Achieving Net-Zero Energy Buildings: Analyzing and Optimizing Strategies Using Sensitivity Analysis

Alireza Asgari Motlagh[1] , Saeideh Havaeji[2*], Mansour Orangian[3]
Alireza Samadani[4]

[1]School of Civil, Mining, Environmental and Architectural Engineering,
University of Wollongong, Australia
[2]Islamic Azad University, Science and Research Branch, Tehran, Iran
[3]IAU South Tehran Branch, Faculty of Engineering, Tehran, Iran
[4]Department of Mechanical and Aerospace Engineering,
North Carolina State University, USA

Abstract

Enhancing building energy efficiency and incorporating renewable energy technologies are crucial for combating climate change and promoting sustainability. This study employed a sensitivity analysis to evaluate the influence of various parameters on building costs and energy consumption. Standardized Regression Coefficients (SRC) were used to measure the sensitivity of each variable. The type of glass, wall construction, window-to-wall ratios, and shading elements were identified as having the most significant impact on building costs and electricity usage. SRC values provided a numerical representation of the strength and direction of the relationship between these factors and the output variables. Furthermore, the study quantified the energy savings achieved through optimization methods. The data indicated an average reduction in consumption of 22%, with variations between 21% and 23% across different floors. These results highlighted the effectiveness of optimizing variables and applying energy-efficient design principles. The findings of this investigation enhance our understanding of the role of sensitivity analysis in optimizing building energy efficiency. They can serve as a reference for making decisions on integrating renewable energy technologies into buildings and designing them. These strategies can help reduce environmental impact, promote sustainable construction practices, and achieve significant energy savings.

Keywords: zero energy building, renewable energy, optimization, sensitivity analysis, energy reduction

*Corresponding author: Saeideh.havaeji@gmail.com
Received: 14 Jun 2024 Accepted: 7 Jul 2024 Published: 17 Jul 2024
Journal of Asian Energy Studies (2024), Vol 8, 51-67, doi:10.24112/jaes.080004

1. Introduction

Energy is fundamental to modern society, powering everything from homes and industries to transportation [1,2]. The predominant reliance on fossil fuels has led to significant environmental challenges [3]. The combustion of coal, oil, and natural gas releases vast amounts of greenhouse gases, primarily carbon dioxide, which trap heat in the atmosphere and drive global warming [4]. This warming leads to severe climate changes, including more frequent and intense weather events, rising sea levels, and disruptions [5,6]. Transitioning to renewable energy sources such as solar, wind, and hydroelectric power is crucial to mitigate these impacts [7]. Renewable energy not only reduces greenhouse gas emissions but also decreases air pollution [8,9]. Additionally, investing in clean energy technologies can create jobs and stimulate economic growth [10]. By embracing sustainable energy solutions, we can protect our planet and ensure a healthier, more resilient future [11, 12]. The role of buildings in energy consumption and emissions is of paramount importance [13]. Globally, buildings account for a significant portion of energy consumption, thereby contributing substantially to energy usage and greenhouse gas emissions [14]. The energy consumed in lighting, air conditioning, heating, and operating appliances in buildings significantly adds to the carbon footprint of the built environment [15]. To effectively curtail energy consumption and mitigate environmental impacts, it becomes crucial to prioritize energy savings [16]. This can be realized through the enhancement of building energy efficiency and the promotion of sustainable construction practices [17]. Key strategies encompass the implementation of energy-efficient designs, the improvement of insulation, the adoption of efficient heating and cooling systems, and the integration of renewable energy technologies [18]. Natural ventilation is also another important factor to reduce energy consumption in buildings [19]. By adopting these measures, we can effectively reduce the energy demands of buildings and decrease carbon emissions, thereby contributing to a greener and more sustainable future [20]. These strategies not only help in conserving energy but also play a significant role in combating climate change, promoting economic growth, and fostering a sustainable and resilient future [21]. Thus, energy conservation in buildings emerges as a critical component in our pursuit of sustainability [22,23].

By putting energy management systems in place and encouraging occupant behaviour changes, buildings can further improve their energy conservation and efficiency. Acknowledging the role that buildings play in energy consumption and implementing measures to enhance their effectiveness and lower emissions can be crucial in accomplishing sustainable development objectives and mitigating climate change. Buildings' activities are responsible for 26% of the world's energy-related emissions and 30% of its final energy consumption. In 2018, the building and construction industry was responsible for 36% of total energy use and 39% of carbon dioxide emissions connected to energy-related processes. In the UK, comprehensive data on total energy usage is offered, including details on the home, industry, transportation, and services sectors. These numbers highlight how crucial it is to increase building energy efficiency to lower carbon emissions and lessen environmental effects. We can drastically lower the energy requirements of buildings and the emissions that go along with them by using energy-efficient designs and technologies. Combating climate change and achieving sustainable development goals are essential steps. Using Net Zero Energy Buildings (NZEBs) is one practical way to fight global warming. Buildings classified as NZEBs have net zero energy consumption from the grid because they generate as much energy as they use over a year. This is accomplished by combining on-site renewable energy generation with energy efficiency techniques [24].

The market for zero-energy buildings is expected to expand from its estimated $71.7 billion in 2021 to $403 billion by 2031, with a compound annual growth rate (CAGR) of 18.7% from 2022 to 2031. In the US, buildings are responsible for 39% of CO2 emissions, 74% of electricity usage, and

40% of primary energy use. Non-zero energy buildings (NZEBs) have the potential to considerably lower greenhouse gas emissions and mitigate global warming by decreasing the need for energy derived from fossil fuel sources. They stand for an innovative and sustainable method of designing and managing buildings. Not only are NZEBs good for the environment, but they can also save money over time by lowering energy costs. Thus, encouraging the use of NZEBs can be a useful tactic in the battle against global warming. The process of integrating solar panels or solar cells into the design and construction of buildings is known as Building-Integrated Photovoltaics (BIPV), and it is a way of integrating photovoltaic systems onto building facades. With this method, solar energy can be used by the building envelope itself to produce power. Building features such as windows, roofs, and facades can be combined with BIPV systems to optimize space utilization and turn the structure into a renewable energy source. Buildings may produce clean, sustainable electricity through the use of BIPV, which lessens their dependency on fossil fuels and cuts carbon emissions. BIPV systems also provide architectural versatility because they may be tailored to match various building styles and designs. Incorporating photovoltaic technology into buildings not only boosts energy efficiency but also encourages the use of renewable energy sources and facilitates the shift to a more sustainable and environmentally friendly built environment [25]. Several attitudes and methods can be employed to optimize energy consumption in buildings some of them also can be utilized from other sectors of engineering such as analyzing thermal satisfaction [26], Lyapunov approach [27], using different wireless management tools [28], utilizing some special materials [29], machine learning approaches [30, 31], sensors based on signal processing and deep learning to optimize the energy usage [32], micro-fluid systems [33], using power electronic [34, 35], heat flux analyzing [36], utilizing thermal storage units [37], controlling methods [38], using alternative energies [39], meta-heuristic algorithms [40], blockchain approaches [41], energy storage [42], remote monitoring [43], internet of things techniques [44], data collection attitudes [45], utilizing some specific materials as insulation [46], human behaviour analysis [47], energy-efficient hardware organization [48], nonlinear model predictive control [49], robots which can detect the energy consumption patterns in buildings [50], and utilizing solar collectors and exergy methods [51].

Building-integrated photovoltaics, estimated at $14.0 billion in 2020, is expected to grow at a compound annual growth rate (CAGR) of 20.1% from 2021 to 2030, reaching $86.7 billion. The market for building-integrated photovoltaics was estimated to be worth USD 19.82 billion in 2022, and between 2023 and 20302, it is projected to increase at a compound annual growth rate (CAGR) of 21.0%2. The Building Integrated Photovoltaic (BIPV) market was predicted to be worth USD 14.4 billion globally in 2020. It is projected to grow at a compound annual growth rate (CAGR) of 20% between 2021 and 2027, reaching a valuation of USD 51.6 billion by the end of the forecast period. These numbers highlight how BIPV can support sustainability and energy efficiency in the built environment.

This study emphasizes the critical role of optimizing building energy efficiency and incorporating renewable energy technologies to address climate change by using a sensitivity analysis with Standardized Regression Coefficients (SRC). These factors include the type of glass used, the construction of walls, the ratio of windows to walls, and the presence of shading elements. The SRC values provided a quantitative measure of how strongly each factor influenced the overall costs and energy usage. For instance, certain types of glass might significantly reduce energy consumption by improving insulation, while specific wall constructions could impact both the thermal performance and the cost of the building.

2. Literature Review

There have been several research initiatives on the topic of net zero energy buildings. An investigation by [52] carried out on a four-storey residential structure in Najran, Saudi Arabia, showed that adding sustainable elements like solar panels, insulation, green walls and roof, and new windows reduces energy use significantly. The building's solar panels provide twice as much electricity as required each month, while energy-efficient windows and insulation help to keep the building's energy efficiency at its peak. The building's spas may be heated daily with renewable energy by installing solar collectors in place of the old heating system. Significant reductions of 11% in electricity use, 85% in gas consumption, 28% in heating consumption, and 83% in cooling consumption have been achieved as a result of these sustainable practices. Using Shanghai as a case study, [53] used an assessment framework to determine the viability of zero-energy buildings using photovoltaic systems at the city level. The findings indicate that while buildings in the outskirts encounter difficulties, those in the core area have a great potential for zero energy consumption. Shanghai's building energy usage can be cut by more than half by using solar energy. The framework can help policymakers create plans for energy conservation and encourage the use of solar energy in buildings. Nanocomposite solar panels were used by [54] for a zero-energy structure. To accurately represent the panels, it employs a hybrid machine learning approach that combines SVM and KNN. PSO improves the performance of the KNN algorithm. By optimising cell characteristics, the MDO boosts solar cell performance by at least 70% and increases panel efficiency by 170%.

[55] investigated the utilization of correctly scaled solar systems and bio-based building materials for energy-efficient rural houses in underdeveloped nations. Plant fibres enhance thermal performance in building materials, which results in notable energy savings. According to a techno-economic analysis, a PV-battery hybrid system can generate inexpensive, emission-free power from renewable resources. This strategy provides a workable alternative for inexpensive, carbon-neutral rural housing. The effectiveness of building-integrated photovoltaics (BIPV) with electric vehicle (EV) charging in Canberra, Australia, is assessed by [56]. BIPV promotes sustainability and lowers energy use. A variety of panel configurations with yearly energy outputs between 7.08 and 8.56 MWh were investigated. With an electricity cost of 0.074 AUD/kWh and an EV charging cost of 0.95 AUD/100 km, the payback period is 4.46 years. The system can reduce greenhouse gas emissions by 160,198 kgCO2e. To address the energy needs of residential buildings on an academic campus, evaluated [57]. The viability of integrating rooftop and façade building-integrated photovoltaics (BIPV). The study looked at three different dwelling typologies, benchmarking and labelling were done using the energy performance index. Depending on the available surface area, the incorporation of façade BIPV improved energy output by as much as 62.5%. With a nominal output of 5.6 MW and an annual generation of 7182 MWh, the proposed grid-connected photovoltaic system can meet the highest residential energy demand on campus. [58] focused on designing zero-energy residential buildings in China. It utilizes multi-objective optimization and building performance modeling to find the most energy-efficient design option. The objectives include reducing investment costs, maximizing photovoltaic generation, and minimizing air conditioning and heating loads. The study establishes a design process and analysis model to compare different climate zones for achieving zero-energy buildings. Through virtually zero-energy buildings (nZEB), [59] studied energy self-sufficiency in urban areas. It highlights the value of renewable energy, especially rooftop solar photovoltaic (PV) installations. It is discovered that the shadow cast by nearby buildings does not affect the production of PV energy. Energy generation is greatly increased by lower buildings with reduced energy usage. Building height distribution must be well-balanced to create an atmosphere that is completely energy-self-

sufficient. To create net zero energy buildings (NZEBs), [60] combined renewable energy with creative architectural design. The suggested solutions provide additional cooling/heating supply and efficient thermal load reduction by integrating energy demand reduction with renewable energy supply. After 30 years of operation, the ideal system, PV+Grid+Battery+TE (S5), has the largest environmental impact with a considerable decrease in CO2 emissions.

3. Methods and Materials

Tehran, the capital city of Iran, experiences a temperate climate characterized by summertime temperatures ranging between 28 and 38 degrees Celsius and wintertime temperatures typically above freezing. The climate in Tehran is notable for its high humidity and significant precipitation. In this study, a four-story residential building in Tehran is selected to assess the feasibility of constructing a net-zero energy building in this particular climate. The effectiveness of passive solutions in reducing the energy demands of buildings is often hindered by the local climate conditions. Additionally, certain urban laws and regulations impose limitations on the application of various passive methods, particularly in metropolitan areas. These regulations encompass restrictions on shading caused by neighbouring structures, as well as architectural design considerations such as roadway width and orientation. Tehran, geographically situated at 35◦ 41′21″N 51◦ 23′20″E (or 35.6892◦ N 51.3889◦ E in decimal degrees), has comprehensive urban development plans that include detailed regulations for different types of buildings. These regulations govern the number of floors allowed in a building and dictate their placement on the land, taking into account factors such as street width and orientation (e.g., east-west or north-south). The objective of this article is to develop a photovoltaic system capable of powering a net-zero energy building, thereby contributing to the mitigation of global warming and reducing CO2 emissions in the process. By overcoming the challenges posed by the local climate and adhering to urban regulations, the aim is to create a sustainable and energy-efficient building that aligns with Tehran's urban development goals.

In this article, the DesignBuilder software has been utilized. In the realm of sustainable building design, DesignBuilder is a potent building energy simulation program that is frequently utilized. It provides an extensive feature set including modelling, simulation, and analysis of building energy performance. With the software, users may specify building systems and components, simulate different energy scenarios, and produce detailed 3D models of buildings. Advanced simulation engines built into DesignBuilder can compute thermal comfort parameters, daylighting levels, heating and cooling loads, and energy consumption. Additionally, it offers a variety of weather data choices, enabling users to precisely model the building's performance under various climate scenarios. One of DesignBuilder's main benefits is its intuitive interface, which speeds up the modelling process and makes it possible for engineers and designers to compare various design approaches and energy-saving techniques. The program facilitates the incorporation of sustainable energy technologies, including photovoltaic arrays, and enables users to evaluate their influence on the building's total energy efficiency. All things considered, DesignBuilder is a useful tool for researchers, engineers, and architects working on energy analysis and sustainable building design. Its skills enhance attempts to prevent climate change by reducing carbon emissions and helping produce net-zero energy buildings.

During the initial stages of building design, a wide range of specifications are established, including factors such as the thermal conductivity coefficient of walls, glazing type, lighting systems, window-to-wall ratio (WWR) on the north and south facades, and the lengths of overhangs on these facades. Subsequently, a sensitivity analysis is conducted to identify the design parameters that have a significant impact. This analysis plays a crucial role in determining the key variables for optimizing energy efficiency and minimizing costs. The sensitivity analysis examines how uncertainties in input variables affect the output variables, allowing the identification of variables that strongly influence the optimization objectives. In terms of artificial lighting, the study focuses on selecting LED lamps due to their well-known energy efficiency and long lifespan. Variables of lesser importance can be disregarded in the optimization process, while those considered important or moderately important for achieving both objectives are retained. This comprehensive approach ensures a thorough and efficient optimization of energy consumption, contributing to the development of sustainable and environmentally friendly building designs. By carefully analyzing the influential design parameters, it becomes possible to create buildings that are energy-efficient, cost-effective, and aligned with sustainable principles.

Cost Function Concerning Glazing and Wall Construction [61]:

$$C(total) = C(base) + a_{glazing} \cdot G + a_{wall} \cdot W \tag{1}$$

Where $C(total)$ is the total construction cost, $C(base)$ is the base cost without additional features, $a_{glazing}$ and a_{wall} are the cost coefficients for glazing and wall construction respectively, and G and W are the glazing and wall construction variables.

Electricity Consumption Function with U-value Adjustment [62]:

$$E_{new} = E_{base} - \beta_{wall} \cdot (U_{new} - U_{base}) \tag{2}$$

Energy Savings Percentage Across Different Floors [63]:

$$Savings_i = \frac{E_{base,i} - E_{opt,i}}{E_{base,i}} \times 100\% \tag{3}$$

Where $Savings_i$ is the percentage of energy savings on the floor(i),$E_{base,i}$ is the base energy consumption on the floor(i), and $E_{opt,i}$ is the optimized energy consumption on the floor(i). These formulas incorporate the principles of sensitivity analysis and optimization to guide the design and retrofitting of buildings for improved energy efficiency and cost-effectiveness. By applying these mathematical models, stakeholders can make informed decisions that contribute to the sustainability and economic viability of building projects.

Glazing Type Impact on Energy Consumption [64]:

$$E_{glazing} = E_{base} \times (1 + G \times SRC_G) \tag{4}$$

Where $E_glazing$ is the energy consumption with the specific glazing type, E_base is the baseline energy consumption, G is the glazing factor, and SRC_G is the SRC value for the glazing type.

Wall Structure Impact on Building Costs [65]:

$$C_{wall} = C_{base} \times (1 + W \times SRC_W) \tag{5}$$

Where C_wall is the cost with the specific wall structure, C_base is the baseline building cost, W is the wall structure factor, and SRC_W is the SRC value for the wall structure.

Window-to-Wall Ratio (WWR) Impact on Energy Consumption [66]:

$$E_{WWR} = E_{base} \times (1 + WWR \times SRC_{WWR}) \quad (6)$$

Where E_{WWR} is the energy consumption with the specific window-to-wall ratio, E_{base} is the baseline energy consumption, WWR is the window-to-wall ratio, and SRC_{WWR} is the SRC value for WWR.

Shading Feature Impact on Power Consumption [67]:

$$P_{shading} = P_{base} \times (1 + S \times SRC_S) \quad (7)$$

Where $P_{shading}$ is the power consumption with shading features, P_{base} is the baseline power consumption, S is the shading factor, and SRC_S is the SRC value for shading features.

Energy Savings from Optimization Techniques:

$$E_{savings} = E_{base} \times (1 - R) \quad (8)$$

Where $E_{savings}$ is the energy consumption after applying optimization techniques, E_{base} is the baseline energy consumption before optimization, and R is the average reduction percentage (expressed as a decimal).

The output power production of solar panels is as follows [68,69]. The cell temperature T_{cy} can be calculated as:

$$T_{cy} = TA + \left(\frac{say \cdot (NOT - 20)}{0.8}\right) \quad (9)$$

The current I_y is given by:

$$I_y = say \cdot (I_{sc} + K_i \cdot (T_c - 25)) \quad (10)$$

The voltage V_y can be determined as:

$$V_y = V_{oc} - K_v \cdot T_{cy} \quad (11)$$

The output power P_{sy} of the solar panels is:

$$P_{sy} = N \cdot FF \cdot V_y \cdot I_y \quad (12)$$

Where the fill factor (FF) is:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{oc} \cdot I_{sc}} \quad (13)$$

4. Results and Discussions

The sensitivity analysis, which shows how input factors affect the output and how changes in each input variable change the outcome, is carried out. The Standardized Regression Coefficient (SRC), which aids in determining which variables are most and least significant, measures the sensitivity of each input variable. Sensitivity analysis plays a vital role in assessing the impact of input changes on building costs and electricity usage. It allows decision-makers and designers to identify the key factors that significantly influence a building's energy efficiency and financial viability. By systematically adjusting input parameters such as material costs, equipment efficiency, and energy prices, sensitivity analysis helps us understand how these variables affect the overall cost and electricity consumption of a building.

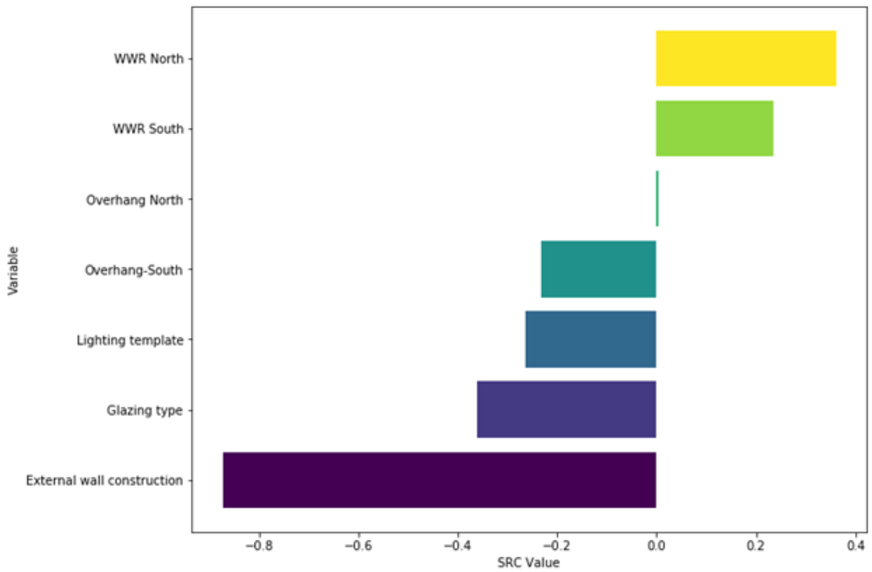

Figure 1: *Sensitivity analysis for the objective function of electricity*

Among the variables considered, the Glazing variable stands out as having a significant impact on the cost function. Increasing the glazing variable leads to higher construction costs due to a positive correlation with the output. The Wall construction variable also has a notable influence on the cost function. On the other hand, the impact of factors like WWR North, WWR South, Overhang-South, lighting template, and Overhang-North on the cost function is relatively minor. This enables optimization efforts to focus on variables that exhibit substantial sensitivity to cost and electricity use while disregarding those with minimal impact. Similarly, the Electricity cost function is significantly influenced by the Wall construction variable, but with an inverse relationship. Increasing the U-value in the Wall construction variable results in a decrease in electricity consumption. Additionally, the variables Lighting template and WWR North have a significant effect on the Electricity cost function. The variables Glazing Type, Overhang-South, and WWR South have a moderate impact, while Overhang-North does not significantly affect electricity consumption and can be excluded from the optimization process. To determine the importance of each input variable, the analysis employs the Standardized Regression Coefficient (SRC). Positive and negative signs indicate a direct or inverse relationship between the variables and the output. Variables with high importance are highlighted in green, medium importance in yellow, and low importance in red. Based on this ranking, the design variables selected for the optimization process are Glazing Type, Wall construction, WWR South, WWR North, and Overhang-South. Conversely, the lighting template and Overhang-North, which have low importance, are removed from the optimization process. By focusing on the significant variables and their impact on energy consumption and costs, this optimization model ensures a comprehensive and effective approach to improving building design and operation. This leads to the development of more environmentally friendly and sustainable buildings with optimized energy usage. Figure 1 illustrates the results of the sensitivity analysis conducted for the objective function of electricity. This analysis provides valuable insights into the influence of different input variables on electricity-related outcomes.

Figure 1 serves as a visual representation of the intricate interplay between various factors and their impact on electricity consumption. Each variable is meticulously listed alongside its corresponding Sensitivity Range Calculation (SRC) value, a measure that quantifies the sensitivity of the electricity function to changes in that variable. The External wall construction variable, with its SRC value of -0.8736, stands out prominently. This negative value signifies that alterations in the construction of external walls could lead to a substantial decrease in the electricity function. Similarly, the Glazing type variable, with an SRC value of -0.3612, suggests that modifications in the type of glazing used could also negatively affect the electricity function. Conversely, the variables WWR North and WWR South exhibit positive SRC values of 0.3612 and 0.236 respectively. This implies that an increase in the window-to-wall ratio (WWR) in the North and South orientations could potentially enhance the electricity function. The remaining variables, Overhang-South, lighting template and Overhang North also bear negative SRC values, indicating that changes in these factors could result in a decrease in the electricity function, albeit to a lesser extent than the External wall construction and Glazing type variables. In essence, the SRC values serve as a compass, guiding us through the labyrinth of variables influencing the electricity function. They shed light on the sensitivity and significance of each variable, enabling us to make informed decisions and optimize these variables to achieve the desired outcomes in terms of electricity consumption. This understanding is crucial in our quest for energy efficiency and sustainability.

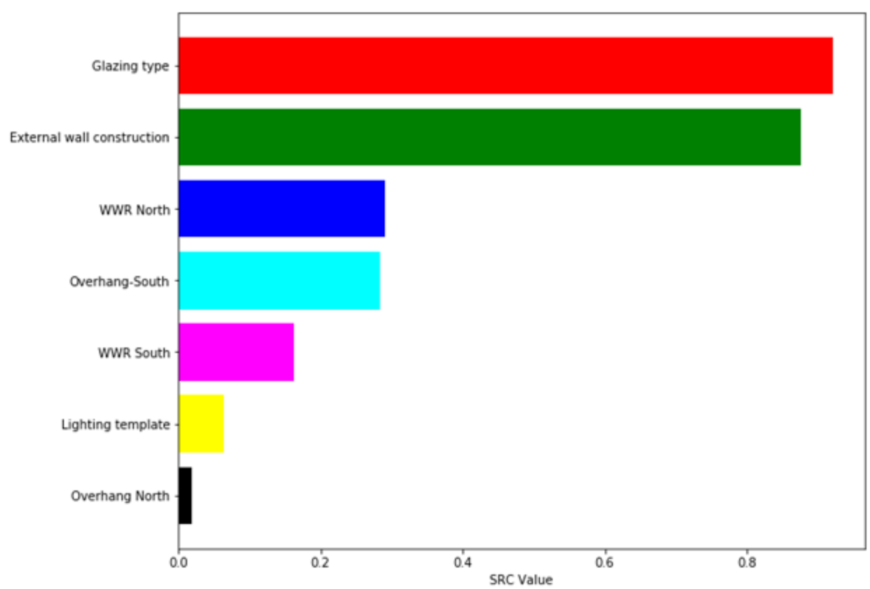

Figure 2: *Analysis of sensitivity of different factors on cost*

Figure 2 provides a compelling visualization of the variables and their corresponding Sensitivity Range Calculation (SRC) values within the cost function. The cost function serves as a critical tool for assessing the influence of each variable on the total cost. A higher positive SRC value signifies that an increase in the variable will yield a more substantial positive impact on the cost function. Conversely, a higher negative SRC value indicates a more significant negative impact. In this table, the Glazing type variable stands out with the highest positive SRC value of 0.9206, suggesting that alterations in the glazing type could lead to a considerable increase in cost. Similarly, the

External wall construction variable, with a high positive SRC value of 0.8763, implies that changes in the construction of external walls could also significantly affect the cost. The variables WWR North, Overhang-South and WWR South possess positive SRC values of 0.2912, 0.2835, and 0.1627, respectively. This indicates that augmenting the window-to-wall ratio (WWR) in the North and South orientations, along with the implementation of overhangs in the South direction, could contribute to cost escalation. The Lighting template and Overhang North variables, although still positively impacting costs, have lower SRC values of 0.0638 and 0.0195, respectively. This suggests their influence on cost, while still present, is relatively minor compared to the other variables. Overall, the SRC values offer valuable insights into the sensitivity and significance of each variable in shaping the cost function. This information can prove instrumental in decision-making processes, facilitating the optimization of variables to minimize costs or allocate resources more efficiently.

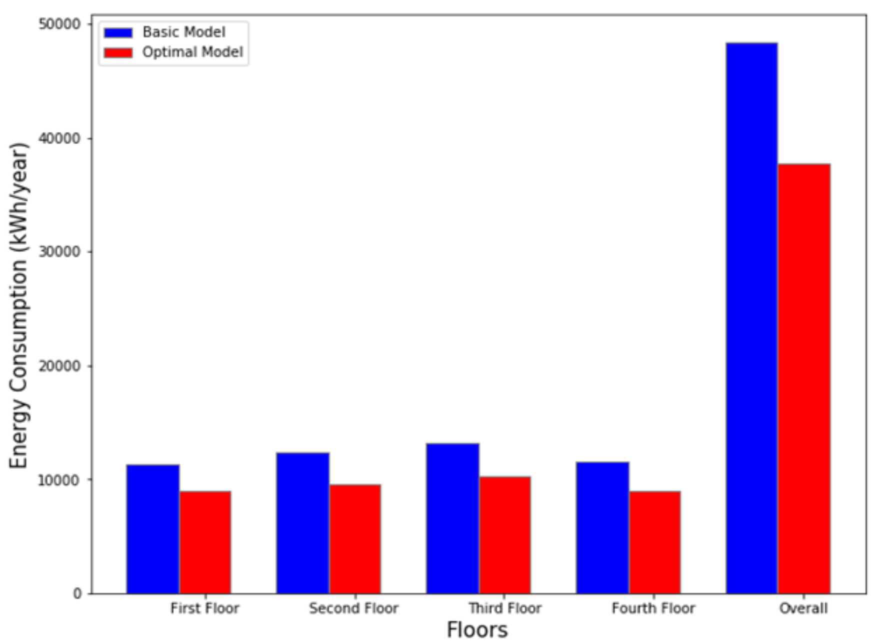

Figure 3: *Energy consumption comparison*

Figure 3 presents a compelling comparison of energy consumption between the basic and optimal models across different floors of a building, as well as the overall energy savings achieved. On the first floor, the basic model consumes 11,320 kWh per year, while the optimal model significantly reduces this figure to 9,013 kWh per year, achieving a remarkable reduction of 21%. The second floor follows a similar trend. The basic model's energy consumption stands at 12,310 kWh per year, which the optimal model manages to decrease to 9,503 kWh per year, resulting in an impressive reduction of 23%. On the third floor, the basic model consumes 13,213 kWh per year. However, the optimal model once again proves its efficiency by lowering this to 10,302 kWh per year, achieving a notable reduction of 22%. The fourth floor mirrors this pattern. The basic model's energy consumption is 11,560 kWh per year, while the optimal model reduces this to 8,921 kWh per year, leading to a significant reduction of 23%. When considering the building as a whole, the basic model's energy consumption is 48,403 kWh per year. In contrast, the optimal model demonstrates its superior efficiency by reducing the total energy consumption to 37,739 kWh per year, resulting in an overall reduction of 22%. These findings underscore the substantial energy savings achieved by implementing the optimal model across all floors. The reduction percentages range from 21% to 23%, with an average reduction of 22% overall. This data highlights the effectiveness of the optimization measures in not only reducing energy consumption but also enhancing the building's overall energy efficiency. The results serve as a testament to the potential of such optimization measures in paving the way towards more sustainable and energy-efficient buildings. Figure 4 and Figure 5 illustrate the daily solar radiation and average daily temperature in Tehran.

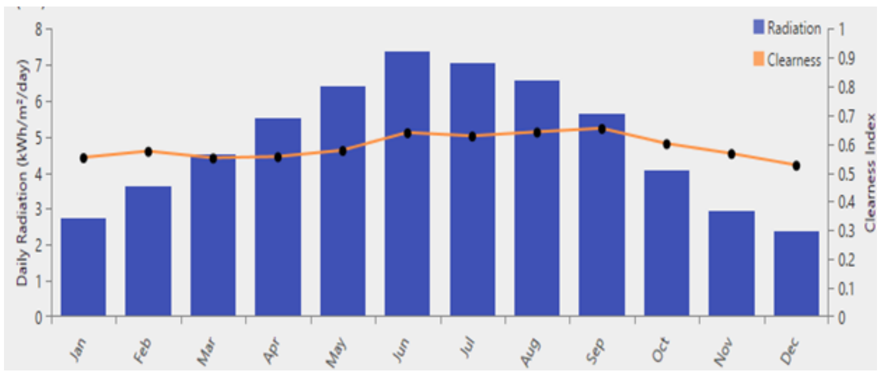

Figure 4: *Daily solar radiation in Tehran*

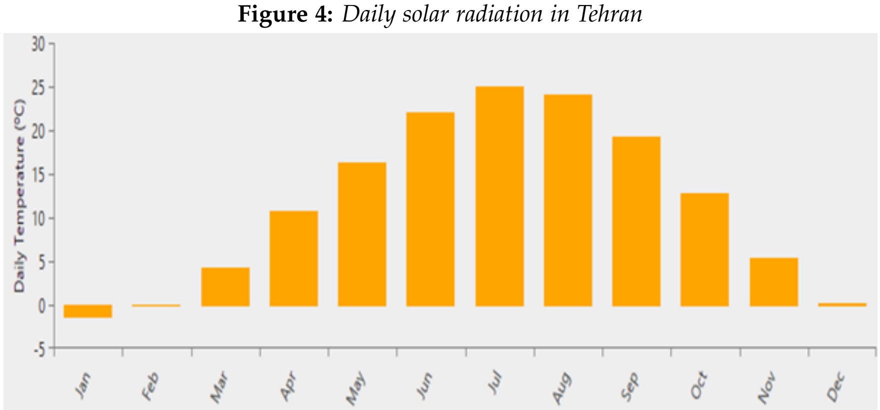

Figure 5: *Average daily temperature in Tehran*

The investigation unveils the cyclical variations in the yield of solar electricity from the photovoltaic cells. The shadow cast by the adjacent structure notably impairs the efficiency of the solar cells on the ground floor. In a similar vein, the shadow from the inclined rooftop on the third level results in a dip in power production. This dip in efficiency is particularly evident during the months with higher solar elevation angles, specifically from May through September. Furthermore, the study probes into the potential of power generation from photovoltaic cells positioned on inclined rooftops facing both the southern and northern directions, with slopes of varying degrees. The findings indicate that the peak power output is attained by panels facing south at an inclination of 38 degrees, which interestingly corresponds closely with the geographical latitude of the site. These insights not only echo the conclusions of preceding studies but also emphasize the critical role of strategic panel placement in harnessing maximum solar energy. The study is presented without the inclusion of any figures or diagrams.

Figure 6 highlights the potential for energy generation from solar panels, emphasizing the significance of their placement. The annual electricity production from the system is outlined as follows: the south-facing sloped roof generates 1203 kWh, while the north-facing sloped roof yields a significantly higher output of 9231 kWh. Additionally, the facades of the first, second, third, and fourth floors contribute 8731 kWh, 1056 kWh, 987 kWh, and 861 kWh, respectively. When there is no shading, the system can generate 1346 kWh. Overall, the cumulative annual electricity production reaches 23415 kWh. These findings underscore the critical role of strategic panel placement in optimizing solar energy generation and reinforce the importance of considering factors such as orientation and shading to maximize efficiency.

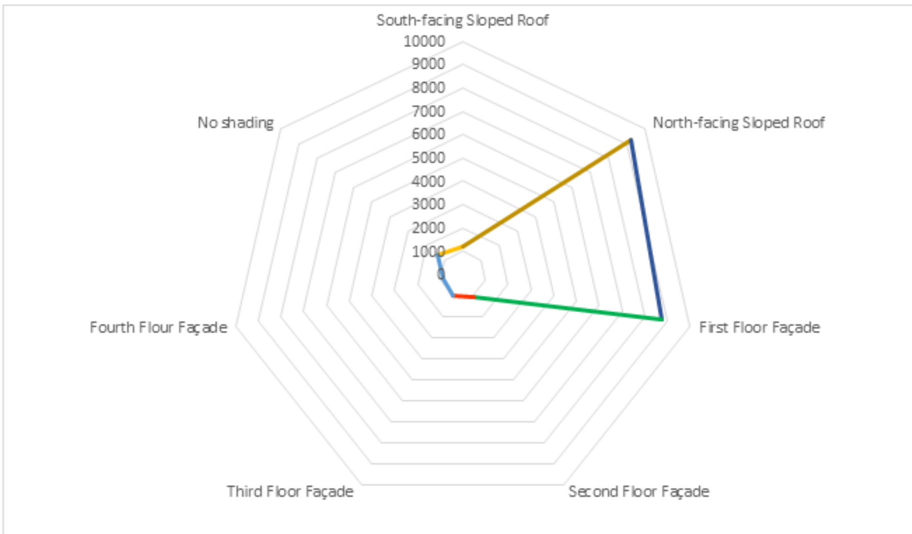

Figure 6: *Harvesting sunlight: Photovoltaic electricity generation*

5. Conclusion

Optimizing building energy efficiency and integrating renewable energy technologies are essential components of sustainable development. A sensitivity analysis was conducted to identify key factors influencing building costs and electricity consumption. The analysis revealed that variables such as glazing type, wall construction, window-to-wall ratios, and shading elements significantly impact these factors. By optimizing these variables, cost-effective and energy-efficient building designs can be achieved. Additionally, strategic placement of photovoltaic panels, considering factors like orientation and shading, can maximize solar energy generation and further enhance energy efficiency. The study's findings emphasized the importance of considering these variables during the design and construction phases of buildings. By implementing optimized designs and integrating renewable energy technologies, significant energy savings can be achieved while minimizing environmental impact. These efforts play a crucial role in mitigating climate change and transitioning towards a more sustainable and energy-efficient built environment. One recommendation for future studies can be penetrating hydrogen into the buildings and the effects on reducing the emissions.

Declaration of interest: None

References

[1] Saedpanah E, Lahonian M, Abad MZ. Optimization of multi-source renewable energy air conditioning systems using a combination of transient simulation, response surface method, and 3E lifespan analysis. *Energy* 2023:272:127200.

[2] Lo K. Asian energy challenges in the Asian century. *Journal of Asian Energy Studies* 2017:1:1-6.

[3] Pourmatin M, Fayaz-Heidari A, Moeini-Aghtaie M, Hassannayebi E, Basirati M. Investigating the Sustainable Development of Charging Stations for Plug-in Electric Vehicles: A System Dynamics Approach. IFIP International Conference on Advances in Production Management Systems 2023 Sep 14 (pp. 400-416). Cham: Springer Nature Switzerland.

[4] Foroughi M, Pasban A, Moeini-Aghtaie M, Fayaz-Heidari A. A bi-level model for optimal bidding of a multi-carrier technical virtual power plant in energy markets. *International Journal of Electrical Power & Energy Systems* 2021:125:106397.

[5] Mirzapour O, Rui X, Sahraei-Ardakani M. Transmission impedance control impacts on carbon emissions and renewable energy curtailment. *Energy* 2023:278:127741.

[6] Heidari M, Soleimani A, Dzikuć M, Heidari M, Dolatabadi SH, Kuryło P, Khan B. Exploring synergistic ecological and economic energy solutions for low-urbanized areas through simulation-based analysis. *AIMS Energy* 2024:12:119-151.

[7] Khedher NB, Boujelbene M, Nabaei SH, Bahari M, Ashtari M, Aliehyaei M. Exergy and energy investigations of ET-150 PTSC with non-Newtonian nanofluid. *Applied Thermal Engineering* 2024:252:123720.

[8] Esmaili A, Oshanreh MM, Naderian S, MacKenzie D, Chen C. Assessing the spatial distributions of public electric vehicle charging stations with emphasis on equity considerations in King County, Washington. *Sustainable Cities and Society* 2024:107:105409.

[9] Soleimani A, Hosseini Dolatabadi SH, Heidari M, Pinnarelli A, Mehdizadeh Khorrami B, Luo Y, Vizza P, Brusco G. Progress in hydrogen fuel cell vehicles and up-and-coming technologies for eco-friendly transportation: an international assessment. *Multiscale and Multidisciplinary Modeling, Experiments and Design* 2024 May 27:1-20.

[10] Zhang X, Zhen Z, Sun Y, Wang F, Zhang Y, Ren H, Ma H, Zhang W. Prediction interval estimation and deterministic forecasting model using ground-based sky image. *IEEE Transactions on Industry Applications* 2022:59:2210-2224.

[11] Heidari AF, Masoumzadeh A, Vrakopoulou M, Alpcan T. Planning for inertia and resource adequacy in a renewable-rich power system. 2023 IEEE PES Innovative Smart Grid Technologies-Asia (ISGT Asia) 2023 Nov 21 (pp. 1-5). IEEE.

[12] Wang X, Lo K. Energy and environmental justice in China: Literature review and research agenda. *Journal of Asian Energy Studies* 2023:7:91-106.

[13] Dehghani A, Alidadi M, Soltani A. Density and urban resilience, cross-section analysis in an Iranian metropolis context. *Urban Science* 2023:7:23.

[14] Dehghani A, Alidadi M, Sharifi A. Compact development policy and urban resilience: a critical review. *Sustainability* 2022:14:11798.

[15] Salmanian M, Mousavi M, Nasirimehr P, Takhmiri H, Ujang NB, Shahidan MF, Dahlan ND. Examining the influence of urban form on the thermal comfort of street canyons in Tehran: A case study of Narmak neighbourhood. *Journal of Architecture, Planning and Construction Management* 2024:14:52-77.

[16] Hemmati M, Messadi T, Gu H, Seddelmeyer J, Hemmati M. Comparison of embodied carbon footprint of a mass timber building structure with a steel equivalent. *Buildings* 2024:14:1276.

[17] Momeni S, Eghbalian A, Talebzadeh M, Paksaz A, Bakhtiarvand SK, Shahabi S. Enhancing office building energy efficiency: neural network-based prediction of energy consumption. *Journal of Building Pathology and Rehabilitation* 2024:9:1-4.

[18] Guedri K, Salem M, Assad ME, Rungamornrat J, Malek Mohsen F, Buswig YM. PV/Thermal as promising technologies in buildings: a comprehensive review on exergy analysis. *Sustainability* 2022:14:12298.

[19] Yazdandoust F. Decision support for the design of a building form coupling daylight and natural ventilation consideration in a dense urban context (Master's thesis, Iowa State University).

[20] Amiraslanpour M, Ghazanfarian J, Nabaei H, Taleghani MH. Evaluation of laminar airflow heating, ventilation, and air conditioning system for particle dispersion control in operating room including staffs: A non-Boussinesq Lagrangian study. *Journal of Building Physics* 2021:45:236-264.

[21] Salmanian M, Ujang N. Emerging need for micro-climatic considerations in urban design process: A review. *Jurnal Teknologi* 2022:84:129-148.

[22] Kusi E, Boateng I, Danso H. Energy consumption and carbon emission of conventional and green buildings using building information modelling (BIM). *International Journal of Building Pathology and Adaptation* 2024.

[23] Solaymani S, Falahati A, Darabi KD, Kaviar H. CO2 emissions mitigation in ASEAN countries: The role of renewable energy use and financial development. *Journal of Asian Energy Studies* 2024:8:17-37.

[24] Sadat SZ, Ledari MB, Dehvari H, Moghaddam MS, Hosseini MR. Aligning Net zero energy, carbon Neutrality, and regenerative concepts: An exemplary study of sustainable architectural practices. *Journal of Building Engineering* 2024:90:109414.

[25] Constantinou S, Al-naemi F, Alrashidi H, Mallick T, Issa W. A review on technological and urban sustainability perspectives of advanced building-integrated photovoltaics. *Energy Science & Engineering* 2024:12:1265-1293.

[26] Mehdizadeh G, Nikoo MR, Talebbeydokhti N, Vanda S, Nematollahi B. Hypolimnetic aeration optimization based on reservoir thermal stratification simulation. *Journal of Hydrology* 2023:625:130106.

[27] Dutta A, Masrourisaadat N, Doan TT. Convergence rates of decentralized gradient dynamics over cluster networks: multiple-time-scale Lyapunov approach. 2022 IEEE 61st Conference on Decision and Control (CDC) 2022 Dec 6 (pp. 6497-6502). IEEE.

[28] Zandi J, Afooshteh AN, Ghassemian M. Implementation and analysis of a novel low power and portable energy measurement tool for wireless sensor nodes. Electrical Engineering (ICEE), Iranian Conference on 2018 May 8 (pp. 1517-1522). IEEE.

[29] Zolfaghary Pour S, Khavasi A, Rejaei B. Design and fabrication of a polarization-independent millimeter-wave absorber using circuit theory and 3D printing. *Journal of Electronic Materials*. 2024:53:525-534.

[30] Abdul Samad SR, Balasubaramanian S, Al-Kaabi AS, Sharma B, Chowdhury S, Mehbodniya A, Webber JL, Bostani A. Analysis of the performance impact of fine-tuned machine learning model for phishing URL detection. *Electronics* 2023:12:1642.

[31] Rajput SP, Webber JL, Bostani A, Mehbodniya A, Arumugam M, Nanjundan P, Wendimagegen A. Using machine learning architecture to optimize and model the treatment process for saline water level analysis. *Water Reuse*. 2023:13:51-67.

[32] Vairachilai S, Bostani A, Mehbodniya A, Webber JL, Hemakesavulu O, Vijayakumar P. Body sensor 5 G networks utilising deep learning architectures for emotion detection based on EEG signal processing. *Optik* 2022:170469.

[33] Saghafian M, Seyedzadeh H, Moradmand A. Numerical simulation of electroosmotic flow in a rectangular microchannel with use of magnetic and electric fields. *Scientia Iranica* 2023.

[34] Noruzi S, Ghoreishy H, Ahmad AA, Tahami F, Ahmadiahangar R, Rosin A. Variable frequency control method of boost converter operating in boundary conduction mode. 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON) 2020 Nov 5 (pp. 1-6). IEEE.

[35] Tahami H, Akbari E, Mohammed AH, Faraji R, Channumsin S. A transformerless enhanced-boost quasi-z-source inverter with low input current ripple for stand-alone RES-based systems. *Energies* 2023:16:2611.

[36] Razzaghi MJ, Asadollahzadeh M, Tajbakhsh MR, Mohammadzadeh R, Abad MZ, Nadimi E. Investigation of a temperature-sensitive ferrofluid to predict heat transfer and irreversibilities in LS-3 solar collector under line dipole magnetic field and a rotary twisted tape. *International Journal of Thermal Sciences* 2023:185:108104.

[37] Kiaghadi M, Sheikholeslami M, Alinia AM, Boora FM. Predicting the performance of a photovoltaic unit via machine learning methods in the existence of finned thermal storage unit. *Journal of Energy Storage* 2024:90:111766.

[38] Kiani S, Salmanpour A, Hamzeh M, Kebriaei H. Learning robust model predictive control for voltage control of islanded microgrid. *IEEE Transactions on Automation Science and Engineering* 2024.

[39] Yazdandoust F, Mirindi D. Harvesting alternative energy: exploring exergy, human power, animal body heat, and noise as sustainable sources. Proceedings of DARCH 2024 April - 5th International Conference on Architecture & Design. 29-30 April, 2024

[40] Havaeji H, Dao TM, Wong T. Optimizing a transportation system using metaheuristics approaches (EGD/GA/ACO): a forest vehicle routing case study. *World Journal of Engineering and Technology* 2023:12:141-157.

[41] Havaeji H, Dao TM, Wong T. Cost prediction in blockchain-enabled pharmaceutical supply chain under uncertain demand. *Mathematics* 2023:11:4669.

[42] Serajian S, Shamsabadi AA, Mohamed SI, Nejati S, Bavarian M. MXenes in solid-state batteries: Current status and outlook. *Journal of Power Sources* 2024:610:234721.

[43] Farrokhi S, Dargie W, Poellabauer C. Human activity recognition based on wireless electrocardiogram and inertial sensors. *IEEE Sensors Journal* 2024:24:6490-6499.

[44] Seifi N, Al-Mamun A. Optimizing memory access efficiency in CUDA Kernel via data layout technique. *Journal of Computer and Communications* 2024:12:124-139.

[45] Salehi F, Razavi M, Smith M, Dixit M. Integrated eye-tracking and EEG data collection and synchronization for virtual reality-based spatial ability assessments.

[46] Fakhri M, Arzjani D, Ayar P, Mottaghi M, Arzjani N. Performance evaluation of WMA containing re-Refined acidic sludge and amorphous poly alpha olefin (APAO). *Sustainability* 2021:13:3315.

[47] Salehi F, Pariafsai F, Dixit MK. The impact of different levels of spatial cues on size perception: a spatial perception study of altered conditions. International Conference on Human-Computer Interaction 2024 Jun 1 (pp. 74-85). Cham: Springer Nature Switzerland.

[48] Mohaghegh S, Kondo S, Yemiscioglu G, Muhtaroglu A. A novel multiplier hardware organization for finite fields defined by all-one polynomials. *IEEE Transactions on Circuits and Systems II: Express Briefs* 2022:69:5084-5088.

[49] Shokouhi S, Mu B, Thein MW. Optimized path planning and control for autonomous surface vehicles using b-splines and nonlinear model predictive control. OCEANS 2023-MTS/IEEE US Gulf Coast 2023 Sep 25 (pp. 1-9). IEEE.

[50] Mohammadi V, Tajdani M, Masaei M, Mohammadi Ghalehney S, Lee SC, Behboodi A. DE-AFO: A robotic ankle foot orthosis for children with cerebral palsy powered by dielectric elastomer artificial muscle. *Sensors* 2024:24:3787.

[51] Aliehyaei M, Nabaei SH, Ashtari M. Exergy, Energy and CO2 emission investigations of Eurotrough-150 Solar System with wind speed variations and non-Newtonian nanofluid. SSRN 4659558.

[52] Alghamdi H, Alviz-Meza A. A novel strategy for converting conventional structures into net-zero-energy buildings without destruction. *Sustainability* 2023:15:11229.

[53] Zhou X, Huang Z, Scheuer B, Lu W, Zhou G, Liu Y. High-resolution spatial assessment of the zero energy potential of buildings with photovoltaic systems at the city level. *Sustainable Cities and Society* 2023:93:104526.

[54] Liu W, Shen Y, Aungkulanon P, Ghalandari M, Le BN, Alviz-Meza A, Cárdenas-Escrocia Y. Machine learning applications for photovoltaic system optimization in zero green energy buildings. *Energy Reports* 2023:9:2787-2796.

[55] El Hassani S, Charai M, Moussaoui MA, Mezrhab A. Towards rural net-zero energy buildings through integration of photovoltaic systems within bio-based earth houses: Case study in Eastern Morocco. *Solar Energy* 2023:259:15-29.

[56] Khan S, Sudhakar K, Yusof MH, Azmi WH, Ali HM. Roof integrated photovoltaic for electric vehicle charging towards net zero residential buildings in Australia. *Energy for Sustainable Development* 2023:73:340-354.

[57] Panicker K, Anand P, George A. Assessment of building energy performance integrated with solar PV: Towards a net zero energy residential campus in India. *Energy and Buildings* 2023:281:112736.

[58] Wu H, Deng F, Tan H. Research on parametric design method of solar photovoltaic utilization potential of nearly zero-energy high-rise residential building based on genetic algorithm. *Journal of Cleaner Production* 2022:368:133169.

[59] Li SY, Han JY. The impact of shadow covering on the rooftop solar photovoltaic system for evaluating self-sufficiency rate in the concept of nearly zero energy building. *Sustainable Cities and Society* 2022:80:103821.

[60] Luo Y, Cheng N, Zhang S, Tian Z, Xu G, Yang X, Fan J. Comprehensive energy, economic, environmental assessment of a building integrated photovoltaic-thermoelectric system with battery storage for net zero energy building. Building Simulation 2022 Nov (Vol. 15, No. 11, pp. 1923-1941). Beijing: Tsinghua University Press.

[61] Ali MH, Mawlood MK, Jalal RE. Minimizing energy losses and enhancing performance of Trombe wall systems through partial evacuation of the air gap. *Energy and Buildings* 2024:307:113959.

[62] Faure X, Lebrun R, Pasichnyi O. Impact of time resolution on estimation of energy savings using a copula-based calibration in UBEM. *Energy and Buildings* 2024:311:114134.

[63] Liu Y, Gao Y, Zhuang C, Shi D, Xu Y, Guan J, Di Y. Optimization of top-floor rooms coupling cool roofs, natural ventilation and solar shading for residential buildings in hot-summer and warm-winter zones. *Journal of Building Engineering* 2023:66:105933.

[64] Roberts F, Yang S, Du H, Yang R. Effect of semi-transparent a-Si PV glazing within double-skin façades on visual and energy performances under the UK climate condition. *Renewable Energy* 2023:207:601-610.

[65] Marwan M. The effect of wall material on energy cost reduction in building. *Case Studies in Thermal Engineering* 2020:17:100573.

[66] Alghoul SK, Rijabo HG, Mashena ME. Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya. *Journal of Building Engineering* 2017:11:82-86.

[67] Song S, Long J, Jiang H, Ran B, Yao L. Characteristics of office lighting energy consumption and its impact on air conditioning energy consumption. *Energy and Built Environment* 2024:54:529-543.

[68] Jamil I, Lucheng H, Habib S, Aurangzeb M, Ahmed EM, Jamil R. Performance evaluation of solar power plants for excess energy based on energy production. *Energy Reports* 2023:9:1501-1534.

[69] Anupong W, Mehbodniya A, L. Webber J, Bostani A, Dhiman G, Singh B, AR MD. Deep learning algorithms were used to generate photovoltaic renewable energy in saline water analysis via an oxidation process. *Water Reuse* 2023:13:68-81.