}} - SOC_{i,\text{ini}}) \times E_{\text{car}}
\]  

(4)

\[
E_{\text{EV,battery}} = \sum_i (1 - SOC_{i,\text{exp}}) \times E_{\text{car}}
\]  

(5)

where \(SOC_{i,\text{ini}}\) is the initial SOC (state of charge) of the \(i\)-th incoming EV, in %; \(SOC_{i,\text{exp}}\) is the expected SOC of the \(i\)-th EV when leaving, in %; and \(E_{\text{car}}\) is the volume of the EV battery, in kWh.

Equations (6) and (7) show the power of each part of the system according to the energy balance:

\[
P_{\text{building}} = P_{\text{PV}} + P_{\text{EV,battery}} + P_{\text{grid}} + P_{\text{PV,curtailed}}
\]  

(6)

\[
P_{\text{system}} = P_{\text{building}} + P_{\text{EV,load}}
\]  

(7)

where \(P_{\text{system}}\) is the total load of the building and parking system, in kW, and \(P_{\text{EV,battery}}\) and \(P_{\text{EV,load}}\) are the charging power of the EV, in kW. When \(P_{\text{EV,battery}}\) is positive, the EV battery powers the building, and when \(P_{\text{EV,battery}}\) is negative, the EV battery is charged by the PV system.

2.3. PV and ESS Strategies

To evaluate the performance of the PV system and three different types of ESSs, the following four strategies are introduced:
• Strategy 1: PV system. Two different installations are assumed: a rooftop PV installation and an external PV installation. Energy sufficiency is introduced to determine the installation parameter of the external PV, which refers to the rate of PV electricity generation compared to electricity demand, calculated as shown in Equation (8):

\[
\text{Energy sufficiency (\%) } = \frac{E_{PV}}{E_{Load}} \times 100(\%)
\]  

(8)

• Strategy 2: PV and battery system. Batteries enable load shifting, which allows the electricity demand during nighttime to be offset by the surplus PV generation during daytime. The daily demand for battery storage was calculated as shown in Equations (9)–(11):

\[
\text{Daily storage demand } = \min (E_{PV,\text{curtailed}}, E_{\text{grid}})
\]  

(9)

\[
E_{PV,\text{curtailed}} = \int P_{PV,\text{curtailed}} \times dt
\]  

(10)

\[
E_{\text{grid}} = \int P_{\text{grid}} \times dt
\]  

(11)

where \(E_{PV,\text{curtailed}}\) is the daily curtailed PV energy, in kWh, and \(E_{\text{grid}}\) is the daily grid supply of energy to the building, in kWh.

• Strategy 3: PV and ice storage system. An ice storage system helps to shift the load of the cooling systems. The daily demand of the ice storage system was calculated as shown in Equations (12)–(14):

\[
\text{Daily ice storage demand } = \min (E_{PV,\text{curtailed}}, E_{\text{ice}})
\]  

(12)

\[
E_{PV,\text{curtailed}} = \int P_{PV,\text{curtailed}} \times dt
\]  

(13)

\[
E_{\text{ice}} = \int P_{\text{ice}} \times dt
\]  

(14)

where \(E_{\text{ice}}\) is the daily supply of energy by the grid to the cooling system in the building, in kWh.

• Strategy 4: PV and EV system. In this strategy, there are two charging relationships between the building and the EV. In the first case, the EV was only considered as a load to the building system, which means that there was only one-way charging, from the building to the vehicle. In the second case, the EV battery was considered as energy storage for the building system, which means that there was two-way charging between the building and the vehicle.

2.4. Energy–Environment–Economy (3E) Analysis

In this study, energy–environment–economy (3E) analysis was adopted for a comprehensive evaluation of PVs and ESSs. This section introduces the indicators for 3E analysis.

2.4.1. Energy Performance

Self-consumption and self-sufficiency were used to analyze the energy performance of PVs and ESSs, as shown in Equations (15) and (16) [61]. Self-consumption indicates the amount of electricity generated by a PV that a building system uses. It presents the ability of the building system to increase the utilization rate of the PV by matching the capacity of the PVs and ESSs. Self-sufficiency indicates the amount of electricity load of the building
that the PVs and ESSs can supply. It presents the ability of the building system to reduce the amount of electricity that it uses from the electric grid.

\[
\text{Self-consumption (\%)} = \frac{E_{PV,\text{Load}} + E_{\text{storage,Load}}}{E_{PV}} \times 100(\%)
\]

\[
\text{Self-sufficiency (\%)} = \frac{E_{PV,\text{Load}} + E_{\text{storage,Load}}}{E_{\text{Load}}} \times 100(\%)
\]

where \( E_{PV,\text{Load}} \) is the electricity generated by the PV for the building load, in kWh; \( E_{\text{storage,Load}} \) is the electricity supplied by the ESSs to the building load, in kWh; \( E_{\text{Load}} \) is the total electricity load of the building system, in kWh; and \( E_{PV} \) is the electricity generated by the PV, in kWh.

2.4.2. Environmental Performance

The environmental performance of the PVs and ESSs was analyzed using the carbon reduction ratio, as shown in Equation (17) [61]:

\[
\text{Carbon reduction ratio (\%)} = \frac{EM_{\text{Base}} - EM_{\text{System}}}{EM_{\text{Base}}} \times 100(\%)
\]

where \( EM_{\text{Base}} \) is the life cycle carbon emission of the building system without a PV and ESS, in kgCO\(_2\), and \( EM_{\text{System}} \) is the life cycle carbon emission of the building system when applying a PV and ESS, in kgCO\(_2\).

On the basis of the life cycle theory [62] and China Standard for Building Carbon Emission Calculation [63], the life cycle carbon emission includes four stages: the building materials production and transportation stage, the construction stage, the operation stage, and the demolition stage. Equation (18) shows the calculation:

\[
\text{Life cycle carbon emission} = EM_{\text{material}} + EM_{\text{construction}} + EM_{\text{operation}} + EM_{\text{demolition}}
\]

where \( EM_{\text{material}}, EM_{\text{construction}}, EM_{\text{operation}}, \) and \( EM_{\text{demolition}} \) are the carbon emissions of the building materials production and transportation stage, the construction stage, the operation stage, and the demolition stage, respectively, in kgCO\(_2\).

Each term in Equation (18) can be calculated using Equations (19)–(22):

\[
EM_{\text{material}} = \sum_{i=1}^{n} M_i \times F_i + \sum_{i=1}^{n} M_i \times d_i \times T_i,
\]

\[
EM_{\text{construction}} = \sum_{i=1}^{n} E_i \times EF_i,
\]

\[
EM_{\text{operation}} = E_{\text{electricity,grid}} \times EF_{\text{electricity}} \times y,
\]

\[
EM_{\text{demolition}} = \sum_{i=1}^{n} E_i \times EF_i,
\]

where \( M_i \) is the weight of i-th building materials, in kg; \( F_i \) is the carbon emission factor of the i-th building materials, in kgCO\(_2\)/kg; \( d_i \) is the distance from the production site to the construction site of the i-th building material, in km, with the default value being 500 km; \( T_i \) is the emission factor of the i-th building material transportation method, in kgCO\(_2\)/km; \( E_i \) is the amount of the i-th energy source used in the construction or demolition stage, in kWh or kg; \( EF_i \) is the emission factor of the i-th energy source, in kgCO\(_2\)/kWh or kgCO\(_2\)/kg; \( E_{\text{electricity,grid}} \) is the energy consumption from the grid per year, in kWh/yrs; \( EF_{\text{electricity}} \) is the emission factor of the China Southern Power Grid, which is 0.3748 kgCO\(_2\)/kWh; and \( y \) is the building lifetime, which was considered to be 50 years in this study.
2.4.3. Economic Performance

Cost savings and payback periods were used to evaluate the economic performance of the PVs and ESSs. This study considered the cost savings on the annual electric tariff and the life cycle cost, calculated as shown in Equations (23) and (24) [64]:

\[
\text{Annual Cost Saving} (\%) = \frac{C_{\text{annual, Base}} - C_{\text{annual, System}}}{C_{\text{annual, Base}}} \times 100(\%)
\]  

(23)

\[
\text{Life Cycle Cost Saving} (\%) = \frac{C_{\text{Base}} - C_{\text{System}}}{C_{\text{Base}}} \times 100(\%)
\]  

(24)

where \(C_{\text{annual, Base}}\) and \(C_{\text{annual, System}}\) are the annual electric tariffs of the building system in the base situation and if PVs and ESSs are installed on the building, respectively, in CNY/yrs, and \(C_{\text{Base}}\) and \(C_{\text{System}}\) are the life cycle capital cost of the building system in the base situation and if PVs and ESSs are installed on the building, respectively, in CNY, calculated as shown in Equation (25):

\[
\text{System Capital Cost} = A_{PV} \times C_{PV} \times R_{PV} + A_{storage} \times C_{storage} \times R_{storage} + C_{\text{annual}} \times y
\]  

(25)

where \(A_{PV}\) is the PV system area, in m\(^2\); \(C_{PV}\) is the PV cost, in CNY/m\(^2\); \(R_{PV}\) is the PV system replacement times during the building life cycle; \(A_{storage}\) is the capacity of ESSs, in kWh; \(C_{storage}\) is the ESSs cost, in CNY/kWh; \(R_{storage}\) is the ESSs replacement times during the building life cycle; \(C_{\text{annual}}\) is the annual electric tariff of the building system, in CNY/yrs; and \(y\) is the building lifetime, which is considered to be 50 years in this study.

The payback period is defined by calculating the time needed (usually expressed in years) to recover an investment [65], as shown in Equation (26):

\[
\text{Payback Period} = \frac{\text{System Initial Investment}}{C_{\text{annual, Base}} - C_{\text{annual, System}}}
\]  

(26)

The system’s initial investment is calculated in Equation (27):

\[
\text{System Initial Investment} = A_{PV} \times C_{PV} + A_{storage} \times C_{storage}
\]  

(27)

The levelized cost of electricity (LCOE) and the carbon cost ratio are introduced to evaluate the economic performance in energy and environmental terms.

The levelized cost of electricity (LCOE), as the name indicates, is the normalized cost of electricity used in building systems [66]. It is calculated by dividing the capital costs over the lifetime by the sum of the electrical energy used over the lifetime, as shown in Equation (28) [37]. It helps to compare different strategies to identify the most competitive and economic one.

\[
\text{LCOE} = \frac{\text{System Capital Cost}}{E_{\text{electricity}} \times y}
\]  

(28)

where \(E_{\text{electricity}}\) is the electricity consumed annually by the building systems, in kWh/yrs.

The carbon cost ratio was used to evaluate the benefits of decarbonizing the building systems. It is defined as the ratio of the system capital cost to the reduction in the carbon emission during the building life cycle, as shown in Equation (29) [67]:

\[
\text{Carbon Cost Ratio} = \frac{\text{System Capital Cost}}{EM_{\text{Base}} - EM_{\text{System}}}
\]  

(29)

3. Case Study

3.1. Building Project in Shenzhen

To investigate the energy, environmental, and economic performance of the PVs and ESSs of a building system, a high-rise residential building project in Shenzhen, southern China, was selected. It consisted of three high-rise residential buildings, 1#, 2#, and 3#, with
a total floor area of 61,921 m². Building 1# had 32 floors aboveground, and the floor area was 11,359 m²; building 2# had 32 floors aboveground, and the floor area was 11,133 m²; building 3# had 32 floors aboveground, and the floor area was 25,604 m². The underground part of the three buildings was a two-story parking lot with a floor area of 13,825 m² and 317 parking spaces. Figure 2a shows the standard floor of Building 1# and the whole building project in the Revit model.

![Building Diagram](image)

**Figure 2.** The standard floor and building project in (a) the Revit model and (b) the energy simulation model in Honeybee.

The building energy consumption is calculated using the building energy simulation tool from Ladybug Tools, a Rhino/Grasshopper plug-in [68]. Honeybee in Ladybug Tools was able to run and visualize the results or energy simulation using EnergyPlus/OpenStudio. Figure 2b shows the energy simulation model in Rhino.

The settings for simulating a building system follow the ASHRAE 90.1-2013 standard [69] and the China Standard for Green Performance Calculation of Civil Buildings [70], as shown in Table 1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Input Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Data</td>
<td>EPW File</td>
<td>CHN_GD_Shenzhen. 594930_TMYx.2007-2021 [71]</td>
<td>-</td>
</tr>
<tr>
<td>Construction Set [72]</td>
<td>Climate Zone</td>
<td>Hot</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Building Vintage</td>
<td>ASHRAE 90.1 2013 / IECC 2015</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Construction Type</td>
<td>Mass</td>
<td>-</td>
</tr>
<tr>
<td>Building Load Values [73]</td>
<td>People per Area</td>
<td>0.046</td>
<td>people/m²</td>
</tr>
<tr>
<td></td>
<td>Lighting Power Density</td>
<td>5</td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td>Electric Equipment Power Density</td>
<td>4.9</td>
<td>W/m²</td>
</tr>
<tr>
<td></td>
<td>Intensity of Outdoor Air Ventilation</td>
<td>0.0083</td>
<td>m³/s</td>
</tr>
<tr>
<td>HVAC Setpoint</td>
<td>Heating Setpoint [74]</td>
<td>18</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>Cooling Setpoint [75]</td>
<td>26</td>
<td>°C</td>
</tr>
<tr>
<td>HVAC System [76]</td>
<td>Effectiveness of Sensible Heat Recovery</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>Effectiveness of Latent Heat Recovery</td>
<td>0.75</td>
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</tr>
</tbody>
</table>

To calculate the life cycle carbon emission, the data of building materials, including typologies and volumes, were collected from Autodesk Revit Architecture. Table 2 shows the weights and the carbon emission factors of the building materials in this building project. Gasoline trucks were selected for building material transportation, with a carbon emission factor of 0.104 kg CO₂/(t·km) and a transportation distance of 500 km [63]. For the construction and demolition stage, the energy consumption was estimated based on the Consumption Quota of Prefabricated Building Engineering [77].
Table 2. Carbon emissions from building materials.

<table>
<thead>
<tr>
<th>Building Material Name</th>
<th>Volume (m$^2$)</th>
<th>Carbon Emission Factor (kg CO$_2$ eq/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>20,396</td>
<td>310</td>
</tr>
<tr>
<td>Wood</td>
<td>212</td>
<td>178</td>
</tr>
<tr>
<td>Glass</td>
<td>59</td>
<td>3390</td>
</tr>
<tr>
<td>Steel</td>
<td>105</td>
<td>18,369</td>
</tr>
<tr>
<td>Brick</td>
<td>2882</td>
<td>335</td>
</tr>
<tr>
<td>Aluminum</td>
<td>135</td>
<td>54,810</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>11,878</td>
<td>574</td>
</tr>
</tbody>
</table>

3.2. Electricity Tariff in Shenzhen

This study employed the tiered electricity pricing system in Shenzhen for calculating economic performance. Since 2012, China has started implementing the tiered electricity pricing system, a system in which the price increases gradually based on the amount of electricity consumed. The electricity price is divided into several tiers, with each tier having a different price that increases in a stepwise manner. It serves as a means of promoting energy conservation and reducing overall electricity consumption in the city.

The electricity tariff in Shenzhen is divided into three tiers, as shown in Table 3.

Table 3. The electricity tariff in Shenzhen [79].

<table>
<thead>
<tr>
<th>Tier</th>
<th>Electricity Consumption (kWh) $^1$</th>
<th>Tariff (CNY/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 1 Summer</td>
<td>0–260</td>
<td>0.68</td>
</tr>
<tr>
<td>Non-summer</td>
<td>0–200</td>
<td></td>
</tr>
<tr>
<td>Tier 2 Summer</td>
<td>261–600</td>
<td>0.73</td>
</tr>
<tr>
<td>Non-summer</td>
<td>201–400</td>
<td></td>
</tr>
<tr>
<td>Tier 3 Summer</td>
<td>$\geq$601</td>
<td>0.98</td>
</tr>
<tr>
<td>Non-summer</td>
<td>$\geq$401</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ The summer electricity tariff applies from May to October, while the non-summer tariff applies for the rest of the year.

3.3. The Parametric Setting of the PV and ESS

In the case study, the PV system and three different types of ESSs are implemented into the building systems, whereby detailed information on them is presented in Tables 4–7. Note that the energy conversion efficiency is considered to be 100%, the aging effect is neglected, and no discount factor is considered.

Table 4. Specifications of the PV panel [80].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Mono-Si</td>
<td>-</td>
</tr>
<tr>
<td>Size</td>
<td>$2465 \times 1134 \times 35$</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum power</td>
<td>125</td>
<td>W/m$^2$</td>
</tr>
<tr>
<td>Price</td>
<td>250</td>
<td>CNY/m$^2$</td>
</tr>
<tr>
<td>Service life</td>
<td>25</td>
<td>years</td>
</tr>
<tr>
<td>Embodied carbon</td>
<td>123 [81]</td>
<td>kgCO$_2$/m$^2$</td>
</tr>
</tbody>
</table>

Table 5. Specifications of the battery system [82].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Li ion</td>
<td>-</td>
</tr>
<tr>
<td>Capacity</td>
<td>10</td>
<td>kWh</td>
</tr>
<tr>
<td>Charging rate</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>Price</td>
<td>2500 [83]</td>
<td>CNY/kWh</td>
</tr>
<tr>
<td>Service life</td>
<td>15</td>
<td>years</td>
</tr>
<tr>
<td>Embodied carbon</td>
<td>76.7 [84]</td>
<td>kgCO$_2$/kWh</td>
</tr>
</tbody>
</table>
Table 6. Specifications of the ice storage system [85].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>200</td>
<td>kWh</td>
</tr>
<tr>
<td>Charging rate</td>
<td>0.5 C</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>350</td>
<td>CNY/kWh</td>
</tr>
<tr>
<td>Service life</td>
<td>20</td>
<td>years</td>
</tr>
<tr>
<td>Embodied carbon</td>
<td>8.75</td>
<td>kgCO₂/kWh</td>
</tr>
</tbody>
</table>

Table 7. Specifications of the battery of the EV [87].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Li-on</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>55</td>
<td>kWh</td>
</tr>
<tr>
<td>Charging rate</td>
<td>0.12</td>
<td>C</td>
</tr>
<tr>
<td>Price</td>
<td>0 CNY</td>
<td></td>
</tr>
</tbody>
</table>

1 As EVs are considered to be the privately owned property of the homeowner, this study’s approach was to include EV batteries in the vehicle-to-grid (V2G) charging behavior. Thus, EVs are not taken as an additional investment.

3.4. The Settings of Four Strategies

To evaluate the performance of the PV system and three different types of ESSs introduced in this building project, four strategies were adopted, illustrated in Section 2.3. A sensitivity analysis was further conducted to investigate the optimized setting of each strategy and to compare the impacts of the PV system and different types of ESSs in terms of the energy–environment–economy performance. Table 8 presents the settings of the four strategies and the sensitivity analysis.

Table 8. The settings of four strategies and the sensitivity analysis.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Strategy Setting</th>
<th>Sensitivity Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18,000 m² PV (S1)</td>
<td>1688 m² PV (S1_Roof)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3600 m² PV (S1−80%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10800 m² PV (S1−40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25,200 m² PV (S1+40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32,400 m² PV (S1+80%)</td>
</tr>
<tr>
<td>2</td>
<td>18,000 m² PV + 3000 kWh battery (S2)</td>
<td>18,000 m² PV + 600 kWh battery (S2−80%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 1800 kWh battery (S2−40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 4200 kWh battery (S2,+40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 5400 kWh battery (S2,+80%)</td>
</tr>
<tr>
<td>3</td>
<td>18,000 m² PV + 3000 kWh ice storage (S3)</td>
<td>18,000 m² PV + 600 kWh ice storage (S3−80%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 1800 kWh ice storage (S3−40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 4200 kWh ice storage (S3,+40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 5400 kWh ice storage (S3,+80%)</td>
</tr>
<tr>
<td>4</td>
<td>18,000 m² PV + 50% EV (S4)</td>
<td>18,000 m² PV + 10% EV (S4−80%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 30% EV (S4−40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 70% EV (S4,+40%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,000 m² PV + 90% EV (S4,+80%)</td>
</tr>
</tbody>
</table>

1 The energy sufficiency was 100%; 2 the battery capacity was 50% of the maximum daily demand for the battery; 3 the ice storage capacity was 50% of the maximum daily demand for ice storage; 4 50% of the vehicles parked in the underground parking lot were EVs; the charging mode was two-way charging; the expected exit SOC was 60%.

In the sensitivity analysis, the same range of variation was selected for the capacity of the PVs, the battery, and the ice storage, as well as the number of EVs, that is, −80%, −40%, +40%, and +80% of the base strategy. For Strategy 1, a situation whereby PV systems were installed on the rooftop was also considered. Table 8 presents the settings of the four strategies and the sensitivity analysis.
4. Results

This section employs the 3E analysis from Section 2 to conduct a comprehensive comparative analysis of the four strategies involving the PV system and three different types of ESSs, with the aim being to investigate the varying impacts of different strategies on building flexibility and market potential. Section 4.1 presents the basic performance of the building project without any strategies. In Section 4.2, the energy–environment–economy performance of the building project under four strategies is analyzed. In Section 4.3, the results of the sensitivity analysis of the four strategies are analyzed.

4.1. Basic Performance

Figure 3 shows the energy simulation results for the building project, represented by the typical weeks in four seasons. The electricity end use of the building systems is divided into five categories: cooling, heating, lighting, equipment, and water heating. Cooling and heating are the major factors influencing electricity consumption, which varies with temperature change, while the latter three end uses retain the same patterns in all four seasons, influenced by human activity schedules.

![Figure 3. The energy consumption in a typical week in four seasons in the building project.](image)

To prove their validity, the simulation results were benchmarked against the China Standard for Energy Consumption of Building [88]. The results are within the constraint value (2800 kWh per year per household) of the energy consumption index in the hot summer and warm winter zones in China.

Figure 4 illustrates the annual energy consumption by the building and the energy generated annually by the PV system. It is evident that the power generated by the PV system will cover only a small portion of the building’s energy demand. The building’s energy consumption curve indicates that the peak energy consumption occurs primarily in the summer months due to hot weather conditions, followed by the winter months with low temperatures. In contrast, the energy demand in the spring and autumn months is relatively low due to moderate temperatures. The PV power generation curve indicates that the annual energy output remains relatively stable. However, for high-rise buildings, the roof PV generation is not sufficient to cover the building energy load.
that the annual energy output remains relatively stable. However, for high-rise buildings, the roof PV generation is not sufficient to cover the building energy load.

Figure 3. The energy consumption in a typical week in four seasons in the building project.

Figure 4. Annual energy consumption by the buildings and electricity generation by the PV system.

Table 9 presents the carbon emissions and their respective proportions during the entire life cycle of the building project. The construction and demolition phases account for only 1% each, due to the prefabricated construction method employed, resulting in lower carbon emissions during the dismantling and assembling processes. In contrast, the material production and transportation phase and the operation phase account for relatively high proportions of emissions, accounting for 32% and 66%, respectively.

Table 9. Carbon emissions in each stage of the whole life cycle of the building project.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Carbon Emission (t CO$_2$eq)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building material production and transportation</td>
<td>31,588</td>
<td>31.43</td>
</tr>
<tr>
<td>Construction</td>
<td>1381</td>
<td>1.37</td>
</tr>
<tr>
<td>Operation</td>
<td>66,284</td>
<td>65.96</td>
</tr>
<tr>
<td>Demolition</td>
<td>1236</td>
<td>1.23</td>
</tr>
<tr>
<td>Total</td>
<td>100,489</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2. Energy Performance Analysis

4.2.1. Energy Performance Analysis

Figure 5 displays the self-consumption and self-sufficiency of the buildings when the four strategies are used. As shown in Figure 5a, for all strategies, the self-consumption of the buildings exceeds 70% in summer, while it is below 60% in winter, indicating that the building energy system is significantly affected by different seasonal climates. With Strategies 2 and 3, self-consumption goes up to 90% in summer, which is nearly 20% higher than that when S1 is used, indicating that without energy storage strategies, there is a significant curtailment of solar energy in summer. However, with Strategy 3, the self-consumption is almost the same as that with Strategy 1 in winter, because the ice storage system mainly saves energy by cooling and has almost no effect in winter, but in summer, it can achieve similar energy-saving effects as with an energy storage battery. Furthermore, the self-consumption with Strategy 3 is almost the same as that with Strategy 2 throughout the year, and the peak value is about 80%, indicating that electric vehicles serve as energy storage devices, which stably promotes self-consumption.

Figure 5b illustrates the self-sufficiency in different seasons when the four strategies are used. The self-sufficiency is higher in spring and autumn but generally less than 65% in summer. This reflects the increase in the energy consumed by the building in summer due to the climate, indicating that even if PVs and ESSs strategies are used, it is impossible to meet the energy demand of the building. The effect of Strategy 2 is the most significant, with self-sufficiency of over 70% throughout the year except for in summer, reaching 100% in April, reflecting the significant role of battery storage in energy flexibility management. Strategy 3 still has no effect in winter, and Strategy 4 can steadily but limitedly improve
the energy self-sufficiency of the buildings throughout the year, but the effect in summer is about 10% lower than that of Strategies 2 and 3.

![Figure 6](image)

**Figure 5.** (a) Self-consumption and (b) self-sufficiency under the four strategies.

The percentage of energy supplied when each of the four strategies was used is shown in Figure 6. In Strategy 1, 18,000 m² of the PV system was installed and it provided 44% of the building’s energy demand. This translates into a reduction in the energy demand from the grid by almost half, highlighting the significant potential of PV systems in low-carbon building energy transitions.

![Figure 7](image)

**Figure 6.** Percentage of energy supply for each part of the building under four strategies.

In Strategies 2 and 3, battery storage and ice storage systems enabled a further reduction in the need for grid energy supply, while maintaining the percentage contribution of the PV system. The contribution of the battery storage system to the building’s energy system was twice that of the ice storage system. This is mainly because the ice storage system operates only during summer seasons.

In Strategy 4, electric vehicles (EVs) increased the building’s total energy consumption by 13%, but the demand from the grid supply remained relatively unchanged. However, the introduction of EVs increased the self-consumption rate of the PV systems, resulting in an increase in the percentage of PV supply. Additionally, the EV battery was capable of supplying nearly 10% of the energy consumed by the building.

4.2.2. Environmental Performance Analysis

Figure 7 illustrates the life cycle carbon emissions and the carbon reduction ratio of the building under the four strategies. PV systems and different ESSs can significantly reduce the life cycle carbon emissions of the building by replacing the grid energy supply with zero-carbon renewable energy supply. Although the embodied carbon of these techniques
may increase the carbon emissions of the whole system, the total life cycle emissions can still be reduced to a certain extent.

Figure 6. Percentage of energy supply for each part of the building under four strategies.

In Strategy 4, electric vehicles (EVs) increased the building’s total energy consumption by 13%, but the demand from the grid supply remained relatively unchanged. However, the introduction of EVs increased the self-consumption rate of the PV systems, resulting in an increase in the percentage of PV supply. Additionally, the EV battery was capable of supplying nearly 10% of the energy consumed by the building.

4.2.2. Environmental Performance Analysis

Figure 7 illustrates the life cycle carbon emissions and the carbon reduction ratio of the building under the four strategies. PV systems and different ESSs can significantly reduce the life cycle carbon emissions of the building by replacing the grid energy supply with zero-carbon renewable energy supply. Although the embodied carbon of these techniques may increase the carbon emissions of the whole system, the total life cycle emissions can still be reduced to a certain extent.

In Strategy 1, PV systems reduced the total life cycle emissions by a quarter (25%). The integration of PVs and ESSs in Strategies 2–4 significantly improved the environmental performance of the buildings. Among the three ESSs, the battery storage system had the highest carbon reduction ratio.

In Strategy 4, the total life cycle emissions and the carbon reduction ratio are similar to those in Strategy 1. This is because the increase in the original demand from the grid and life cycle carbon emissions due to the introduction of EVs is balanced by the decrease in the demand from the grid via the use of EV batteries as storage.

Figure 7. Life cycle carbon emissions and carbon reduction ratios of the building under four strategies.

4.2.3. Economic Performance Analysis

Table 10 displays the economic performance of the four strategies evaluated in this study. All strategies demonstrate a decrease in the annual electric tariff, ranging from 46% to 72%, with Strategy 2 (PV + battery) exhibiting the highest cost savings. The life cycle cost savings from the four strategies, taking into account the investment in the PV system and ESSs, range from 38% to 51%. Strategy 3 (PV + ice storage) yields the highest life cycle cost savings due to the lower investment required for the ice storage system than for the battery system. The annual cost savings and life cycle cost savings from Strategy 4 are comparable to those from Strategy 1. Additionally, Strategy 3 presents the shortest payback period, which is less than the lifespan of the PVs and ESSs. This implies that users can obtain a return on their investment during the system’s lifespan.

Table 10. The economic performance under different strategies.

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual cost saving (%)</td>
<td>-</td>
<td>46%</td>
<td>72%</td>
<td>59%</td>
<td>46%</td>
</tr>
<tr>
<td>Life cycle cost saving (%)</td>
<td>-</td>
<td>38%</td>
<td>40%</td>
<td>49%</td>
<td>38%</td>
</tr>
<tr>
<td>Payback period (yrs)</td>
<td>-</td>
<td>4.00</td>
<td>6.81</td>
<td>3.83</td>
<td>4.02</td>
</tr>
<tr>
<td>Levelized cost of electricity (CNY)</td>
<td>0.69</td>
<td>0.43</td>
<td>0.42</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td>Carbon cost ratio (CNY/kgCO₂)</td>
<td>-</td>
<td>0.31</td>
<td>0.95</td>
<td>0.29</td>
<td>0.36</td>
</tr>
</tbody>
</table>

In terms of the LCOE, Strategies 3 and 4 exhibit lower LCOEs than Strategies 1 and 2. Specifically, Strategy 4 demonstrates economic performance comparable to that of Strategy 1 across other indicators, but with a lower LCOE. This is due to the introduction of electric vehicles, which leads to an increase in the total electricity demand, although the total cost remains largely unchanged. The carbon cost ratio represents the effectiveness of reducing the same amount of carbon at a lower cost. Although Strategy 2 yields the largest carbon reduction ratio, it also yields the highest carbon cost ratio, highlighting the need for users to weigh the trade-offs between economic and environmental performance when selecting...
Strategy 2. In contrast, Strategies 1, 3, and 4 exhibit similar values for the carbon cost ratio, ranging from 0.29 to 0.36 CNY/kgCO₂. Notably, Strategy 3 outperforms the other strategies in terms of the carbon cost ratio.

4.3. Sensitivity Analysis

This study selected four strategies as single factors and changed their magnitudes by ±40% and ±80% to analyze the impact of different degrees of change within the same strategy on the self-consumption of the building energy system. Figure 8 presents the results of the sensitivity analysis on self-consumption for the four strategies, showing that changes in the four strategies at different levels would lead to corresponding increases or decreases in self-consumption. The overall trend remained consistent.

Figure 8d investigates the impact of increasing the proportion of two-way EV charging, with EV batteries showing a similar performance to the batteries used in Strategy 2. As the proportion of EVs increases, self-consumption steadily increases, peaking at 90% in S4_+80%. The self-consumption increases consistently with each additional proportion of electric vehicles.

Figure 8a illustrates the impact of varying the area of PV installation on building PV self-consumption. In S1_Roof, the ability of the building to effectively consume the electricity generated by a rooftop PV system results in the self-consumption rate fluctuating around 100%. However, as the PV installation area increases, the peak self-consumption value gradually decreases. In S1_+80%, the peak value drops by about 30%, while in S1_−80%, it increases to 100%. This suggests that when the PV area increases, more electricity is generated. However, the building’s energy consumption remains unchanged, leading to ineffective utilization of the PV-generated electricity.

Figure 8b demonstrates the effect of adjusting the battery capacity on building self-consumption. Strategy 2 is a reference standard. The curve shows that a larger battery capacity can lead to higher PV self-consumption rates and self-consumption can reach nearly 100% in summer in S2_+40% and S2_+80%.
Figure 8c indicates that ice storage has a similar effect in summer, while, in winter, its impact on the PV self-consumption rate is almost negligible.

Figure 8d investigates the impact of increasing the proportion of two-way EV charging, with EV batteries showing a similar performance to the batteries used in Strategy 2. As the proportion of EVs increases, self-consumption steadily increases, peaking at 90% in S4_+80%. The self-consumption increases consistently with each additional proportion of electric vehicles.

Figure 9 presents the self-sufficiency under different strategies. Figure 9a illustrates that an increase in the PV installation area results in a continuous improvement in the building’s self-sufficiency, as electricity generated by the PV system offsets a portion of the grid-provided electricity. The peak self-sufficiency value of 50% is reached when the installation area is 18,000 m², and after which, further increases result in only slight improvements.

Figure 9b shows that an increase in battery capacity corresponds to higher self-sufficiency. In S2_+40%, the self-sufficiency improvement is saturated, with only a 5% increase observed in S2_+80%. However, even with an 80% increase in battery capacity, self-sufficiency in summer remains below 70% for Strategy 2. Figure 9c demonstrates that ice storage follows a similar trend to that followed by PVs. After an increase in ice storage capacity of 40%, self-sufficiency shows little improvement.

Figure 9d indicates that the contribution of EVs to self-sufficiency is limited. Even when 80% of the EVs are two-way charging with the building, the peak self-sufficiency value remains below 70%. The seasonal trend for EVs is similar to that observed for batteries.

Figure 10 compares the life cycle carbon emissions and carbon reduction rates across different strategies. In Strategy 1, an increase in the area of PV installations can reduce
the life cycle carbon emissions of buildings, with the carbon reduction ratio peaking at 24.8% when the deployment area reaches 18,000 m². However, a further increase in the deployment area decreases the carbon reduction ratio, because buildings are unable to absorb all of the electricity generated by the PV during the operation phase, and larger deployment areas lead to increased carbon emissions during the materials production and transportation phases.

Figure 10. Life cycle carbon emissions and carbon reduction rates under different strategies: (a) PV system, (b) battery, (c) ice storage system, and (d) EV battery.

In Figure 10b, it is evident that an increase in battery capacity significantly improves the environmental performance of buildings, with carbon reduction ratios ranging from 29% to 44%. However, the growth rate of the carbon reduction ratio gradually decreases as the battery capacity increases.

Similarly, Figure 10c reveals that the effect of ice storage on carbon reduction is comparable to that of batteries, but with a lower magnitude of improvement, as the carbon reduction ratio ranges between 27% and 36%.

Figure 10d illustrates that the increase in the proportion of electric vehicles (EVs) in the parking area leads to a slight increase in the life cycle carbon emission, with the carbon reduction ratio ranging between 26% and 24%. In other words, although EVs increase the load on buildings, they also provide energy storage capabilities, resulting in a negligible impact on the life cycle carbon emission. Therefore, the overall impact of EVs on the life cycle carbon emission is not significant.

Figure 11 presents the cost saving and the payback period resulting from various strategies. The former is further divided into annual cost saving and life cycle cost saving, where a higher value indicates a better economic performance of the strategy. The latter represents the time required for the benefits to cover the costs, where a lower value indicates a faster cost recovery.
Figure 11d demonstrates that the cost saving and the payback period of different settings in Strategy 4 do not change significantly, indicating that the proportion of two-way charging EVs has a minimal impact on the overall economic performance.

Figure 11. Cost saving and payback period under different strategies: (a) PV system, (b) battery, (c) ice storage system, and (d) EV battery.

When Strategy 1 is implemented, as per Figure 11a, there is a steady increase in the annual cost saving and the payback period with an increase in the installed area of PVs. The life cycle cost saving reaches its maximum value of 38.5% when the installed area is 18,000 m² (S1), and then continuously decreases. This indicates that when the installation area exceeds 18,000 m², the additional investment in PV installation will result in relatively less return.

A similar trend is observed with Strategy 2, as shown in Figure 11b. S2_+80%, with an 18,000 m² PV + 5400 kWh battery, can achieve an annual cost saving of 76%, but its payback period also increases to a relatively long 10 years, which means that consumers need a longer period to recoup their investments even if they achieve more cost savings each year. The peak of the life cycle cost saving, 42%, occurs in S2_40%, i.e., with an 18,000 m² PV + 1200 kWh battery. Its adjacent parameter settings (S2_−80% and S2) also result in a life cycle cost saving of nearly 40%.

Regarding Strategy 3, involving the implementation of a PV system and ice storage, Figure 11c illustrates that with an increase in the capacity of the ice storage system, the annual cost saving and life cycle cost saving show a slight increase, ranging from 49% to 61% and from 41% to 49%, respectively, while the payback period remains almost unchanged, at around 4 years.

Figure 11d demonstrates that the cost saving and the payback period of different settings in Strategy 4 do not change significantly, indicating that the proportion of two-way charging EVs has a minimal impact on the overall economic performance.

Figure 12 presents two economic evaluation indicators of different strategies throughout the life cycle of the building: the levelized cost of electricity (LCOE) and the carbon cost ratio. The LCOE reflects the electricity generation cost over the building’s lifespan, and the smaller the value, the better the economic performance of the strategy. The carbon cost ratio represents the ability of the building systems to reduce the same amount of carbon at a lower price.

As demonstrated in Figure 12a, as the PV area increases, the LCOE first decreases, reducing to a minimum value of 0.43 CNY/kWh at S1_−40% and S1, and then begins to increase because of the increased PV cost, which weakens the economic benefits of the increased PV area. However, the carbon cost ratio continually increases as the PV area increases.

Figure 12b indicates that with an increase in the battery capacity, the carbon cost ratio increases, reaching a high of 1.44 CNY/kWh when the battery capacity is 10,800 kWh, reflecting the high cost of the battery strategy. The lowest LCOE appears in S2_40%.

In Strategy 3, the LCOE and the carbon cost ratio do not change significantly, with the lowest LCOE appearing in S3. As the ice storage capacity increases, the carbon cost ratio decreases slightly, stabilizing at 0.35 CNY/kWh when the ice storage capacity reaches 3000 kWh.
ratio. The LCOE reflects the electricity generation cost over the building’s lifespan, and the smaller the value, the better the economic performance of the strategy. The carbon cost ratio represents the ability of the building systems to reduce the same amount of carbon at a lower price.

Figure 12. LOCE and carbon cost ratio under different strategies: (a) PV system, (b) battery, (c) ice storage system, and (d) EV battery.

As demonstrated in Figure 12a, as the PV area increases, the LCOE first decreases, reducing to a minimum value of 0.43 CNY/kWh at $S_1_{-40\%}$ and $S_1$, and then begins to increase because of the increased PV cost, which weakens the economic benefits of the increased PV area. However, the carbon cost ratio continually increases as the PV area increases.

Figure 12b indicates that with an increase in the battery capacity, the carbon cost ratio increases, reaching a high of 1.44 CNY/kWh when the battery capacity is 10,800 kWh, reflecting the high cost of the battery strategy. The lowest LCOE appears in $S_2_{40\%}$.

In Strategy 3, the LCOE and the carbon cost ratio do not change significantly, with the lowest LCOE appearing in $S_3$. As the ice storage capacity increases, the carbon cost ratio decreases slightly, stabilizing at 0.35 CNY/kWh when the ice storage capacity reaches 3000 kWh.

Similarly, in Strategy 4, the LCOE and the carbon cost ratio do not change significantly, indicating that an increase in the proportion of electric vehicles has little impact on the economic performance of the system.

5. Discussion

Although this study focused on a single case study in China, the proposed 3E analysis framework utilized in this study can be applied to other locations. Regarding the
conclusions, it is important to note their applicability in the local context. In international settings, the results may differ due to variations in solar potential, energy consumption habits, carbon emission factors, and economic conditions. The most localized feature is the economic performance, as the costs of PV and ESS processing, installation, and maintenance may differ due to variations in labor fees and technological capabilities. Differences in grid charges may also affect their potential benefits. Additionally, the energy structure of the local grid can lead to different carbon emission factors [78], resulting in different environmental benefits. Furthermore, energy usage is related to the local climate, and for cold regions with high latitudes, ice storage is not a suitable option and thermal storage facilities should be used instead.

The study has several limitations that should be acknowledged. First, the analysis did not account for the impact of equipment aging on the performance of the PVs and ESSs. Over time, both the PV panels and batteries degrade, which can reduce their capacity and lifespan [89]. Second, the discount rate is neglected in the economic performance evaluation. Although the discount rate is a contentious input in the LCOE equation and can significantly influence the results, we could not provide a sufficient reason for a specific value in this study. Additionally, it should be noted that the local government in Shenzhen provides subsidies for PV and storage projects, which can improve their economic attractiveness.

Beyond addressing the identified limitations regarding the aging effect and economic analysis, future studies can address the following. First, the effects of the integration of different ESSs could be evaluated to investigate the optimal configuration of capacity and the supply order of priority. Second, similar evaluation can be applied to other building typologies, such as offices, commercial buildings, and education buildings. These buildings have different operational timetables and energy curves, which may influence the performance of PVs and ESSs. Lastly, it would be insightful to further investigate the sharing economic model for PVs and ESSs in the community [90] to propose an effective and feasible solution for the coordination of communities.

6. Conclusions

This study presents a case study of a building project in Shenzhen, China, where energy–environment–economy (3E) analysis was employed to evaluate the various benefits of PV and ESS technologies under four different strategies. Furthermore, a sensitivity analysis was conducted for each strategy.

Due to the variation in climate, building energy consumption fluctuates, resulting in changes in self-consumption and self-sufficiency when the four strategies are implemented during summer. Strategies 2 and 3 exhibit the best regulating effect on building energy consumption, with the self-consumption exceeding 90% during summer, but Strategy 3 is almost ineffective during winter. Strategy 4 exhibits a trend similar to that of Strategy 2 but with an overall lower effect.

The life cycle carbon emissions of a building when Strategy 2 is implemented are the smallest, and its carbon reduction ratio is the highest, indicating its optimal environmental performance. The values of Strategy 1 and Strategy 4 are the same, and their carbon reduction ratios are both below 25%, reflecting their lower environmental performance.

Although Strategy 2 achieves the highest annual cost saving and carbon cost ratio among the four strategies, its corresponding payback period reaches 6.81 years, indicating the poor economic performance of the battery storage system. Strategy 3 has better economic indicators, with a payback period of only 3.83 years, indicating the best economic performance among the four strategies. Although the indicators of electric vehicles and photovoltaics are similar, the LCOE of electric vehicles is lower than that of photovoltaics.

The sensitivity analysis identified an optimal capacity range for Strategies 1 and 2, and beyond which, the energy and carbon benefits decrease and the economic investment increases. With Strategy 1, the optimal PV capacity was found to be 18,000 m², while with Strategy 2, the battery capacity range of 600–1200 kWh showed the best performance. Regarding Strategy 3, increasing the ice storage capacity gradually improved its energy
and environmental benefits. Specifically, the carbon reduction ratio increased from 27% to 34%. This strategy exhibited excellent economic performance, with a stable payback period of around 4 years and life cycle cost savings of 41% to 49%. Additionally, increasing the proportion of EVs in Strategy 4 improved overall energy performance. However, it also increased the total electricity demand, resulting in little change in the overall economic and environmental benefits. Its carbon reduction ratio was around 24 ± 1%, and the payback period remained stable at 4 years.

The limitations of the study include the failure to consider the impact of equipment aging on the performance of PVs and ESSs and the neglect of the impact of discount rates on economic benefits. Future research should include the evaluation of the joint effects of different ESSs, a comparison of the 3E performance of different types of buildings, and the consideration of collaborative management at the community level. Via the application of 3E analysis, this study evaluated the comprehensive benefits of different low-carbon strategies, which can provide accurate references for sustainable building design and decision making in low-carbon technology applications.

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