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Decision support model for PV integrated shading system: Office building case

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Abstract

Office buildings have a high amount of internal heat, solar gain, daytime energy consumption and occupancy schedules. Therefore, the increment in the cooling energy demand highlights the shading systems to provide efficient energy retrofit for office buildings. Shading surfaces, to prevent the high amount of solar radiation, are suitable for the collection of solar energy and the integration of photovoltaic systems onto the building envelope. However, the impact of the shading surface on the cooling, heating, and lighting energy consumption and the amount of energy produced by the PV system is a great task as a decision-making problem with multiple independent and dependent variables. This study searches for the installation of a PV integrated shading system to an office building through a decision support methodology. Independent variables such as the shading surface area, and angle and the dependent variables such as the energy, embodied carbon, and cost indicators are analysed within the decision support methodology. The results provide a definitive structure for such decision-making problems. Moreover, findings highlight that although Mono-Si PV options are more efficient in terms of energy generation, Poly-Si PV options are found to be the ideal solutions, due to the lower cost and embodied carbon.

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Keywords: Decision-support; Shading strategy; Photovoltaic integration; Cost; Embodied carbon; Energy performance

1. Introduction

Global land and ocean average surface temperatures have risen approximately 1 °C above the 20th-century average (base year) due to the augmentation of greenhouse gas levels mainly produced from fossil fuels [1]. Therefore, after the Paris agreement, 55% of greenhouse emissions reduction is set as one of the European Union (EU) sustainability policies by the scope of the Green Deal to achieve carbon neutrality by 2050 [2]. In this context, the energy supply from renewable energy sources is targeted to rise from 32% [3] to 40% [2] of the total EU energy use.

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Building stock, responsible for 40% of total EU energy use, has been in transformation in the last decades to improve energy efficiency and carbon emissions as asked by the Directives [4,5]. Moreover, it is targeted that 49% of the energy supply by 2030 will be provided by renewable energy sources such as photovoltaic panels, wind tribunes, etc. for building stock in the EU. In this regard, the integration of renewable energy supply systems onto the building envelope has been examined in terms of renewable energy production, nearly zero energy building, and building optical and thermophysical performance in some studies [6–8] as reported by the research [9]. Moreover, the optimum angle, length, and type of the photovoltaic panels have been studied in terms of energy generation in different climates [10,11].

In this paper, an office building with high envelope transparency as a problematic case in terms of energy performance was studied for retrofitting by applying PV integrated shading system options to achieve the ideal solution through the TOPSIS decision-making method. In the scope of this study, shading surface and so PV area, type and angle are examined as independent variables in terms of building energy performance, PV embodied carbon and energy-related costs as dependent variables.

2. Method

The study is based on a decision support model for the integration of PV systems to the external horizontal shading devices considered for the south façade of an office building. The methodology covers firstly the parameterization through the shading and PV options in terms of the type, angle, and length to define the alternatives, secondly the energy, cost, and embodied carbons calculations to obtain the criteria values, and finally the application of the TOPSIS method to obtain the ranking of alternatives.

2.1. Analysis of the office building case

The office building is located in İstanbul, which has typical temperate-humid climate region characteristics. The office building plan scheme has a 1:1 aspect ratio, with the open office areas oriented in east-south-west directions and the core oriented in the north direction, as given in Fig. 1. The building has 11 office floors with a 493 m^2 office area on each floor.

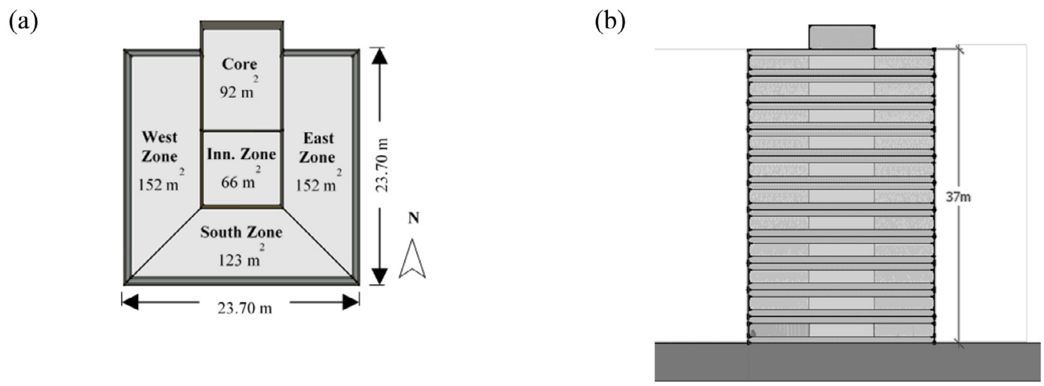

Fig. 1. (a) Plan scheme of the office building and the thermal zones for the energy model, (b) front view (south) of the office building.

2.2. Analysis of solar photovoltaic panel options

The solar PV panel is one of the focal systems to generate renewable energy due to its mature technologies. Although it is the third most applied renewable energy technology after hydro and wind systems [12], it emits low carbon emissions than the other two technologies [13].

PV cells offer various types such as the first generation of monocrystalline and polycrystalline (c-Si) solar cells, the second generation of thin film, semiconductor-controlled solar cells, etc. Moreover, c-Si solar cell accounts for %80 of the global market [14]. Therefore, monocrystalline and polycrystalline solar cell options were selected among the options in the local market for this study as reported in Table 1.

Table 1. Solar cell properties [15,16].

Cell type	Efficiency (%)	Power (W/m^2)	Embodied carbon (kgCO$_2$-eq/m^2)	Cell size (cm)
Monocrystalline	20.03	200	213.9	15.6 × 15.6
Polycrystalline	17.85	173.14	173	15.6 × 15.6

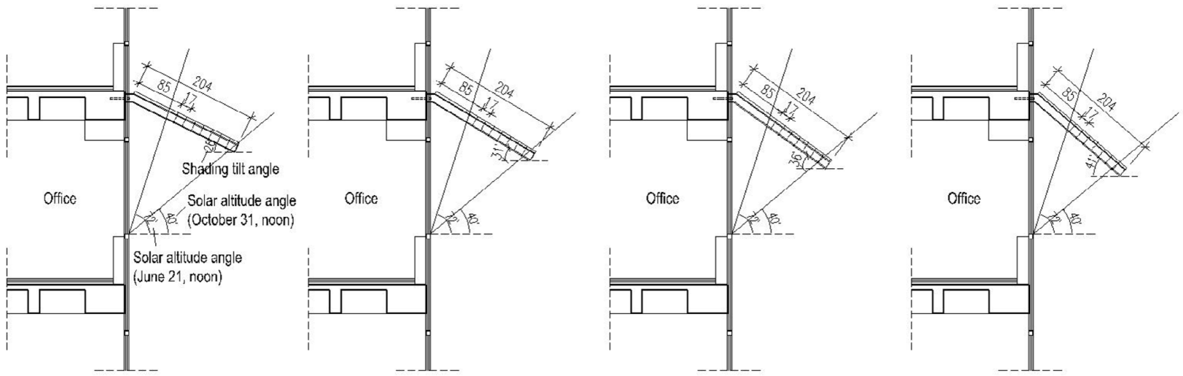

Fig. 2. Shading alternatives with the variation of length and tilt angle.

2.3. Determination of shading strategies

External horizontal shading options to be adapted to the south façade of the building, are varied through the length and the tilt angle of the shading surface. The length of the shading, which varies between 85 cm and 204 cm with intervals of 17 cm representing the dimensions of a solar cell grid, determines eight alternatives for the shading length. The tilt angle of the shading varies as 26°, 31°, 36°, and 41°, related to the maximum altitude angle of the sun (June 21st), the relevant solar altitude angle of the cooling period of the building, and its intervals. Thus, 8 shading length options with four tilt angle options define 32 total shading alternatives for the decision matrix (see Fig. 2).

2.4. Energy modelling and cost calculations

EnergyPlus v.9.0.1 is used for the calculations of the energy consumption and production rates of the building and the photovoltaic (PV) systems with six-time steps per hour. Inside surface convection, outside surface convection, and heat balance are calculated through the TARP, DOE-2, and conduction transfer function algorithms, respectively. The average climatic data between 2003 and 2017 was designated as the weather file for the aforementioned calculations.

EPBD Recast [5] introduced the cost optimality concept to find out the balance between the investment costs and cost savings compared to the base case to achieve energy-efficient cost-effectiveness. In this respect, the life cycle cost of energy and energy-related interventions are calculated by the global cost introduced by EN 15459-1 [17]. Moreover, economic parameters and values were involved in the calculation from a recent study [9].

2.5. Decision support model using the TOPSIS method

The technique for order preference by similarity to an ideal solution (TOPSIS), developed by Hwang and Yoon [18], is a method that is based on the evaluation of the alternatives according to the Euclidean distance to the ideal and the negative-ideal solution. According to the TOPSIS method, the decision matrix $\left(x_{ij}\right)_{mxn}$ consisting of m alternatives and n performance criteria is normalized by using Eq. (1) and the weighted normalized decision matrix $\left(t_{ij}\right)_{mxn}$ is obtained by applying the weights w_j to the normalized matrix. S_{ib} and S_{iw} representing the distance of each alternative to the ideal and the negative-ideal solution are calculated by Eq. (2), where A_j^+ and A_j^-

represents the ideal and negative-ideal values for the jth criteria. The performance score, R_i of each alternative, is then calculated by the division of S_{ib} to the sum of S_{iw} and S_{iw}.

$$\overline{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{1}$$

$$S_{ib} = \left[\sum_{j=1}^{m} \left(A_{ij} - A_j^+ \right)^2 \right]^{0.5}, S_{iw} = \left[\sum_{j=1}^{m} \left(A_{ij} - A_j^- \right)^2 \right]^{0.5} \tag{2}$$

3. Results and discussion

Results show that the south zone cooling energy demand varies between 34.3 kWh/m^2 a (204 cm, 36°) and 46.7 kWh/m^2 a (85 cm, 26°), and south zone heating energy varies between 16.6 kWh/m^2 a (85 cm, 31° and 36°) and 29.2 kWh/m^2 a (204 cm, 41°), and south zone lighting energy varies between 11.3 kWh/m^2 a (85 cm, 26°) and 16.1 kWh/m^2 a (204 cm, 41°), pointing to the conflict between the cooling, heating, and lighting energy performances.

The amount of energy produced by the PV system varies between 10.9 kWh/m^2 a (85 cm, 26°) and 26.7 kWh/m^2 a (204 cm, 31° and 36°) for the Poly-Si photovoltaic panels and between 12.3 kWh/m^2 a (85 cm, 26°) and 29.9 kWh/m^2 a (204 cm, 31° and 36°) for the Mono-Si photovoltaic panels, highlighting the 31°–36° range as the ideal solution for the PV system.

The life cycle cost (LCC) of the alternatives varies between 142.6 €/m2 (Mono-Si, 204 cm, 31°) and 244.7 €/m2 (Poly-Si, 85 cm, 41°), showing that the increase in the amount of energy produced by the PV system increases the cost performance of the building.

Embodied carbon values vary in accordance with the surface area for PV installation. A range from 34.9 kgCO_2/m^2 to 83.7 kgCO_2/m^2 is obtained for Mono-Si PV installation and 28.2 kgCO_2/m^2 to 67.7 kgCO_2/m^2 is obtained for Poly-Si PV installation.

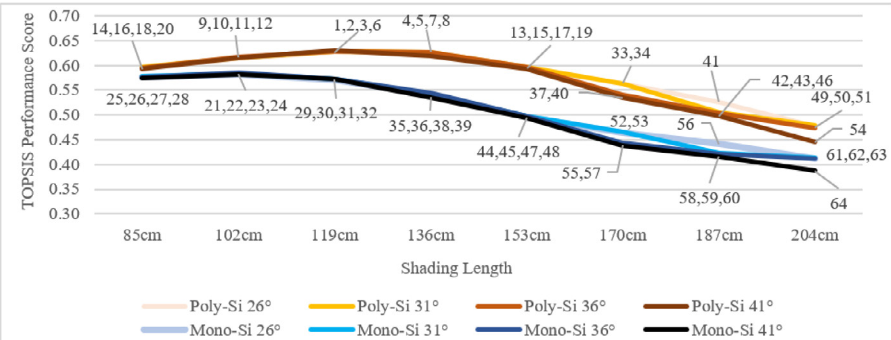

Fig. 3. TOPSIS performance scores of the alternatives.

The overall performances of the alternatives are given in Fig. 3, as the curve obtained from the TOPSIS performance scores of the alternatives. The decision support model that is proposed in this study, for the PV integrated shading system, performs reasonable results to increase the overall performance of the building. Ideal solutions, with higher TOPSIS performance scores, are existing within the decision matrix boundaries. Poly-Si alternatives have a performance curve above the Mono-Si alternatives, due to the lower cost and environmental impact values. However, Poly-Si alternatives with a shading length higher than 153 cm lead to lower performances than the Mono-Si alternatives with a shading length lower than 136 cm.

It is evident from the decision-making results that, the best solutions address the Poly-Si PV options, due to the products' lower cost and embodied carbon levels. Besides, 119 cm and 136 cm options mark the lowest overall energy level, including the cooling, heating, and lighting requirements. The ideal alternatives that are pointed out by the decision support model indicate the success of the decision model within the decision matrix and provide a definitive structure for such decision-making problems.

4. Conclusion

An office building retrofitting was handled by applying PV integrated shading system options in terms of PV area, type and angle considering energy performance, PV embodied carbon and energy-related costs to achieve the ideal solution through the TOPSIS decision-making method.

The impact of the embodied carbon level, as a performance indicator, performs as a good penalty parameter to avoid an excessive amount of PV installation on the building façade, where the PV system provides an advantage for energy production but negatively affects the building's overall energy behaviour.

In further studies, it is targeted to involve more dependent variables in the decision support process such as useful daylight illuminance, and thermal comfort to improve the sensitivity of the decision making.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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