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Mitigating the Energy Consumption and Carbon Emissions of a Residential Area in a Tropical City Using Digital Twin Technology: A Case Study of Bertam, Penang

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Abstract: As of 2022, roughly 79.8% of Malaysia's population resides in urban areas, increasing the population density of its cities. The hot and humid climate in Malaysia necessitates the constant use of air conditioning, especially in cities, resulting in high residential electric consumption and carbon emissions. The residential sector significantly contributes to global climate change, accounting for 27% of global energy consumption and 17% of carbon emissions. To address this concern, the local framework of the National Low Carbon Cities Masterplan (NLCCM) is advocating for a minimum 33% reduction in carbon emissions by 2030 in urban settings, aligning with the commitments made at the 15th Conference of Parties (COP 15). The aim of this study was to determine the energy consumption and carbon emission of residential areas in a tropical city, as well as explore potential energy and carbon savings. Utilizing the Intelligent Communities Lifecycle–Intelligent Community Design (iCL-iCD) energy simulation software, a digital twin of Bertam City, Penang, was developed. This digital model included 65.4% residential housing, which, in the specific scenario under study, accounted for 36% of the city's electrical energy consumption for cooling purposes only. An early simulation of the residential areas of the city estimated the baseline energy consumption and carbon emissions to be 607 GWh and 314,736 tCO_2e, respectively. Several energy-efficient measures were applied to the residential area of Bertam City, revealing a potential saving of 37.3% in both energy and carbon emissions.

Keywords: building simulation; energy savings; carbon reduction; digital twin technology; low-carbon city

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1. Introduction

The impact of urbanization in a country can be assessed by examining its rising urban population data. According to the United Nations (UN), more than 56% of the world's population currently resides in cities, and this figure is expected to reach 68% by 2050 [1]. In Malaysia, the urban population has experienced a growth of 12.4% over a span of two decades, surging from 66% in 2001 to 78.4% in 2023 [2]. This suggests that approximately 26 million Malaysian citizens live in urban areas nationwide, constituting over two-thirds of Malaysia's total population of 33.2 million [3]. Expanding urban areas has led to a surge in demand for electric energy, resulting in higher carbon emissions. Urgent action is imperative to investigate alternative and sustainable energy sources to mitigate the impact of global warming. Malaysia's electrical energy consumption in 2020 amounted to 13,007 ktoe, or 151.3 million kWh, reflecting a 31% increase over the past ten years [4]. Research indicates that 80% of Malaysia's carbon emissions stem from urban areas, contributing to approximately 200 million tCO_2e of carbon released into the atmosphere [5]. Thus, Malaysia's per-capita carbon emission was calculated to be 7.6 tonnes in 2021. As a comparison, other developing countries such as China, Thailand, Indonesia, and India have emitted 8.4, 3.8, 2.2, and 1.9 tonnes of carbon emissions per capita, respectively [6].

Malaysia primarily relies on coal and natural gas for power generation [7]. The electricity produced from these sources, through natural gas and coal-fired power plants, accounts for at least 36% of Malaysia's total greenhouse gas (GHG) emissions [8]. The depletion of global reserves of coal and natural gas, coupled with the detrimental effects of burning these non-renewable energy sources, has prompted the Malaysian government to create a much cleaner renewable energy option. Among the alternatives, solar energy is widely considered in the country due to its relatively high sun intensity. It is expected to bypass other alternative renewable energy options in Malaysia by 2050 due to proactive and encouraging government policies [9].

In alignment with the 21st Conference of Parties (COP) in Paris, France, the Malaysian government is committed to reducing carbon emissions in cities. In 2021, the Green Technology Application for the Development of Low Carbon Cities (GTALCC) introduced the National Low Carbon Cities Masterplan. This masterplan targets a minimum 33% reduction in carbon emissions across 33 major Malaysian cities by 2030, with the ultimate goal of achieving carbon neutrality by 2050 and beyond [10]. As part of this initiative, a specific city was selected for a case study. Bertam City, located in the Seberang Perai district, is among the cities included in this program. Leveraging digital twin technology, a virtual counterpart of Bertam City was modeled and simulated to obtain its energy consumption and carbon emissions. Using the software to model the city, the residential housing constitutes 80% of the total city area, generating 2464 dwelling units from a total of 3077 building models.

This paper aimed to obtain the total energy consumption and carbon emissions in Bertam City and its residential area. Additionally, the study aimed to determine the percentage of potential energy and carbon savings applicable to the residential areas within the entire city.

2. Literature Review

The retrofit approach is widely applied in most publications to reduce the energy consumption of buildings. These involve the application of three energy efficiency strategies: improving the HVAC system [11–14], lowering the U-value of building envelopes [14], and installing solar PV panels [15].

The hot and humid climate in Malaysia results in a significant need for air conditioning in buildings to maintain indoor thermal comfort, consequently leading the demand for electrical energy in the country. This is substantiated by the findings of Kubota et al., who demonstrated that air conditioning has the highest electric energy demand in a residential area in Johor, Malaysia [16]. Another study also predicts a yearly increase of approximately 50,000 air conditioning units in Malaysian households from 2000 to 2020 [17]. The prediction closely corresponds to the actual data, as in 2019, the demand for air conditioning units amounted to 1 million, reflecting an increase of 40,000 units from the previous year [18].

In their paper, Aldhshan et al. state that the building sector alone accounts for 14.3% of the total energy consumption, with 53% of this energy being utilized by commercial and residential areas [19]. While the primary contributor to energy consumption in these sectors is the air conditioning systems, there is a small factor involving the U-value of building components that affects indoor thermal comfort. One study outlines how construction materials used in residential buildings contribute to global warming in Malaysia [20]. The heat transfer coefficient (U-value, measured in Watt/m^2-Kelvin) significantly affects the thermal performance of spaces within buildings [21]. In terms of building design, the selection of building materials could potentially play a major role in improving the energy performance of buildings [22].

A few studies incorporate digital twin technology into the examination of smart energy cities. In a study by Jin, Zhang, and Bharule, the focus was on integrating IoT/Cloud models to activate port cities, fostering a smart and sustainable logistic transition [23]. Hosseinihaghighi et al. utilized digital twins for planning a housing retrofit program. In their study, the technology was used to develop inputs for housing energy modeling and mapping using various data such as heating permits and smart thermostat data [24]. Digital twin technology has also been applied as a method to regulate smart energy systems in housing areas [25,26]. However, all of these studies have only been conducted in temperate and continental climate areas.

Studies analyzing energy consumption and carbon emissions in cities using digital twin technology are scarce, especially in tropical countries. An example is a study in India that combines federated learning with digital twin technology for smart city applications [27]. Building on this gap in research, this study aimed to further investigate the potential of digital twin technology in developing low-carbon cities in Malaysia. It incorporated several passive and active design strategies using digital twin technology, along with employing simulation methods to determine the number of energy offsets achievable through the prospective implementation of solar roof panels in the Bertam residential area.

One of the chosen passive design strategies was the reduction in the heat transfer coefficient (U-value) of residential building models' envelopes. Additionally, this study aimed to determine the impact on the energy performance of HVAC systems used in Malaysian housing by implementing more efficient systems than those commonly used. An analysis of potential energy and carbon savings of the city models was performed, relying on the reports of energy use and carbon emissions generated during the simulation process. This study, being a pioneering one in the country, can serve as a benchmark for local authorities and municipalities in planning sustainable cities. Moreover, this research has the potential to offer valuable insights into energy savings and carbon reduction on a city level, particularly in residential areas, contributing to the attainment of national objectives.

2.1. Digital Twin Technology

The inception of the digital twin concept was first described by Dr. Michael Grieves at an industry presentation held by the University of Michigan in 2002. The first example of a digital twin is believed to date back to 1970, when NASA utilized this concept to address the damage to the Apollo 13 spacecraft. In this case, a model copy of the spacecraft was created to facilitate the safe return of the crew to Earth. There are two systems: a physical system existing in the real world and a virtual system containing all the data of the physical system. Both systems mirror each other and remain in both real and virtual spaces. Digital twin technology is also noted for its efficiency in saving time, coupled with the high accuracy of its data in representing the real-time world, either virtually or vice versa [28].

2.2. IES Software—Intelligent Community Lifecycle (iCL-iCD)

This research adopted a simulation-based approach as its main investigatory method. The software used to assess the city's energy consumption is known as Intelligent Communities Lifecycle–Intelligent Community Design (iCL-iCD). It originates from Integrated Environmental Solution (IES), a technology firm specializing in providing solutions for climate change and built environments. Its founder, Don McLean, stated that their software is designed to facilitate the development of low-energy buildings and communities [29]. iCL-iCD incorporates digital twin technology to decarbonize the built environment and develop a healthy and resilient built environment [29]. A similar approach has been taken in studies conducted on Gaza City [30] and Morocco [21]. The combination of digital twin technology and iCL-iCD enables the creation of a built environment aiming for zero carbon, with the help of various energy-saving measures implemented through the software.

iCL-iCD serves as a simulation tool to investigate the city's energy consumption and carbon emissions. The initial step involves obtaining the city's baseline energy consumption and carbon emissions. Secondly, the software functions as a simulation tool to analyze the impact of selected passive and active techniques on the energy consumption of models situated in Bertam. The selection of iCL-iCD for this research is driven by its ability to generate comprehensive energy reports for large-scale models, including cities or even entire countries. Table 1 provides a comparison between the iCL-iCD v.2021.1 software and other well-established energy simulation software such as EnergyPlus, Design Builder, and Sefaira.

Table 1. Comparison between iCL-iCD and other energy simulation software [31].

Software	iCL-iCD v.2021.1	EnergyPlus v.2.0	Design Builder v.1	Sefaira v.1
3D model size simulation	City	Single	Single	Single
Provide quick energy analysis	Yes	No	Yes	Yes
Provide weather data and extensive libraries of building components	Yes	Yes	Yes	Yes
Provide HVAC Selection	Yes	Yes	Yes	Yes
Provide guidelines on adhering to building codes and rating systems	BREEAM, LEED, UK Building Regulations	-	LEED	BREEAM, LEED, Building Code of Australia
Allow examination of sensitivity and uncertainty in key design parameters	Yes	Yes	No	-
Potential solar PV energy savings	Yes	Yes, but limited	-	Yes

3. Research Design

3.1. The Bertam Digital Twin City

iCL-iCD uses OpenStreetMap (OSM) to build a comprehensive city model, using OSM as the geodata foundation for the digital twin models. This helped the software to develop a geographically accurate digital twin representation of Bertam City. By entering the coordinates of landmarks in Bertam City, OSM modeled the landmark building along with the adjacent buildings within 300 m of its radius. This research collected 15 landmark buildings: residential areas, schools, universities, healthcare facilities, religious buildings, hypermarkets, government facilities, and a golf resort. Each of the models imported possessed unique specifications and essential attributes, such as estimated built-up areas, heights, and dimensions. The attributes were verified and edited using the building data gathered firsthand through a site visit conducted at the outset of the study, as well as with the help of Google satellite images.

The software generated 3077 building models, encompassing a total gross floor area (GFA) of 3.66 km^2. Figure 1 below displays the proposed digital twin city model of Bertam generated in the simulation software.

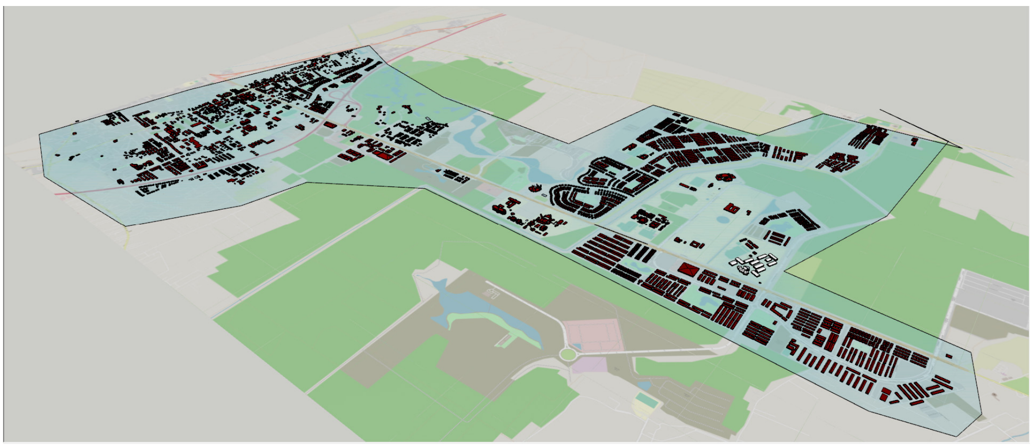

Figure 1. Bertam digital twin city model.

The residential area in Bertam City was determined to cover an expanse of 0.364 km^2. The areas highlighted in red in Figure 2 show the residential models in the digital twin city. There are approximately 2464 house models that were generated by the software. The building models described as single-family pertain to dwelling units constructed on individual lots, whereas multi-family denotes residential properties with more than one housing unit. In this research, simulations were conducted for both types of residential housing models to determine their energy usage and carbon emissions.

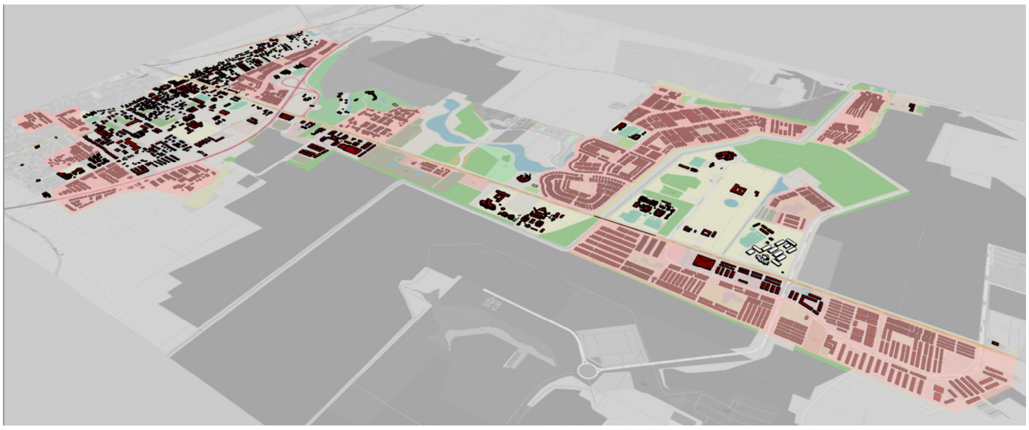

Figure 2. Residential area in Bertam digital twin city model.

Four scenarios were designed to fulfil the research objectives. Scenario 1 was developed to acquire baseline data on the energy consumption rate and carbon emissions of residential areas in Bertam. Meanwhile, Scenario 2 aimed to determine the energy and carbon reduction achieved by reducing the heat transfer coefficient of the building materials compared to the baseline scenario settings. In Scenario 3, the estimated energy consumption and carbon emissions of the city were obtained after incorporating an improved energy performance Heating, Ventilating and Air Conditioning (HVAC) system compared to the one used in the baseline scenario. Scenario 4 involved evaluating the digital twin city for potential solar roof installations, determining the total estimated energy offsets from solar energy usage. Finally, an analysis of the digital twin city's potential for energy and carbon savings was conducted by comparing the estimated energy consumption and carbon emissions across the four scenarios.

3.2. Assumption of Data

In order to effectively determine the impact of passive strategies on buildings in Bertam, it was important to obtain information on the construction types, building materials, and common HVAC system used in the area. However, due to time constraints, it was impossible to identify all the different construction types for houses in the city. To overcome this limitation, the study opted to observe a single-family and a multi-family house in Bertam, both developed by a renowned property developer, Bertam Properties. To date, this developer has built at least nine residential areas in the city: Bertam Lakehomes; Taman Bertam Indah; Bertam Perdana Phases 1, 2, 3, 4, and 5; Bertam Lakeside; and Taman Bertam Permai [32]. The types of construction used for these developments are similar, varying only in terms of the number of storeys and the house typology (bungalow, semi-D, and terraces). Based on the site visit observation, there is no significant difference in the type of building materials in constructing the residential units, as indicated in Table 2. Thus, the study opted to implement the construction type used in the observed house buildings for the remaining residential models in the study.

Table 2. Comparison of building envelopes used in constructing real houses in Bertam and in the simulation software for Scenario 1.

Building Envelopes	Types of Building Envelopes (of Two Houses in Bertam City)	Types of Building Envelopes (iCL-iCD)	Heat Transfer Coefficient (U-Value)/W/m^{2}K
		Scenario 1	
Roof	Sloping roof	Sloping roof—domestic	3.38
Ceiling	Plaster ceiling	12 mm plaster ceiling with TG boards on 400 joist center	1.69
Internal Wall	115 mm of single-leaf brickwork (plastered on both sides)	115 mm single-leaf brickwork (plastered on both sides)	1.97
External Wall	115 mm of single-leaf brickwork (plastered on both sides)	Brickwork of single-leaf construction with dense plaster	2.18
Internal Windows	Single-glazed windows	Single-glazed windows—domestic	3.3
External Windows	Single-glazed windows	Single-glazed windows—domestic	4.83
Floor	Un-insulated concrete slab ground floor	Un-insulated solid ground floor	0.71
Door	Wooden door	Wooden door	2.19

Secondly, the assumption is that all residential models in the digital twin city have the same HVAC system in Scenario 1 and 3—a constant-volume dual duct and fan coil systems. Both systems are widely used in a single thermal zone or small areas such as houses and small buildings. This assumption is grounded in the rationale that approximately 80% of Bertam consists of residential areas. Small buildings, representing over three-quarters of the total number of buildings in Bertam, typically have a height below 7 m or are double-story, with the majority being single-story houses.

4. Results

4.1. Scenario 1 to Scenario 2

An initial simulation was conducted for the entire city to obtain the total energy consumption and carbon emissions before focusing on the residential area. iCL-iCD generated reports indicating a total estimated energy consumption of 928 GWh and a building energy intensity of 253 kWh/m^2. Carbon emissions from electrical sources were recorded at 479,123 tCO_2e. Then, the total energy consumption in the residential area was reported to be 607 GWh, covering 65.4% of the total city's energy usage. The carbon emissions for Bertam's residential areas amounted to 314,736 tCO_2e. Table 3 details comprehensive data on the residential energy consumption by energy use purposes in the baseline scenario. The breakdown of building energy consumption within the residential areas reveals that a predominant share of energy demand is attributed to cooling and auxiliary purposes throughout the year. Specifically, energy consumption for cooling purposes accounted for 37% of the total residential energy consumption, amounting to 227 GWh. For clarification, auxiliary energy in this simulation included the energy consumed by fans, pumps, and controls. Therefore, the energy recorded under auxiliary use can be combined with energy use for air conditioning use as part of the secondary system. Collectively, the energy consumption in the residential areas for cooling and auxiliary purposes constitutes 69.7% of the total energy usage for the models.

In Scenario 2, modifications were made to the selection of building envelopes for all the residential models in the city. Table 4 shows the specifications of the new materials and their U-values, which have been considerably lowered. Ultimately, there was a total reduction of 10.01 W/m^{2}K in the U-value for the building envelopes between Scenario 1 and 2.

Table 3. Breakdown of building energy consumption based on energy purposes for Scenario 1.

	Purpose	Heating	Cooling	Lighting	Derived Hot Water (DHW)	Auxiliary	Equipment
Month	**Energy Consumption Rate/GWh**						
January		N/A	18.7	8.42	2.59	16.3	4.61
February		N/A	17.1	7.65	2.36	14.9	4.19
March		N/A	20.4	8.51	2.62	17.2	4.67
April		N/A	19.3	8.23	2.53	16.4	4.51
May		N/A	19.9	8.42	2.59	16.9	4.61
June		N/A	19.7	8.23	2.53	16.5	4.51
July		N/A	19.8	8.49	2.62	16.8	4.65
August		N/A	19.4	8.44	2.59	16.6	4.63
September		N/A	18.6	8.23	2.53	16.1	4.51
October		N/A	18.7	8.42	2.59	16.3	4.61
November		N/A	18.2	8.23	2.53	15.9	4.51
December		N/A	18.0	8.51	2.62	16.0	4.67
	Total		227	99.8	30.7	196	54.7

Note: N/A indicates the data is not available due to no usage.

Table 4. Building envelopes and their U-values in Scenario 2.

Building Envelope	Type of Building Envelope	Heat Transfer Coefficient (U-Value)/W/m^{2}K	Reduction in U-Value (from Scenario 1)
	Scenario 2		
Roof	19 mm of asphalt; 13 mm of fibreboard; 25 mm of air; 75 mm of battens; 10 mm of gypsum board	0.4	−2.98
Ceiling	8 in lightweight concrete deck with false ceiling	0.81	−0.88
Internal Wall	13 mm of lightweight plaster; 100 mm lightweight concrete block; 13 mm of lightweight plaster	1.05	−0.92
External Wall	2 in of insulation with 8 in of common brick	0.56	−1.62
Internal Windows	Low-emission double glazing windows—domestic	1.74	−1.56
External Windows	Low-emission double glazing windows—domestic	2.07	−2.76
Floor	Solid ground floor	0.41	−0.3
Door	Wooden door	2.19	0

Following the baseline data, the digital twin city model was simulated for Scenario 2. As a result, the residential total energy consumption and carbon emissions of the digital twin city reduced to 556 GWh and 288,013 tCO_2e, respectively. Table 5 presents the energy breakdown for Scenario 2. Notably, there was a reduction in energy consumption for cooling and auxiliary purposes, accumulating to 67% of the total energy use in the residential area. Thus, following the decrease in the U-value of building envelopes, iCL-iCD projected the energy and carbon savings of 8.4% for Bertam's residential areas.

4.2. Scenario 2 to Scenario 3

The study investigated the potential for reducing electrical load in residential buildings by transitioning from the baseline HVAC system to one with better energy performance. To obtain energy and carbon savings in Scenario 3, the study compared the energy performance of Scenarios 2 and 3. Initially, both Scenario 1 and Scenario 2 utilized a constant-volume dual-duct system as the default selection. Scenario 3 implemented a fan coil system as the replacement for the initial HVAC system in the building models. To calculate the potential benefits of this transition, the study analyzed energy savings and carbon reduction (see Table 6). From the data, the analysis revealed a significant potential for energy and carbon savings of 39.5% after the HVAC system upgrade. Furthermore, Table 7 indicates the breakdown of energy consumption for all residential building models in the digital twin city, categorized by their specific energy purposes. Notably, a substantial decrease of 55.8% in energy use for cooling and auxiliary purposes was observed between Scenario 2 and Scenario 3 data.

Table 5. Breakdown of building energy consumption based on energy purposes for Scenario 2.

	Purpose	**Heating**	**Cooling**	**Lighting**	**Derived Hot Water (DHW)**	**Auxiliary**	**Equipment**
Month	**Energy Consumption Rate/GWh**						
January		N/A	15.9	8.41	2.60	14.6	4.6
February		N/A	14.6	7.65	2.37	13.3	4.18
March		N/A	17.5	8.51	2.64	15.3	4.65
April		N/A	16.5	8.22	2.55	14.6	4.5
May		N/A	17.2	8.42	2.60	15.1	4.6
June		N/A	16.8	8.22	2.55	14.7	4.5
July		N/A	17.0	8.48	2.64	15.1	4.64
August		N/A	16.6	8.43	2.61	14.9	4.61
September		N/A	15.9	8.22	2.55	14.4	4.5
October		N/A	16.1	8.41	2.6	14.7	4.6
November		N/A	15.7	8.22	2.55	14.4	4.5
December		N/A	15.7	8.51	2.64	14.6	4.65
	Total		196	99.7	30.5	176	54.5

Note: N/A indicates the data is not available due to no usage.

Table 6. Comparison of energy consumption and carbon emissions between building models with VAV and fan coil HVAC systems.

Types of HVAC Systems	**Total Energy Consumption/GWh**	**Carbon Emission/tCO_2e**
Constant-Volume Dual-Duct (Scenario 2)	556	288,013
Fan Coil System	336	143,426

Table 7. Breakdown of building energy consumption based on energy purposes in Scenario 3.

	Purpose	**Heating**	**Cooling**	**Lighting**	**Derived Hot Water (DHW)**	**Auxiliary**	**Equipment**
Month	**Energy Consumption Rate/GWh**						
January		N/A	7.49	3.25	7.76	7.8	1.51
February		N/A	7.03	2.95	7.02	7.16	1.37
March		N/A	8.51	3.28	7.78	8.22	1.52
April		N/A	8.16	3.17	7.53	7.92	1.47
May		N/A	8.52	3.25	7.76	8.22	1.51
June		N/A	8.28	3.17	7.53	7.97	1.47
July		N/A	8.14	3.26	7.78	8.07	1.51
August		N/A	7.9	3.26	7.76	7.97	1.51
September		N/A	7.66	3.17	7.53	7.73	1.47
October		N/A	7.46	3.25	7.76	7.78	1.51
November		N/A	7.33	3.17	7.53	7.59	1.47
December		N/A	7.16	3.28	7.78	7.68	1.52
	Total		93.6	34.8	91.5	94.1	17.8

Note: N/A indicates the data is not available due to no usage.

4.3. Scenario 4

Following the successful evaluation of HVAC system upgrades, the research investigated the potential for solar roof utilization in Bertam City's residential areas. Leveraging the capabilities of the iCL-iCD v.2021.1 simulation software, the study aimed to calculate attainable energy gains and carbon offsets through the installation of rooftop solar photovoltaic (PV) panels. However, due to technological limitations at the time of the study, applying solar PV roof panels to all 2464 building models available in the virtual city proved infeasible. The application would only be possible with the use of higher-performance computer devices, which was not possible at the time of this study. To overcome this constraint, a small residential section in Bertam covering an area of 0.324 km^2 was chosen as a case study. Bertam Lakehomes consists of 371 single-family and 52 multi-family model houses. This is depicted through the highlighted area in Figure 3. Figure 4 shows the solar PV panel generation on the roofs of Bertam Lakehomes.

Figure 3. Chosen Bertam Lakehomes area for solar roof potential data.

Figure 4. Solar PV panels on the roofs of Bertam Lakehomes.

This area's estimated solar roof potential served as an initial estimation of the PV contribution to the digital twin city. Table 8 demonstrates the analysis of the total PV contribution and potential carbon emissions offset by the PV panels. The total PV energy contribution for the residential area was estimated to be 14.7 GWh out of the total 38 GWh, equaling 38.7% of alternative energy contribution to the entire residential area. The equation used to calculate the residential potential solar PV contribution is as follows:

$$\frac{\text{GFA B}}{\text{GFA r}} \times \text{er} \quad (1)$$

GFA B = Gross floor area of the residential area in Bertam;
GFA r = Gross floor area of Bertam Lakehomes;
er = Energy consumption of Bertam Lakehomes.

Scenario 4 of the Bertam digital twin city model demonstrated an estimated residential zone energy consumption of 261 GWh. Following emission offset application, the resultant carbon emissions were reported to be 91,793 tCO_2e. This analysis enabled the identification of a potential 22.3% reduction in carbon emissions achievable through a combined strategy of carbon offsetting and solar PV implementation.

Table 8. Analysis of total PV contribution and potential carbon emission offset.

Total Electric Consumption/GWh	Total Energy Offset from PV/GWh	Total Carbon Emissions from Electrical Energy/tCO_2e	Total Carbon Emission Offset from PV/tCO_2e
38	14.7	19,698	7623

This study introduced a digital twin city model method for low-carbon city planning in Malaysia. The virtual city underwent four distinct scenarios of a sustainable masterplan to obtain an analysis of energy savings and carbon reduction. Figure 5 illustrates the energy reduction for the residential zone across all scenarios in this study.

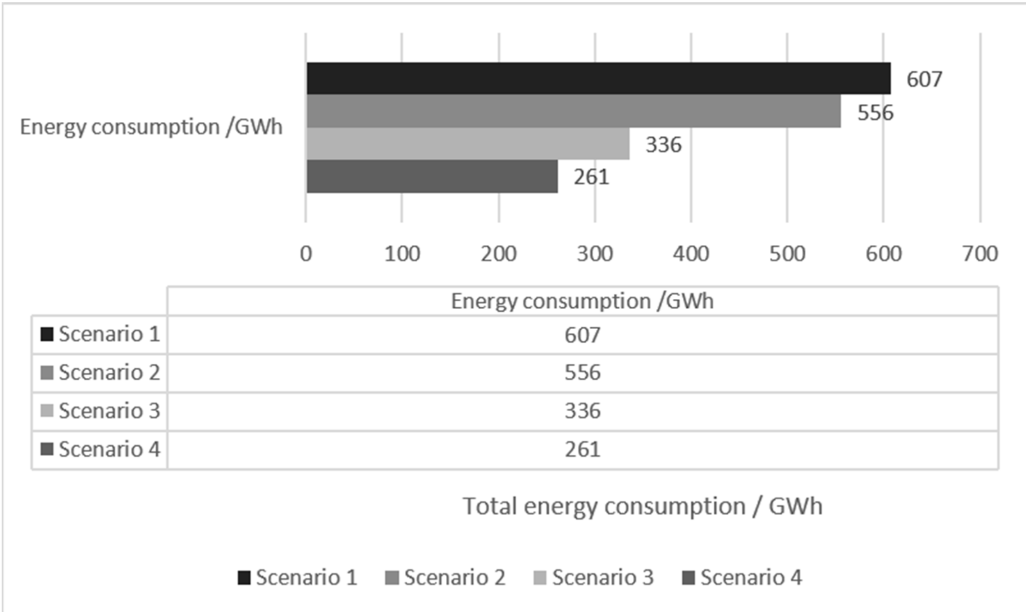

Figure 5. Potential energy savings for residential areas in Bertam digital twin city.

Overall, the digital twin simulation of Bertam City residential areas demonstrates a total potential energy saving and carbon reduction of 70%. However, this figure represents the isolated potential within this specific zone. To assess the city's overall impact, a comparative analysis with the comprehensive Bertam carbon and energy report is essential. Focusing specifically on the residential areas, the current study estimated a 37.3% reduction in energy and carbon, surpassing the NLCCM program's target. This outcome underscores the substantial potential of strategically targeted interventions in residential zones for achieving broader decarbonization goals.

4.4. Study Limitations

This study's evaluation of energy efficiency was limited to data obtained from literature reviews and common construction practices in Malaysia. Future research incorporating life cycle cost analysis (LCCA), which was not conducted in this research, could yield more refined outcomes.

5. Conclusions and Discussion

By applying digital simulations, this study successfully obtained Bertam City's baseline energy consumption and carbon emissions. The iCL-iCD simulation software estimated an energy consumption of 928 GWh and carbon emissions of 479,123 tCO_2e for the tropical city. Meanwhile, the residential areas alone accounted for 607 GWh of energy consumption and emissions of 314,736 tCO_2e, representing a substantial 65.4% contribution to the city's energy consumption. Therefore, this salient disparity highlights the strategic priority of targeting residential areas for emission reduction efforts in this city, thereby justifying the study's focus.

This study used a digital twin city model to assess the effectiveness of various energy efficiency measures in mitigating energy consumption and carbon emissions within Bertam City. Three distinct scenarios were implemented: Scenario 2 focused on lowering the U-value of building envelopes, resulting in an 8.4% reduction in energy consumption and carbon emissions compared to the baseline scenario. Scenario 3 implemented better HVAC systems, achieving a further 39.5% reduction compared to Scenario 2. Meanwhile, Scenario 4 explored the integration of solar panel PVs, yielding a 22.3% reduction compared to Scenario 3.

The study demonstrates the potential of digital twin technology in estimating carbon reduction for other local cities, especially those listed under the NLCCM program. Examining Bertam City suggested that achieving the program's 33% carbon reduction objective may be feasible. Based purely on the simulation results, the potential energy and carbon savings of the residential areas in Bertam City have passed the target by 4.5%. However, this study only calculated the estimated operational carbon of the city, leaving significant room for further emission reductions across the city. Evaluating the cost-effectiveness of the proposed energy measures requires considering their initial costs. The current parameter variations do not support generalizing conclusions to other cities in the program. Future researchers could explore energy conservation and carbon reduction measures in diverse city typologies, enabling more accurate representation and broader applicability.

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