Enhancing Energy Efficiency in Subtropical Green Buildings: Integrating Active and Passive Systems through Building Energy Modeling with Environmental and Economic Analyses

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Project Summary

Buildings contribute significantly to global energy consumption and greenhouse gas emissions, intensifying environmental and energy challenges. Subtropical climates, such as Estero, Florida, intensify these issues due to high humidity, temperature fluctuations, and substantial solar radiation. Traditional building designs often fail to address these challenges efficiently, leading to high energy demands for cooling and ventilation. The need for innovative, sustainable building practices drives this research, which aims to enhance energy efficiency through the integration of active and passive building systems. The goal is to develop practical solutions that reduce environmental impacts, promote economic feasibility, and contribute to global efforts in mitigating climate change.

This study investigates how building systems can be integrated to enhance energy efficiency in green buildings within subtropical climates. To address this, I will develop and compare energy performance between a conventional building model and a green building model. Expected outputs include total energy consumption per scenario, possible CO2 emission reduction, and cost savings from electricity consumption to quantify the environmental and economic impacts of integrated.

This research will use a quantitative, model-based simulation approach to evaluate energy consumption, cooling loads, and renewable energy generation. Tools such as OpenStudio, Revit, and PVWatts will support these analyses. The green building model will incorporate high-efficiency HVAC systems, hybrid ventilation, photovoltaic panels, and passive strategies like advanced insulation, phase change materials (PCM, and optimized shading. These configurations will be compared to a conventional building model to assess energy savings, return on investment (ROI), and greenhouse gas reductions. Economic and environmental data will be sourced from reliable resources, including the National Solar Radiation Database (NSRDB) and ASHRAE standards.

The expected results include significant energy savings, reduced greenhouse gas emissions, and a payback period of less than eight years for the green building systems. Deliverables include simulation models, energy and economic analyses, and a final report detailing findings and recommendations.

The study's broader impacts include advancing academic knowledge on integrated energy-efficient systems and promoting sustainable building practices in subtropical regions. These findings aim to influence policymakers, architects, and engineers in adopting greener construction methods, contributing to global sustainability goals.

Introduction

The rising demand for energy in buildings is a growing challenge with profound implications for environmental sustainability, energy infrastructure, and economic development. Buildings account for a significant portion of global energy consumption, highlighting pressures on grid capacity and contributing substantially to greenhouse gas emissions. In subtropical climates, the challenge is magnified by unique thermal conditions, such as high humidity, frequent temperature fluctuations, and ventilation challenges, including mold growth, which necessitate innovative approaches to energy efficiency. (Xu et al., 2024) While energy demand is often seen as an opportunity for energy companies to increase revenue, it simultaneously emphasizes the urgent need for sustainable solutions that reduce environmental impact and support energy resilience.

Subtropical climates, exemplified by regions like Estero, Florida, require an approach to green building design. Thermal control in these areas demands a delicate balance between passive strategies, such as insulation and shading, and active systems, like efficient HVAC systems and renewable energy integration, to maintain indoor comfort while minimizing energy use. High temperatures, elevated humidity levels, and intense solar radiation present both significant challenges and valuable opportunities for advancing green building practices, highlighting the critical importance of research in this area. For example, intense solar radiation poses a challenge by placing a heavy load on HVAC systems, leading to higher electricity consumption to maintain comfortable indoor temperatures. However, it also presents an opportunity by offering an ideal scenario for the integration of photovoltaic (PV) systems to harness solar energy and offset cooling demands.

Previous studies have explored various energy-efficient strategies in the context of subtropical climates. For instance, the uhuMEB methodology from Melgar et al. (2018) focuses on creating minimum energy buildings through advanced insulation and airtight construction, while Gómez Melgar et al. (2020) address retrofitting strategies for existing structures using similar principles. Gao et al. (2018) emphasize the energy-saving potential of distributed energy systems (DES) combined with district cooling systems (DCS), achieving significant reductions in cooling energy demands. Additionally, phase change materials (PCM) have demonstrated effectiveness in regulating indoor temperatures, as highlighted by Abden et al. (2022). Innovations such as electrochromic windows, often called “smart windows” paired with hybrid ventilation (Suzuki et al., 2022) and zero-energy solar households (Usman et al., 2021) further underlines the potential for localized, system-specific solutions for subtropical climates.

Although these studies provide valuable insights, significant gaps remain. Research studied focuses on individual systems, neglecting the synergies between active and passive approaches. Furthermore, few studies have evaluated the economic and environmental impact of integrating these systems, particularly in the context of subtropical climates, most of the research examined focuses on either of the trade-offs. For instance, Usman et al. (2021) address the economic feasibility (payback periods) and Melgar et al. (2018) and Gómez Melgar et al. (2020) study the environmental benefits (CO_2 reduction). This lack of comprehensive frameworks makes it difficult to apply these strategies in real-world projects and scale them for broader adoption. This research seeks to address these gaps by investigating how multiple building systems, both active and passive, can be integrated to maximize energy efficiency in an enhanced design for green buildings in subtropical climates, while assessing their economic and environmental impacts.

Research Objectives

The study aims to answer three key questions: (1) How can multiple building systems be integrated to optimize energy efficiency in green building designs for subtropical climates? (2) Is it feasible to integrate green building design with passive and active systems in the actual economy? (3) What are the environmental and economic benefits of these integrations? What is the environmental impact (CO_2 reduction) this model has?

This research has three main objectives to answer these key questions. First, to develop a building model that allows for the comparison of a conventional design and an energy-efficient design; second, to evaluate the environmental and economic impacts of transitioning from conventional to energy-efficient systems; and third, to provide actionable insights and recommendations for architects, engineers, and policymakers. This study aims to address research gaps by developing a framework for integrating energy-efficient practices in subtropical building designs, focusing on reducing energy consumption, improving thermal performance, and lowering greenhouse gas emission with active and passive strategies.

Methods

This research adopts a quantitative model-based simulation approach to address the integration of multiple building systems to maximize energy efficiency in green building designs for subtropical climates. The study seeks to identify optimal configurations of active and passive systems, quantify their environmental and economic benefits, and provide actionable insights for sustainable construction practices.

Study Site

The study focuses on a two-story, small commercial office building (10,000 sq. ft.) in Estero, Florida, a region with a subtropical climate characterized by high humidity, rapid temperature fluctuations, and significant solar radiation. This setting was chosen because it presents unique challenges in thermal regulation and energy efficiency, making it a representative site for evaluating the proposed green building strategies. The findings will have broad applicability to similar regions and building types.

Parameters

As this study progresses, the building parameters and material specifications will be refined to accurately reflect the context of a two-story, small commercial building in Estero, Florida. The initial design represents a typical office space with a total floor area of approximately 10,000 square feet, situated in a subtropical climate.

A building model will be developed with different parameters for comparison: one representing a conventional design and another integrating the proposed green building systems. The conventional model, without any additional energy-efficient system) will serve as the baseline for evaluating energy consumption, economic costs, and environmental impacts, while the green building model will incorporate active and passive energy-efficient systems tailored to subtropical climates.

While the exact building materials and structural details are yet to be defined, the study will explore options that align with the goal of maximizing energy efficiency. For instance, insulation materials with high R-values will likely be included to minimize heat transfer through walls and roofs. Phase change materials (PCM) will be considered for their ability to regulate indoor temperatures by storing and releasing thermal energy. The study will also evaluate window technologies, such as electrochromic glass, to optimize natural lighting and control solar heat gain. Reflective roofing materials and airtight construction methods will likely form part of the design to further enhance thermal performance.

The building will incorporate a cooling system designed for the needs of subtropical climates. The HVAC system parameters will include efficiency ratings, such as the Coefficient of Performance (COP), and may integrate hybrid ventilation systems that combine natural airflow with mechanical cooling. Solar energy systems, including photovoltaic panels, will be assessed for their efficiency, tilt angle, and energy generation capacity, with potential inclusion of energy storage systems to improve reliability. Lighting solutions will prioritize LED systems integrated with occupancy and daylight sensors to reduce unnecessary energy use.

Parameter	Traditional Building	Energy-Efficient Building
HVAC	Standard HVAC system (Moderate efficiency)	High-efficiency HVAC with hybrid ventilation
Windows	Single-pane windows (Minimal thermal control)	Double-pane low-E windows
Insulation	Standard insulation (Low R-value)	Advanced insulation (High R-value)
Lighting	Incandescent lighting	LED lighting with daylight sensors
Renewable Energy	None	Integrated PV system
Shading	No external shading devices	Optimized shading devices

Table 1. Comparison of Parameters and Configurations between Traditional and Energy-Efficient Buildings

Economic and environmental parameters will also play a critical role in the study. Installation and maintenance costs, energy price data, and projected operational savings will be analyzed to evaluate the financial viability of the proposed systems. Metrics such as the payback period, return on investment (ROI), and net present value (NPV) will be used to assess economic performance. From an environmental perspective, the study will calculate reductions in greenhouse gas emissions and energy consumption, focusing on the long-term sustainability of the building design.

Data Collection Methods

Weather data, including temperature, humidity, solar irradiance, and wind speed, will be sourced from the National Solar Radiation Database (NSRDB) for a 10-year period (2015–2025) to capture climatic conditions. This database is provided by the PVWatts software and has data from all over the United States including Estero. Building material specifications, such as insulation R-values, PCM thermal capacities, and electrochromic window performance, will be obtained from ASHRAE standards and manufacturer data to ensure realistic thermal properties. These materials will be compared or adjusted to the built-in materials in the software used. Economic data, including installation costs, maintenance expenses, and energy prices, will be sourced from state energy reports and market analyses to evaluate financial metrics like payback periods and ROI. HVAC system performance metrics, such as the Coefficient of Performance (COP), and photovoltaic system specifications will also be integrated into the models using manufacturer data and tools like

PVWatts. PV panel to be used is the Canadian Solar 390W Solar Panel 108 Cell All-Black HiKu 6 CS6R-390MS-HL. Solar inverters are yet to be defined depending on solar system space, quantity of panels to be installed with their respective solar arrays.

Simulation Tools and Data Inputs

To carry out this research, Building Energy Modeling (BEM) tools will be employed. OpenStudio will serve as the primary platform for simulating HVAC performance and assessing thermal performance. Revit will complement this by providing detailed architectural modeling and enabling the integration of passive systems, such as insulation and shading. The PVWatts tool will calculate photovoltaic energy production, leveraging regional solar radiation data specific to Estero solar radiation data from the National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB).

Each of these tools addresses distinct aspects of the study. OpenStudio facilitates a comprehensive analysis of energy performance, while Revit ensures accurate architectural representations. PVWatts, in turn, focuses on renewable energy potential. These tools collectively allow for a holistic understanding of system interactions and performance.

The data inputs for these models include historical and projected weather data sourced from the National Solar Radiation Database (NSRDB) provided by the PVWatts tool. Inputs from this tool include:

- System size: depending on the total power installed from the quantity of panels.
- Quantity of panels: depending on the roofing space.
- Location: Estero, Florida.
- Module Type: Premium (based on panel’s efficiency)
- Array Type: Fixed (roof mounted)
- Array Tilt: 20° (tilt of panel from an x-axis, optimal positioning for Estero)
- Array Azimuth: 90° (facing south)

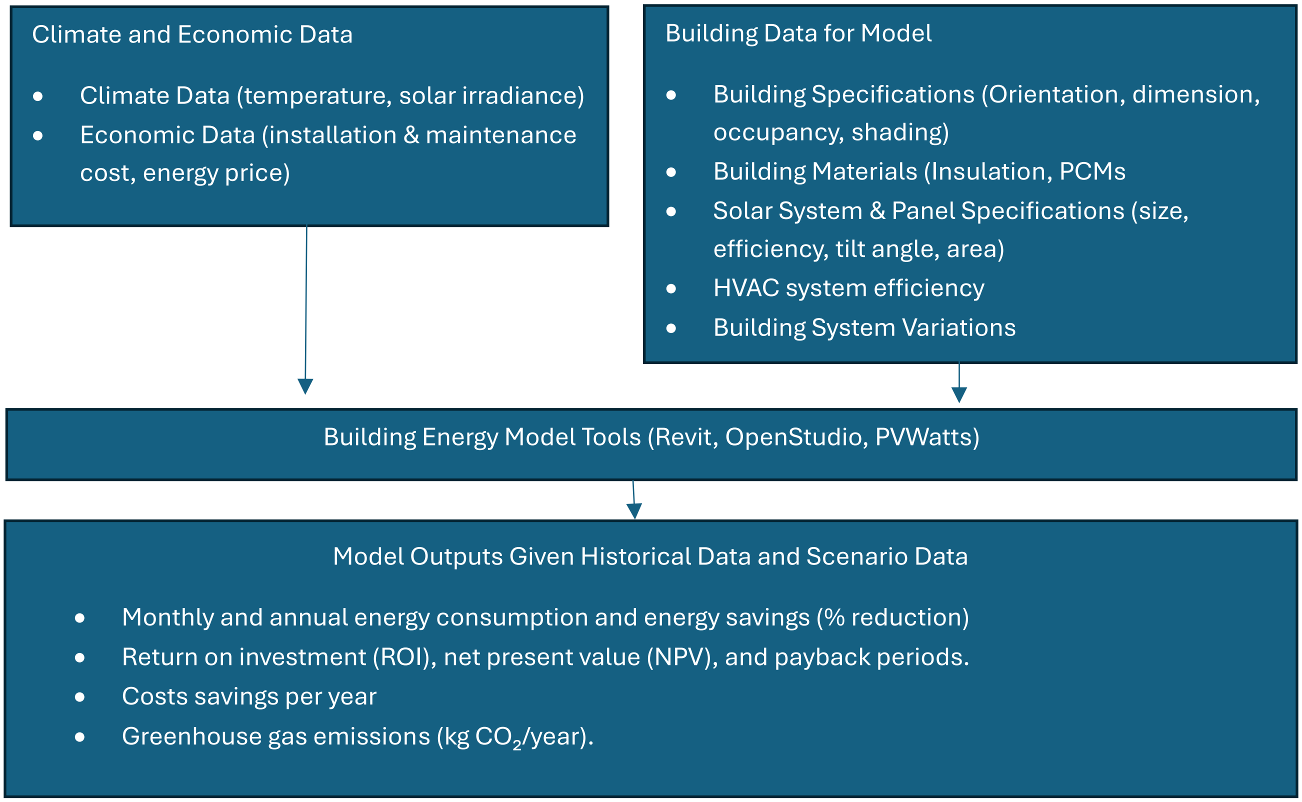

Figure 1. Overview of Model Inputs, Tools, and Ouputs.

System Configurations and Simulation Design

The study will evaluate integrated building system configurations for the green building model, combining both active and passive approaches. Active systems include high-efficiency HVAC with District Cooling Systems (DCS) and hybrid ventilation, photovoltaic panels for renewable energy generation, and dynamic technologies such as smart windows and intelligent lighting systems. Passive strategies will focus on high-performance insulation, airtight construction, the application of phase change materials (PCM) for thermal regulation, optimized building orientation, and shading devices to minimize heat gain.

The conventional building model, serving as the baseline for comparison, will represent a typical small commercial office building in subtropical climates without energy-efficient strategies. This design will include standard HVAC systems with moderate efficiency, no integration of hybrid ventilation, and traditional single-pane windows with minimal thermal or solar control properties. The building envelope will lack advanced insulation or airtight construction, relying on typical construction materials with average R-values. Additionally, the conventional model will not incorporate renewable energy systems, such as photovoltaic panels, or advanced technologies like smart lighting. Shading devices and phase change materials (PCM) for thermal regulation will also be excluded. This baseline model will provide a clear contrast to the green building model, highlighting the impact of integrating energy-efficient systems under identical climate and usage conditions.

Each system configuration will be simulated under identical climate and usage conditions, ensuring that the comparison of results is both fair and consistent. Key assumptions, such as maintaining indoor temperatures at 75°C during cooling seasons and 80% occupancy, will guide the simulations to reflect typical operating conditions.

Data Analysis

The outputs from these simulations will undergo analysis to evaluate energy efficiency, economic benefits, and environmental impacts. Energy efficiency will be assessed as a percentage reduction in energy consumption compared to conventional designs. This energetical analysis will be developed through the BEM software, which will compare both designs. The economic analysis will include metrics such as net return, return on investment (ROI), and payback periods. Economic metrics will be calculated as follows:

- Net return: Calculated by subtracting the total cost from the lifetime electricity savings (calculated on a 20-year period)
- ROI: Calculated by dividing the net return against the total cost
- Payback period: Dividing the total cost by the savings per year

Environmental impacts will be measured through reductions in greenhouse gas emissions and lifecycle environmental costs for a 20-year period. This evaluation will include a comparative analysis of the carbon footprint reduction in relation to decreased energy consumption.

Ethical Considerations

Ethical considerations are minimal due to the virtual nature of this study. Data used in simulations will adhere to FAIR principles, ensuring transparency, accessibility, and reusability. Real-world data, when incorporated, will be anonymized and handled with strict confidentiality to prevent any ethical concerns.

Expected Results

Anticipated Findings

This research is expected to reveal significant insights into the integration of active and passive energy-efficient systems in subtropical climates. The green building model is anticipated to demonstrate considerable energy savings compared to the conventional baseline model, with reductions in cooling loads and overall energy consumption. Passive strategies, such as high-performance insulation, phase change materials (PCM), and shading devices, are expected to significantly lower peak cooling demands and improve thermal regulation. Active systems, including high-efficiency HVAC, photovoltaic panels, and hybrid ventilation, are projected to contribute to substantial reductions in greenhouse gas emissions. Moreover, the study anticipates that the payback period for the additional investment in energy-efficient technologies will fall within an acceptable range, likely under ten years, confirming their financial feasibility. By combining active and passive systems, the research aims to highlight the synergistic benefits of integrated approaches, showcasing their ability to achieve higher energy efficiency.

Deliverables

The project will produce several key deliverables to address the research objectives. First, two fully developed building models will be created: a conventional baseline model and a green building model integrating active and passive systems. These models will be used to simulate energy consumption, cooling loads, and renewable energy generation under identical conditions. Additionally, the research will produce an economic analysis report that includes metrics such as net return, return on investment (ROI), and payback periods for the green building systems. An environmental analysis report will also be delivered, quantifying greenhouse gas emissions reductions achieved through the integrated systems. The final deliverable will be a comprehensive research report summarizing the methodology, findings, and actionable recommendations for architects, engineers, and policymakers.

Outputs, Outcomes, and Impacts

The immediate outputs of the research will include simulation data that provide detailed insights into energy savings, cooling load reductions, and the performance of renewable energy systems. Additionally, economic metrics such as payback periods and ROI, along with environmental data quantifying greenhouse gas emissions reductions, will emerge directly from the study.

The outcomes of these outputs will be an enhanced understanding of how active and passive systems can be effectively integrated to optimize energy efficiency in subtropical climates. This includes the identification of the most effective strategies and the development of a validated framework for comparing conventional and green building designs. These outcomes will provide practical, data-driven recommendations for architects and engineers, aiding in the adoption of energy-efficient building practices.

The study aims to achieve broader societal and academic impacts. It seeks to contribute to global efforts to mitigate climate change by promoting sustainable construction practices and encouraging the adoption of energy-efficient technologies in subtropical regions. The research is expected to enhance knowledge on the synergistic benefits of combining active and passive systems, influencing future studies and frameworks. Ideally, the findings may also influence building codes, architectural designs, and policymaking, paving the way for more sustainable and energy-resilient construction practices. Ultimately, the research will serve as a stepping stone toward creating a more sustainable built environment in subtropical climates.

Timeline

This research project is structured into four primary phases: Data Collection, Model Creation, Data Analysis, and Findings, each with specific milestones, deliverables, and deadlines. The timeline ensures alignment with the research scope, available resources, and deadlines. The project spans 14 weeks, beginning on January 6, 2025, and concluding with the final report submission on April 14, 2025. Figure 1 illustrates key milestones and activities, including model setup, simulations, data analysis, and reporting.

Data Collection (Weeks 1–3)

This phase focuses on gathering critical inputs for the study, including material specifications, economic data such as installation and maintenance costs, and building parameters such as dimensions, orientation, and occupancy schedules. These data points will be sourced from reliable databases and local resources, ensuring accuracy and relevance to subtropical climates. The deliverables for this phase include a complete dataset to be used in the simulation models. Potential delays, such as sourcing specific material details, will be mitigated by using standard values as placeholders until the precise data is available.

Model Creation (Weeks 4–8)

This phase involves developing two building models: a conventional design to serve as a baseline and a green building model integrating energy-efficient strategies. The conventional model will use standard construction techniques and systems, while the green model will incorporate active systems like high-efficiency HVAC, photovoltaic panels, and hybrid ventilation, along with passive approaches such as high-performance insulation, phase change materials (PCM), and shading devices. Once configured, these models will be tested using tools such as OpenStudio, Revit, and PVWatts.

	OpenStudio	Revit	PVWatts
Brief Description	An open-source platform for building energy modeling and simulation.	A BIM software for architectural design and documentation.	An online tool developed by NREL to estimate solar energy production.
Use in Research	Used to simulate HVAC performance, energy consumption, and building airtightness.	Used for creating detailed architectural models and integrating passive design strategies.	Used to calculate photovoltaic system performance and renewable energy generation.
Input Data Required	Building geometry, HVAC system specifications, material thermal properties, occupancy.	Building geometry, material specifications, insulation and shading details.	Location, solar panel specifications (tilt angle, orientation, capacity), weather data.
Output Data Generated	Energy consumption, heating/cooling loads, energy savings, system efficiency.	Detailed architectural models, visualizations, and material takeoffs.	Monthly and annual solar energy generation to calculate energy savings.
Licensing and Access	Open-source, available for academic research and freely accessible.	Licensed, with academic access provided by the university.	Free online tool, accessible through NREL's official website.

Table 2. Overview of Software Tools and Their Integration in the Research

The primary deliverables for this phase include fully functional simulation models and preliminary outputs. Potential software calibration issues will be addressed by consulting documentation or support resources, and simplified models may be used temporarily to maintain progress. Resources will include guidance from professors and industry professionals, as well as training materials and documentation available on official software websites.

Data Analysis (Weeks 9–11)

This phase focuses on analyzing the simulation results to evaluate the performance of the two building models. Key tasks include compiling outputs related to energy consumption, economic metrics such as return on investment (ROI) and net present value (NPV), and environmental impacts such as greenhouse gas emissions reductions. During this stage, a financial-economic analysis will be created, this will measure energy consumption in the sustainable model and compare it to the baseline conventional model to determine the payback period for the increased initial investment in energy-efficient technologies. The deliverables for this phase include a detailed analysis report summarizing the energy savings, cost benefits, and environmental impacts of the green building model compared to the conventional design. In case of inconclusive results, the study will revisit input parameters or refine statistical methods to focus on the core research questions. I will consult with professors and professionals in the field to ensure the analysis is conducted rigorously and accurately.

Findings (Weeks 12–14)

This phase involves synthesizing the results into actionable insights and compiling the final research report. The report will detail the research methodology, key findings, and recommendations for architects, engineers, and policymakers. Visualizations such as charts and graphs will accompany the report to effectively communicate the outcomes. To address potential delays in writing or visualizing results, additional working hours will be allocated during this phase, ensuring the timely completion and submission of the report by the deadline.

Contingency Plan

If software issues occur during model development, support resources from professors who are specialized in BEM, like Dr. Daniel Linares. Also, a simplified version of the models will ensure continuity. For inconclusive results during the analysis phase, adjustments to input parameters or alternative approaches will be employed. An alternative approach would be to use the EDGE energy calculator to measure energy savings based on efficient design. This software utilizes the general characteristics, materials, and design to calculate potential energy savings, carbon emissions reductions, and overall efficiency improvements. These strategies ensure that the project remains on track to meet its objectives within the proposed timeframe.

Research Timeline:

Research Activity Schedule

ID	Task Name	Duration	Start	Finish
1	**Pre-Project Milestones**	**0 days**	**Mon 1/6/25**	**Mon 1/6/25**
2	Proposal Submission	0 days	Mon 1/6/25	Mon 1/6/25
3	Proposal Approval	0 days	Mon 1/6/25	Mon 1/6/25
4	**Data Collection (Weeks 1-3)**	**16 days**	**Mon 1/6/25**	**Mon 1/27/25**
5	Source Building Material Specifications	4 days	Mon 1/6/25	Thu 1/9/25
6	Collect Economic Values (Costs & Prices)	4 days	Fri 1/10/25	Wed 1/15/25
7	Document Building Parameters (e.g., Dimensions, Orientation)	8 days	Thu 1/16/25	Mon 1/27/25
8	**Model Creation (Weeks 4-8)**	**25 days**	**Tue 1/28/25**	**Mon 3/3/25**
9	Configure Base Model	5 days	Tue 1/28/25	Mon 2/3/25
10	Develop Green Building Model	5 days	Tue 2/4/25	Mon 2/10/25
11	Develop Solar Energy Study	5 days	Tue 2/11/25	Mon 2/17/25
12	Input Parameters	5 days	Tue 2/18/25	Mon 2/24/25
13	Perform Simulations	5 days	Tue 2/25/25	Mon 3/3/25
14	**Data Analysis (Weeks 9-11)**	**15 days**	**Tue 3/4/25**	**Mon 3/24/25**
15	Compile Simulation Outputs	5 days	Tue 3/4/25	Mon 3/10/25
16	Perform Statistical & Economical Study	10 days	Tue 3/11/25	Mon 3/24/25
17	**Findings (Weeks 12-14)**	**15 days**	**Tue 3/25/25**	**Mon 4/14/25**
18	Synthesize Results into Actionable Insights	5 days	Tue 3/25/25	Mon 3/31/25
19	Write the Final Report	10 days	Tue 4/1/25	Mon 4/14/25
20	Project Completion	0 days	Mon 4/14/25	Mon 4/14/25

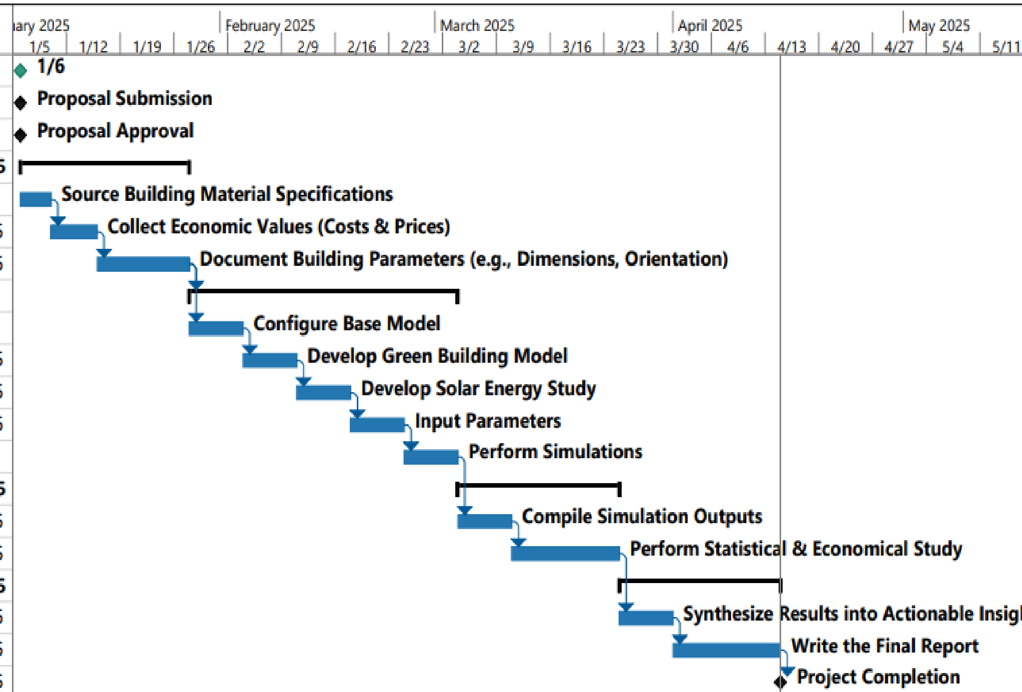

Figure 2

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Appendices

Data Management Plan

This project adheres to FAIR principles (Findable, Accessible, Interoperable, and Reusable) to ensure transparency, reproducibility, and accessibility of data. The study will utilize diverse datasets, including climate data from the NSRDB, material properties from ASHRAE standards, economic data from state energy reports, and simulation outputs detailing energy consumption, greenhouse gas emissions, and economic metrics. All datasets will include detailed metadata and a data dictionary to document sources, units, and assumptions. Metadata will document the data source, collection date, units of measurement, variable definitions, and any preprocessing or assumptions applied during analysis. For example:

- Climate Data: Metadata will specify the geographic region (Estero, Florida), the temporal range (2015–2025), and variables such as temperature (°C), solar irradiance (W/m^2), and humidity (%).
- Material Properties: Metadata will include R-values ($m^2 \cdot K/W$), latent heat capacities for PCM (kJ/kg), and manufacturer specifications.
- Simulation Outputs: Each result will be annotated with details on the model configuration, key assumptions (e.g., set indoor temperatures and occupancy rates), and metrics calculated (e.g., energy savings in kWh).

Data will be securely stored on institutional servers with automated backups, supplemented by weekly backups on cloud storage platforms. During the research phase, access will be restricted to project team members. Upon project completion, datasets will be shared via open-access repositories like Zenodo or Dryad and archived in Florida Gulf Coast University's institutional repository for future academic research. Data will be formatted in widely used standards and documented for reuse, with standardized terminologies ensuring interoperability.