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Integrated Approaches to Urban Energy Efficiency and Carbon Sequestration: A Framework for Implementing Urban Digital Twins

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ABSTRACT

Energy efficiency and carbon sequestration are fundamental components of sustainable urban development, as cities account for majority of global energy consumption and carbon emissions. This research explores Urban Digital Twins (UDTs) as an innovative approach to optimizing operational energy use and enhancing carbon sequestration in urban environments. UDTs integrate real-time data processing, simulation models, and public participation to drive sustainable energy management and emissions reduction. The study examines two pilot buildings in Thailand and Vietnam, using energy data to evaluate the feasibility of UDTs. Key implementation challenges, including regulatory barriers, setup costs, and limited public engagement, are analyzed, with proposed strategies to address them. A digital twin-based energy framework enables cities to integrate renewable energy systems, intelligent controls, and carbon sequestration strategies, optimizing energy use while reducing emissions and costs. This research aligns with UN Sustainable Development Goals (SDGs) 7 and 11, supporting clean energy adoption and sustainable urban development.

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1. Introduction

The rapid urbanization of cities across the globe has exacerbated the challenges of managing energy consumption and reducing carbon emissions. Urban areas now account for more than 70% of global energy demand and over 60% of carbon emissions, making them central to achieving sustainability goals (Ghafoor et al., 2020; Thi Mai et al., 2024). As urban populations continue to grow, the need for optimizing energy use and integrating sustainable practices into urban planning has become paramount. One promising solution gaining traction is the use of Urban Digital Twins (UDTs), which offer an innovative approach to urban sustainability. UDTs are digital replicas of physical urban environments, utilizing real-time data and advanced simulation techniques to optimize energy systems, reduce emissions, and support carbon sequestration (Coors & Padsala, 2024; Francisco et al., 2020). These systems enable the integration of renewable energy solutions, such as solar energy, within urban infrastructure, driving smarter and more sustainable urban transformations (Neumann et al., 2021). This research focuses on the potential of UDTs to enhance energy efficiency and promote sustainable urban development, with a particular emphasis on pilot studies conducted in rapidly urbanizing cities in Thailand and Vietnam. By examining the feasibility of UDTs in these contexts, the study addresses key barriers to implementation, such as regulatory challenges, high initial costs, and limited public engagement, and aims to propose a comprehensive framework for incorporating UDTs into urban energy systems. This approach supports the UN Sustainable Development Goals (SDGs) 7 and 11, which advocate for clean energy adoption and the development of sustainable cities (UN Habitat WCR Report, 2020; Chen et al., 2024).

1.1 Background and Context

Urban areas are central to the global efforts aimed at sustainable development, as they are responsible for more than 70% of global energy consumption and over 60% of carbon emissions (UN Habitat WCR Report, 2020). As hubs of economic and social activity, cities face an escalating demand for energy, which exacerbates climate change challenges (Ghafoor et al., 2020). With urban populations continuously growing, the need to optimize energy consumption and improve sustainability becomes more pressing. Therefore, innovative approaches that enhance energy efficiency and promote carbon sequestration are crucial in mitigating urban environmental impacts (UN Habitat WCR Report, 2020). The embracement of Urban Digital Twins (UDTs), which can be defined as a digital replica of an urban environment and can use real-time data to model, simulate, and manage urban systems, such as energy infrastructures, buildings, and other urban transportation networks, is one of such solutions (Neumann et al., 2021; Coors & Padsala, 2024). With the integration of cutting-edge technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and machine learning, UDTs can offer data-based decision-making visions that would allow urban planners to make the energy systems and environmental footprints leaner (Francisco et al., 2020). Such technologies are essential in creating smart cities, as they provided a structure not only to help the existing system achieve the best energy outcomes but also guide more sustainable urban changes (Neumann et al., 2021; Coors & Padsala, 2024).

Energy efficiency in urban areas is particularly concerning, as buildings remain the largest contributors to a city's carbon footprint due to their high energy consumption (Ghafoor et al., 2020). Improving energy efficiency involves adopting solutions that minimize energy use while maintaining quality of service. Technologies such as better insulation, renewable energy integration, and intelligent building systems are commonly employed to achieve this (Francisco et al., 2020). However, barriers such as high upfront costs, the complexity of energy systems in urban areas, and the need for public engagement must be addressed to ensure the widespread adoption of energy-efficient practices (Biresselioglu et al., 2024).

Another critical strategy for reducing urban carbon emissions is carbon sequestration, which involves capturing and storing atmospheric CO2. Urban settings can contribute to carbon sequestration by increasing green spaces, incorporating CO2-absorbing building materials in rooftops, and implementing carbon capture technologies. These strategies are vital for mitigating climate change, especially in cities, which are most vulnerable to the risks posed by climate change (Wu et al., 2021). By combining carbon sequestration with energy efficiency measures, cities can significantly lower their carbon footprints and play a key role in global climate mitigation efforts (Zhao & Zhang, 2024).

1.2 Problem Statement and Research Gap

Urbanization plays a critical role in driving economic growth but presents significant challenges in terms of energy consumption and environmental sustainability. While technological advancements have led to the development of energy-efficient systems, many cities, particularly in developing countries, still struggle to integrate these solutions effectively. Barriers such as outdated infrastructure, high initial costs, and limited public awareness hinder the widespread adoption of these technologies (Biresselioglu et al., 2024; Ghafoor et al., 2020). Although renewable energy solutions, like solar energy, are gaining momentum, their implementation in emerging urban environments remains underexplored, especially in regions such as Southeast Asia.

The integration of solar energy with agri-voltaic technology, solar angle adjusters, and carbon sequestration under rooftop solar panels presents a significant opportunity to enhance energy efficiency in urban areas. Such technologies can help cities to decrease energy consumption, carbon emissions, and support city sustainable development (Neumann et al., 2021; Zhao & Zhang, 2024). Nevertheless, the number of analytical studies of the viability and effects of the practical management of such decisions using Urban Digital Twins (UDTs) in quickly developing cities, especially in Southeast Asia, is inadequate.

This research aims to address this gap by investigating how solar energy systems, integrated with agri-voltaic technology and solar angle adjusters, can improve energy efficiency and carbon sequestration within urban environments. By assessing two pilot study buildings in Thailand and Vietnam, the study will evaluate the effectiveness of these technologies in optimizing energy consumption, reducing costs, and facilitating the integration of Urban Digital Twins for enhanced energy efficiency. The study's findings will offer valuable insights into the practical application of UDTs in energy systems, providing a pathway to a more sustainable urban future in Southeast Asia (Coors & Padsala, 2024; Francisco et al., 2020).

1.3. Research Questions

This research aims to fill the gap by exploring the integration of Urban Digital Twins (UDTs) as a tool to enhance energy efficiency and support carbon sequestration in urban environments. The study seeks to answer the following key research questions:

1. How do citizens perceive and engage with energy efficiency practices in urban environments, and what barriers hinder greater participation?
2. How can Urban Digital Twin technologies be adapted to incorporate citizen feedback and drive engagement to promote the development of positive energy districts (PEDs)?
3. What potential does the integration of renewable energy systems, particularly solar energy, have for enhancing energy efficiency, reducing costs, optimizing energy use, and facilitating carbon sequestration?

1.4. Aim and Objectives

This research aims to evaluate the feasibility of integrating Urban Digital Twins (UDTs) with renewable energy systems, specifically solar energy, to enhance energy efficiency and support carbon sequestration in urban settings. The following research objectives guide the study:

1. To evaluate citizen attitudes, behaviors, and engagement levels toward energy efficiency practices in urban environments and identify key barriers that hinder wider adoption of sustainable practices.
2. To analyze the feasibility of implementing a comprehensive UDT framework that supports data-driven energy efficiency solutions and facilitates the integration of renewable energy systems such as solar power in urban areas.
3. To examine how citizen feedback can be incorporated into Urban Digital Twins to create adaptable, community-centered energy solutions that promote sustainable energy practices and engage citizens in the transition to sustainable urban living.
4. To assess the impact of integrating renewable energy systems, particularly solar energy, on improving energy efficiency, achieving cost savings, optimizing energy consumption, and enhancing carbon sequestration in urban environments.

1.5. Structure of the Paper

This paper is organized into several sections to provide a comprehensive understanding of the research and its findings. Section 2 presents the Literature Review, which examines existing research on solar energy systems, energy efficiency, carbon sequestration strategies, and the potential of Urban

Digital Twins (UDTs) for optimizing energy use in urban environments. It focuses on the assimilation of renewable technologies and the solar energy into the city energy systems highlighting the existing gaps in the literature and the necessity of UDT applications within the urban sustainability.

In Section 3, the methodology of this research and the research design is elaborated, in which the methodology of this research study will be given, the data collection methods, the sample size, and methods of data analysis used in this research study to test the viability of integrating solar energy system and UDTs on pilot building sites in Thailand and Vietnam. The coming up with an elaborate framework that combines solar energy, energy efficiency and carbon sequestration strategies has also been highlighted in this section supplemented by the addressing of the issue of perception of the urbanites on the use of UDTs as an effective means of managing energy in a city.

Findings based on the pilot studies are given in Section 4. Some of the important elements that are addressed by this section are energy use, cost reduction, carbon sequestration as well as the involvement of the community in the implementation of solar energy systems and UDTs. It considers the efficiency of the combination of the renewable energy systems and UDTs in urban areas and the energy efficiency specifically.

Section 5 contains the Discussion in which the findings are explained concerning prior studies. This part discusses feasibility, cost-effectiveness, and public participation in the integration of UDTs to urban energy management systems as the challenges and opportunities. It also carries the wider implications of urban sustainability and policy making and provides practical details that urge urban planners and policymakers that hope to integrate UDTs and renewable energy technologies in their implementation.

At last, Section 6 presents a conclusion of the paper summarizing the results and their significance to this research in energy efficiency, renewable energy integration and sustainability in urban areas. Future research and policy recommendations on how UDTs can assist the cities to shift to smart urban energy systems and facilitate the fulfillment of long-term sustainability targets are also provided in this section.

2. Literature Review

UDTs have grown to be one of the most significant tools to optimize the energy system of a city and effect sustainability. UDTs also offer the opportunity to better manage energy consumption, decrease carbon emissions, and advocate the switch to renewable energy like solar energy, therefore harnessing the power of real-time data. Researchers emphasize that UDTs can greatly increase energy efficiency of building construction by supporting real-time control and monitoring of energy consumption that eventually will result as more sustainable usage of the energy (Coors & Padsala, 2024; Francisco et al., 2020). These computerized simulators developed the virtual fac-simile of the physical city, which could be applied in planning, enhancing energy flows and integrating renewable energy, and supporting sustainable urban change processes (Neumann et al., 2021). UDTs also support carbon sequestration by simulating green infrastructure such as urban forests and green roofs, alongside renewable technologies like solar panels (Zhao & Zhang, 2024).

Despite the promising benefits of UDTs, their widespread implementation faces significant challenges, including high implementation costs, regulatory barriers, and the need for adequate infrastructure, particularly in emerging regions (Elsehrawy et al., 2024; Ghafoor et al., 2020). Public engagement plays a crucial role in overcoming these barriers, as UDTs provide a platform for citizen participation in energy management through the use of real-time data (Fathy et al., 2021; Coors & Padsala, 2024). This research aims to develop a framework for integrating solar energy systems with UDTs to enhance energy efficiency and support carbon sequestration strategies in emerging cities, offering valuable insights for policymakers and urban planners. Although UDTs show considerable promise for advancing urban sustainability, further research is required to address the challenges of their effective implementation, particularly in integrating renewable energy solutions.

2.1. Energy Insights in Thailand & Vietnam

The integration of energy-efficient technologies and renewable energy systems in urban areas is essential for achieving sustainable development, particularly in rapidly urbanizing countries such as Thailand and Vietnam. These nations are experiencing increasing challenges related to energy demand, infrastructure strain, and carbon emissions. Urbanization has led to a dramatic increase in energy consumption and a greater strain on existing infrastructure, exacerbating the challenges of mitigating carbon emissions and ensuring access to affordable and reliable energy (Thi Mai et al., 2024). As urbanization accelerates, these countries must adopt innovative energy solutions that address not only energy consumption but also contribute to the reduction of carbon emissions and promote long-term sustainability, as shown in Figure 2.1.

The combination of such technologies as Urban Digital Twins (UDTs) and renewable energy systems, allow converting urban areas in such countries into more sustainable and resilient systems. The research paper seeks to explore how UDTs can maximize the utilization of energy, minimize energy emissions, as well as promote the adoption of renewable energy options, including solar energy, in Thailand and Vietnam cities, as part of the wider objective of embracing the concept of sustainable urban development.

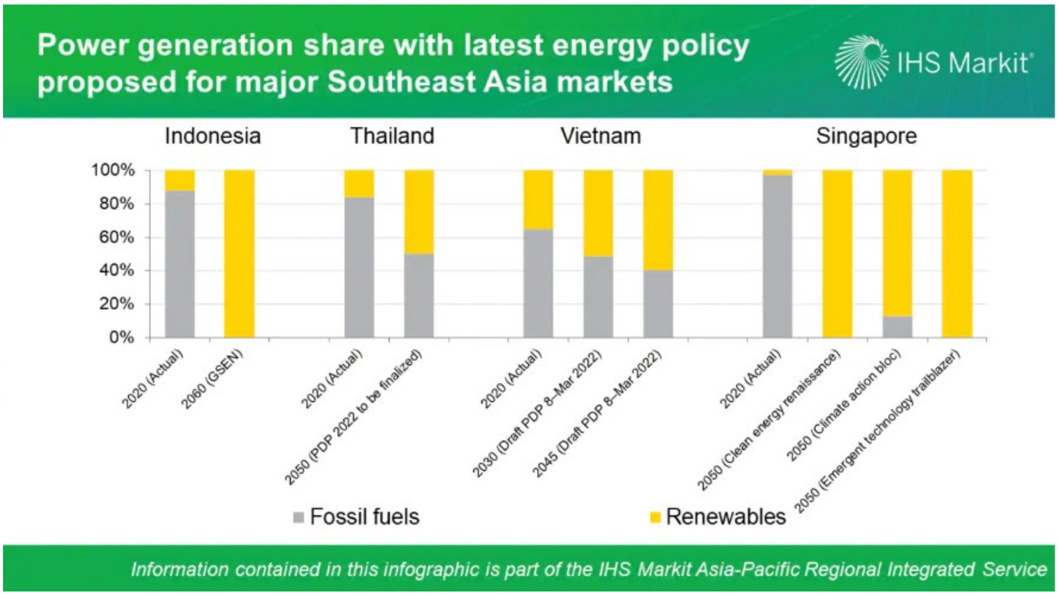

Figure 1: Comparison of renewable energy adoption in Thailand and Vietnam (Source: Asia-Pacific Regional Integrated Service)

2.2. Urban Energy Efficiency

Urban energy efficiency is critical for reducing energy consumption, lowering carbon emissions, and fostering sustainable development in cities. UN-Habitat defines urban energy efficiency as the process of optimizing energy use in urban environments through improved performance in buildings, transportation, and infrastructure, while simultaneously promoting renewable energy technologies (UN Habitat WCR Report, 2020).

The main area of urban energy efficiency is enhancement of building energy efficiency. A large amount of energy and carbon emissions in the cities is used by buildings. Greening buildings means energy optimization with regards to conservation as well as increasing the efficiency of systems and usage of buildings such as heating, cooling lighting and appliances. The more efficient insulation, energy-efficient windows, or smart systems can highly improve the energy efficiency of building (Cespedes-Cubides & Jradi, 2024). Furthermore, it can also help become energy-efficient by incorporating renewable energy resources, like the solar panels, that will make buildings less dependent on the external energy sources.

Building Operational Energy Use is another crucial factor in improving energy efficiency. While embodied energy (energy used during the construction phase) is important, operational energy (energy used during the building's lifecycle) is often more significant. The study narrows down to optimization of operational energy in buildings, which is concerned with heat, cooling, lights and machinery. Sustainable development of cities could be realized by managing the operational energy efficiently, which minimizes the environmental impact of buildings (Li et al., 2020).

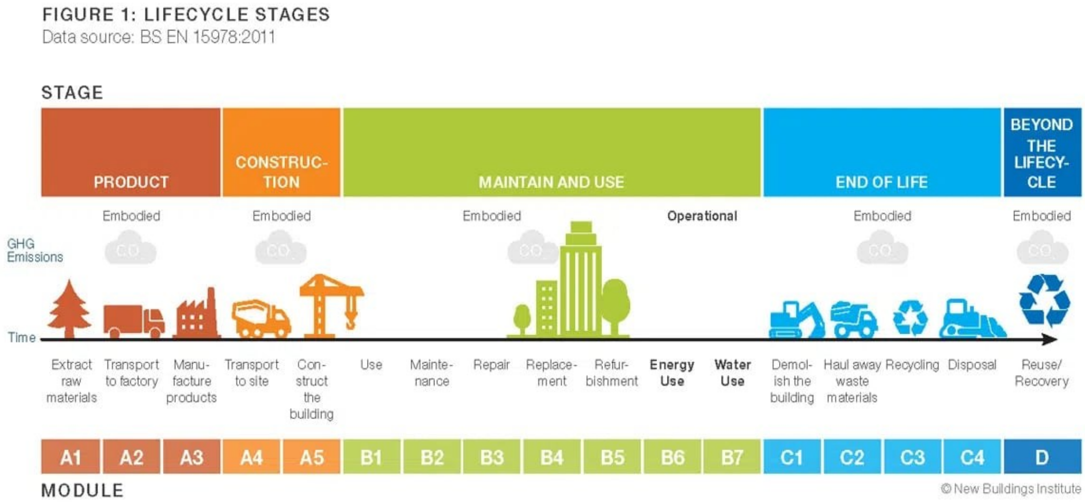

Figure 2: Life-cycle embodied and operational energy and emissions; this research focuses on Building Operational Energy use (Source: BS EN 15978:2011, New Buildings Institute)

2.3. Proposed Solutions for Building Energy Efficiency

Several solutions can improve building energy efficiency, with solar energy integration being one of the most effective strategies:

2.3.1 Use of Renewable Energy like Solar Energy

The contribution of renewable sources of energy such as the solar energy is highly beneficial in reducing the dependency on fossil fuels and the consumption of energy in entire buildings. Installed on the roofs, solar panels can be regarded as one of the most effective ways with which urban areas can create clean energy and minimize their carbon footprint. UDTs also contribute to the streamlining of this process due to the optimization of solar power consumption by buildings and optimization of energy systems (Ghafoor et al., 2020; Francisco et al., 2020).

2.3.2 Intelligent Control Systems like Urban Digital Twins (UDTs)

Smart control systems that observe urban systems, including UDTs, allow real-time monitoring and model urban systems with an optimized use of energy in buildings and infrastructure (Coors & Padsala, 2024). As an example, the Virtual Singapore project entails the application of UDTs in the simulated scenarios of energy savings that help planners make informed choices regarding energy consumption and integration (Francisco et al., 2020).

2.3.3 Optimization of Energy Consumption through Positive Energy Districts (PEDs

Positive Energy Districts (PEDs) are urban areas that produce more energy than they consume, thanks to the integration of renewable energy sources, energy-efficient buildings, and smart grid systems. UDTs play a critical role in managing energy flows within PEDs by using real-time data to optimize energy production and consumption. For example, smart grids in Stockholm use UDTs to monitor and adjust energy distribution in real time, reducing power loss and maximizing renewable energy use (Karvonen et al., 2021).

Examples of solar energy, Urban Digital Twins (UDTs), and Positive Energy Districts (PEDs) can be seen in various global initiatives. One notable example is the integration of solar panels in urban environments, which plays a crucial role in reducing dependence on fossil fuels. Cities around the world, including many urban centers, are increasingly adopting rooftop solar panels as a key component of their efforts to support energy-efficient urban development (Francisco et al., 2020). Another example is Virtual Singapore, where UDTs are used to simulate energy systems and optimize their integration across the city, enhancing energy management and sustainability (Dassault Systèmes). In the UK, the Solcer House project stands as a prominent example of how PEDs can achieve energy self-sufficiency. This project demonstrates the integration of energy-efficient buildings and renewable energy systems, showcasing how PEDs contribute to sustainable urban living (Welsh School of Architecture, UK).

Carbon sequestration, which refers to the process of capturing and storing CO2 to mitigate climate change, is another essential strategy for reducing urban carbon emissions. Urban green infrastructure such as green roofs and urban forests plays a crucial role in capturing carbon and improving air quality. Combining solar energy systems with green infrastructure can enhance carbon sequestration. For example, solar-powered green roofs generate energy while absorbing CO2, contributing to urban sustainability (Shafique et al., 2020). Agri-voltaic technology combines solar energy production with agricultural practices, allowing rooftops to support both energy generation and plant growth. By shading plants, solar panels protect them from extreme weather, while plant transpiration cools the panels, increasing their efficiency. This approach contributes to energy generation and supports urban agriculture and carbon sequestration (Zhao & Zhang, 2024).

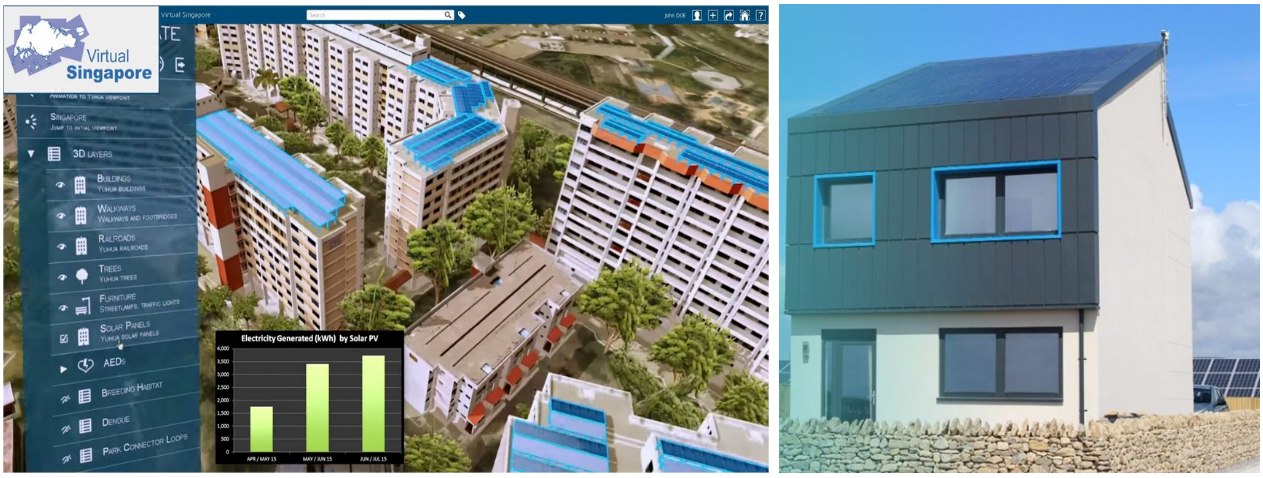

Figure 3: Examples of Solar energy, UDTs, and PEDs – Virtual Singapore (left) and Solcer House (right) (Source: Dassault Systèmes, France and Welsh School of Architecture, UK)

2.4. Contributions of the Research

The study adds to the existing literature on urban energy efficiency and carbon sequestration because it maps out the integration of Urban Digital Twins (UDTs) and solar energy systems installation in the emerging cities in Thailand and Vietnam. The research attributes two pilot buildings within such countries to investigate the viability and successfulness of UDTs in the optimization of energy consumption and sustain carbon sequestration by integrating consolidated solar energy systems. The study addresses the issue of opportunities and challenges of introducing UDTs to urban energy systems with some useful information to credit to the policymakers, urban planners, and sustainability practitioners. Moreover, it highlights how UDTs can enhance citizen engagement in urban sustainability efforts, allowing citizens to actively monitor and manage their energy use and contribute to more sustainable urban lifestyles. The research will also offer recommendations for improving public participation in energy management and carbon sequestration initiatives.

2.5. Conceptual Framework

The conceptual framework for this research is built around key components designed to optimize energy use and promote sustainability in urban environments. The first step is to gather data on energy consumption, carbon emissions, and energy efficiency improvements in the pilot buildings. This data will serve as the foundation for developing targeted strategies to enhance building energy efficiency by leveraging solar energy, UDTs, and smart infrastructure. The next step is to implement these solutions in real-world urban settings to assess their practicality and effectiveness. Monitoring and evaluation will be conducted to track the performance of these technologies in terms of energy savings, cost reduction, and environmental impact. Public awareness campaigns will engage citizens in energy-saving practices and encourage their active participation in sustainability efforts. Finally, feedback and improvement mechanisms will ensure the continuous refinement of energy efficiency solutions, utilizing both data and citizen input to optimize outcomes. The framework aims to achieve energy efficiency goals by combining solar energy systems, UDTs, and carbon sequestration strategies into a cohesive, sustainable approach to urban development.

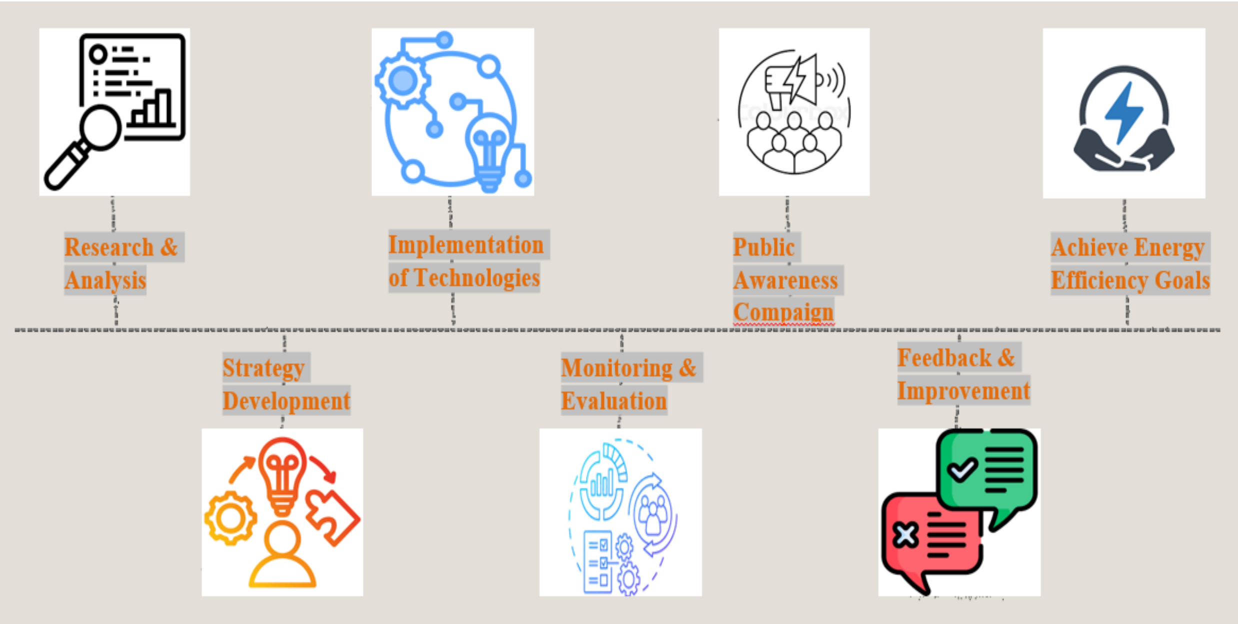

Figure 4: Conceptual Framework of this Research.

3. Material and Methods

This section describes the methodology employed to determine the contribution of Urban Digital Twins (UDTs) to improving urban energy efficiency, and carbon sequestration within urban settings, namely through the retrofitting of rooftops with agri-voltaic technology. The work mainly dwelled within the assessment of solar and grid power consumption in two demonstration buildings in Thailand and Vietnam. It was a mixed-method study that used the quantitative survey of energy consumption and the cost savings with qualitative data collected in surveys and interviews. The purpose of the study was to investigate whether it is possible to combine UDTs with renewable energy systems, namely, such as agri-voltaic systems and solar angle adjusters, to provide improved sustainability in urban areas.

3.1. Research Design

The main objective of this paper has been to assess the capacity of Urban Digital Twins (UDTs) optimizing energy usage to the extent they are combined with solar energy systems that have an agri-voltaic feature on roof spaces of cities and its subsequent support of carbon sequestration in the urban physical structures. Such important research questions are how the agri-voltaic technology could maximize energy efficiency and enable carbon sequestration inside the solar energy system, what makes solar angle adjusters effective in increasing solar energy capture and minimizing the energy dependence on the grid, and how the UDTs could enable the use of the renewable energy solution within the urban setting. The study employed a mixed-methods design, with quantitative data collected through energy consumption measurements, energy savings, and carbon sequestration assessments, while qualitative data were gathered from surveys and interviews. The study focused on pilot buildings in Pathum Thani, Thailand, and Ho Chi Minh City, Vietnam, which represent rapidly urbanizing cities in Southeast Asia.

Figure 5: Research Framework for implementing Urban Digital Twins using Citizen-centric approach by utilizing Renewable Energy and Positive Energy Districts

3.2. Participants and Study Locations

Two pilot buildings were selected for the study. The first was a solar café located at Thammasat University, Rangsit Campus, in Pathum Thani, Thailand. This building featured agri-voltaic technology on its rooftop, along with solar panels for energy generation, functioning as a small-scale urban energy solution. The second building, located in Ho Chi Minh City, Vietnam, was a mixed-use facility operated by Vinova Pte. Ltd., which also included solar panels and a hybrid solar-grid energy system. The participants in the study included residents of these pilot buildings, particularly those directly involved with or affected by the energy systems, and building managers responsible for overseeing energy consumption and operations. The inclusion criteria for participants required that residents had lived in the buildings for at least six months, and that building managers had experience in energy management and sustainability practices. All participants provided informed consent before engaging in surveys or interviews to ensure privacy and voluntary participation.

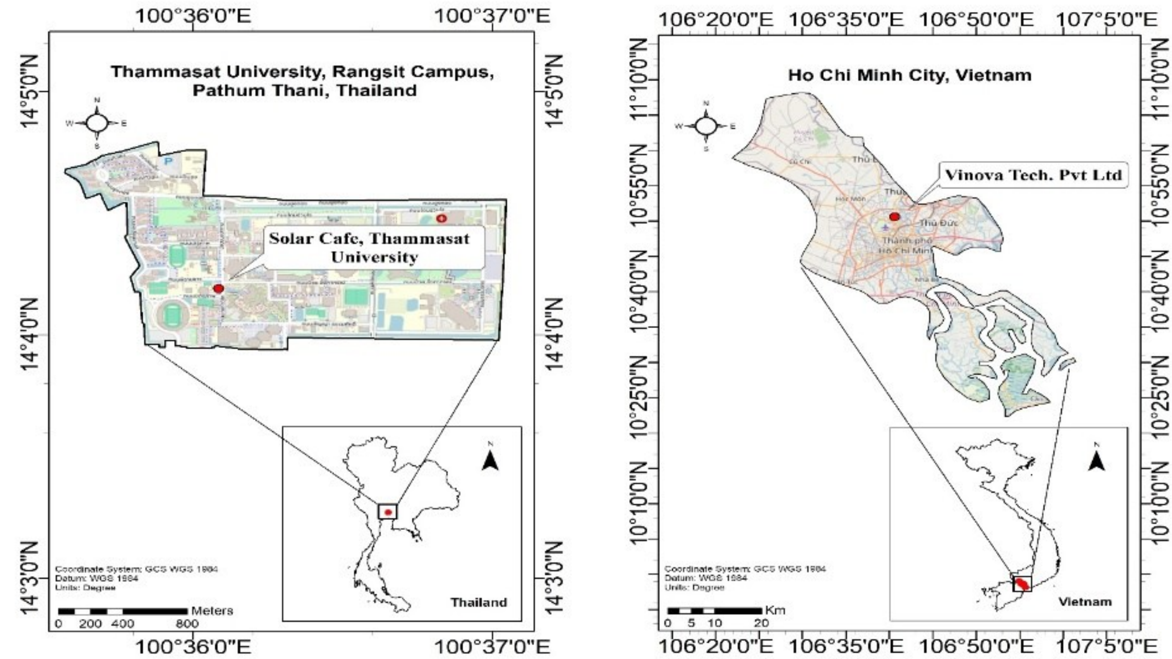

Figure 6: Pilot study sites of Thailand and Vietnam (Left for Solar café, Thammasat University, Thailand and Right for Vinova Tech. Pvt Ltd, Vietnam)

3.3. Data Collection Methods

Energy consumption and carbon sequestration measurements were conducted using various instruments and methods, including solar energy systems, agri-voltaic technology, and solar angle adjusters. Quantitative data were collected to compare energy consumption and assess cost savings, while qualitative data were gathered from surveys and interviews with residents, building managers, and urban planners. The qualitative data focused on energy savings, solar energy infrastructure, and willingness to adopt UDTs for managing energy use in the future.

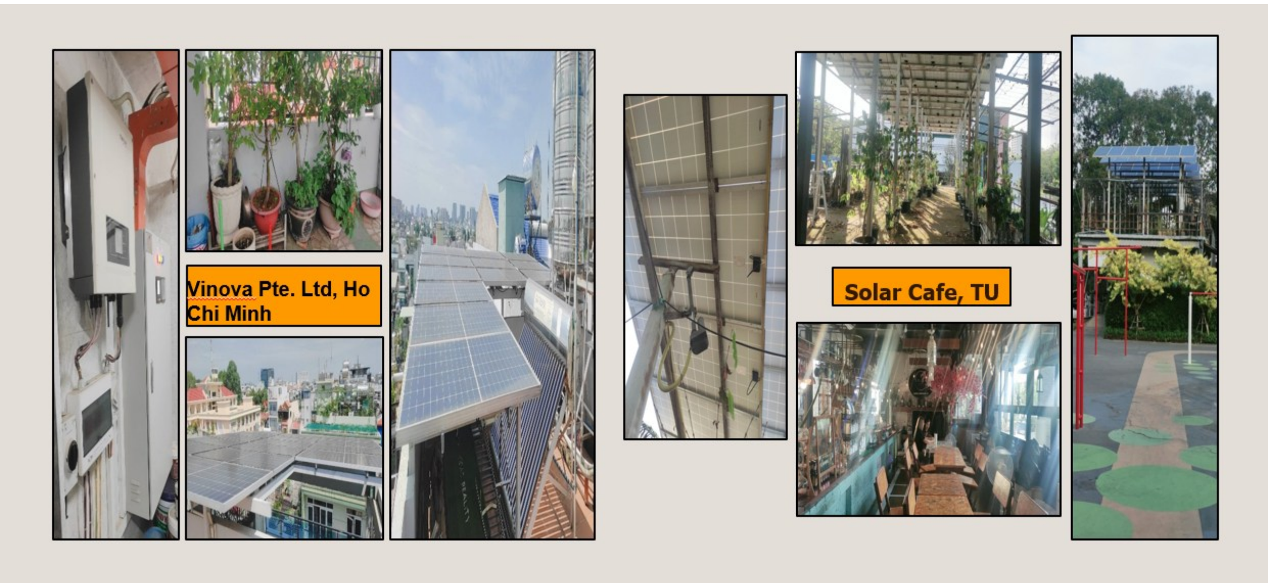

Figure 7: Pilot studies site overview of Thailand and Vietnam (Left for Vinova Tech. Pvt Ltd, Ho Chi Minh City, Vietnam, and Right for Solar café Thammasat University, Pathum Thani, Thailand).

3.4. Data Analysis

Statistical analysis of the quantitative data was applied with use of descriptive statistics to determine the amount of energy consumed, the amount of cost saved and solar energy generated. A comparative study has been presented to determine the efficiency of the agri-voltaic systems and solar angle adjustable in maximizing the energy use and facilitating the process of carbon sequestration. Thematic analysis was performed to analyze the qualitative data, and the major findings included such concepts as energy-saving habits, using renewable energy technologies, and people perception of UDTs.

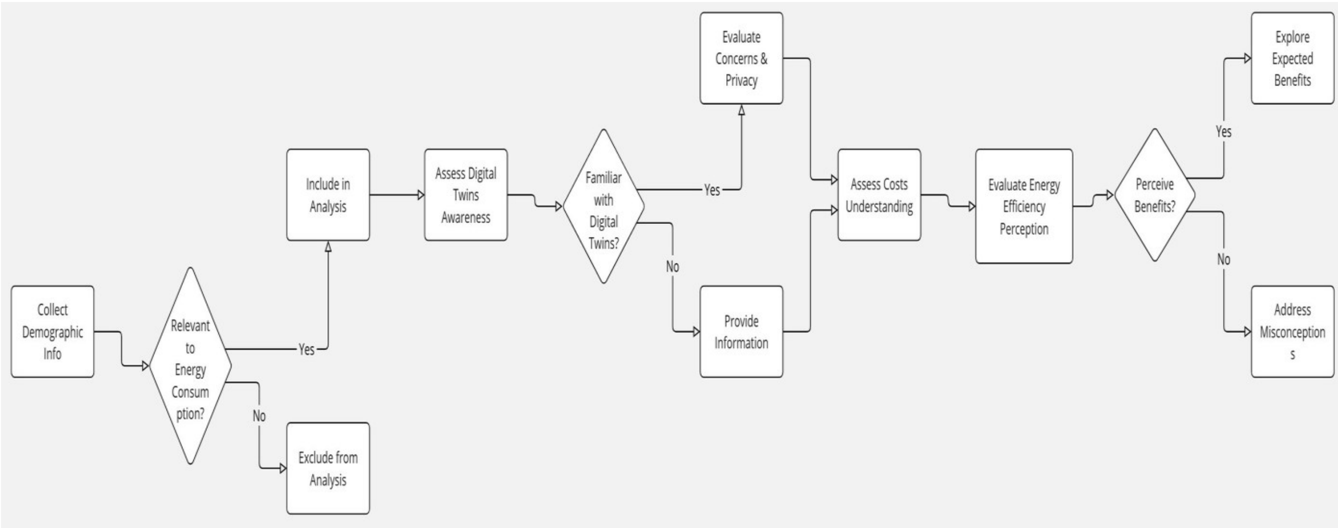

Figure 8: Pilot Studies Survey Framework

3.5. Ethical Considerations

Ethical principles were observed during the design and implementation period of study where informed consent is sought to all the participants and the data was further anonymized to guarantee the confidentiality of data collected in order to keep the participants anonymous.

Appendix A: Sample Questionnaire

Survey Title: *Citizen Perspectives on Energy Efficiency Through Digital Twin Technology*

1. **Demographic Information**:
   - Age: [ ] Under 25 [ ] 25-34 [ ] 35-44 [ ] 45-54 [ ] 55+
   - Income level: [ ] Low [ ] Medium [ ] High
   - Education level: [ ] Primary [ ] Secondary [ ] Tertiary
2. **Awareness of Digital Twins**:
   - Have you heard of Digital Twin technology before this survey?
     [ ] Yes [ ] No
   - How familiar are you with the concept of Digital Twins?
     [ ] Very familiar [ ] Somewhat familiar [ ] Not familiar
3. **Perceptions of Energy Efficiency**:
   - On a scale of 1-5, how important is energy efficiency to you?
     [ ] 1 (Not important) [ ] 2 [ ] 3 [ ] 4 [ ] 5 (Very important)
   - What motivates you to adopt energy-efficient technologies?
     [ ] Financial savings
     [ ] Environmental benefits
     [ ] Government incentives
     [ ] Other (please specify): ____________
4. **Concerns Regarding Digital Twins**:
   - What concerns do you have about Digital Twin technology?
     [ ] Privacy and data security
     [ ] Cost of adoption
     [ ] Lack of understanding
     [ ] Other (please specify): ____________
5. **Expected Benefits**:
   - What benefits would encourage you to adopt Digital Twin technology?
     [ ] Real-time energy monitoring
     [ ] Reduced energy costs
     [ ] Better control of energy usage
     [ ] Other (please specify): ____________

Appendix B: Interview Guide

Title: *Exploring Citizen Engagement with Digital Twins for Urban Energy Efficiency*

1. **Introduction**:
   - Thank participants for their time and briefly explain the concept of Digital Twin technology.
   - Explain that their insights will help shape the development of urban energy efficiency strategies.
2. **Questions**:
   - How do you currently manage your household energy consumption?
   - Have you ever used any digital tools to monitor or control your energy usage?
   - What are your first thoughts on the concept of a Digital Twin that could help improve your energy efficiency?
   - What do you see as the main challenges or benefits of using such technology in your household?
   - Would you be willing to adopt this technology if it were available? Why or why not?
3. **Conclusion**:
   - Summarize the main points discussed.
   - Ask if the participant has any additional thoughts or concerns.
   - Thank the participant again for their valuable insights.

Figure 9: Survey Forms and Interview Questionnaire

3.6. Limitations

This study had several limitations, including a small sample size of two pilot buildings, which may affect the generalizability of the findings. Variations in data availability and the presence of technological barriers, such as issues with solar energy storage and solar system optimization, were also noted.

4. Results

This section presents the findings from the study, which examined the feasibility of Urban Digital Twins (UDTs) and the use of solar energy to enhance energy efficiency and support carbon sequestration through the integration of agri-voltaic technology on rooftops in two pilot buildings in

Thailand and Vietnam. The results are organized into descriptive statistics and inferential statistics, followed by a discussion of the key findings related to energy savings, solar energy performance, and citizen engagement. Tables and figures are included to summarize the key results.

4.1. Energy Consumption and Savings

4.1.1. Descriptive Statistics

The data collected on energy consumption in buildings with agri-voltaic systems and solar angle adjusters showed significant reductions in energy use in both the Thailand and Vietnam case studies. The integration of solar panels and solar angle adjusters contributed to these energy savings by optimizing solar performance and improving overall energy efficiency.

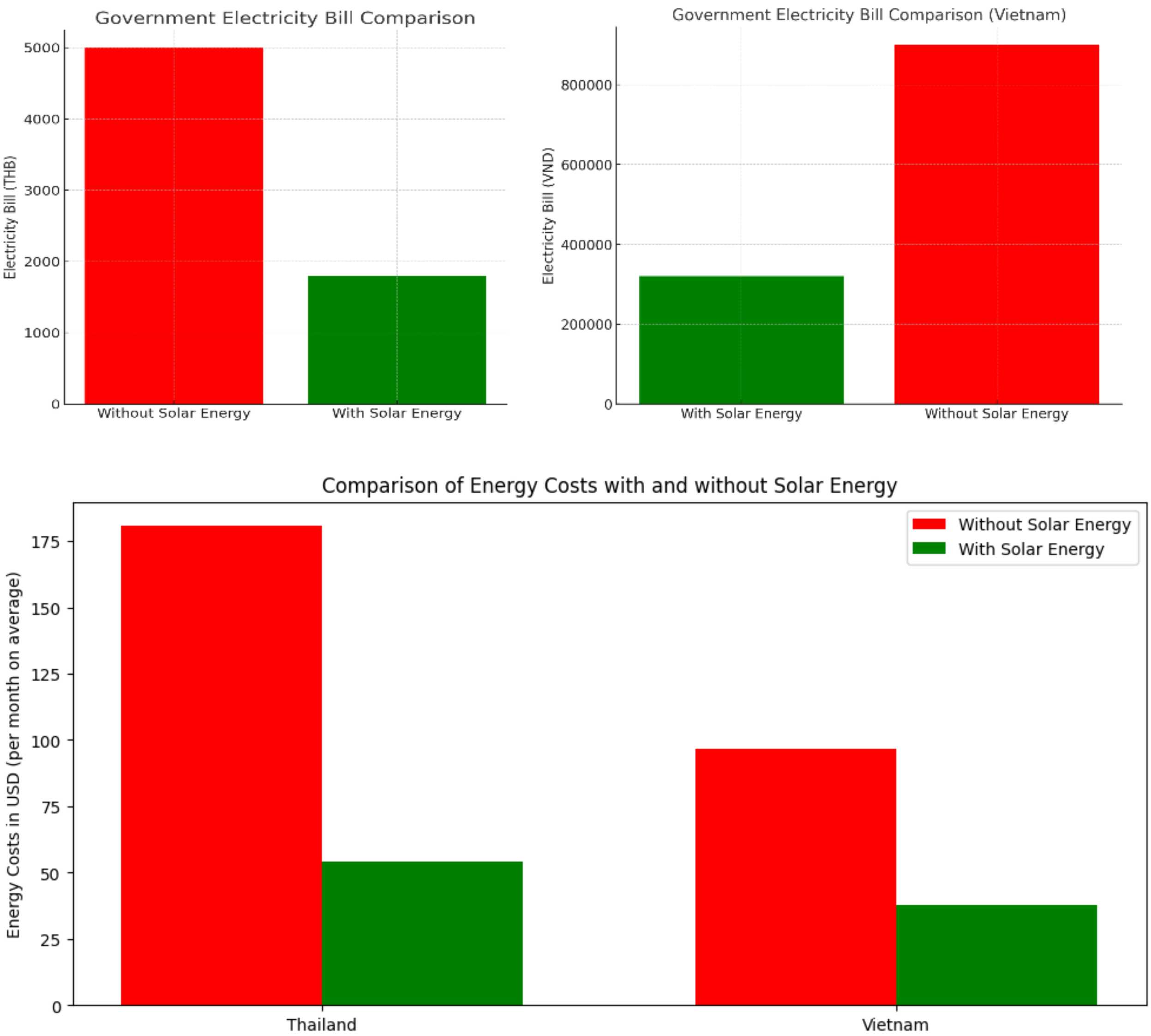

Figure 10: Energy consumption and cost savings with or without solar energy; the upper left shows electricity bill comparison in Thai Baht (THB), upper right shows the comparison in Vietnamese Dong (VND), and the lower section compares both for energy costs in United States Dollar (USD).

4.1.2. Energy Optimization and Solar Performance

Further analysis showed that integrating agri-voltaic technology and using manual solar angle adjusters in the Thailand case study significantly improved energy efficiency. In contrast, the Vietnam case study, which lacked solar angle adjusters, captured less energy during suboptimal sun exposure, although it still contributed excess energy to the grid, which reduced overall electricity bills.

4.2. Citizen Engagement and Willingness to Adopt UDTs

Surveys and interviews were conducted to gauge residents' and building managers' willingness to adopt UDTs for energy optimization and sustainability efforts in the future. The survey included questions on their understanding of renewable energy integration, their experiences with solar and grid energy systems, and their interest in using digital twins for future energy management.

4.2.1. Descriptive Statistics

The survey results indicated a high level of interest in adopting UDTs for energy optimization and renewable energy integration, with Thailand showing slightly more interest than Vietnam. This difference can be attributed to the more visible benefits of solar energy integration in the Thailand case study.

4.2.2. Qualitative Insights

Interview responses highlighted key insights into citizen engagement, participants in the Thailand case study were enthusiastic about the potential for real-time energy monitoring and saw it as an opportunity to reduce their energy bills and contribute to environmental sustainability. In the Vietnam case study, while there was interest in adopting UDTs, participants expressed concerns about the cost of implementation and the technical complexity of managing the system.

4.3. Limitations

While the study provided valuable insights, several limitations were noted. First, sample size the study was limited to two buildings, which restricts the generalizability of the findings to other urban settings. Further studies involving multiple buildings across different urban contexts are necessary. Second, data availability means the availability and quality of energy consumption data varied between buildings, which could have affected the consistency of the results. Third, panel adjustments in the Vietnam case study, the lack of manual solar panel angle adjustments led to lower energy capture during certain periods, which may have skewed the comparison between the two cases.

4.4. Summary of Key Findings

These findings suggest that Urban Digital Twins (UDTs), when integrated with agri-voltaic technology and solar energy systems, can significantly enhance energy efficiency and contribute to carbon sequestration in urban environments. The following table summarizes the key findings from the pilot studies:

Table 1: Summary of the Key Findings from Pilot Studies.

Category	Thailand Case Study (Solar Café)	Vietnam Case Study (Vinova PTE.)	Similarities	Differences	Lessons Learned
Energy System Overview	15-kW rooftop solar system	20-kW rooftop solar system	Both use hybrid systems with solar during the day and grid at night	Vietnam has a larger capacity and uses two separate solar systems	Larger systems provide greater energy independence
Panel Configuration	9 rows, 2 categories: 280W (Rows 1-3), 330W (Rows 4-9)	6 rows, 2 categories: 445W (Rows 1-3 with agri-voltaic technology & 4-6 without agri-voltaic technology)	Both categorize panels based on power capacity	Vietnam has higher wattage panels and fewer rows	Higher wattage panels enhance efficiency
Hybrid Energy System	Solar energy used during the day; grid at night	Solar energy used during the day and night	Both integrate solar and grid power for continuous operation	Vietnam supplies excess energy to the grid for bill reduction	Grid interaction maximizes cost efficiency
Energy Cost & Savings	Monthly bill reduced from 4,000-6,000 THB to 1,800 THB (47% savings)	Monthly bill reduced from 2,300,000 VND to 900,000 VND (60% savings)	Both significantly reduce electricity costs using solar	Vietnam has lesser savings (60% vs. 70%) due to single agri-voltaic setup and no solar angle adjuster	Selling excess energy to the grid maximizes savings
Solar Energy Use & Maintenance	No battery storage due to cost, manual panel adjustment, lifetime 4-5 years	No battery storage, no angle adjustments, lifetime 25-30 years	Both avoid battery storage due to cost	Vietnam uses more durable panels but lacks adjustment features	Investing in long-lifespan panels improves system longevity
Optimized Installation	Elevated panels with plants below (agri-voltaic technology)	One system uses agri-voltaic, the other does not	Both use Agri-voltaic for efficiency	Thailand applies it to the entire setup, Vietnam only in one system	Agri-voltaic technology enhances cooling and efficiency
Operations & Energy Consumption	Operates from 9:00 AM - 5:00 PM, relies mainly on solar during the day, grid at night	Operates from 9:00 AM - 5:00 PM, uses both solar and grid power during the day and night	Both operate during peak solar hours	Vietnam uses more energy-intensive equipment, requiring a mix of solar and grid power	Energy-intensive businesses need diversified power sources
Energy-Consuming Equipment	6 refrigerators, 2 ovens, 2 coffee machines, 2 ceiling fans, 2 ACs (3600W each), 1 TV	60 laptops, 2 refrigerators, 12 ACs, kitchen appliances, washing machine, 4 fans, 18 lights	Both rely on energy-intensive appliances	Vietnam has higher overall electricity consumption	Solar systems must be sized to meet specific energy needs
Findings - Energy Savings	Bill reduced to 1,800 THB	Bill reduced to 900,000 VND	Both achieve significant cost reductions	Vietnam saves more by feeding excess power into the grid	Selling excess power enhances financial benefits
Findings - Solar Potential	Effective for daily energy use but requires grid at night	Used both day and night, excess energy sold to grid	Both reduce grid dependency	Vietnam has additional savings from supplying excess energy	Dual interaction with the grid improves economic feasibility

5. Discussion

This part discusses the findings of the study and compares them to the existing literature, providing insights into the plausibility of Urban Digital Twins (UDTs) to improve energy efficiency and increase the carbon sequestration in cities, especially when the agri-voltaic technology is linked to it. The results from the Thailand and Vietnam case studies demonstrated significant reductions in energy consumption after integrating agri-voltaic systems and solar panels. In Thailand, a reduction of 70% in energy use was achieved, while Vietnam saw a 60% decrease. These findings align with previous studies that indicate that integrating renewable energy systems, such as solar energy, leads to substantial energy savings (Francisco et al., 2020). The performance of solar systems highlighted the importance of solar angle adjusters, especially in Thailand, where these adjusters enhanced solar performance during peak daylight hours. This finding suggests that optimizing solar panel positioning is a key factor in improving energy capture, as supported by Neumann et al. (2021). In contrast, the Vietnam case study, which did not include solar angle adjusters, captured less energy, particularly during suboptimal sun angles, emphasizing the need for adaptive technologies in regions with varying climates.

The integration of solar energy and agri-voltaic technology further contributed to carbon sequestration, especially in Vietnam, where larger rooftop areas allowed for more carbon capture.

This supports the findings of Wu et al. (2021), who emphasized the role of urban green spaces in carbon sequestration. The lack of solar angle adjusters in Vietnam reflects the challenges highlighted by Ghafoor et al. (2020) and Biresselioglu et al. (2024), who noted that technological barriers and high upfront costs can hinder the optimal performance of renewable energy systems in urban settings. The study, however, had some limitations. The small sample size of only two buildings limits the generalizability of the findings. Future research should include a broader range of buildings in different urban settings to better understand the applicability of UDTs. Variations in the quality of data, especially regarding energy consumption, could have influenced the consistency of the results. Technological barriers, such as delays in data processing and inconsistent energy meter readings, may have affected the accuracy of the study. Future studies should focus on developing robust infrastructure and ensuring seamless real-time data integration to improve data reliability.

The findings suggest that integrating UDTs with agri-voltaic technology and solar energy systems can significantly optimize energy efficiency and enhance carbon sequestration in urban environments. While these technologies can reduce energy consumption and grid dependency, challenges such as high initial costs and technological barriers require supportive regulatory frameworks and public-private partnerships, especially in emerging cities. Citizen engagement played a crucial role in both the Thailand and Vietnam case studies, with participants showing strong interest in adopting UDTs and renewable energy solutions. Future research should expand these studies to include diverse urban environments, assess the long-term impact of UDTs, and explore the role of citizen engagement in sustainable urban energy management. Developing a comprehensive digital twin-based framework will help cities transition to more energy-efficient and sustainable systems.

6. Conclusions

6.1. Summary of Main Findings

This research examines the viability of Urban Digital Twins (UDTs) and understands the energy efficiency potential of solar power systems with agri-voltaic technology to facilitate carbon sequestration within urban buildings. The survey discovered that, in Thailand, 70 percent fewer energy resources were used as a result of the combination of agri-voltaic systems, and solar panels whereas in Vietnam; energy use has been reduced by 60 percent due to the combination. Solar angle adjusters in Thailand improved solar performance, particularly during peak daylight hours, optimizing energy capture. Agri-voltaic systems contributed to carbon sequestration, with Vietnam showing greater carbon storage due to its larger rooftop area. Citizen engagement was high in both case studies, with a strong interest in adopting UDTs for energy optimization and renewable energy integration.

6.2. Significance of the Findings

Findings of the study have important implication in urban sustainability. With the incorporation of solar energy systems and the agri-voltaic technology, UDTs offer a feasible method to maximize energy consumption and cut down on the carbon intensity and mitigate climate change. This paper demonstrates the opportunities of digital twins in the management of urban energy systems and sustainability processes. At the policy level, it would be best advised to urban officials to build smart energy systems, and since the citizen activity in this area is rather high, it demonstrates a clear interest among the population to switch to renewable energy production.

6.3. Recommendations for Future Research

Research on the following aspects should be done in the future:

1. Increasing the size to identify more buildings in various urban environments in order to enhance generalizability of the results.
2. Exploring the effects of UDTs, renewable energy systems and agri-voltaic systems in the long term on the consumption of energy, carbon sequestration and cost reductions.

3. Research on how automated renewable energy systems, including automated angle settings on solar, enhance energy performance.
4. Conduct more research on citizen engagement to learn more about what impacts people to embrace the use of smart energy systems.

6.4. Final Statement

Overall, this paper has shown that urban buildings can become carbon sequestration as well as energy-efficient by incorporating the renewable energy system into the agri-voltaic technology. Such results confirm the increasing significance of UDT technologies and becomes the basis of further research and policies on improving the sustainability of urban conditions.

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Conflicts of Interest

The Author declares that there is no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Muhammad Rahat Jamil, upon reasonable request.

Institutional Review Board Statement

Not applicable.

Credit author statement:

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References

Awan, U. and Knight, I., 2020. Domestic sector energy demand and prediction models for Punjab Pakistan. Journal of Building Engineering, 32, p.101790. https://doi.org/10.1016/j.jobe.2020.101790

Bibri, S. E., Huang, J., Jagatheesaperumal, S. K., & Krogstie, J. (2024). The synergistic interplay of artificial intelligence and digital twin in environmentally planning sustainable smart cities: A comprehensive systematic review. Environmental science and ecotechnology, 100433. https://doi.org/10.1016/j.ese.2024.100433

Biresselioglu, M.E., Demir, M.H., Solak, B., Savas, Z.F., Kollmann, A., Kirchler, B. and Ozcureci, B., 2024. Empowering energy citizenship: Exploring dimensions and drivers in citizen engagement during the energy transition. Energy Reports, 11, pp.1894-1909. https://doi.org/10.1016/j.egyr.2024.01.040

Cespedes-Cubides, A.S. and Jradi, M., 2024. A review of building digital twins to improve energy efficiency in the building operational stage. Energy Informatics, 7(1), p.11. https://doi.org/10.1186/s42162-024-00313-7

Chen, L., Li, X., & Zhu, J. (2024). Carbon peak control for achieving net-zero renewable-based smart cities: Digital twin modeling and simulation. Sustainable Energy Technologies and Assessments, 65, 103792. https://doi.org/10.1016/j.seta.2024.103792

Coors, V. and Padsala, R., 2024. Urban Digital Twins Empowering Energy Transition: Citizen-Driven Sustainable Urban Transformation towards Positive Energy Districts. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48, pp.51-56. https://doi.org/10.5194/isprs-archives-XLVIII-4-W10-2024-51-2024

Elsehrawy, R., Kumar, B. and Watson, R., 2024. Critical realism as an underpinning philosophy for the implementation of digital twins for urban management. Journal of Critical Realism, 23(2), pp.187-223. https://doi.org/10.1080/14767430.2023.2301277

Fathy, Y., Jaber, M. and Nadeem, Z., 2021. Digital twin-driven decision making and planning for energy consumption. Journal of Sensor and Actuator Networks, 10(2), p.37. https://doi.org/10.3390/jsan10020037

Francisco, A., Mohammadi, N. and Taylor, J.E., 2020. Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking. Journal of Management in Engineering, 36(2), p.04019045. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000741

Ghafoor, G.Z., Sharif, F., Khan, A.U., Hayyat, M.U., Farhan, M. and Shahzad, L., 2020. Energy consumption and carbon dioxide emissions of residential buildings in Lahore, Pakistan. Polish Journal of Environmental Studies, 29(2), pp.1613-1623. https://doi.org/10.15244/pjoes/109305

Habitat, U. N. (2020). The value of sustainable urbanization. World Cities Report.

Li, Z., Lin, B., Zheng, S., Liu, Y., Wang, Z., & Dai, J. (2020, August). A review of operational energy consumption calculation method for urban buildings. In *Building Simulation* (Vol. 13, pp. 739-751). Tsinghua University Press. https://doi.org/10.1007/s12273-020-0619-0

Mazzetto, S., 2024. A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development. Sustainability, 16(19), p.8337. https://doi.org/10.3390/su16198337

Neumann, H.M., Hainoun, A., Stollnberger, R., Etminan, G. and Schaffler, V., 2021. Analysis and evaluation of the feasibility of positive energy districts in selected urban typologies in Vienna using a bottom-up district energy modelling approach. Energies, 14(15), p.4449. https://doi.org/10.3390/en14154449

Omrany, H., & Al-Obaidi, K. M. (2024). Application of digital twin technology for Urban Heat Island mitigation: review and conceptual framework. Smart and Sustainable Built Environment. https://doi.org/10.1108/SASBE-05-2024-0189

Ramnarine, I. D., Sherif, T. A., Alorabi, A. H., Helmy, H., Yoshida, T., Murayama, A., & Yang, P. P. (2025). Urban revitalization pathways toward zero carbon emissions through systems architecting of urban digital twins. Environment and Planning B: Urban Analytics and City Science, 23998083251318142. https://doi.org/10.1177/23998083251318142

Stroh, F.F., 2020. The new role of citizens as co-creators of socio-digital innovations and urban development: A case-study of participation and co-creation in the smart city development of Barcelona (Master's thesis, Universität Tübingen). http://dx.doi.org/10.15496/publikation-39016

Thi Mai, A. N., Xuan, V. N., Mai, H. L., Xuan, H. P., & Thi Phuong, T. N. (2024). Population, carbon dioxide emissions and renewable energy consumption nexus: New insights from Vietnam. Energy Exploration & Exploitation, *42*(5), 1763-1798. https://doi.org/10.32479/ijeep.9229

Wang, X., & Ma, D. (2024). Smart city landscape architecture for sustainable urbanization in digital twin: Practical sustainable and reliable renewable based smart cities energy hub development. Sustainable Energy Technologies and Assessments, 65, 103785. https://doi.org/10.1016/j.seta.2024.103785

Wu, J., Dang, Y., Jia, H., Liu, X. and Lv, Z., 2021, September. Prediction of energy consumption in digital twins of intelligent factory by artificial intelligence. In 2021 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP) (pp. 354-359). IEEE. https://doi.org/10.1109/ICT-PEP53949.2021.9601051

Xu, W. and Liu, S., 2024. Novel economic models for advancing urban energy management and transition: Simulation of urban energy system in digital twin. Sustainable Cities and Society, 101, p.105154. https://doi.org/10.1016/j.scs.2023.105154

Zhang, A., Wang, F., Li, H., Pang, B., & Yang, J. (2024). Carbon emissions accounting and estimation of carbon reduction potential in the operation phase of residential areas based on digital twin. Applied Energy, 376, 123155. https://doi.org/10.1016/j.apenergy.2024.123155