A Systematic Design Framework for Zero Carbon Campuses: Investigating the Shanghai Jiao Tong University Fahua Campus Case

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Abstract: Since the global zero carbon goal was proposed, most higher education institutions around the world are still in the process of transitioning towards carbon neutrality. However, there is still a research gap in the systematic design strategy for a zero carbon campus. This study adopts a qualitative literature analysis approach to establish a theoretical framework for a zero carbon campus design. The framework hierarchically outlines the One Top-Down vision of carbon neutrality, two complementary paths of carbon emission reduction and carbon sink, specific implementation strategies based on the coupling of the social, technological, and ecological dimensions, as well as the establishment of a carbon-neutral smart services platform. Subsequently, a case study was conducted at the Fahua campus of Shanghai Jiao Tong University, guided by this theoretical framework. This study not only completed the modeling and visualization of the carbon-neutral systematic design of the campus but also attempted to conceive of people-centered services under the zero carbon commitment and emphasized the critical role of university campus culture and historical connotations in the carbon-upgrading process. The results showed that the establishment of this theoretical framework can inspire innovative localized carbon-neutral solutions for campus, empower the replicability of advanced zero carbon campuses, and more effectively promote the carbon neutrality development of communities and cities.

Keywords: university campus; theoretical framework; systematic design; zero carbon campus; carbon neutrality; higher education institutions

1. Introduction

As the 21st century unfolds, the global climate predicament has intensified considerably. In an effort to address climate change, the 2016 Paris Agreement delineated comprehensive arrangements for the mitigation of worldwide greenhouse gas (GHG) emissions, committing to initiatives aimed at constraining temperature escalations to within 1.5 °C above pre-industrial levels [1]. In 2020, the European Commission proposed that Europe achieve “carbon neutrality” by 2050, which entails reducing Europe’s net GHG emissions to zero by the year 2050 [2]. Studies showed that universities contribute approximately 2% of the total GHG emissions in the United States, a magnitude analogous to the combined impact of commercial aviation or landfill operations within the country [3]. A university can be viewed as a mini-city or a higher education-focused industrial park, given its considerable size, population, and concentration of activities conducted within the campus. Higher education institutions (HEI) exhibit a pronounced environmental footprint regarding resource and energy consumption, reflecting their significant ecological impact [4]. The primary concerns identified encompass waste generation, energy consumption, and transportation. Consequently, universities hold a pivotal position in mitigating GHG emissions and fostering the transition toward a carbon-neutral society [5]. Simultaneously,
HEIs possess the capacity to not only impart carbon neutrality cognizance among younger generations but also to actively involve the broader public, thereby further facilitating the progression towards a carbon-neutral societal transformation [6]. Universities offer invaluable expertise to various segments of society, acting as a cornerstone within both local and global communities. Their prominent position at the vanguard of scientific and technological advancements enables them to contribute significantly to research endeavors and the education of skilled professionals [7]. They serve as optimal testing grounds for the implementation and demonstration of zero carbon development strategies within cities and communities, effectively transforming them into living laboratories. It has been substantiated that district and campus-centric initiatives can bolster sustainability and decarbonization efforts on an urban scale [8].

Universities worldwide have taken proactive measures to achieve carbon neutrality objectives. The Leuphana University of Lueneburg in Germany transitioned to a renewable energy supply by implementing energy balance for heat, electricity, cars, and business trips and achieved carbon neutrality in 2014 [9]. Charles Sturt University was certified as Australia’s first carbon-neutral university in 2016 by retrofitting to renewable energy, including rooftop solar and cogeneration, upgrading existing buildings for energy efficiency, and applying sustainable building principles and behavior change programs [10]. The University of San Francisco surpassed its goal of net zero carbon dioxide (CO₂) emissions by 2050 ahead of schedule in 2019 through the installation of microturbines on campus for heat and electricity generation, and by purchasing carbon offsets [11]. However, the number of carbon-neutral universities is currently low, and more are in the process of transitioning to carbon neutrality. Carbon neutrality targets are becoming a prevalent priority for university authorities. As vital platforms for manpower training and technological innovation, universities should set an exemplary standard in addressing climate change. The construction of zero carbon campuses is integral to the country’s carbon-neutral development and represents an optimal model for the future development of smart campuses [12].

Currently, research on zero carbon campus strategies is primarily focused on quantifying the carbon footprint of campus operations. The carbon footprint is calculated as tons of CO₂, or CO₂ equivalents if other GHGs are also included [13]. Such studies commonly adopt the GHG Protocol as a framework for quantifying and reporting GHG emissions [14]. Specifically, these studies examine direct emissions (Scope 1), electricity-related indirect emissions (Scope 2), and other indirect GHG emissions (Scope 3) on campus to identify the primary sources of emissions and develop targeted strategies for further emissions reductions [15]. These strategies may involve the use of renewable energy sources, adoption of energy-efficient appliances, deployment of electric vehicles, and participation in reforestation and afforestation programs [16,17]. Furthermore, there is a body of research that is concentrated on the optimization of the design of energy systems for campuses, with the primary aim of meeting seasonal demands for electricity, heating, and cooling while simultaneously optimizing the energy system’s configuration [18,19]. These studies also investigate the potential utilization of renewable energy sources, such as distributed photovoltaic power generation, from several standpoints, including electricity generation capacity, carbon emission reduction, and economic viability. Meanwhile, a limited number of studies have explored the carbon-neutral design of campus buildings, the carbon footprint of campus mobility, and the measurement of campus carbon sinks. However, there are few examples of zero carbon campuses worldwide, and the approach and perspectives are singular. The methods primarily consist of calculating and diagnosing campus GHG emissions, proposing action strategies to deliver energy efficiency and reduce emissions, and purchasing a certain quantity of carbon offsets to attain carbon neutrality. Rarely have studies considered the inclusion of zero carbon gradients in a more systematic way with the cultural and historical heritage of the campus, as well as the inclusion of campus carbon sinks in the carbon accounting mechanism. In the future,
building and operating a zero carbon campus will also be inextricably linked to building and monitoring a zero carbon intelligent service system, which remains to be discussed.

As a carbon-emitting country in Asia, the tremendous pressure on China to reduce emissions has heightened the urgency for Chinese universities to be the pioneers of carbon-neutral practice in the country’s cities and communities, and to further reinforce the achievement of China’s carbon neutrality targets in both theory and practice. For now, the development of zero carbon campuses in China is in its infancy. Tongji University in Shanghai established and administered an online structured survey to track students’ energy consumption patterns, behavioral tendencies and willingness to engage in energy saving, thereby calculating the students’ carbon footprint and recommending measures to reduce emissions [20]. Huazhong University of Science and Technology in Wuhan employed an ecological footprint to assess the sustainability of the campus, with machine learning methods to recognize and predict the crucial influential factors in the students’ carbon footprint and propose effective suggestions on the basis of qualitative and quantitative evaluation [12]. Tianjin University of Technology combined ecological footprint evaluation (EFE) with life cycle assessment (LCA) to qualitatively appraise a low carbon campus and quantitatively evaluated it with an ecological footprint index (EFI) [21]. In summary, there is a lack of practical and theoretical research related to zero carbon campuses in China, and there is an imperative requirement for more profound empirical and theoretical research to form a highly adaptable system design framework that can be replicated and scaled up in a flexible and localized manner, thus making a significant contribution to China’s carbon neutral transition.

Higher education institutions around the world are increasingly calculating their carbon footprint in an effort to achieve their carbon-neutral goals. Nonetheless, a significant challenge that persists is the absence of globally acknowledged approaches for measuring, reporting, and validating the offsetting of GHG emissions from HEIs in a uniform and comparable manner. Consequently, research on carbon footprints frequently produces highly divergent outcomes, rendering them arduous to compare [22]. Studies showed that traditional environmental sustainability initiatives have limitations. Therefore, the implementation of systematic management plans for environmental systems in universities offers significant benefits. Such plans necessitate increased focus on energy, the social responsibility of institutions, and stakeholder education [23]. To guide universities towards sustainable development, the creation of a comprehensive framework that disseminates and monitors the impact and feasibility of crucial campus actions, thereby promoting strategic planning and action [24]. In the current field of zero carbon research in university campuses, there is a lack of established systematic theoretical frameworks that are goal-oriented towards achieving zero carbon targets and guiding sustained development in reducing campus carbon emissions.

Given the above situation, the purpose of this paper is to gain a deeper understanding of the current state of zero carbon campus research and identify research gaps, while establishing a replicable zero carbon campus systematic design framework. To support the objectives of this study, a combination of literature review and case study methods was employed. The research objectives will be achieved by addressing the following research questions:

- What is the role of top-level strategic planning and goals in achieving zero carbon campuses?
- What is the implementation pathway for universities to achieve net zero CO2 emissions?
- How do the various strategies for achieving zero carbon campuses interact in the social, technological, and ecological dimensions?
- How can emerging technologies empower the full lifecycle operation of zero carbon campuses and promote smart governance?

In the following sections, this study outlines the research methodology in Section 2 and Section 3 provides a thematic literature review, offering a comprehensive exposition
of the research background and introducing the theoretical framework developed in this paper. Section 4 elaborates on the zero carbon campus systematic design framework established in this study, which was implemented through a combination of theoretical and practical approaches, leading to innovative solutions for the zero carbon systematic design at Shanghai Jiao Tong University’s Fahua campus. Section 5 analyzes and summarizes the research findings, identifies limitations of the study, and suggests future research directions. Finally, Section 6 provides the conclusion of the entire paper.

2. Methodology

This paper combines theoretical research with practical exploration and mainly adopts methods of literature analysis and case studies. The effectiveness of this method lies in the fact that all data comes from authoritative institutions and actual university campus projects, ensuring the authenticity of the data and the reliability of the research [25]. From the perspective of the entire chapter, literature analysis and case analysis are the most effective methods of this study because critical reflection on previous research results can better leverage the innovativeness of researchers in establishing theoretical frameworks in this field. At the same time, this paper’s research methods also refer to similar theoretical framework papers to further enhance the logical and rigorous nature of this research method [26].

2.1. Literature Review Method

As the concept and definition of a zero carbon campus have not been clearly established, conducting a literature review on related topics is critical for establishing the theoretical framework of this paper. To provide the latest reports and understanding of the current carbon-neutral process of university campuses, the literature review of this paper is based on the Web of Science Core Collection literature search database, which is also the most commonly used database for literature reviews of similar papers. To obtain more accurate search results, the selected search fields are Title, and the selected editions are Science Citation Index Expanded and Social Sciences Citation Index. Relevant literature in the field since 2000 was retrieved using keywords, with document types limited to “Article” and “Review”. The search equation used was (TI = (“higher education institution” OR “university” OR “campus”)) AND TI = (carbon). The initial search result yielded 147 articles, and a second search was conducted using the references of the retrieved articles. After screening, 25 articles that were most relevant to the research topic were selected for qualitative analysis. Due to the small number of primary sources, this paper uses a qualitative analysis approach to categorize the research on zero carbon campuses based on research topics and analyze them accordingly. This provides a solid theoretical foundation for building a framework for zero carbon campus design in the future.

2.2. Case Study Method

Achieving zero carbon emissions at the university campus level generally requires the implementation of systemic intervention measures [27]. Considering the practical nature of zero carbon campus research, a case study is the most appropriate research method. This paper conducts a qualitative and critical literature review to reflect on the complex factors involved in implementing zero carbon campus strategies, and to create a theoretical framework with clear definitions, top-level goals, and implementation paths. To validate the practicality of this framework and its ability to empower campus innovation for zero carbon solutions, this paper analyzes the zero carbon system design and renovation of the Fahua Campus of Shanghai Jiao Tong University as an example, exploring the application of the zero carbon campus system design framework. Based on a summary of related literature and practical case studies, this paper conducts a systematic analysis and organization to present the research results.
3. Literature Review

3.1. Definition and Carbon Neutrality Strategies for Zero Carbon Campuses

A zero carbon campus can be defined as a university campus that, within a specific temporal and spatial boundary, eliminates its GHG emissions and achieves net zero carbon emissions through source reduction, sequestration, and management innovation [28]. Hence, the central aspect of establishing and managing a zero carbon campus is to attain an equilibrium between carbon emissions and sequestration. The achievement of a carbon-neutral campus necessitates the computation of GHG emissions, whereby it is crucial for the campus to distinctly specify the boundary for carbon accounting, emission sources, and monitoring techniques [29]. Based on the literature review, HEIs mainly used GHG protocols as the primary carbon accounting method [12,30]. The campus carbon accounting boundary could be divided into three scopes: Scope 1 covered direct GHG emissions within the campus operational boundary that were owned or controlled by the institution, Scope 2 included indirect emissions from purchased electricity on campus, and Scope 3 encompassed all other indirect emissions from campus activities, such as waste, wastewater, business travel, and faculty, staff, and student commuting [31]. Research indicated that obtaining data for Scope 3 was challenging for HEIs, as many campuses used selective estimates. To achieve carbon neutrality, the formula for campuses is to subtract carbon sinks from carbon emissions and obtain the subscribed Chinese Certified Emission Reduction (CCER). Currently, Carbon Capture, Usage, and Storage (CCUS) technology on campuses is not widely implemented and, therefore, not considered in the formula [32].

After defining the concept of a zero carbon campus, this paper follows the basic strategy of carbon neutrality and divides the literature review into two sub-topics: the establishment of a carbon emission inventory and carbon sequestration under the carbon neutrality strategy. The reference list for these two sub-topics is presented in Table 1.

<table>
<thead>
<tr>
<th>Research Topics</th>
<th>Research Sub-Topics</th>
<th>List of Literature</th>
<th>Status of Research</th>
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<tbody>
<tr>
<td>Carbon neutrality strategies for zero carbon campuses</td>
<td>From the aspect of carbon emission reduction: The establishment of campus carbon inventories.</td>
<td>Rubén Mendoza-Flores et al. [30] Ketija Bumbiere et al. [33] Natalia Cano et al. [31] Eckard Helmers et al. [29] Pablo Yañez et al. [33]</td>
<td>Electricity consumption and transportation within university campuses are the primary sources of carbon emissions in campus carbon inventories. Therefore, transitioning to renewable energy sources and promoting electric mobility are identified as the primary options for mitigating campus carbon emissions. HEIs worldwide have taken a proactive approach to researching strategies to reduce their campuses’ overall carbon footprint, and there is increasing interest in the role of carbon sinks in the process of achieving a zero carbon campus.</td>
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<td>From the aspect of carbon sink: Monitoring and quantifying campus carbon sinks.</td>
<td>Glin, D. and van den Bosch [34] William Fox et al. [35] Seong-il Park and Jung-Sup Um [36] Rebecca Tonietto et al. [37] Helen M. Cox [38]</td>
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HEI: Higher education institution.

Many studies have highlighted that electricity consumption and transportation within university campuses are the primary sources of carbon emissions in campus carbon inventories. Therefore, transitioning to renewable energy sources and promoting electric mobility are identified as the primary options for mitigating campus carbon emissions [15]. Rubén Mendoza-Flores et al. [30] employed the GHG Protocol to assess the GHG
emissions of the Cuajimalpa campus of the Autonomous Metropolitan University in 2016. This inventory provided a basis for formulating a GHG abatement and mitigation policy for the campus, which could yield environmental and economic benefits. Ketija Bumbiere et al. [33] qualitatively reviewed the potential for carbon reduction at Riga Technical University and suggested that modifying user behavior would be the main focus of adjustments. Natalia Cano et al. [31] measured the carbon footprint of the main campus of the Universidad Nacional de Colombia, Medellin using UNE-ISO 14064-1 and the WRI/WBCSD GHG Protocol Corporate Standard, with results indicating that transportation processes, wastewater treatment, and electricity consumption were the largest sources of GHG emissions for the university. Eckard Helmers et al. [29] quantified the impact of retrofitting a university campus to a fully renewable energy supply using the Umwelt Campus Birkenfeld (UCB) in Germany as a case study. They emphasized the need for a holistic approach to significantly reduce a university’s carbon footprint by considering all campus-based implications, including upstream sources. Pablo Yañez et al. [33] analyzed the emissions of The University of Talca (UT) from Scope 1 to Scope 3, revealing that the mobility of students and teaching staff to and from campus was one of the primary sources of emissions. Their study provided a guideline and comparative metric for other HEIs.

Several studies have utilized various methods to estimate carbon storage on campus for the purpose of monitoring and quantifying campus carbon sinks, including the use of unmanned aerial vehicle-based light detection. HEIs worldwide have taken a proactive approach to researching strategies to reduce their campuses’ overall carbon footprint, and there is increasing interest in the role of carbon sinks in the process of achieving a zero carbon campus. An appraisal method that integrated ground measurements and unmanned aerial vehicle-based light detection and ranging (LiDAR) data had been used to calculate the carbon storage of urban trees at the Vancouver campus of the University of British Columbia (UBC) in Canada, according to Gulcin, D. and van den Bosch, C.C.K. [34]. William Fox et al. [35] conducted a case study on the carbon storage in the aboveground and belowground portions of all living trees on the main campus of the University of Georgia, suggesting that a multi-faceted approach to offsetting or reducing overall carbon emissions should be adopted. Seong-II Park and Jung-Sup Um [36] used synergistic near-infrared (NIR) and visible signatures from unmanned aerial vehicles (UAVs) to identify the main types of carbon sinks and sources on campus, demonstrating that collaborative drone imagery could complement existing MRV systems. Rebecca Tonietto et al. [37] compared remote sensing methods on natural lands at the University of Michigan (U-M) to identify accurate and valid protocols for land assessment and valuation of ecological services, while Helen M. Cox [38] inventoried trees on campus to quantify the associated carbon sequestration and produced a GIS geodatabase containing relevant information.

Research on carbon-neutral campuses has primarily focused on quantifying campus carbon footprints and analyzing key sources of impact using consistent approaches in different countries and regions. The challenge for HEIs transitioning to carbon neutrality is to restructure their energy use and optimize commuting efficiency on campus. However, current studies separate the measurement and calculation of campus carbon emissions and sequestration, excluding the combination of carbon emissions reduction and carbon sinks to assess the campuses’ distance from carbon neutrality. Universities, as a pioneering sector in the country's progress towards carbon neutrality, are the ideal laboratory for zero carbon cities and communities, leveraging the latest theoretical and technological innovations. Therefore, campuses should approach carbon neutrality as a closed-loop system, holistically quantifying both carbon emissions reduction and carbon sequestration, to more effectively pursue the goal of carbon neutrality through macro-level planning coupled with micro-level optimization strategies.

3.2. Zero Carbon Campus Systematic Design Dimensions
The ongoing case studies on zero carbon campuses have demonstrated that converting a university into a sustainable, carbon-neutral campus is a gradual process. It involves a cyclical and iterative approach that includes calculating a carbon footprint, developing strategies to reduce emissions, and implementing them. The transformation of a university campus into a carbon-neutral campus can serve as a model for change for the local community and stakeholders, thereby spreading the impact of carbon neutrality across all levels of society [39]. However, there is currently no standardized methodology for achieving a carbon-neutral campus. Along with calculating carbon footprints, HEIs worldwide have also explored various dimensions of designing a zero carbon campus, including energy, building, transportation, and social participation. The reference list on zero carbon campus systematic design dimensions is showed in Table 2.

Table 2. Zero carbon campus systematic design dimensions.

<table>
<thead>
<tr>
<th>Research Topics</th>
<th>Research Sub-Topics</th>
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<th>Status of Research</th>
</tr>
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<tbody>
<tr>
<td>From the aspect of comprehensive campus energy planning.</td>
<td>Ruishi Li et al. [40]</td>
<td>Current campus energy planning investigations can be classified into two categories: developing energy efficiency strategies for existing infrastructure and transitioning to renewable energy.</td>
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<td></td>
<td>Anthony Emeakaroja et al. [41]</td>
<td>In the higher education sector, campus buildings are a significant source of GHG emissions, driven by expanding infrastructure and activities. The functional grouping of buildings and the type of activity significantly affect electricity consumption.</td>
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<td></td>
<td>Yu-Feng Ho et al. [42]</td>
<td>Lesser studies probed the realization of campus carbon neutrality from the perspective of campus transportation, social participation and system evaluation.</td>
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<td>Alper Kerem [43]</td>
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<tr>
<td>From the aspect of campus building transformation.</td>
<td>Adriana Del Borghi et al. [44]</td>
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<td>Gabriel Legorburu and Amanda D. Smith [45]</td>
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<td>Anthony Emeakaroja et al. [46]</td>
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<td>Vasiliki Kourgiozou et al. [47]</td>
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<tr>
<td>From the aspect of campus transportation, social participation and system evaluation.</td>
<td>Sishen Wang et al. [48]</td>
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<td>Bruce Appleyard et al. [28]</td>
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<td>Stefan Zimmermann et al. [49]</td>
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<td></td>
<td>Suresh Jain et al. [50]</td>
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GHG: Greenhouse gas.

The pursuit of climate neutrality by HEIs in response to national decarbonization targets and increasing energy demand necessitates campus energy transformation. Ruishi Li et al. [40] developed a theoretical framework for the water–energy–carbon nexus at the campus level, which examined carbon source and sink spatial patterns and explored nexus characteristics in various functional areas. They identified that the main sources of carbon emissions are heat and electricity consumption, and that the water–energy–carbon nexus is mainly influenced by building characteristics, energy mix, population density, and human behavior. Anthony Emeakaroja et al. [41] applied IPTED (Integration of Persuasive Technology and Energy Delegate) in a student residence to reduce energy consumption. Their results suggested that the adoption of a real-time feedback system and human energy delegates significantly reduced energy consumption, and the impact of real-time feedback and weekly email reminders outweighed that of other factors. Yu-Feng Ho et al. [42] proposed a decision-making model for campus energy conservation and
renewable energy using multi-objective linear programming (MOLP) and a fuzzy two-stage algorithm. The authors studied the Chaoyang University of Technology campus as an example and developed a non-inferior scheme for energy-efficient design of a low-carbon campus. Alper Kerem [43] presented an efficiency study and seven energy-saving strategies for the exterior lighting system of Avşar Campus of Kahramanmaraş Sütçü İmam University, Turkey. They focused on dimming methods, optimizing luminaire operating time, and retrofitting luminaires with emerging technologies to identify the strategy that maximizes potential energy savings. As a highly complex control system, programming campus energy systems requires optimal resource allocation. Therefore, comprehensive campus energy planning should be an integral part of a systematic study on zero carbon campuses. Current campus energy planning investigations can be classified into two categories: developing energy efficiency strategies for existing infrastructure and transitioning to renewable energy. Due to the gap in the digital transformation of campus energy systems and the integration of smart technology interactions, it is essential to embed campus smart energy system planning within a more human-centered, service-oriented conceptual framework for zero carbon system design, in conjunction with technological innovation.

In the higher education sector, campus buildings are a significant source of GHG emissions, driven by expanding infrastructure and activities [51]. The functional grouping of buildings and the type of activity significantly affect electricity consumption, with some buildings having intensive service and equipment requirements exclusive to the campus. Adriana Del Borghi et al. [44] compared the GHG accounting methods and operational strategies of two universities, the University of Genoa (UNIGE) in Italy and Florida International University (FIU) in the USA, to convert their buildings into carbon-neutral structures. The comparison revealed that FIU has more than three times higher Scope 1+2 GHG emissions per person than UNIGE on a global scale. Gabriel Legorburu and Amanda D. Smith [45] proposed a technique to analyze the internal loads of heating, cooling, and occupancy for various building types by utilizing observed energy and weather data. Their multi-objective optimization framework demonstrated that the total building carbon emissions of the University of Utah could be reduced by 15%, with only a 2.4% increase in life-cycle costs. Anthony Emeakaroha et al. [46] designed, configured, and implemented a persuasive feedback support system (PFSS) at the University of Kent, showcasing the potential for creating a sustainable, real-time feedback system to encourage users to decrease their electricity consumption. Vasiliki Kourgiozou et al. [47] reviewed the latest research on smart building principles and smart energy systems for university campuses in the UK, showing that zero carbon design and integrated energy planning can be achieved by adopting “smart” principles. In order to achieve a zero carbon campus, it is necessary to adopt a holistic approach that incorporates both the design of carbon-neutral campus buildings and integrated campus energy planning. This should be accompanied by the development of smart infrastructure, which can be used to upgrade the smart services that are related to the smart campus. By doing so, a comprehensive and efficient paradigm of smart planning for the zero carbon campus can be established [52,53].

Apart from that, lesser studies probed the realization of campus carbon neutrality from the perspective of campus transportation, social participation and system evaluation. Sishen Wang et al. [48] conducted a life-cycle assessment (LCA) comparison of carbon footprints between the bike-share and bus transit systems in the four-campus transit system at Rutgers University. The study found that the operational phase of the campus bus system and the raw material phase (mining and upstream production) of the bike-share system were the main sources of CO2 emissions and energy consumption. Bruce Appleyard et al. [28] proposed a geospatial analysis approach to establish a zero carbon transport network by curbing demand for internal combustion engine vehicles, improving access to walking, cycling, public transit and shared mobility technologies, expanding housing near campus, and transitioning to renewable energy sources. Hybrid systems of optimal carbon reduction for campus public transportation and bike-share systems can
contribute to a reduction in carbon emissions in this area. Regional services that encourage more housing around campus to minimize commuting distances, combined with the deployment of renewable energy for mobility, can facilitate further progress towards zero carbon campuses. Concerning public participation, Stefan Zimmermann et al. [49] presented a stage model depicting the psychological parameters of a successful participation process as a basis for locating appropriate participation interventions for differing project contexts. Their research found a valuable application in the “climate-neutral city campus” living lab at the Stuttgart University of Applied Sciences Stuttgart. In the context of systematic appraisals, Suresh Jain et al. [50] developed a multi-institutional Carbon Neutrality and Sustainability in Educational Campuses (CaNSEC) framework to assess the carbon footprint and overall sustainability of educational institutions, empowering them to validate their sustainability status through qualitative and quantitative methods.

In summary, it is worth noting that current zero carbon campus research has categorized campus carbon emissions according to various dimensions. However, campus energy, buildings, transportation, and human-centered services form a dynamic and coordinated system. The overall carbon emissions of HEIs should consolidate the carbon footprints of these dimensions. Therefore, solving the coupling and game relationships among them is crucial to maximize the outcomes of emission reduction strategies. A zero carbon campus systematic design can clarify these complex factors and facilitate the tight integration of campus comprehensive energy and carbon-neutral buildings. Meanwhile, there is a research gap in the integration of campus cultural and historical values in the zero carbon upgrade process, which neglects consideration of human needs while emphasizing environmental benefits as the evaluation criterion.

3.3. Practical Development of Zero Carbon Campus Systematic Design

The systematic design model of the Zero Carbon Campus can also be broadened to encompass entire communities and cities. Higher education institutions are at the hub of innovation, driving scientific and sociological paradigm shifts [54]. However, the further development of a zero carbon campus presents many challenges. How to allocate and utilize the limited infrastructure and service facilities to effectively reach the ambition of carbon neutrality on campus and to deliver a humanized service experience to staff and students on campus is a pivotal issue in the design of the zero carbon campus system.

Primarily, the concept of a zero carbon campus systematic design framework is seldom mentioned. Most global university campuses are in the midst of transitioning to a zero carbon campus. Establishing a more holistic campus carbon inventory or mitigating campus carbon emissions from more concrete aspects of integrated campus energy management, campus building retrofits, and campus commuting are all bottom-up carbon emission abatement strategies [55]. Few studies have targeted zero carbon campuses and instituted top-down zero carbon systematic schemes with layers and dimensions, therefore attributing the complexity of campus carbon emissions to organized interlinked and dynamically interacting manipulated nodes. The top-level design approach is especially applicable to the construction and operation of a zero carbon campus, which should initially have carbon neutrality as a macro goal. Based on this explicit objective of carbon neutrality, the development of micro-strategies for carbon emission reduction and carbon sinks can be more effectively coordinated within the life cycle of campus operations. The optimization strategies involving the main carbon emission factors of campus energy, buildings and transportation can be further probed through the analysis of the social, technological and ecological dimensions for inter-system coupling.

Rather, there is a lack of research on the integration of carbon emissions and carbon sinks on campuses. Current research on zero carbon campuses concentrated on building campus carbon inventories using the GHG Protocol and others, and identifying key influencing factors and developing improvement strategies. However, how downstream carbon emissions related to campus operations are integrated into the carbon accounting process requires further exploration [56]. The achievement of carbon neutrality does not only
lie in a reduction in carbon emissions, but also in carbon sequestration measures, and the combination of both. Current research on campus carbon sinks is focused on monitoring and calculating the carbon sequestration capacity and annual carbon storage of existing vegetation and has not yet considered how to maximize campus carbon sinks within the existing planning layout. Different combinations of vegetation have different carbon sequestration capacities. Ecological carbon sinks can also be integrated with architectural design, such as greening of building facades and greening of roofs, among other measures. In-depth investigation and development of ecological carbon sinks and further exploration of the use of carbon capture techniques on campus are important components to achieve carbon neutrality.

Meanwhile, emerging technologies are not yet widely used in carbon neutral campus research. Higher education institutions are increasingly inclined to lead the global GHG reduction quest through the development of carbon neutral campuses, digital campuses, and smart campus strategies [57]. Current articles on carbon neutrality in university campuses have not yet delved into the use of emerging technologies such as 5G, IoT, digital twin, and artificial intelligence. Digital convergence brought about by the adoption of new information and communication technologies (ICT), such as ubiquitous sensing through IoT technologies, can support advanced and proactive monitoring, leading to efficient operation of integrated campus facility management. From one side, campus smart energy systems can contribute to carbon reduction on campus by using energy resources more intelligently to achieve business goals and respond to grid signals [58]. Moreover, by collecting data and events through IoT devices, predictive models can be generated using AI/ML technology to support zero carbon campus operations’ optimization [59]. Digital empowerment is one of the keys to the realization of a zero carbon campus that can fully integrate the zero carbon transition of energy and building and transportation systems.

The precious social and cultural values of university campuses can be overlooked on the way to zero carbon. As a condensed mini society, the university campus has a coupling between three subsystems: social, technological and ecological [60]. Current research on carbon neutral campuses has focused on functional carbon neutral upgrades or retrofits in relative isolation from a technical and ecological perspective. Although achieving carbon neutrality is the primary goal of a zero carbon campus, a campus is a social system formed by the interaction of multiple stakeholders (including government, education department, students, faculty, staff, and the public). Researchers usually base their studies on carbon emission sources, energy management, building retrofits, and campus transportation, lacking a multi-stakeholder perspective. In the social dimension, government policy guidance and government funding sponsorship have a direct role in promoting the formation of a carbon-neutral campus. The design of a zero carbon campus system also needs to consider the needs of decision makers, administrators, staff, faculty and students at all levels of the campus, and establish a service model that is relevant to their needs, so as to achieve environmental benefits while taking into account the well-being of students, faculty, staff and other stakeholders. In addition, each university campus has its own unique culture and history, and these infrastructures or iconic buildings, which carry the human values of the campus, can be included in the design of the zero carbon campus system as a combination of campus culture, technology and ecology.

As sustainable communities and cities are transitioning to smart ones, the trend for zero carbon campuses will be the integration of smart technologies [61]. Within a university campus, the adopted smart infrastructure can be further developed to incorporate smart services associated with the smart campus paradigm. The evolution from a traditional campus to a digital or smart campus is based on the optimization of the value system of the university campus. University campuses will adapt to change by leveraging smart technologies to meet the needs of relevant users [62]. There is a need for zero carbon campuses to evolve from assets to service providers that implement carbon neutral commitments [63].
In general, the current zero carbon campus practices are explored from a single perspective. Most studies originate from the study of technology, neglecting the attention and preservation of the historical values of campus culture, while lacking the integration of emerging technologies and proactive service measures oriented to user needs. Zero carbon is a specific form of future university campus development and requires system design thinking to articulate the strategies involved in the social, technological, and ecological dimensions of this goal. This study uses a combination of theoretical research and practical exploration to develop an adaptive system design framework for a zero carbon campus. It is essential to establish this design framework, and the system plan organizes and transforms many complex pieces of information on campus into usable information that can influence campus carbon neutral decision making and management, which can effectively empower the campus and create value for the university campus to achieve carbon neutrality from a human-centered perspective.

4. Case Study
4.1. Theoretical Framework

4.1.1. Components of the Zero Carbon Campus Systematic Design Framework

In the context of global efforts towards carbon neutrality, the pathway towards achieving carbon neutrality in HEIs is equally significant. As a collective entity, university campuses can minimize the negative environmental, economic, social, and health impacts of their resource use at regional or global levels, fulfilling their functions of education, research, and engagement, and helping society transition towards more sustainable lifestyles [64]. Universities around the world have expressed their commitment to reducing their carbon footprint and enhancing campus sustainability [57,60,65]. There are two main ways for HEIs to plan their carbon neutrality pathways: integrating carbon neutral projects into sustainable development plans or developing separate carbon neutral action plans. Some customized methods and frameworks have already been implemented in many campuses, however, there still exists a research gap in adaptive carbon-neutral system design planning [66]. A clear and hierarchical system design framework is needed for university campuses to advance strong carbon-neutral initiatives, enabling different institutions to help colleges and universities around the world that lag behind in achieving zero carbon by sharing common carbon-neutral goals and governance experience.

The key issues discussed in Section 3.3 of this study regarding the development of zero carbon campuses are the challenges that must be faced in constructing or renovating such campuses, but they also present opportunities. The focus of this paper is to establish a localized and replicable design framework for zero carbon campuses that systematically addresses the complex factors involved in the process of achieving carbon neutrality. This framework can motivate HEIs to produce innovative and inclusive zero carbon system design solutions from a systematic perspective. Section 4.1 uses systems design thinking to decompose and reconstruct the internal elements and interrelationships of the zero carbon campus system from different dimensions and outlines a logically clear framework for achieving carbon neutrality and governance to guide specific planning at various system levels. Drawing on interdisciplinary perspectives and global experience with zero carbon park practices, the design elements of a zero carbon park system can be summarized as: One Top-down Vision, Two Complementary Paths, Three Coupling Dimensions, and a Carbon-neutral Smart Services Platform.

1. One Top-down Vision: Carbon neutrality

Carbon neutrality is the essential feature of a zero carbon campus, as shown in Figure 1. This vision is not only the primary principle for constructing or retrofitting a zero carbon campus, but also the fundamental basis for developing operational strategies. A comprehensive management and operational system must be established around the goal of carbon neutrality, covering the main areas involved in carbon emissions calculation. Reducing carbon emissions is a gradual process, so the formulation of campus carbon
reduction policies should follow a complete methodology under this vision. The theoretical research and technological innovation atmosphere in universities can promote the generation of innovative zero carbon design solutions, providing a continuous driving force to achieve the ultimate goal of carbon neutrality [67]. Overall, the explicit proposal of this vision is beneficial for promoting the generation of a carbon-neutral closed-loop for zero carbon campuses, and for conducting cyclical iterations of design strategies after reaching the target, adhering to the people-oriented service concept under the carbon neutrality standard.

Figure 1. One top-down vision for the framework of zero carbon campus systematic design.

2. Two Complementary Paths: Carbon emission reduction and carbon sink

The specific implementation of carbon neutrality in a zero carbon campus is mainly approached from two aspects: reducing carbon emissions and expanding carbon sinks, as shown in Figure 2, while also considering whether national certified emission reduction credits need to be purchased. Firstly, in terms of reducing carbon emissions, previous research has shown that campus carbon emissions are mainly from electricity consumption and transportation [68]. Higher education institutions can actively expand renewable energy sources such as solar, wind, and geothermal energy, and establish a three-dimensional energy supply system based on smart energy systems [69]. At the same time, by using Internet of Things devices to collect electricity usage data and events for campus buildings and infrastructure, AI/ML technology can be used to analyze electricity usage characteristics and generate prediction models to support the operation and optimization of campus energy systems. The production of renewable energy and on-site energy storage can reduce the campus’s dependence on external electricity. The solution to campus transportation carbon emissions mainly involves expanding new energy public transportation and providing shared bicycle services [70]. In addition, reasonable scheduling of transportation vehicles based on campus traffic flow and aggregation characteristics is also a key solution, while ensuring an enhanced user experience. Secondly, the carbon sink on campus needs to be given more attention. Unmanned aerial vehicle-based light detection or remote sensing methods can be used to comprehensively monitor and calculate the current carbon sequestration capacity and annual carbon sequestration amount of the vegetation on campus [71]. Different vegetation combinations have different carbon sequestration effects, and the combination of campus buildings and greening measures has not yet received sufficient research attention. Carbon emission reduction and carbon sink as the two basic paths to achieve carbon neutrality are complementary in the system design framework, and this integrated concept must be deepened in policies and project priorities to enhance and achieve deep-level carbon emission structural transformation on campus.
3. Three Coupling Dimensions: Social, Technical, and Ecological dimensions

Currently, research on zero carbon campuses is technology-centered, relatively isolated, and deeply focused on technology promotion. There is still no close connection between parallel discussions on social and ecological issues. First, the physical and time boundaries of campus carbon footprint calculation should be determined, and then the school’s energy usage (electricity and gas), transportation mileage and type, food, and waste management should be collected. Higher education institutions use carbon footprint calculation tools to analyze the results and compare them with the average values of other schools or industries to assess the school’s carbon performance and improvement space [72]. These are passive bottom-up responses to the existing carbon emissions sources on campus, which may miss key interactions between the social, technical, and ecological components of the campus system, limiting their potential impact. In the increasingly complex global climate context, a single technology-oriented approach is no longer sufficient to maximize the economic and ecological benefits of community and urban development [73]. Establishing social, technical, and ecological thinking in the zero carbon campus system design framework can expand the interdisciplinary vision of campus zero carbon strategies and the well-being of multiple stakeholders, as shown in Figure 3. In the social dimension, zero carbon campus system design needs to consider the diverse interests and needs of campus decision-makers, managers, classrooms, students, and other staff [74]. For campus managers, it is critical to manage and operate a zero carbon campus through monitoring and automation. A decision-making model needs to be established under the overall design of the zero carbon campus system to allocate reasonable decision weights to different stakeholders, encouraging people to respond and cooperate with government policies, thus more effectively optimizing the performance of reducing campus carbon emissions, such as zero carbon commitments, operational optimization, and enhanced user experience.
Figure 3. Three coupling dimensions for the framework of zero carbon campus systematic design.

In the technical dimension, key enabling technologies such as digital, advanced, and low-cost sensing technology, cloud computing, and ML/AI will further promote campus digital transformation [75]. Defining intelligence is not the technology itself, but the value extracted from the data by the enabling technology and how to benefit the campus from it [76]. In the context of zero carbon campuses, some goals may be conflicting, so digital technology is needed to develop data-driven models using a large amount of data to support more effective operations. Carbon, cost, user experience, and other related terms will become indicators for campus decision-makers to make judgments.

In the ecological dimension, zero carbon campuses must fully utilize local advantages of natural resources, such as solar energy, geothermal energy, and wind energy, based on local geographical information (such as terrain, sunshine, precipitation, and climate zone) [77]. Campus carbon sinks are not an independent project but must be integrated into campus intelligent building and infrastructure planning, establishing a multi-level and multi-dimensional campus ecosystem and exploring how to increase carbon storage and sequestration rates in the region [78].

This article proposes that the zero carbon campus paradigm broadens its focus through a variety of interrelated social, technical, and ecological solutions to support a true transformation of traditional campuses towards zero carbon. Linking technology transformation with the ecological usage of campus infrastructure, supporting democratic decision-making inclusively, and systematically connecting social, technical, and ecological agendas.

4. Carbon-neutral Smart Services Platform

This intelligent service platform is the core content of the zero carbon campus system framework. It conceptualizes the complexity involved in campus-level carbon neutrality and visualizes real-time intelligent zero carbon governance on campus [79]. The integration of intelligent technology on this platform provides an opportunity for people to better understand the complex dynamics of campuses in real-time and across temporal and spatial scales [80]. Through this service platform, intelligent solutions for campus carbon neutrality can be integrated into infrastructure and technology investments driven by social and ecological factors through carbon emission monitoring and carbon sink monitoring [81]. The key to the carbon neutrality intelligent service platform is its ability to differentiate and refine the content of the system design framework and focus on the various measures of intelligent zero carbon campuses in different ways. At the same time, the platform can also establish direct links between stakeholders and zero carbon system design components, concretely presenting cross-domain and scale interaction states [75].
visualization of the carbon neutrality intelligent service platform is a good complement to this top-down systematic framework, which not only demonstrates the coordination between the campus intelligent energy system, campus intelligent building system, and interconnected infrastructure in real-time data, but also supports diversified participation of different stakeholders in zero carbon campus governance.

4.1.2. The Framework of Zero Carbon Campus Systematic Design

As an innovation center, university campuses can serve as pioneers in driving digital transformation and the transition to intelligent, zero carbon campuses. The small-scale urban model that HEIs possess also paves the way for more widespread promotion of intelligent, zero carbon cities [82]. Current practice and theoretical research aim to develop optimal technology and energy system performance, not treating system change as an external problem, but addressing it from within the campus system [83]. This type of research focuses on investigating factors that affect carbon emissions, but a more comprehensive and systemic conceptual framework has not yet been proposed [84]. At the same time, social and ecological factors on campus are being ignored, and the carbon reduction awareness of faculty and staff should be fully studied [85]. There is a lack of zero carbon consensus and interaction among multiple levels of stakeholders on campus. Research shows that it is necessary to develop a user experience-focused, integrated conceptual framework related to intelligent technology, intelligent energy systems, and intelligent infrastructure under a zero carbon commitment to achieve sustainable value for a zero carbon campus.

This article’s research question is to establish a system design framework for a zero carbon campus based on systems thinking and combining the current research and development status of carbon-neutral campuses. This framework combines top-down goals and carbon-neutral implementation paths with bottom-up analysis of the social, technological, and ecological dimensions, establishing a campus carbon-neutral and intelligent service platform that is people-oriented. The framework emphasizes the decomposition and systematic reconstruction of the many complex factors under the zero carbon commitment on campus, facilitating efficient development of zero carbon innovative design action strategies and accelerating the process of universities towards carbon neutrality. It encourages decision-makers and managers to consider the zero carbon project concept guided by the coupling effect between the social, technological, and ecological dimensions, ultimately allowing university campuses to achieve carbon neutrality goals steadily.

Based on in-depth research and analysis, as well as communication and interaction with related professionals, this article proposes a zero carbon campus system design framework to clarify the composition and interrelationships of the design elements of a zero carbon campus, providing reference for future zero carbon campus renovation or construction. The zero carbon campus system design framework is guided by a vision goal, with two implementation paths as specific carbon-neutral directions, three implementation dimensions as the starting point for strategy formulation, and a carbon-neutral service platform as the operating system, comprehensively and intelligently governing the zero carbon campus, as shown in Figure 4. This zero carbon campus system design framework has universality, adaptability, and openness, and its framework examples can also be extended to communities and cities.
4.2. Application of the Zero Carbon Campus Systematic Design Framework

4.2.1. Planning Background

The Fahua Campus of Shanghai Jiao Tong University is located at 535 Fahuazhen Road in Changning District, Shanghai, as shown in Figure 5. It is situated near the intersection of Daguan Highway and is adjacent to the main urban roads of Fahuazhen Road and Dingxi Road. The campus is conveniently located near subway lines 4, 10, and 11, as well as bus route 76. The surrounding area has a comprehensive range of facilities, including Shanghai Guanghua Integrated Chinese and Western Medicine Hospital, Shanghai Library, and East China University of Political Science and Law Affiliated High School, all within a radius of 3 kilometers.
This study has identified the Fahua Campus as a case study project, given its moderate size and central location in the city, and the significant impact that its zero carbon transformation could have on the community and the city. Furthermore, the campus has established favorable human resource organizations.

The Fahua Campus is located in an area of developed regional economy, rich cultural, educational, and historical resources, and has a competitive advantage with good interaction with its surrounding environment. At the same time, the campus’s teaching and living systems are relatively complete, and there is ample space for building renovation. The campus has strong identity, locality, and plasticity. However, some local buildings, equipment, and living facilities are aging, resulting in decreased service capabilities and additional economic expenditures due to increased energy consumption. Improving the campus’s era-specific characteristics and living environment is essential. With the promotion of China’s “dual-carbon” policy and local policies in Shanghai, the demand for zero carbon market is further expanding, and low-carbon and low-energy consumption building renovation is becoming more urgent. In March 2023, a research group composed of five teachers and students launched a zero carbon system design study of the Fahua Campus. Their organizational approach included using brainstorming and expert evaluation methods to generate divergent design thinking. They then conducted field research, photography, and on-site discussions before establishing the campus system design approach based on the aforementioned theoretical framework and gradually made it more specific. The current situation of the campus’s building group and main buildings are shown in Figure 6. The campus’s buildings mainly consist of the main building, south building, north building, and apartment, as shown in Figure 6a. The specific scenes of the main building, north building, and south building are shown in Figure 6b.
4.2.2. One Top-Down Vision: Carbon Neutrality

Based on the zero carbon campus system design framework proposed in this article, Fahua campus has established a top-down carbon neutrality vision through brainstorming and expert evaluation, which includes a series of specific goals. Firstly, the campus transformation aims to establish a carbon-neutral demonstration campus. Secondly, the campus planning provides a tour and visit service system and outputs the historical and cultural values of the campus, two innovative designs based on the campus’s characteristics. In addition, the system transformation study attaches importance to the integration of digital technology and strives to enhance the overall user experience of faculty and students. The transformation of the zero carbon campus achieves the rebirth of the old environment through “micro-intervention” and “self-circulation”. “Micro-intervention” means minimal demolition of the original campus buildings and more use of existing resources to quickly transform them. “Self-circulation” refers to low input, high vitality, and renewable space design orientation. From the carbon-neutral perspective, the design of the campus transformation needs to be tailored to local conditions, while considering economic and operational feasibility, and continuously deepening the zero carbon process under the overall guidance of the carbon-neutral vision.

In this case study, the role of the One Top-Down Vision is to incorporate the analysis of specific design strategies and boundary conditions into the systematic transformation framework, so that the carbon-neutral concept can always play a key guiding role in the system design framework. As the only standard, this vision screens the most exemplary carbon-neutral innovative design schemes, promotes target-oriented zero carbon campus building design methods, and promotes the deep integration of architectural, energy, and cultural design systems. The One Top-Down Vision is both a starting point and a target value, constraining the campus transformation system design process towards optimal results. The systematic design diagram for the zero carbon Fahua Campus is shown in Figure 7.

![Figure 7. The visualization of the zero carbon systematic design of Fahua Campus.](image)

4.2.3. Two Complementary Paths: Carbon Emission Reduction and Carbon Sink

After determining a top-down carbon-neutral vision with localized campus features, comprehensive integration of strategies for both carbon emission reduction and carbon sequestration design is carried out based on the guidance of the zero carbon campus system design framework. In terms of carbon emission reduction, a comprehensive energy system for the Fahua campus is established. The first step is to establish a suitable renewable energy system within the campus. Currently, China’s decarbonization of the power grid cannot meet the constantly growing energy demands and the need to integrate local renewable energy sources on a regional scale. Furthermore, energy storage is often not integrated with energy efficiency plans, demand response plans, and two-way
communication with a wider energy system. The integration requirements for various energy carriers, renewable energy, and distributed energy on university campuses are becoming increasingly urgent. This study proposes a “point-cluster-integration” renewable energy system design, as shown in Figure 8a.

![Figure 8. Renewable energy systems in zero carbon campus systematic design. (a) Overall design concept. (b) Specific design strategies.](image)

In terms of the “point” design, wind–solar complementary streetlamps are used on campus roads, making full use of local natural resources such as solar and wind energy to create a wind–solar complementary system on campus. The selected wind–solar complementary streetlamps are mainly composed of three modules: a wind turbine generator, a solar panel module, and a power control unit. In terms of “cluster” design, solar cell arrays are installed on the roofs of several major buildings on campus, which are connected to battery packs through solar charging controllers to provide power for DC or AC equipment on campus. In terms of “integration” Building Integrated Photovoltaics (BIPV) are fully explored, and locally distributed photovoltaic panels or photovoltaic film roofs are used on some buildings, making full use of existing building structures. Figure 8b shows in detail the three major structures and their technical principles of the renewable energy system on this campus, which are the wind–solar complementary system, the solar cell array system, and the distributed photovoltaic panel/film system. The solar photovoltaic panel coverage area of this campus is about 4000 square meters, with an installed capacity of about 900 kW. The annual electricity production per 1 kW is about 1200 kWh, and the entire campus can generate 1,080,000 kWh of clean electricity per year.

Meanwhile, the campus also uses geothermal energy for central heating and provides domestic hot water, as shown in Figure 9. Ground-source heat pump is a technology that uses underground heat energy for air conditioning and heating, utilizing the temperature difference underground through a series of buried heat exchangers. Compared to traditional gas boilers or air conditioning systems, ground-source heat pumps are more efficient, have lower operating costs, and are more environmentally friendly. In the specific implementation process of the campus comprehensive energy project, this study suggests that the strategy should be implemented step by step according to the site conditions, installing ground-source heat pumps, air-source heat pumps, wind and solar-related equipment, energy storage systems, and charging piles in the main building, south building, north building, buildings 1–4, 7–8, functional rooms, and cafeteria.
4.2.4. Three Coupling Dimensions: Social, Technical, and Ecological Dimensions

Many studies on zero carbon campuses have been technology-centered, increasingly disconnected from parallel discussions on social and ecological sustainability and have overlooked the key roles of campus ecosystems and solutions based on campus historical and cultural connotations [86]. This research calls for a true transformation of the zero carbon campus paradigm through three coupling dimensions of systemic thinking [87]. Zero carbon campus system design needs to clearly and critically incorporate zero carbon commitments with a care for people, by linking campus infrastructure transformation with user services and emphasizing the deep integration of campus cultural symbols with zero carbon transformation, so that the technical aspects of campus carbon neutrality can bring tangible well-being to users in their daily lives.

In the dimension of social and technological coupling, this study attempts to establish a carbon-neutral guidance system that connects the entire campus’s zero carbon transformation in the form of a guidance service, forming a complete campus tour route, as shown in Figure 11. The design of this guidance system not only facilitates teachers and students to quickly understand and integrate into campus life after zero carbon transformation but
also helps to convey the concept of carbon neutrality to surrounding community residents, bringing China’s dual carbon policy into concrete implementation in every aspect of people’s daily lives. The focus of three coupling dimensions is to establish a connection between carbon emission reduction technology and carbon sink design for achieving carbon neutrality with users’ lives, expanding the interaction between multiple stakeholders and system components through interdisciplinary perspectives and scales. Under the zero carbon campus system design framework proposed in this study, the abstract concept of a zero carbon campus gradually materializes, implemented from carbon emission reduction and carbon sink design paths to specific base measures transformation coupled with social, technological, and ecological dimensions.

Figure 11. Carbon-neutral guidance system in zero carbon campus systematic design.

The carbon-neutral tour route forms a complete loop around the main campus road, with infrastructure transformation strategies shown in Figure 12. First, the guidance system design sets up a carbon-neutral data display screen at the entrance of the campus gate, showing the campus’s intelligent zero carbon governance dynamics in real-time to teachers, students, and staff. In the South Building, vertical greening and graywater/rainwater utilization equipment are arranged, photovoltaic ground is added at the entrance of the South Building, and solar photovoltaic panels are laid on the roof of the South Building. The “Drinking Water, Thinking of Its Source” stone tablet in front of the main building adopts softened hard paving and is transformed into a ground greening facility in the form of a rainwater garden. Secondly, a facade greening logo is designed for the main building, and an adaptive facade is added to the south facade of the office building according to the actual situation. This is a building exterior wall system that can adjust its functions and performance according to environmental conditions and user needs, thereby improving the building’s energy efficiency, comfort, visual effects, and aesthetics, such as adjustable external sunshades or solar photovoltaic panels. The roof of the main building can also be covered with solar photovoltaic panels, and power-generating bicycles are designed at the staff home on the roof, providing an ecological experience of sports power generation for campus users. In addition, the campus guidance system fully considers the daily life scenes of teachers and students inside the buildings and suggests that future transformations should select energy-saving air conditioners, energy-saving
elevators, ergonomically designed desks and chairs, and innovative people-centered healthy workstations during the implementation process.

**Figure 12.** Analysis of carbon neutrality guided tour routes.

In the dimension of technological and ecological coupling, the zero carbon system transformation of the campus features ecological experience design as one of its characteristics, as shown in Figure 13. University campuses showcase how buildings, infrastructure, and natural environments interact, compete, coexist, and share resources [88]. This interactive relationship also poses challenges to the carbon-neutral development of communities and cities. For university campuses, the coupling of technology and ecology is ubiquitous, and the aforementioned carbon-neutral guidance system also involves the close relationship between low-carbon building transformation technology and the daily teaching and living of teachers and students on campus. Other scattered infrastructure components within the campus also provide interfaces for the coupled system of technology and ecology, allowing us to explore how technology and ecology are coupled and play a role in the zero carbon campus system design by monitoring the use of the environment and infrastructure. In the design of the ecological experience system, power-generating bicycles and scaffoldings added to the staff home, as well as solar pavilions added to the campus, and the bounce fountain that attracts users to participate in the bouncing game, establish a connection between the daily activities and rest of teachers and students with the generation of green energy.

**Figure 13.** The transformation of ecological experiential infrastructure in zero carbon campus systematic design.
This study suggests further linking the coupling relationship between technology and ecology with the ecological impact of campus infrastructure transformation. Sensor-based monitoring technology is embedded in infrastructure construction, providing ecological information to users in the form of variables, supporting users’ understanding of the campus energy and ecological status and dynamics.

In the dimension of social and ecological coupling, this study envisions a cultural inheritance and innovation model for the Fahua campus’s zero carbon transformation, as shown in Figure 14, which is also a key focus of this campus zero carbon upgrade research. The Fahua campus was originally the site of the Fahua Zen Temple. The temple was first built in the third year of Kaibao of the Northern Song Dynasty (AD 970) and has undergone several renovations, and the town of Fahua was named after it. The peonies planted in the Fahua Zen Temple were moved to Zhongshan Park in 1958 to continue their historical context. Two 200-year-old ginkgo trees, which are now the only remaining ancient ginkgo trees of the Fahua Zen Temple, are left on the campus and are under national secondary protection. In the carbon-neutral guidance route, the ancient ginkgo trees are emphasized as a cultural heritage site representing the important historical origin of the campus. At the same time, they are also part of the campus’s carbon sink system. Due to their significant historical meaning, they can attract widespread visual and psychological attention after blending with the carbon-neutral concept, thus becoming the landmark vegetation in the campus transformation process.

In the tenth year of Xianfeng (1860), the Taiping Army stored gunpowder in the Man Yue Pavilion of the Fahua Zen Temple. A fire broke out on the second day of the seventh lunar month of the same year, and the temple gradually collapsed, being rebuilt in the early years of the Republic of China. In 1930, the temple was demolished, and the Zhengshi Middle School was built on the original site, with the current North Building of the Fahua campus being the original auditorium of Zhengshi Middle School. After 1949, it became the Shanghai Municipal Party Committee School of the Communist Party of China, and in 1959, the Municipal Party Committee handed over the school to Shanghai Jiao Tong University, which has been used as the foundation department of Shanghai Jiao Tong University since 1961. In 1986, the School of Management of Shanghai Jiao Tong University (now Antai College of Economics and Management) moved there. In October 1926, on the occasion of the 30th anniversary of the university, alumni donated a free flowing well to their alma mater, symbolizing “drinking water and thinking about its source.” In April 1933, during the 37th anniversary celebration of the school, students, grateful for their alma mater’s nurturing, built a fountain centered on the school emblem in front of the Zhixin West Dormitory where they lived, and erected a stone tablet inscribed with
“drinking water and thinking about its source.” The motto of Jiao Tong University, “Thinking about the Source,” came from this. In the renewable energy system design, this free-flowing well will be combined with a ground source heat pump for transformation, serving as both a landmark facility embodying the motto of Shanghai Jiao Tong University and a symbolic building of the zero carbon campus system, as well as playing an important functional role in the campus’s carbon-neutral process. In addition, this study also designs the area around the “drinking water and thinking about its source” stone tablet as a rainwater garden, an essential part of the ground greening in the campus carbon sink design. Applying social and ecological coupling analysis, embedding attention to carbon neutrality in campus cultural and historical connotations, this hybrid infrastructure can establish various connections between social and ecological dimensions by promoting green diversity, recreational aspects, social cohesion, and a sense of local value, combined with its technical diversity.

4.2.5. Carbon-Neutral Smart Services Platform

Intelligent technology can provide new opportunities for campus energy management, carbon sink monitoring, and infrastructure usage [89]. The role of digital technology in smart carbon-neutral campuses is gradually transitioning from auxiliary to leading. Technologies such as 5G, AI, cloud computing, and IoT will provide campuses with extensive connectivity and computing capabilities. Open digital platforms, integrating data and technology, enable business collaboration and agile innovation, providing comprehensive support for improving the campus experience, optimizing operational management, and adding business value. For example, through virtual reality, multisensory wearable sensors, and other new technologies, users can be provided with real-time quantitative data on the interaction between humans and the environment [90]. Data visualization also makes our dependence on ecology more visible and relatable [91]. In campus operations, this study believes that further advancement of smart control upgrades should be pursued, establishing an intelligent zero carbon operation system that integrates energy management with the overall smart campus cloud, covering building control products, frequency converters, EBO building operation systems, and PME energy management systems [92]. At the same time, it is necessary to implement a microgrid-based EMA overall photovoltaic, energy storage, and charging solution to ensure that the entire campus achieves carbon neutrality during the operation phase.

In terms of multi-stakeholder participation, the Fahua campus also needs such a carbon-neutral smart service platform to closely connect users with infrastructure and ecological conditions, granting different types of stakeholders more capabilities and rights to access relevant information. In the system design of this campus, the carbon-neutral data display screen located at the main entrance serves as the carbon-neutral information display interface for general users. It presents campus carbon-neutral process changes in an intuitive and vivid manner, carrying the key task of integrating and expressing the physical world and the information world of the campus.

4.3. The Iterative Framework for the Systematic Design of the Zero Carbon Campus

In summary, the Zero Carbon Campus System Design Framework, as a set of universal and adaptable guiding principles, covers the major aspects of university campus transformation towards zero carbon and emphasizes the positive impacts brought about by the interaction of technology, society, and ecology. It encourages HEIs to innovate and explore zero carbon-driven innovative designs with campus cultural and historical characteristics. The case study of the Fahua Campus further clarifies the practical application methods of this framework and effectively stimulates innovative spaces. Under the guidance of this theoretical framework, an orderly upgrading and renovation plan is constructed using the Fahua Campus as an example. Due to the complexity of the carbon-neutralization process, this is a sustainable and iterative process rather than a one-time effort, and the carbon-neutralization goal of the campus cannot be achieved solely through
a single planning study. It is necessary to further clarify the iterative nature of this system design framework, as shown in Figure 15.

![Figure 15. The iterative framework for the systematic design of the zero carbon campus.](image)

Firstly, starting with the campus carbon footprint and carbon sequestration capacity accounting, key carbon emission impact factors are identified. Secondly, the specific goals of campus carbon neutrality are clarified. Based on the current situation of campus buildings, energy utilization, and infrastructure, the objectives of the zero carbon transformation plan are customized, with emphasis on preserving and highlighting the inherent historical and cultural features of the campus and integrating campus cultural connotations into the transformation details. Next, carbon emission reduction and carbon sequestration integration strategies are formulated, targeting high-impact carbon emission factors. In this step, the focus is on energy conservation and emission reduction, as well as technology to plan the next phase of zero carbon transformation for the campus. Furthermore, expanding the interaction of the social, technological, and ecological dimensions, the carbon-neutralization-related technology and the interaction between the social and ecological dimensions of the campus are systematically considered. Emphasizing the people-oriented proactive service principle, low-carbon technology is deeply integrated with users’ daily lives and campus ecological environments for innovation. Finally, with the Carbon Neutralization Smart Service Platform as the core of the zero carbon drive, cloud-based collection of campus carbon emissions and carbon sequestration data, building energy consumption, and infrastructure usage data are collected, and data models are established to predict future development trends. Valuable information is presented through a visual interface, and different stakeholders are invited to participate in campus zero carbon governance. After completing a system design process, the carbon footprint accounting at the starting point is returned to, further screening key impact factors, cycling through the system design framework process, until the campus achieves the carbon-neutralization goal.
5. Discussion

This article presented a qualitative literature review on zero carbon campus research, categorizing related studies based on the fundamental logic of carbon neutrality and varying research dimensions. It elucidated the research gaps in this field, primarily focusing on the investigation of university campus carbon emissions inventories and carbon sequestration from a technical perspective. The study underscored the lack of integrated carbon-neutral strategies and coherent analysis, insufficient consideration for human needs and campus culture, and the unexplored potential of digital technologies for the systemic design of zero carbon campuses. Consequently, a theoretical framework for systemic design targeting zero carbon campuses was established and applied to the design transformation study of Shanghai Jiao Tong University’s Fahua Campus.

The research findings were guided by the concept of One Top-Down Vision, which set the top-level goal of establishing a carbon-neutral demonstration campus. The study innovatively formulated a zero carbon campus tour service system and integrated the historical and cultural values of the campus, emphasizing the necessity and innovation-driving nature of the top-level goal design. Subsequently, the study adhered to Two Complementary Paths: Carbon emission reduction and carbon sink, representing the fundamental logic of carbon neutrality. A context-specific renewable energy system plan for the campus was established, adopting a “point-cluster-integration” renewable energy system design. Additionally, the study proposed utilizing geothermal energy for central heating and the domestic hot water supply. From the perspective of campus carbon sequestration, an integrated design strategy of “ground landscape–breathing green wall–sky garden” was developed, aligning with the general offset calculation method for carbon neutrality and considering the campus’s architectural and infrastructural conditions.

The three coupling dimensions system-thinking approach was employed. In the social-technical dimension, the research attempted to establish a carbon-neutral guidance system, connecting the entire campus’s zero carbon transformation through a cohesive tour route. In the technical-ecological dimension, the campus’s zero carbon system transformation was characterized by an ecological experience design, embedding sensor-based monitoring technologies within the infrastructure construction. In the social-ecological dimension, the study envisioned an innovative cultural heritage model for Fahua Campus’s zero carbon transformation, embedding carbon neutrality concerns within a hybrid infrastructure. This was the most innovative aspect of the research, reflecting a people-centric philosophy and emphasizing the integration of campus history and culture within the zero carbon transformation.

The creation of a carbon-neutral smart service platform for campuses was proposed, linking user carbon information awareness with infrastructure and ecological conditions, and utilizing emerging technologies for the intelligent management of zero carbon campuses. The limitations of this research lay in the lack of in-depth analysis of on-campus commuting and personal carbon footprint impacts on teachers and students due to limited resources.

This study suggested that future zero carbon campus research should strengthen interdisciplinary collaboration. Carbon neutrality goals required the integration of energy and fuel, engineering, chemistry, mechanical, environmental science, computer science, and other natural sciences in a more systematic manner. This necessitated the involvement of humanities and social sciences, improving overall planning and operational efficiency. The participation of these disciplines needed to be further enhanced, and the coupling of technology and social systems required more exploration and practice.

In the future, more in-depth research on campus carbon neutrality practices is planned. By employing a systemic design approach and combining interdisciplinary knowledge and methods, the creativity and motivation of this framework could be better harnessed to advance the carbon neutrality process in university campuses.
6. Conclusions

This article employed a literature analysis and case study methodology to explore a systemic design framework for the transition of university campuses towards zero carbon campuses under the global carbon neutrality target. Initially, the article conducted a literature review, analyzing the definition and carbon-neutral strategies of zero carbon campuses, the dimensions of zero carbon campus system research, and the challenges and opportunities faced by the development of zero carbon campus practices. Consequently, an innovative systematic design theoretical framework for zero carbon campuses was proposed, guiding the carbon-neutral transformation of university campuses in case studies. Subsequently, the study used Shanghai Jiao Tong University’s Fahua Campus as an example, detailing the innovative ideas for carbon-neutral transformation under the guidance of this theoretical framework. Under the One Top-Down Vision, the transformation goals for achieving a carbon-neutral demonstration campus were established, along with the zero carbon facility renovation design objectives deeply integrated with the campus’s historical and cultural values. Guided by Two Complementary Paths: Carbon emission reduction and carbon sink, the carbon-neutral goal was embodied in two complementary paths of carbon emissions reduction and carbon sequestration design. Further, based on Three Coupling Dimensions: Social, Technical, and Ecological dimensions, carbon neutrality was specified for campus construction strategies, advocating the positive impact of integrating technology with social and ecological factors, and envisioning a Carbon-neutral Smart Services Platform emphasizing the incorporation of digital technologies. Finally, the study suggested using campus carbon footprint accounting as an evaluation criterion to promote the continuous iteration of the systemic design framework until university campuses genuinely achieve zero carbon emissions, representing a spiraling systemic design process.

Author Contributions: Conceptualization, J.H., L.W., X.Y. and M.F.; methodology, J.H., L.W., X.Y. and M.F.; software, L.W., X.Y., M.F. and H.S.; validation, L.W., X.Y., M.F. and H.S.; formal analysis, J.H., L.W., X.Y., M.F. and H.S.; investigation, L.W., X.Y., M.F. and H.S.; resources, L.W.; data curation, L.W.; writing—original draft preparation, L.W.; writing—review and editing, L.W., X.Y. and M.F.; visualization, X.Y.; supervision, L.W.; project administration, J.H. and L.W.; funding acquisition, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (2022YFB3402001), the National Natural Science Foundation of China (No.52035007, 51975360), Major Project of National Social Science Foundation of China (No. 17ZDA020), Ministry of Education “Human Factors and Ergonomics” University Industry Collaborative Education Project (No.202209LH16).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Authors acknowledge the administrative and technical help from School of Design, Shanghai Jiao Tong University-Shanghai Minhang Real Estate Group, Joint Research Center of Zero Carbon Intelligent Park. Authors express their deepest gratitude to the abovementioned institutions for their support.

Conflicts of Interest: The authors declare no conflict to interest.

Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CCER</td>
<td>Chinese certified emission reduction</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>CCUS</td>
<td>Carbon capture, usage and storage</td>
</tr>
<tr>
<td>HEI</td>
<td>Higher education institution</td>
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<tr>
<td>EFE</td>
<td>Ecological footprint evaluation</td>
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<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
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<td>EFI</td>
<td>Ecological footprint index</td>
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References


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