Solar Energy Potential and Integration in Alabama Residential Buildings: A Photovoltaic System Feasibility Study

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https://doi.org/10.52202/077496-0014

Abstract

This study examines the feasibility of integrating photovoltaic (PV) systems into residential buildings in Alabama to optimize solar energy use. Using Autodesk Revit 2024 for solar analysis on a prototype model from the U.S. Department of Energy, it assesses the efficiency, cost benefits, and payback periods of different PV panel types across five major Alabama cities. Results show substantial variations in energy output and savings, with payback periods between 11.6 to 14.1 years. Additionally, the study reviews Alabama's policy landscape, identifying gaps in net metering and suggesting improvements, including financial incentives and investment in solar technology. The findings offer valuable insights for advancing sustainable energy in Alabama's residential sector.

Keywords: solar photovoltaic, residential buildings, solar energy, Revit

Introduction

Energy consumption in Alabama's residential buildings accounts for around 20% of the state's total energy use, contributing significantly to carbon dioxide emissions and climate change (2024 Electricity Rates by State, 2024). Solar energy offers a sustainable solution by meeting energy needs while reducing CO_2 emissions (Alabama, 2024.; Electric Rates & Providers in Tuscaloosa County, AL, 2024). Developing solar energy in Alabama's residential sector is a critical step toward aligning with global shifts to renewable energy sources.

Alabama's climate, with approximately 200 sunny days per year and four to five peak sunlight hours daily, makes it ideal for solar energy development, particularly rooftop photovoltaic (PV) systems (Aljundi et al., 2016). The state's conditions are favorable for solar production. Installing PV systems on residential rooftops holds significant potential for leveraging these advantages. However, Alabama's fragmented regulatory framework poses challenges. The absence of statewide net metering and reliance on individual utility companies complicate the adoption of solar energy. While financial incentive programs like AlabamaSAVES exist (Baghi et al., 2021), regulatory gaps and a lack of comprehensive data on residential solar installations, especially in cities like Birmingham and Montgomery, remain hurdles to broader implementation. Despite these challenges, advancements in solar technology and evolving policies present opportunities for future solar development in Alabama. As solar panel technology improves and legislation evolves, the potential for increased adoption of solar energy in the state's residential sector grows (Alabama Solar Incentives, 2023; Climate of Alabama, 2024; Jones et al., 2020).

This study used Autodesk Revit to assess the thermal performance of buildings and optimize PV panel placement. Revit's solar analysis tool helped evaluate the sun path and solar radiation impacts, enhancing solar energy efficiency (Kahle, 2024; Kneifel, 2012). Our analysis focuses on five major Alabama cities, assessing various PV panel types, energy production capacities, cost savings, and return on investment. Factors

 https://doi.org/10.52202/077496-0014

such as temperature, humidity, and solar irradiance are considered. The findings highlight the significant potential for energy production and cost savings despite the regulatory challenges.

Methodology

Residential building model

In this study, we used the U.S. Department of Energy prototypical residential building model, which can accurately reflect the characteristics of typical residential structures across various U.S. regions. A single-family residential prototype building model with three bedrooms was chosen, which aligns with the 2021 International Energy Conservation Code. Illustrated in Figures 1 and 2, the building's orientation positions its longer axis east to west, with a length of 12 meters and a width of 9 meters from north to south, resulting in a total conditioned floor area (CFA) of 108 m^2. The ceiling height on the first floor is set at 2.45 m. The roof, with a 4:12 slope, is equipped with one-foot overhangs on both the north and south facades, covering the CFA (Kumar et al., 2022).

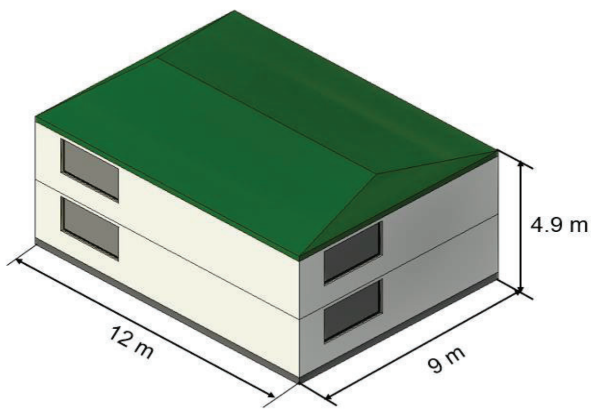

Fig. 1. Model 3D view of the building model

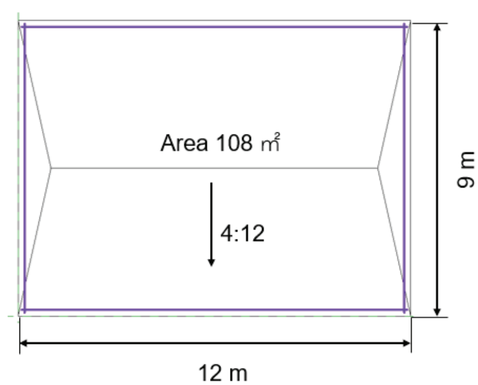

Fig. 2. Roof floor plan view of the building model

Selected cities and climate conditions

To evaluate the potential and efficacy of solar PV systems across Alabama, this residential building model was examined in five major cities: Huntsville, Birmingham, Montgomery, Mobile, and Tuscaloosa. Huntsville, situated in the northern part of Alabama, experiences a humid subtropical climate, typically cooler than the western city of Tuscaloosa. Birmingham, located in the central-northern region, shares a similar climate to Huntsville but tends to have slightly cooler temperatures than the state's southern cities. Montgomery, positioned centrally, is characterized by hot summers and mild winters, indicative of its humid subtropical climate. Mobile, at the southern edge of Alabama, benefits from a Gulf-influenced subtropical climate, with notably hot, humid summers. Tuscaloosa, located in western Alabama, exhibits a humid subtropical climate

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with hot summers and mild winters, consistent with much of the state. Alabama is located in climate zone 3A, which is significant for solar PV system consideration (Larosa, 2024). The geographic and climatic characteristics of these cities are outlined in Table 1.

Table 1. The geographic information and climate conditions of the five major cities in Alabama

Region	**City**	**Geographic Location**			**Temperature**		
		Latitude	Longitude	Altitude	Highest	Lowest	Average
Northern	Huntsville	34.73	-86.59	581 ft	91°F	30°F	50°F - 70°F
Central-Northern	Birmingham	33.52	-86.81	597 ft	91°F	31°F	50°F - 70°F
Central	Montgomery	32.38	-86.30	220 ft	92°F	35°F	50°F - 70°F
Southern	Mobile	30.69	-88.04	33 ft	91°F	40°F	50°F - 70°F
Western	Tuscaloosa	33.219	-87.57	222 ft	94°F	32°F	60°F - 70°F

Solar Analysis in Revit

The Solar Analysis plugin for Autodesk Revit is a powerful tool to assess and visualize solar radiation on buildings. This plugin offers visual feedback through color-coded maps, indicating solar radiation distribution on building roofs (Kahle, 2024).

Using this Solar Analysis plugin, we evaluated solar radiation on the building model's roof through examining cumulative insolation, PV energy, and payback periods, comparing three types of PV panels integrated within Revit for each city. This analysis offers valuable insights into the solar energy potential. Here, cumulative insolation refers to the total amount of solar radiation energy received on the building's roof over a specific period, typically measured in kWh/m². PV energy refers to the estimated energy production of PV panels, which is based on their placement, size, and efficiency. The payback period is the duration required for the initial investment in solar PV panels to be recovered through the savings from the electricity they produce. The analysis also considered seasonal variations in solar radiation such as daylight duration, cloud cover, and specific local climate conditions.

In Revit, three types of panels are categorized based on their efficiency and cost: Type 1 with 16.0% efficiency at $2.86 per installed watt; Type 2 with 18.6% efficiency at $3.47 per installed watt; and Type 3 with 20.4% efficiency, also at $3.47 per installed watt. To calculate the PV energy cost for each city, we used the average electricity cost for residential buildings in each city expressed in dollars per kilowatt-hour (Padhee & Pal, 2018), as indicated in Table 2.

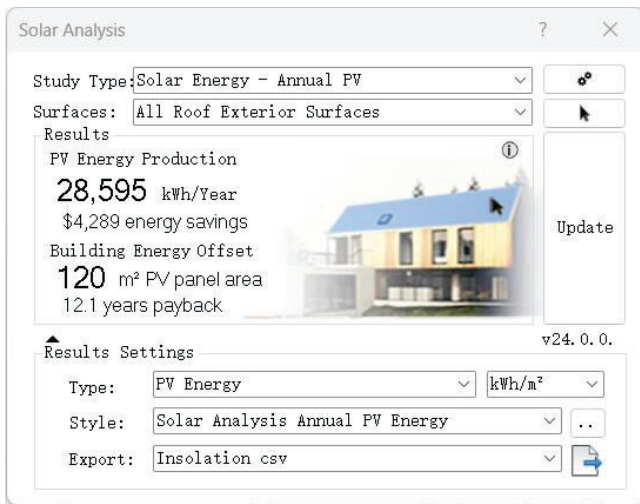
https://doi.org/10.52202/077496-0014

Table 2. The average electricity price for residential buildings in the five major cities in Alabama ($/kWh)

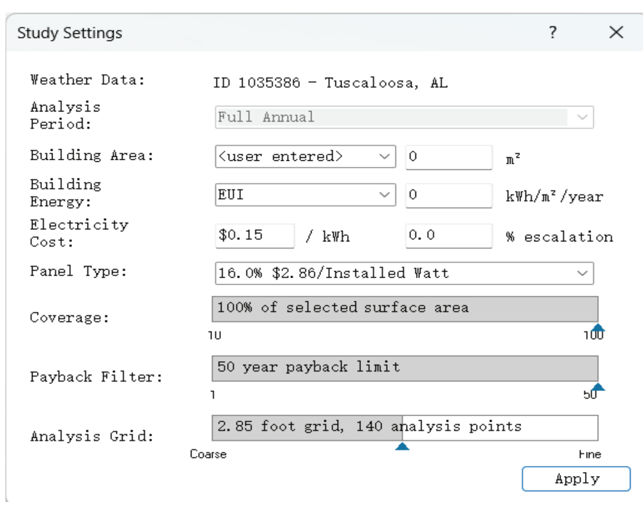
City	Huntsville	Birmingham	Montgomery	Mobile	Tuscaloosa
Electricity Cost	0.1146	0.1573	0.1174	0.1573	0.1525

Results

As illustrated in Fig. 2(a), the “Study Type” was configured for “Solar Energy-Annual PV”, and the “Surfaces” was set to “All Roof Exterior Surfaces,” targeting a date range from 01/01/2023 to 12/31/2023. The “Style” in the results settings was set as “Solar Analysis Annual Insolation”, and the “Type” was set as “cumulative insolation”, “PV energy”, and “payback periods (years)” respectively.



(a) Solar Analysis Setting and Results interface



(b) Study settings

Fig. 3. Solar Analysis Setting and Results Interface

Also, adjustments to the average residential electricity cost were made through the “Double gears” icon, identified as the study settings, shown in Fig 3(b). Fig. 3(a) shows the cumulative insolation results in Tuscaloosa. The analysis began upon selecting the “Update” option, and upon its completion, the results were summarized in the Solar Analysis dialog and visualized in a 3D view. Fig. 4 shows the 3D view of the solar analysis results. Yellow or orange color indicates that the area or surface receives a moderate amount of sunlight and is in a partially sunlit area. All results, including annual cumulative insolation, PV energy production, energy savings, and payback periods for the building model across five cities, will be summarized and elaborated on in the subsequent sections.

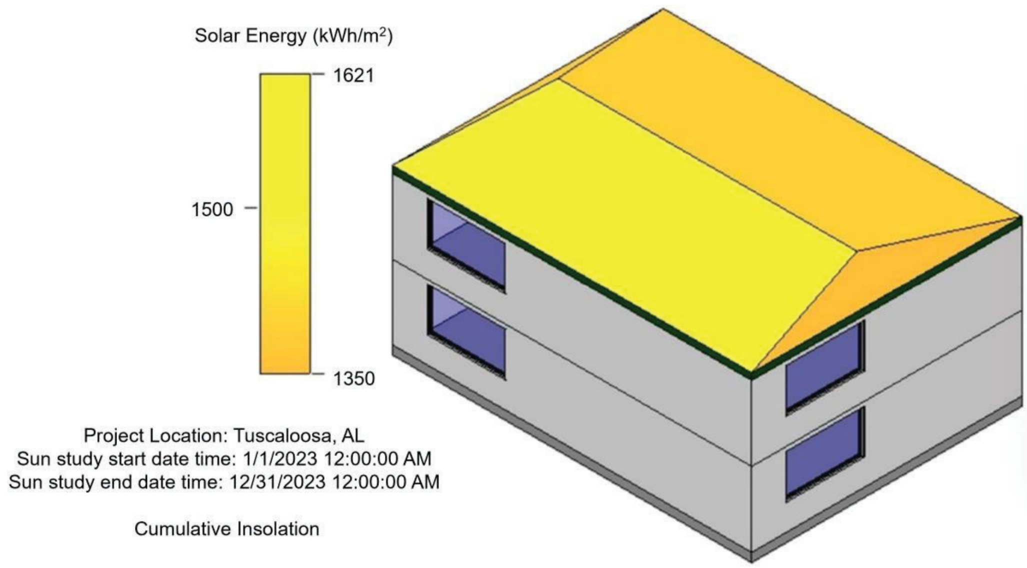


Fig. 4. 3D view of the solar analysis results

Solar Energy

Table 3 presents the annual solar irradiance data for five cities in Alabama. Montgomery receives the highest amount of sunlight, with 180,638 kWh, which is 17% higher than Huntsville, the city receiving the lowest, at 153,898 kWh. Similar amounts of solar energy arrive at Birmingham, Mobile, and Tuscaloosa, with the differences among these three cities being less than 1.2%. These variations demonstrate the significance of geographical location and local climate in evaluating solar energy potential across different areas.

Table 3. Annual cumulative Insolation for the five cities (kWh)

Huntsville	Birmingham	Montgomery	Mobile	Tuscaloosa
153,898	177,691	180,638	179,891	179,197

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PV Energy Production

Figure 5 reveals that the annual potential solar energy output from PV systems varies across Alabama. As the efficiency of PV panels increases from 16.0% to 20.4%, the annual PV energy production in Huntsville, Birmingham, Montgomery, Mobile, and Tuscaloosa increases by 6,754 kWh, 7,789 kWh, 7,926 kWh, 7,894 kWh, and 7,863 kWh, respectively. Higher efficiency PV modules, with improved conversion rates, can increase energy production. These results illustrate a clear efficiency-cost correlation. Regardless of the type applied to the residential building model, the annual PV energy production in Montgomery is always the highest, while that in Huntsville is the lowest. For instance, using Type 3 PV, Montgomery's output of 36,750 kWh surpasses Huntsville's output of 31,315 kWh by 5,435 kWh. This is because the flat terrain of Montgomery provides optimal conditions for PV installations, allowing for more exposure to sunlight and more efficient energy conversion, which is aligned with the maximum amount of sunlight received in Montgomery.

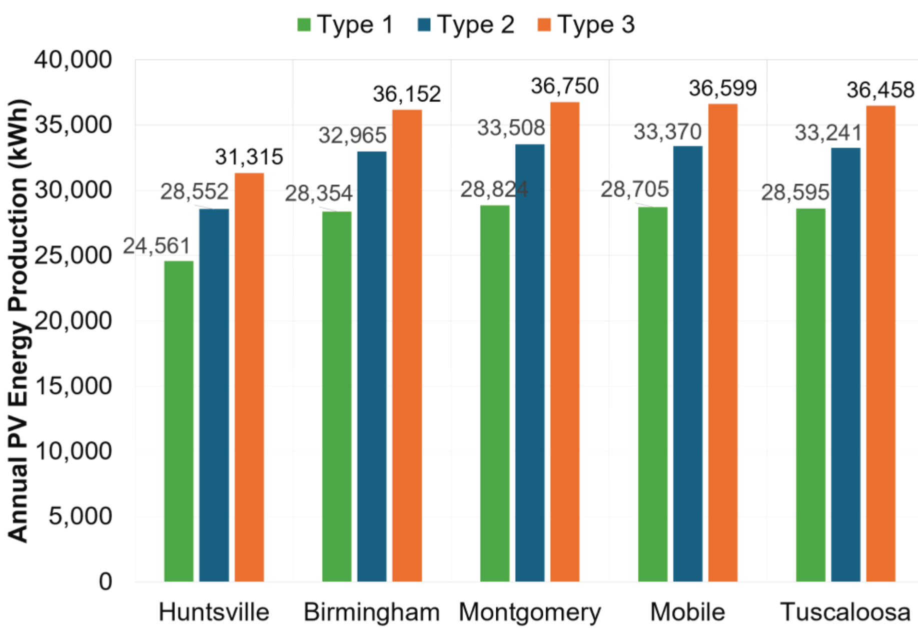

Fig. 5. Annual PV energy production for the five cities

Energy Savings

Figure 6 demonstrates that higher-efficiency panels with higher installation costs will save more money in the field. Mobile has the highest energy savings, which range from \$4,593 to \$5,856 per year (increased by \$1,263) based on PV Type 16.0%- to 20.4%-efficiency panels. In comparison, Huntsville has the least energy savings, ranging from \$2,702 to \$3,445 (increased by \$743). This trend of higher-efficiency panels incurring greater initial costs reflects a widespread market phenomenon which is due to the sophisticated technology and materials required for superior performance, a factor that

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remains constant across different locations. We believe that higher-efficiency panels with higher installation costs can be used in each city. However, the extent to which this translates into cost-effectiveness for the homeowner can vary by city due to differences in solar insolation, local electricity rates, and other related factors which affect the overall savings and payback period.

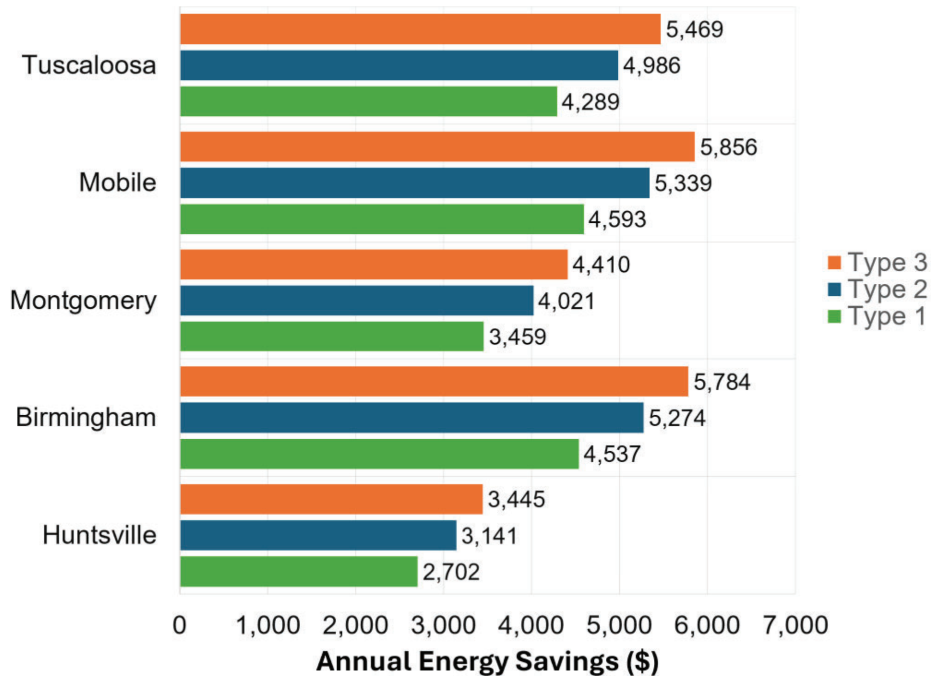

Fig. 6. Annual energy savings for the five cities

Payback Period

From Figure 7, it is noticeable that the payback periods for solar panel installations in the five cities vary depending on the panel type, electricity costs, and locations. Higher solar energy production leads to greater electricity savings, reducing the payback period assuming electricity rates and other conditions are constant. Since Mobile has the highest energy savings, we should expect Mobile to have a shorter payback period (14.1 years) compared to the other cities we have analyzed. Huntsville has the lowest energy savings, so its payback period is also the longest (24.1 years). The difference in return on investment can be as much as 10 years just because of a few minor changes. This assumes that the factors like local electricity rates and solar insolation are favorable and that the increased savings from higher-efficiency panels outweigh the higher installation costs.

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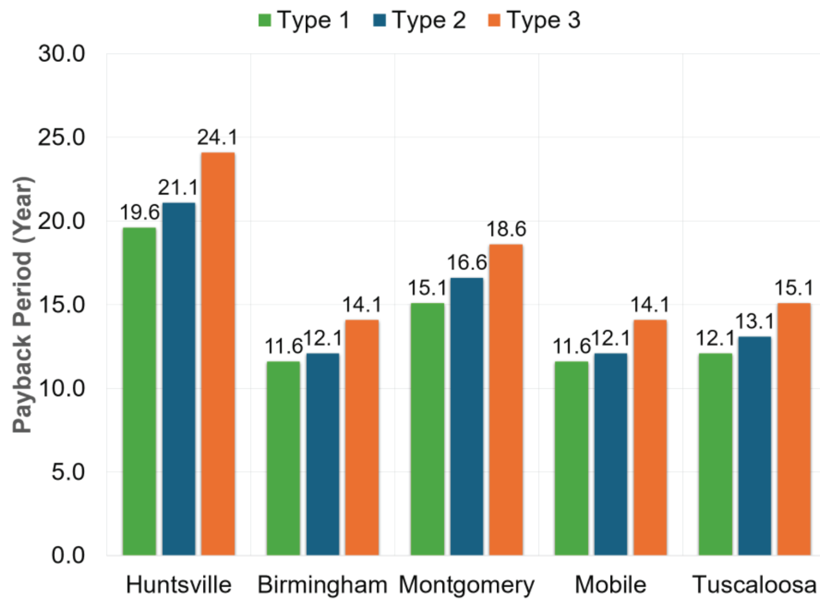

Fig. 7. Payback periods for the five cities

Discussion

Based on the calculation and analysis of the solar potential in five different cities in Alabama, we can see:

1) Montgomery, located in central Alabama, receives the highest amount of sunlight and could generate the highest annual PV energy output: 36,750 kWh. Birmingham (3,6152 kWh), Mobile (3,6599 kWh), and Tuscaloosa (3,6458 kWh) have similar amounts of solar insolation and annual PV energy outputs. Huntsville, situated in northern Alabama, receives the lowest amount of sunlight and could generate the lowest annual energy output: 31,315 kWh. This indicates that more sunshine hours and higher solar radiation make PV energy systems more efficient due to climatic conditions and geographical location.

2) Mobile offers the highest energy savings, ranging from $4,593 to $5,856 per year, based on PV panel efficiency. In contrast, Huntsville has the least energy savings, ranging from $2,702 to $3,445. Energy production capacity is influenced by the efficiency of PV panels used. While high-efficiency PV panels come with a higher price tag, they offer superior solar radiation conversion, leading to greater annual energy output. This efficiency-to-cost tradeoff plays a vital role in optimizing returns on solar investments for residential buildings. Therefore, assessing the feasibility of solar PV installations in Alabama's homes must take into account both location and technological advancements to maximize benefits.

3) Mobile and Birmingham have shorter payback periods compared to the other cities, while Huntsville has the lowest energy savings and the longest payback period. The findings suggest that the PV systems integrated in residential buildings present a compelling avenue for advancing sustainable energy practices. While the energy output

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and financial savings vary across different regions, the overall trend indicates a promising potential for energy independence and economic benefits for homeowners.

Moreover, the analysis has shed light on the critical role of state policies and incentives in fostering the adoption of solar technologies. According to the Solar Energy Industries Association, Alabama has experienced significant growth in solar power generation, which comprised 3% of the state's renewable energy production in 2021 (Solar Energy Industries Association, 2024). The southeastern and Gulf Coast regions hold the best solar resources within the state (Alabama Solar Incentives, 2023).

Despite this growth, Alabama's solar landscape faces challenges, including the dominance of utility-scale solar generation and limited small-scale residential installations. Alabama's solar capacity growth, primarily through large-scale projects, contrasts with the nationwide trend of rapid solar expansion supported by federal policies and cost reductions. The state's approach to solar energy, particularly for homeowners, is hindered by minimal support from the state legislature and public utilities commission.

The primary incentives available in Alabama include the following:

1) The AlabamaSAVES loan program provides low-interest loans to Alabama businesses and nonprofits for energy efficiency and renewable energy projects, including solar installations.

2) Local utility rebate programs provided by some utility companies in Alabama offer rebate programs that provide financial incentives for installing solar panels.

3) The federal Solar Investment Tax Credit (ITC) offers a tax credit of 30% of the cost of installing a solar energy system.

4) Net metering programs are offered by some utilities which credit solar panel owners for excess electricity generated. This can lead to reduced utility bills over time.

5) Alabama provides a property tax exemption for renewable energy systems, ensuring that the value added by solar installations does not increase the property taxes (Guide to Alabama Incentives & Tax Credits, 2024; Why Choose Solar Panels?, 2024; Larosa, 2024).

However, Alabama Power, the largest utility, offers minimal compensation for excess solar energy generated by residential installations, contributing to longer payback times for solar panels, among the nation's worst (Whatstheweatherlike, 2024). Alabama does not mandate net metering statewide, although some local utilities may offer such programs. This restriction makes it difficult for solar owners to receive fair compensation for the electricity they generate and contribute back to the grid (Baghi et al., 2021). These factors create a challenging environment for the adoption of solar PV in Alabama, indicating a need for a strategic reassessment of policy and incentive structures.

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Conclusion

This paper has examined the potential, challenges, and future direction of solar PV system integration in Alabama, with a focus on residential buildings. The feasibility study confirms that residential PV systems in Alabama offer a viable strategy for reducing CO_2 emissions and utility costs. With payback periods ranging between 11.6 to 14.1 years, the financial case for PV systems is clear, notwithstanding the initial investment. However, the study also indicates a unified policy approach is needed to maximize adoption and effectiveness. Recommendations include implementing statewide net metering policies, increasing investment in solar technology research, and providing financial incentives to lower entry barriers for homeowners. The use of Autodesk Revit 2024 for solar analysis demonstrates the importance of software tools in optimizing PV panel placement and efficiency. While improvements in building energy efficiency benefit overall energy savings, they do not directly affect the solar radiation received or the PV panels' efficiency as modeled in this study. These technological advancements facilitate precise calculations of energy production and savings, empowering stakeholders to make data-driven decisions.

Conflict of Interest

This project is supported by the DOE award: Alabama Building Training and Assessment Center.

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