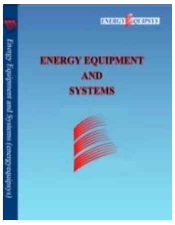
Energy Equip. Sys. / Vol. 13/No. 1/March 2025/ 75-92

ENERGY QUIPSYS

Energy Equipment and Systems

www.energyequipsys.com



Multi-objective techno-economic-environmental optimization of the building integrated photovoltaic (BIPV) system: A high-rise building

Manuscript Type
Research Paper

Authors

Hamed Amini [a,b]
Behrang Sajadi [a*]
Pouria Ahmadi [a]

[a] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

[b] Department of Energy and Mechanical Engineering, Aalto University, Espoo, Finland

Article history:

Received: 10 October 2023
Revised: 21 December 2023
Accepted: 23 February 2024

ABSTRACT

This paper presents a multi-objective optimization framework for the optimal design of building integrated photovoltaic (BIPV) systems. This approach is conducted using the non-dominated sorting genetic algorithm (NSGA-II) to find the best solution that satisfies the technical, economic, and environmental criteria formulated in this study. The optimization process is performed using EnergyPlus and jEPlus+EA software. Decision variables are the building orientation, depth of overhang panels, angle of overhang panels, the width of facade panels, and panel technology that can vary in every target surface. Also, the occupants' thermal discomfort hours, system return on investment (ROI), and carbon equivalent of pollution are assumed as objective functions. The energy required to produce PV panels is considered in formulating environmental factors to present a more comprehensive approach. The final optimal solution is selected using the weighted sum method. Based on the results, implementation of the optimal system not only supplies 867 MWh of electrical energy in the first year (equivalent to 23% of total energy consumption) but also reduces the HVAC energy consumption by 16%. The optimized system's return on investment (ROI) in the first year of operation is 21.7%. Furthermore, for the final optimal BIPV system, the occupants' thermal discomfort time, total energy consumption, and pollutant emission were reduced by 33%, 5.7%, and 27%, respectively, compared to the initial case. The energy and carbon payback times of the optimized case are estimated as 6 and 2.5 years, respectively. The results show that facade-integrated solar systems are technically, economically, and environmentally justifiable. They can decrease the energy consumption and emission of the building while increasing the occupants' thermal comfort.

Keywords: Building Integrated Photovoltaic (BIPV); Multi-Objective Optimization; Payback Time; Building Simulation; EnergyPlus.

1. Introduction

Energy is one of the most severe challenges in human history all over the world. Energy consumption growth in industries and many other aspects of people's lives increases the subject's importance [1, 2]. A significant share of energy consumption is related to residential and commercial buildings. Electric energy used for heating, cooling, and other electrical devices, is the primary form of energy in the building sector. Buildings are responsible for over 30% of energy consumption and 28% of global CO_2 emissions [3, 4]. In addition,

* Corresponding author: Behrang Sajadi
School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran.
Email: bsajadi@ut.ac.ir

transmission line losses from power plants to urban areas are another problem. The power grid electricity loss was reported at 8.25% worldwide in 2014 [5].

Today, fossil fuels are the biggest energy supplier in almost all countries because of their low price and abundance. Nevertheless, the limited source of fossil fuels will be depleted if alternative fuels do not replace these sources [6]. Almost all fossil fuel reserves, except coal, will vanish after 2042 by continuing the current energy consumption pattern [7]. Moreover, pollution and greenhouse gases produced from fossil fuel consumption cause irreparable environmental damage [8]. These concerns about the future of energy have prompted researchers to discover viable and suitable alternatives. In this regard, renewable energy resources are one of the most popular substitutes for fossil fuels [9]. The high availability and eco-friendly nature of renewable energy resources, like wind and solar energy, make them appropriate alternatives to ancient fuels [10-12]. Solar energy can be harnessed directly and indirectly using different techniques that can be coupled with the building sector [13]. Photovoltaic (PV) panels, as one of these techniques, can be utilized for producing power in either small-scale (e.g., buildings) or large-scale (e.g., power plants) [14]. In this regard, designing net-zero and nearly net-zero energy buildings (ZEBs and nZEBs) based on renewable technologies not only can supply building energy demand using free and renewable sources but also reduce transmission line losses through on-site energy production [15, 16].

Building-integrated photovoltaics (BIPV), and building-applied photovoltaics (BAPV) are promising techniques for integrating building and solar energy [17]. In this regard, many studies have investigated different aspects of implementing these systems. For instance, Ghosh [2] reviewed the potential of different kinds of present and future building-attached or building-integrated photovoltaic systems. They briefly reviewed three generations of PV cells and compared them based on their advantages and disadvantages. Sánchez-Pantoja et al. [18] focused on people's opinions about the aesthetics of buildings equipped with solar systems. They revealed that PV panels integrated with building facades are more acceptable than building-attached photovoltaics. Shirazi et al. [19] focused on the potential of solar facades in high-density urban areas. They presented a techno-economic evaluation method to help designers and architects identify the most appropriate facade surfaces for PV installation in urban areas. Liu et al. [20] investigated the advantages and environmental benefits of BIPV systems. They asserted that these systems can play an important role in enhancing the sustainable development of the building sector, increasing the aesthetic pleasure of buildings, and supplying the buildings' energy requirements. In another study, Maghrabie et al. [21] noted that implementing BIPV systems decreases the pollution emission of buildings by supplying their energy consumption and positively affects their heating and cooling loads. Alsema [22] determined the energy needed to produce different types of solar cells according to their production process and calculated the energy payback time. This study answered whether solar cells could produce enough energy compared to the energy required in their production process. Kumar et al. [23] compared two building PV configurations (BAPV and BIPV) in Malaysia's tropical climate. They calculated the system performance parameters for three PV technologies: crystalline silicon (c-Si) panels, Copper, indium, and selenium (CIS) panels, and Cadmium telluride (CdTe) panels. Based on the results, CdTe panels were the best choice in most cases. However, their study did not include the PV cells' cost and energy payback time.

Some studies have focused on the design and operation optimization of BIPV systems. Jayathissa et al. [24] developed a multi-objective optimization framework for dynamic BIPV shadings. They optimized the energy performance of the building by adjusting the solar panels angle. Cuce et al. [25] conducted a single objective optimization to achieve the maximum energy efficiency of BIPVs by defining the tilt angle as the decision variable. Youssef et al. [26] designed a multi-objective optimization framework for BIPV systems to optimize the building energy consumption, energy generation of PV panels, and the economic criteria of the system. In another research work, Sue et al. [27] optimized a green roof-integrated PV system economically and environmentally. Tharushi et al. [28] performed a techno-economic optimization for the BIPV envelope. They proposed a multi-objective optimization framework to find the optimal PV-related variables, e.g., its type and angle and the window-to-wall ratio. Buonomano et al. [15] studied the effect of building integrated flat-plate photovoltaic and thermal (BIPVT) system implementation on the building energy performance by simulating three different systems in TRNSYS. In another research work, Zeraatpisheh et al. [29] modeled three different buildings equipped with PV systems in EnergyPlus software. They compared the performance of different integrated solar systems with various sizes based on economic analysis.

The economic evaluation of BIPV systems is another popular aspect that has been addressed in the literature. In this regard, Gholami et al. [30] addressed the economic feasibility of BIPV systems as a part of the building facade and calculated the system's operating cost in European countries. Sorgato et al. [31] evaluated technically and economically roof and facade-integrated cadmium telluride (CdTe) panels in six different Brazilian cities. This study presented an economic estimation for replacing old buildings' facades and roof materials with solar cells. Gholami et al. [5] emphasized the environmental and social importance of BIPV systems. They proposed an innovative system economic analysis strategy incorporating social and ecological impacts, including transmission line cost, transmission line loss, social carbon costs, and material prices. They tried to present a complete evaluation of BIPV systems; however, they did not involve BIPV's effect on building energy consumption. On the other hand, implementing PV panels on the external surface of buildings affects the energy performance and consequently thermal comfort of occupants. Yadav et al. [32] evaluated the thermal performance of roof-integrated semi-transparent PV panels with the optimal tilt angle in India. They stated that using this system as the roof could significantly increase the room temperature and decrease the occupants' thermal comfort on warm days. Ghosh et al. [33] evaluated thermal comfort in a room equipped with BIPV-vacuum glazing using numerical solutions for the United Kingdom climate. In this research, the effect of this technology on building thermal comfort was studied. Miyazaki et al. [34] investigated the effect of building-integrated thin-film solar cells on energy saving in office buildings. They demonstrated that these panels supply the energy requirement of the building and have a positive effect on the cooling and heating loads. They concluded that the overall energy consumption of the building decreases by implementing these systems.

Additionally, to provide a comprehensive evaluation of BIPV systems, different aspects of the design, operation, and management of these systems have been addressed. In this regard, Olivieri et al. [35] mentioned that retrofitting buildings with semi-transparent solar cells provides a remarkable potential for energy saving. Aguacil et al. [36] proposed a new methodology to choose active surfaces for implementing BIPV systems on buildings with a high facade-to-roof ratio based on specific building characteristics such as consumption, orientation, and urban texture. Nkuissi et al. [37] studied the impact of the thin-film photovoltaics production process on the environment. The results indicated that some materials used in this process could be hazardous to the environment. Yadav et al. [38] presented a numerical investigation to specify the shadow effect of adjacent buildings on BIPV performance. In this paper, the optimal tilt and azimuth angles of the BIPV system were determined due to the shadow analysis of adjacent buildings.

Although BIPV system performance and feasibility have been discussed in many research works, there are doubts about the optimal implementation of the system. Therefore, an optimization scheme is essential to find the optimal system design properties considering economic, environmental, and comfort factors simultaneously. In this research paper, we aim to find the most optimal design configuration of a facade-integrated PV system for a high-rise building in Iran. To that end, a new multi-objective techno-economic-environmental optimization framework (developed in JEPlus+EA) is coupled with the building performance simulation model (developed in EnegyPlus). Firstly, the occupants' thermal comfort is assumed as the technical objective function while the return on investment of the system is utilized for the economic objective. Also, in the proposed approach:

- A novel criterion is proposed for quantifying the environmental impacts of the system, a more comprehensive formula that takes into account the energy consumed to manufacture implemented panels,
- As another novelty, this study explores the possibility of equipping the building with a variety of panel types that possess different thermal resistances, prices, energy efficiency, and embedded energy.

Afterward, the energy performance of the building equipped with the final optimal BIPV system is compared with the initial building without PV panels. As a result, implementing the designed façade-integrated PV system not only enhances the occupants' thermal comfort but also minimizes the building energy consumption and pollution emission.

Numerical

a-Si	Amorphous silicon
BAPV	Building-applied photovoltaics
BIPV	Building-integrated photovoltaics
BIPVT	Building-integrated photovoltaic and thermal system
CdTe	Cadmium telluride
CIS	Copper, indium, and selenium
DOE	The United States Department of Energy
ECEC	Electricity carbon equivalent coefficient
ET	Export tariff
FIT	Feed-in tariff
HVAC	Heating, ventilation, and air-conditioning
mc-Si	Multi crystalline silicon
NCEC	Natural gas carbon equivalent coefficient
NE	Net energy
NPV	Net present value
NSGA	Non-dominated sorting genetic algorithm
PE	Produced energy
PPE	Energy required to produce PV panels
PV	Photovoltaic
ROI	Return on investment
RP	Electricity retail price
SCE	Self-consumption energy
SE	Surplus energy

2. Methodology

To achieve the desired objectives, the case study building is modeled in Sketchup and the energy performance of the building and its energy systems is simulated using EnergyPlus software. Then, the intended decision variables and objective functions are defined in jEplus software to define the optimization problem. The multi-objective simulation-based optimization is conducted based on the non-dominated sorting genetic algorithm (NSGA-II) using jEplus+EA software. As a result of the optimization process, a series of optimal design solutions are reported. Afterward, the final optimal configuration is selected among them based on the weighted sum method. Finally, the energy performance of the final optimal solution is compared with the initial building.

2.1 Case Study

In high-rise buildings with a high facade-to-roof area ratio, it is convenient to attach solar cells to buildings' facades and hangovers. So, to evaluate the performance of the BIPV systems, a large office building is considered. The United States Department of Energy (DOE) has presented 16 pre-designed representative models as reference commercial buildings for energy simulation studies. These models provide details of the building design and play an important role in evaluating the energy performance of different types of buildings using building energy simulation software such as EnergyPlus. These reference buildings cover about 70% of the US buildings [39]. In this research, the DOE's big office building is evaluated as a case study. Solar cells are installed on the exterior walls of the building as well as over the window shades. Figure 1 shows the three-dimensional model of the mentioned reference building in SketchUp software [40]. The building is located in Tehran, the capital of Iran. Its latitude, longitude, and elevation are 35.7 °N, 51.4 °E, and 1219 m, respectively.

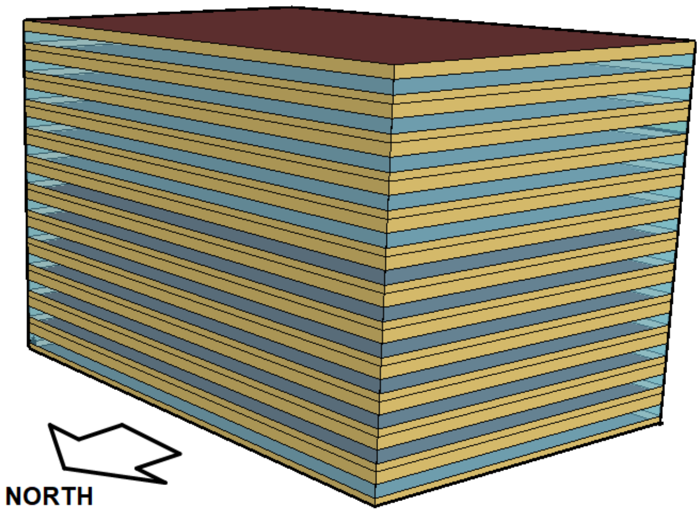


Fig.1. Three-dimensional sketch-up model of the DOE's big office reference building

The length and width of the building are 73.1 and 48.7 meters, respectively. The boundary condition for all walls, windows, and facade components of the building as well as the building roof are "Outdoors" which means that they are exposed to the outside weather conditions and solar irradiation. Also, the building's first floor is on the "Ground" whose temperature is automatically calculated by EnergyPlus. The peak occupation density is 18.6 m^2 per person. Also, the maximum lighting is 8.5 Watts per m^2 floor area. The building has a packaged terminal heat pump (PTHP) whose cooling and heating setpoint temperatures are 22°C and 25°C, respectively. Also, a set-back temperature of 4°C is assumed for the thermostat temperature in uncrowded times [41]. The windows, making up 36% of the exterior facade of the building, are 7 mm double-layer clear glazing type equipped with PV panels embedded as overhangs. Other specifications of the model can be found in [39].

The building materials in the initial case without solar cells are listed in Table 1, extracted from the EnergyPlus database. Solar cells are placed as the wall's outer layer and play the role of the building facade. The solar cells studied in this study are selected from the first (poly-Si cells) and the second generations (CdTe, CIS, and a-Si cells) of solar cells to compare their performance. These cells are the most common panel types used in BIPV systems. Table 2 shows the specifications and thermal properties of the selected solar cells.

Table 1. Building materials for the initial case [40]

Item	Construction (Outside to Inside)	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
Wall	Normal-weight concrete	0.20	2.31	2322	832
	Gypsum	0.013	0.16	800	1090
Roof	Built-up roofing	0.0095	0.16	1120	1460
	Roof insulation	Thermal resistance = 5.31 (m^2 K/W)			
	Metal surface	0.0008	45.3	7824	500
Floor	Normal-weight concrete	0.10	2.31	2322	832
	Carpet pad	Thermal resistance = 0.22 (m^2 K/W)			

Table 2. Solar PV specifications and thermal properties

Name	Panel Type	Ref.	Area (m^2)	Open Circuit Voltage (V)	Short Circuit Current (A)	Voltage at Maximum Power (V)	Current at Maximum Power (A)	Power (W)	Thermal Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)	Thickness (mm)
Uni-Solar US-32	a-Si	[38]	0.52	23.6	2.40	16.5	1.94	32	1.000	2.501	719	31.8
First Solar FS-272	CdTe	[38]	0.72	94.6	1.18	70.6	1.01	73	1.000	2.504	719	6.8
Solar Frontier SF-160s	CIS	[39]	1.22	112	2.03	86.7	1.83	160	1.020	2.508	718	8.8
Sharp NE-H120E1	poly-Si	[40]	0.96	32.3	5.30	25.7	4.67	120	0.234	1.920	890	46.0

2.2 Multi-objective Optimization

Multi-objective optimization problems have more than one objective function, which usually does not change in the same direction. The solution to these questions is not unique and includes a set of answers. These solutions, which have no superiority over each other, are called the Pareto front. NSGA-II is one of the most popular multi-objective optimization algorithms [45], widely used to optimize renewable energy systems [28, 46]. The flowchart of NSGA-II is shown in Fig. 2. The process and its different stages are explained in the figure to provide a better understanding of the NSGA-II algorithm.

In this research, multi-objective simulation-based optimization is performed using EnergyPlus, jEPlus, and jEPlus+EA software. Figure 3 shows the connection between simulation software and the optimization algorithm. To achieve the desired outputs, the building and implemented BIPV system are simulated in EnergyPlus. The objective functions and decision variables are defined in jEPlus. Finally, jEPlus+EA executes the optimization process on scenarios created by jEplus and simulated in EnergyPlus. As a result of continuous interactions between the simulation and optimization process, the resultant Pareto front containing optimal solutions is reported. The objective functions and decision variables are defined in the following sections.

2.3 Objective Functions

The proposed multi-objective optimization framework aims to optimize three objective functions: thermal comfort index, economic criterion, and environmental indicator.

2.3.1 Thermal Comfort

Thermal comfort is a state of mind in which a person feels comfortable about the thermal environment and does not want to change his surrounding thermal condition. ASHRAE 55 standard defines thermal comfort as a sensory condition in which there is a sense of satisfaction with thermal conditions. Thermal comfort is achieved when the heat produced by the human body's metabolism can disperse to the environment [47, 48]. Thermal comfort indexes combine six main factors, including four physical variables including mean radiant temperature, air velocity, air temperature, and air relative humidity, and two personal variables

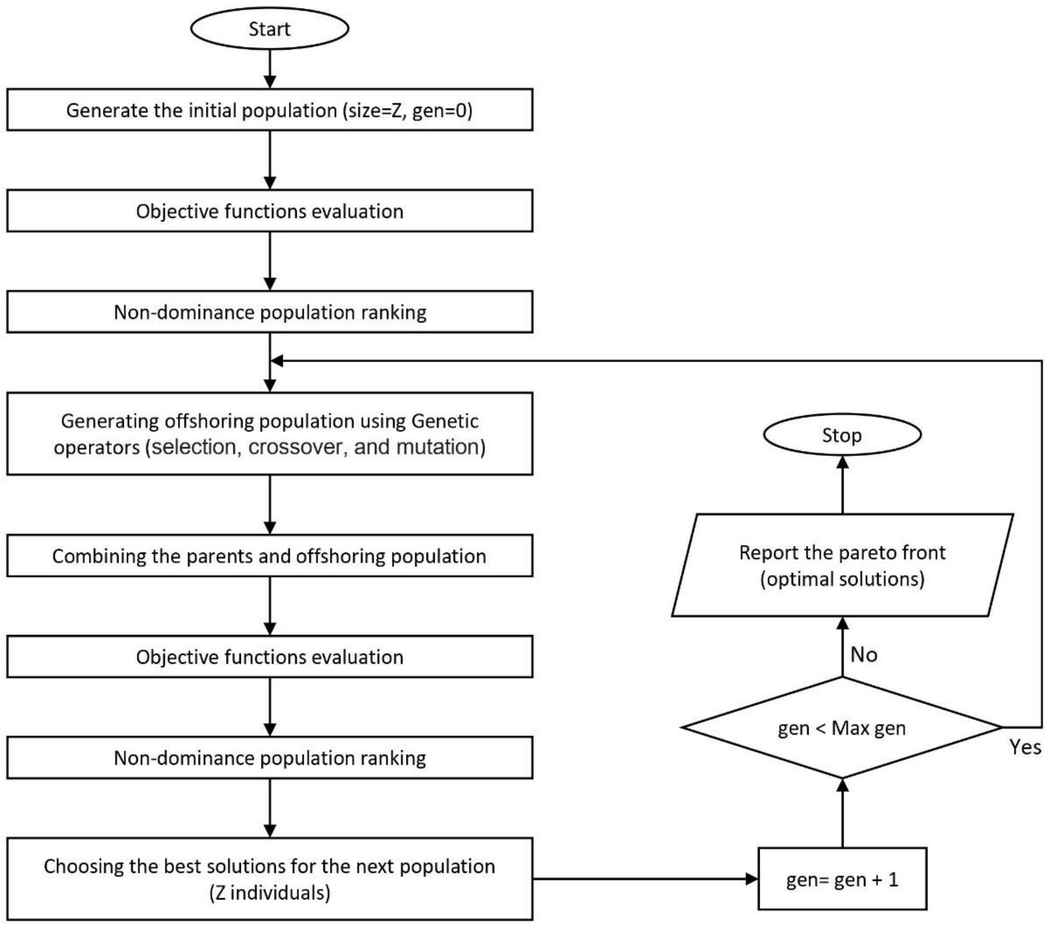


Fig.2. NSGA-II optimization algorithm flowchart

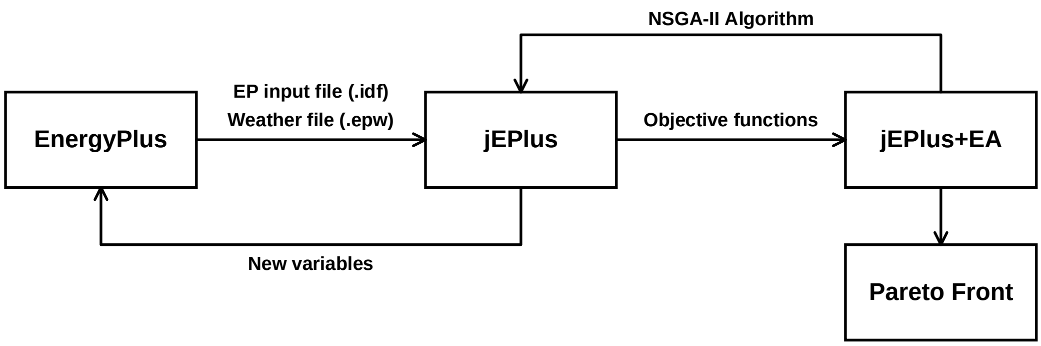


Fig.3. The link between simulation software and optimization algorithm

of clothing insulation and activity level. There are several indexes for determining and declaring thermal comfort. In this study, the thermal comfort of the occupants is directly assumed as the technical objective of the optimization process. To that end, thermal discomfort time is determined as the occupants' thermal comfort indicator that should be minimized. This parameter equals the number of hours when the combination of air temperature and humidity is not in the ASHRAE 55 standard summer or winter clothes thermal comfort zones [47].

2.3.2 Economic Evaluation

The economic analysis of the system is investigated in two general parts: the system's income and the initial investment. The designed BIPV system is an on-grid system. So, the building supplies its energy shortage from the power grid and sells the surplus energy produced by the system to the grid. The building bill is calculated based on support policies for clean electricity generators. Three significant supporting policies available are:

1. Gross-metering: In this strategy, the generated energy purchase tariff is higher than the retail electricity price. So, all generated energy is sold to the grid, and all required energy is supplied from the grid. The difference between these two parameters is the system profit.
2. Net-metering: The building and the power grid are completely connected in the net metering policy, and export and import electricity tariffs are equal. The building uses the BIPV system to produce energy for self-consumption. So, the excess energy is sold to the grid during high production hours. The energy is purchased from the grid when the energy consumption exceeds the BIPV system output.
3. Feed-in tariff: This strategy is one of the most common strategies that establishes a multi-year contract between the producer and the electricity supplier. Under the contract, the building receives a bonus for electricity production. The BIPV system provides the building self-consumption and sells its excess energy to the grid at an export tariff. In this regard, according to the FIT strategy that is being implemented in the UK, Feed in Tariff (FIT), export tariff (ET), and electricity retail price (RP) are determined as 0.02, 0.074, and 0.17, respectively, for every kWh of generated electricity [49].

Hence, To calculate the system revenue based on the feed-in tariff policy [49]:

$$Income = (PE \times FIT) + (SE \times ET) + (SCE \times RP) \quad (1)$$

where PE, SE, and SCE are the produced energy, the surplus energy, and the self-consumption energy, respectively.

The required investment for the BIPV system depends on several parameters, including the initial cost of panels and inverters, the replacement cost of inverters (the inverters' lifespan is about 10 years while it is approximately 25 years for the panels [50]), and the installation, repair, and maintenance charges. The initial cost of purchasing panels accounts for the largest share of the initial investment, estimated according to [51].

In this study, the return on investment (ROI) is considered as the economic evaluation parameter. In fact, the optimization process aims to find the optimal solutions that possess higher ROI in their first year of operation. This parameter is calculated by dividing the system net income in the first year by the net present value (NPV) of all system-related costs over its 25-year working life [52]:

$$ROI = \frac{Income}{NPV} \quad (2)$$

This research considers the pollution reduction due to the BIPV system implementation and the amount of pollution resulting from the PV panels production process. The energy required to produce each square meter of a-Si, CIS, CdTe, and Poly-Si panels are 1200, 2300, 1803, and 4600 (MJ), respectively [22] [53, 54].

The pollution production is evaluated using the carbon equivalent of emissions from the building's net energy consumption and the panels' embedded energy. In the first and second cases, the forms of the used energy is electricity and natural gas, respectively [55, 56]. Unlike formulas presented previously in some studies, this formula also considers the energy required to manufacture the panels implemented:

$$C_{eq} = NE \times ECEC + \frac{PPE \times NCEC}{25} \quad (3)$$

where NE and PPE are the net energy consumption of the building and the energy required to produce PV panels, respectively. Also, ECEC and NCEC are the electricity and natural gas carbon equivalent coefficients, respectively, available in [55].

2.4 Decision Variables

As shown in Fig. 4, the decision variables, which may be discrete or continuous, are building orientation, PV panels technology, and depth, width, and angle of overhang panels. It is important to note that the specifications of overhang panels (type, depth, width, and angle) may differ for various facades. Also, the type of wall and overhang panels installed in each facade may be non-identical. Table 3 summarizes the decision variables and their ranges.

3. Results and Discussion

To better organize the research paper, the results are presented in three sections. Firstly, the Pareto front and the optimized decision variables of the optimal solutions are investigated. Then, the final optimal solution is selected using the weighted sum method, and its indicators are investigated in detail. Finally, the performance of the optimal model is compared with the initial one to evaluate the effect of using the BIPV system.

3.1 Multi-objective Optimization

shows the Pareto front of the multi-objective optimization in 3D as well as 2D views. Each point of the Pareto front represents one of the system's optimal solutions based on the feed-in tariff policy. Based on the results, the objective functions of the optimal solutions, including thermal discomfort time, return on investment (ROI), and carbon equivalent of the produced emission in the first year of the system operation, is between 250 to 350 hr, 20 to 32 %, and 5 to 6 million tons of carbon, respectively.

Table.3. Description and the lower and upper bounds of the considered decision variables

Variable	Range
Orientation (°)	[0, 90]
Overhang panels depth (cm)	[20, 120]
Overhang panels angle (degree)	[20, 80]
Facade panels width (cm)	[20, 140]
Panel type	No PV, a-Si, CdTe, CIS, poly-Si

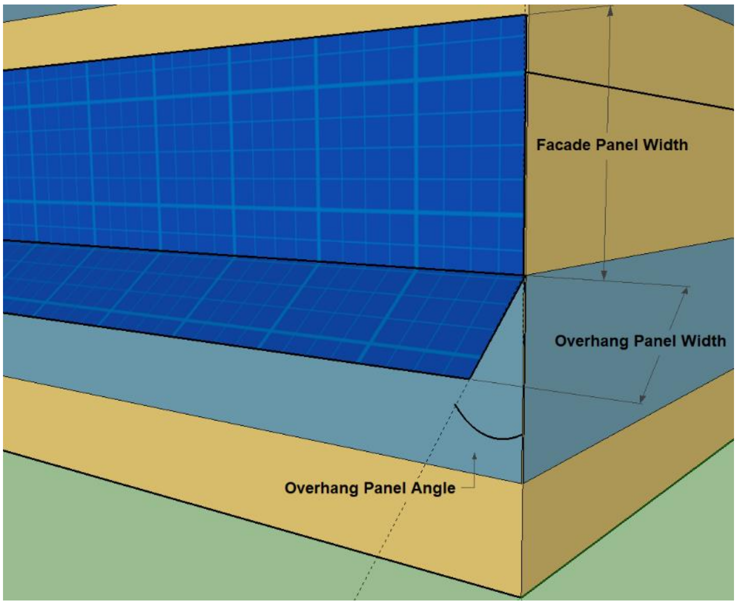
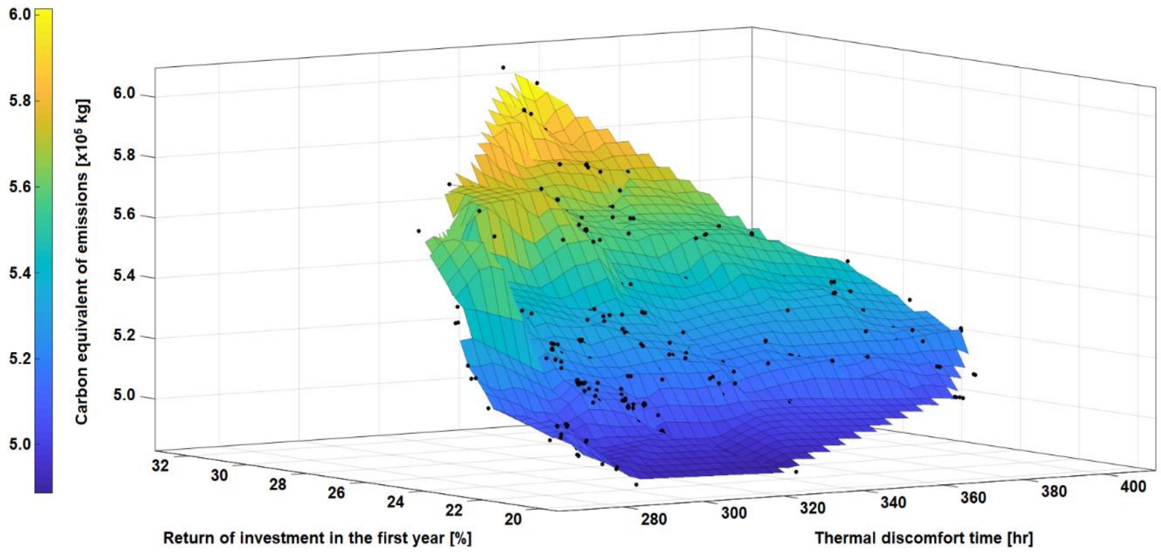
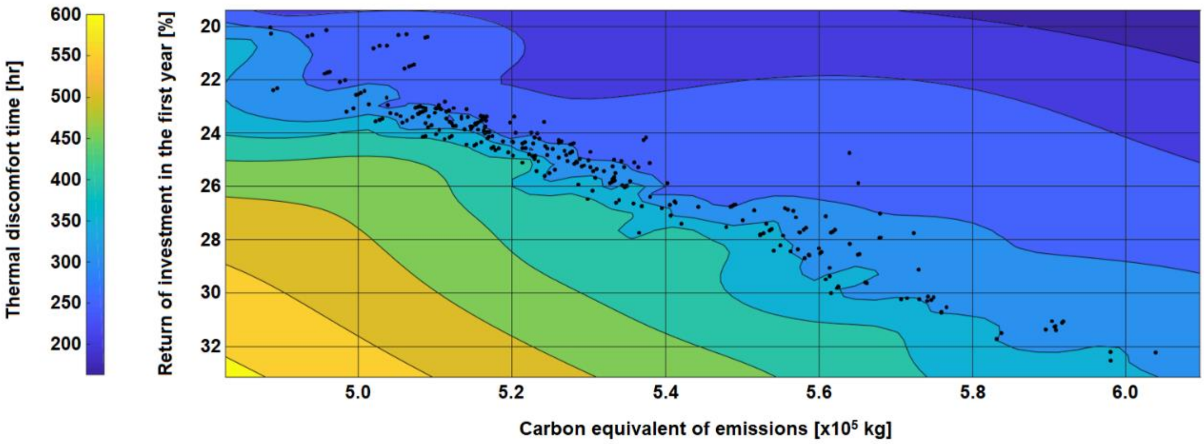


Fig.4. Implementation of the facade-integrated solar system and its decision variables



(a) 3D view



(b) 2D view

Fig.5. Pareto front of the multi-objective optimization: (a) 3D view, (b) 2D view

Figure 6 represents the decision variables' value for all optimal solutions. Figure 6(a) includes all the optimal solutions. Figure 6(b)-(d) shows the configuration of the most optimal solutions for thermal discomfort time, ROI, and emissions carbon equivalent, respectively. According to Fig.6, the economic and environmental functions behave oppositely, which means that a building equipped with a more profitable BIPV system produces more pollutants. From this research point of view, the building faces are toward the cardinal directions in almost all optimal solutions, so designing the building toward the ordinal directions is improper. Based on the results, the optimal depth of south overhang panels is 120 cm (maximum value) in all solutions. Overhang panels with extended depth cause the facade panels' width reduction because their shadow on the facades decreases the solar irradiation to the facade panels. Increasing the depth of overhang panels in the south, west, and north facades is the best choice. However, in the eastern facade, there should be a balance between the facade and overhang panels. Besides, the optimal angle of the south, east, and west overhang panels are between 42° to 54°, 34° to 68°, and 40° to 80°, respectively.

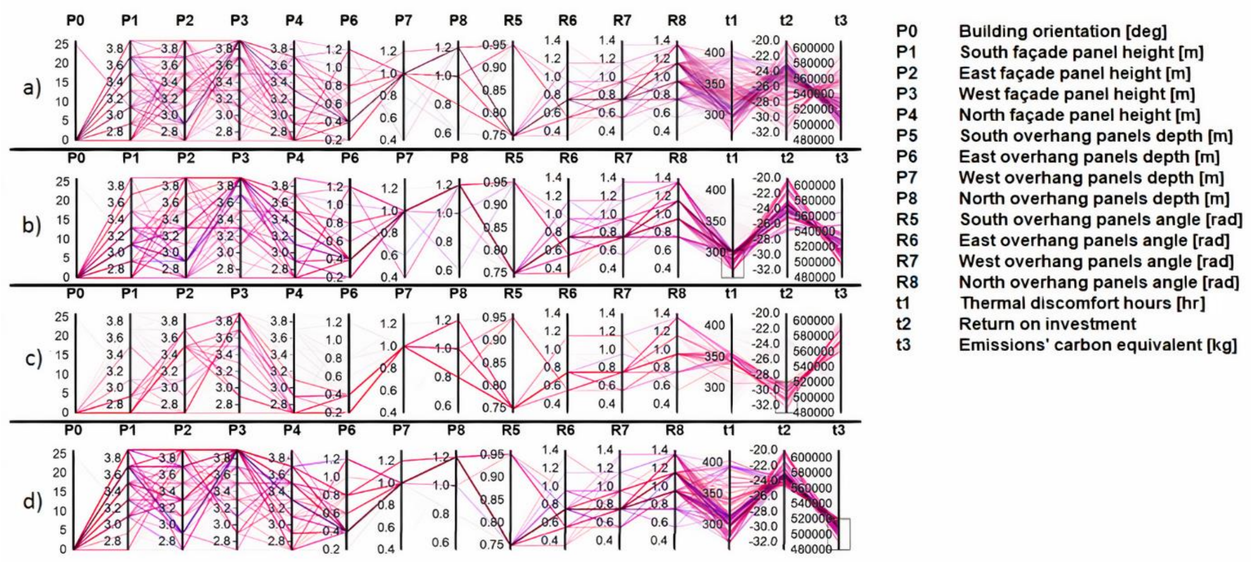


Fig.6. Decision variables configuration of the optimal solutions (including continuous variables in different solutions): (a) all objective functions, (b) thermal discomfort time, (c) ROI, and (d) emissions of carbon equivalent

Based on the results, all building facades and overhangs are equipped with PV panels in optimal solutions. This fact confirms that the building-integrated photovoltaic system is technically, economically, and environmentally acceptable. However, the type of panels should be selected with caution. The share of various types of panels used in optimal designs is shown in Fig.7. According to the results, CIS panels are the dominant choice for the south, east, and west overhangs, receiving considerable solar irradiation. These panels can produce more energy per area than other studied types. So, the more solar irradiation, the more share of CIS panels. On the other hand, a-Si panels are the most suitable solutions for the north overhangs. Specifically, a-Si cells have low efficiency and cost, making them reasonable choices for surfaces that receive low solar irradiation. They have a shorter payback period than other types of cells because of their high energy production-to-price ratio.

Polycrystalline cells are the most suitable panels for all facades except the north one. This type of PV cell has one of the highest efficiencies among the studied types. Also, it increases the building envelope's thermal resistance more than others due to its thickness. As a result, using polycrystalline panels as the facade's outer layer enhances the system's environmental impact and the occupants' thermal comfort. CdTe cells, produced from toxic and hazardous substances, have the lowest share among other options. Also, on the north facade, a-Si cells are the most proper type of panels, as discussed previously for the overhang panels.

3.2 Final Optimal Configuration

The optimal solutions extracted using the multi-objective optimization process have no advantages over each other. So, a decision-making method should be selected to find the final solution. In this study, the weighted sum method is used in which three objective functions are converted to a single objective using Eq. (4) [42]:

$$f_{WS}(x)=\sum_{i=1}^{3}a_i\cdot\frac{f_i(x)-f_i(x)^{\min}}{f_i(x)^{\max}-f_i(x)^{\min}} \tag{4}$$

in which $f_1(x)$, $f_2(x)$, and $f_3(x)$ are thermal discomfort hours, ROI, and carbon equivalent of produced emissions, respectively. $f_i(x)^{\min}$ and $f_i(x)^{\max}$ are the minimum and maximum values of each objective function among optimal solutions, respectively. Also, a_i is the weighting factor of each objective function [57]. In this research, the economic and environmental functions weighting factors, i.e., a_2 and a_3 are assumed equal. Also, preliminary sensitivity analysis by the Morris method [58] showed that the effect of these variables on the final solution is more remarkable than the

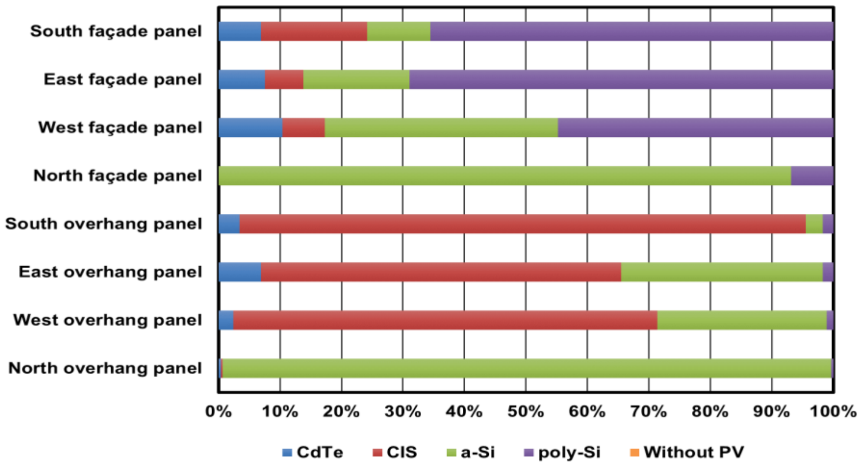


Fig.7. Share of various types of panels in the optimal solutions

thermal discomfort hour. Therefore, using a preliminary parametric study, a_1, a_2, a_3 are selected as 0.2, 0.4, and 0.4, respectively:

$$f_{WS}(x) = 0.2 \times \frac{f_1(x) - f_1(x)^{\min}}{f_1(x)^{\max} - f_1(x)^{\min}} + 0.4 \times \frac{f_2(x) - f_2(x)^{\min}}{f_2(x)^{\max} - f_2(x)^{\min}} + 0.4 \times \frac{f_3(x) - f_3(x)^{\min}}{f_3(x)^{\max} - f_3(x)^{\min}} \quad (5)$$

Table 4 shows the values of decision variables, objective functions, and the essential outputs of the final optimal design. Based on the results, the building is equipped with a facade and overhang integrated solar system whose return on investment is 21.7% in the first year of operation. This system can generate 867 MWh of electrical energy in the first year, equivalent to 23% of the office building energy consumption. In addition, the energy required to produce the solar cells used in the optimal system is 5190 MWh which means that the system energy payback period is approximately 6 years.

Table 4. Decision variables and output indicators of the final design

Decision Variable	Value	Indicator	Value
Building orientation	0°	Thermal discomfort time	285 hr
South facade panels width	110 cm	Return on investment (one year)	21.7%
East facade panels width	140 cm	Carbon equivalent (one year)	469,260 kg
West facade panels width	140 cm	Produced energy (one year)	867,770 kWh
North facade panels width	30 cm	Sold energy (one year)	20,050 kWh
South overhang panels depth	120 cm	Purchased energy (one year)	2,926,870 kWh
South overhang panels angle	43°	Building required energy (one year)	3,774,510 kWh
East overhang panels depth	40 cm	PV panels production emission	272,868 kg
East overhang panels angle	43°	Investment	625,852 $
West overhang panels depth	100 cm	Fit strategy income	162,931$
West overhang panels angle	43°	south facade panels density	0.51 $1/m^2$
North overhang panels depth	120 cm	East facade panels density	0.59 $1/m^2$
North overhang panels angle	43°	West facade panels density	0.59 $1/m^2$
South facade panels type	poly-Si	North facade panels density	0.19 $1/m^2$
East facade panels type	poly-Si		
West facade panels type	poly-Si		
North facade panels type	poly-Si		
South overhang panels type	CIS		
East overhang panels type	CIS		
West overhang panels type	CIS		
North overhang panels type	a-Si		

Figure 8 shows the amount of energy produced by the BIPV system during various months. The energy output of all solar panels, except the south facade ones, is the highest during the summer months. The south facade panels produce maximum energy during winter when the sun's elevation angle is low, and the shading effect of the overhangs is minor. The south solar panels have the highest energy output due to the highest irradiation. Also, the lowest energy production belongs to the north cells. Although the north panels do not receive direct sunlight in winter, the results showed that their installation is reasonable provided that inexpensive types of cells are used. The acceptable energy production rate of the east and west panels shows these faces have considerable power generation potential, which is not usually considered in the design of solar systems.

3.3 BIPV System Effectiveness

To evaluate the effect of using BIPV on the building's performance, the annual energy consumption, thermal discomfort hours, and emissions production of the final optimal building are compared with the initial one. As shown in Fig.9, adding solar cells to the building reduces its annual energy consumption by 5.7%. Also, the annual energy consumed by the HVAC system was reduced by 16%, which resulted in 8% and 68% reduction in cooling and heating energy requirements, respectively. For windows, PV cells act as overhangs and reduce the solar heat gain. On the other hand, wall-integrated cells have two different roles. They reduce energy loss from walls by reducing the overall heat transfer coefficient. At the same time, they can heat the building by increasing the outside temperature of the walls. Therefore, the BIPV system considerably decreases the annual heating energy consumption. In warm months, the rise of the walls outside temperature can increase the cooling energy. However, as depicted in Fig.9, the annual cooling energy consumption of the optimized building is less than the initial one, mainly due to the shading effect of the overhang panels. The overhang PVs also prevent the wall cells from overheating. Based on the results, the average temperature of the facade cells is between 19.9°C and 22.7°C; the highest is at the south cells, and the lowest is at the north ones.
According to Fig.10, the thermal discomfort hours in the optimized building are 33% less than in the initial case without the BIPV system. The indoor thermal comfort enhancement is accompanied by 0.5°C increments in the mean zone temperature. So, adding the BIPV system to the building improves the occupants' thermal comfort and reduces the building's energy consumption simultaneously.

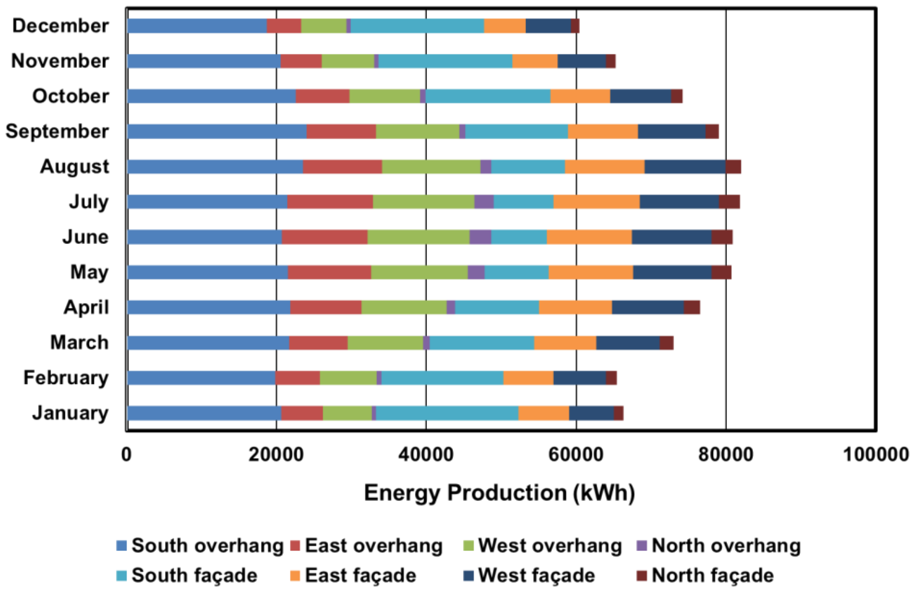


Fig.8. Energy production of the BIPV system in various months

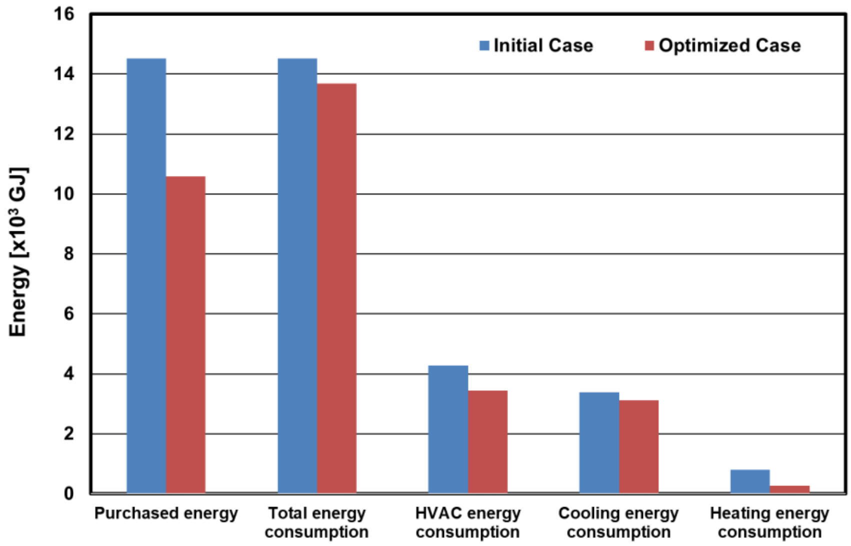


Fig.9. The effect of using the BIPV system on the building's annual energy consumption in the first year of operation

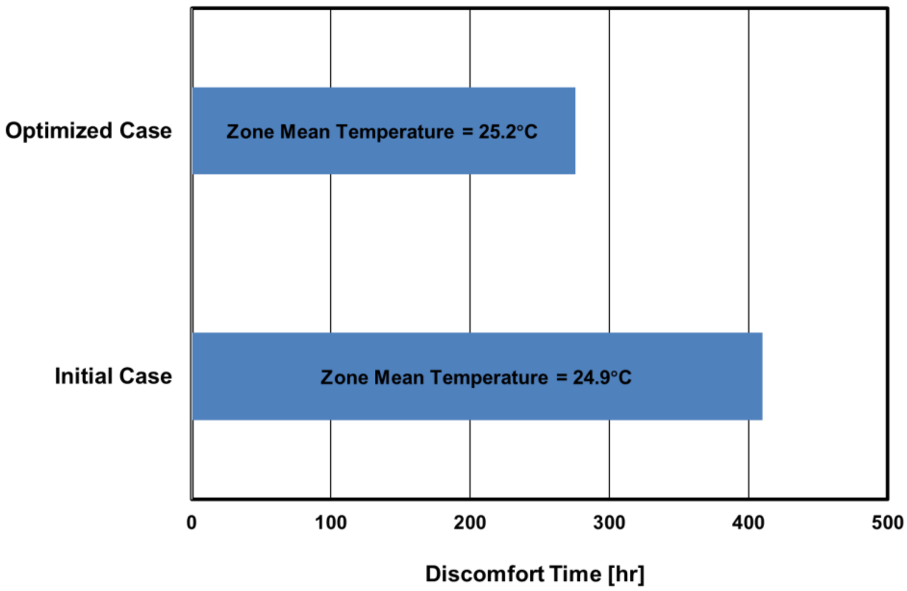


Fig.10. The effect of using the BIPV system on the thermal discomfort hours in the first year of operation

Environmental issues are one of the most important reasons for turning to renewable energy resources. Assuming that the initial building's energy source is electricity, the emitted pollutants can be estimated by EnergyPlus software, which uses the "pollutant emission factor" concept [55, 56].

This presents the pollutants emission in the optimal building equipped with the BIPV system with the initial case. To better compare the results, Fig.11 shows the annual CO_2 emission and the carbon equivalent of all pollutants. Based on the results, implementing the BIPV system decreases the annual CO_2 emission and the carbon equivalent of the building's emitted pollutants by 27%. Using the BIPVs reduces the annual energy consumption and supplies a considerable amount of the required energy from the solar source. In addition, as mentioned previously, pollutants emitted in the solar cell production process are compensated after 2.5 working years. So, it can be concluded that the embedded pollution of solar cells is much less than the pollution reduction due to their usage.

Table 5. The effect of using the BIPV system on the emitted pollutants

Emission	Mass (Kg)	
	Initial Case	**Optimal Case**
CO_2	2,443,480	1,783,333
CO	610	445
CH_4	20.3	14.8
NO_x	5962	4351
N_2O	35.1	25.6
SO_2	12,566	9,171
PM 10	262	191
PM 2.5	167	122
Non-methane volatile organic compounds	54.0	39.4

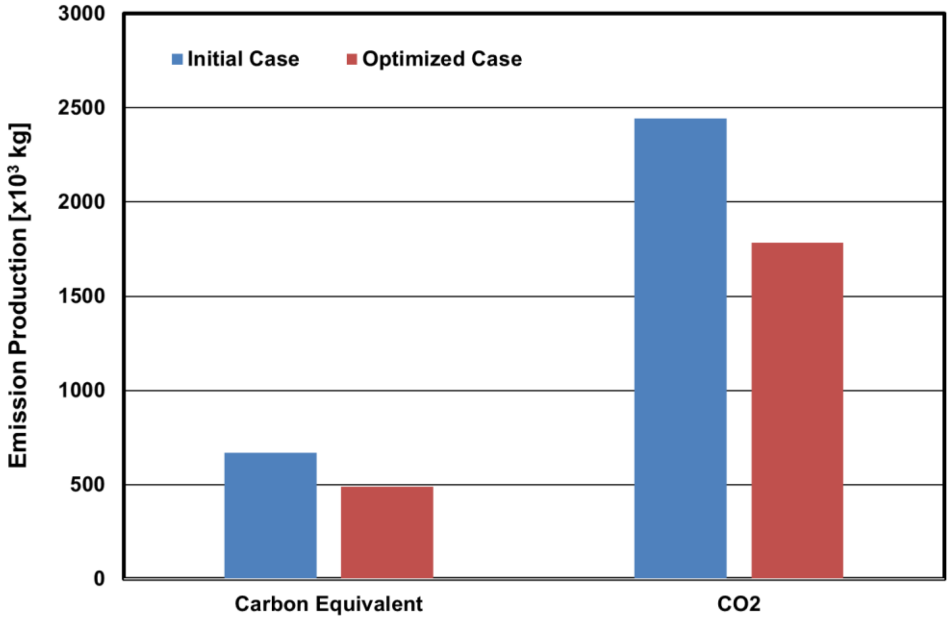


Fig. 11 The effect of using the BIPV system on the CO2 and emissions carbon equivalent in the first year of operation.

4. Conclusion

In this research study, a building-integrated photovoltaic (BIPV) system was optimized from technical, economic, and environmental points of view. As a result, the effect of using the BIPV system on reducing the building's energy consumption and pollutant emission, and enhancing the indoor thermal comfort was evaluated. The major results of the research can be summarized as follows:

- All facades and overhangs of the optimized building were equipped with PV panels, even the northern ones that received the least solar irradiation.
- Selecting various types of cells for the building indicated that installing a single PV panel type on all surfaces is improper. Each surface needs a specific PV panel type based on solar irradiation. Accordingly, for all surfaces, except the northern ones, the dominant choices for the wall and the overhang surfaces are -Si and CIS, respectively. For the northern surfaces, a-Si cells are the best option.
- The optimal systems are economically feasible as they can retrieve 20% to 32% of their initial investment in the first year.
- The average temperature of the wall-integrated cells was between 19.9°C and

22.7°C, which means that the shading effect of the overhang panels protects them from overheating.

- Equipping the building with the final optimal BIPV system reduces the pollution production and the occupants' thermal discomfort hours by 27% and 33%, respectively. Also, it resulted in 8%, 68%, 16%, and 5.7% reduction in the annual cooling, heating, HVAC, and total energy consumption, respectively.
- The energy and carbon payback times of the final optimal BIPV system were 6 and 2.5 years, respectively.

The current research was performed in Tehran in a cold semi-arid climate. The effect of climate conditions on the results can be an interesting topic for future research works to propose proper BIPV system specifications for each climate.

References

[1] Coyle ED, Simmons RA. Understanding the global energy crisis: Purdue University Press; 2014.

[2] Ghosh A. Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive review. Journal of Cleaner Production. 2020;276:123343.

[3] Zabalza I, Gesteira LG, Uche J. The impact of building energy codes evolution on the residential thermal demand. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2022;44(12):588.

[4] Ebrahimi-Moghadam A, Ildarabadi P, Aliakbari K, Arabkoohsar A, Fadaee F. Performance analysis of light shelves in providing visual and thermal comfort and energy savings in residential buildings. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2020;42(9):484.

[5] Gholami H, Røstvik HN, Müller-Eie D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. Energy and Buildings. 2019;203:109461.

[6] Jia T, Dai Y, Wang R. Refining energy sources in winemaking industry by using solar energy as alternatives for fossil fuels: A review and perspective. Renewable and Sustainable Energy Reviews. 2018;88:278-96.

[7] Shafiee S, Topal E. When will fossil fuel reserves be diminished? Energy policy. 2009;37(1):181-9.

[8] Lelieveld J, Klingmüller K, Pozzer A, Burnett R, Haines A, Ramanathan V. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. Proceedings of the National Academy of Sciences. 2019;116(15):7192-7.

[9] Barnham K, Mazzer M, Clive B. Resolving the energy crisis: nuclear or photovoltaics? Nature materials. 2006;5(3):161-4.

[10] Jäger-Waldau A. Photovoltaics and renewable energies in Europe. Renewable and Sustainable Energy Reviews. 2007;11(7):1414-37.

[11] Sadi M, mohammad Behzadi A, Alsagri AS, Chakravarty KH, Arabkoohsar A. An innovative green multi-generation system centering around concentrating PVTs and biomass heaters, design and multi-objective optimization. Journal of Cleaner Production. 2022;340:130625.

[12] Makki A, Omer S, Sabir H. Advancements in hybrid photovoltaic systems for enhanced solar cells performance. Renewable and sustainable energy reviews. 2015;41:658-84.

[13] Arabkoohsar A, Ismail K, Machado L, Koury R. Energy consumption minimization in an innovative hybrid power production station by employing PV and evacuated tube collector solar thermal systems. Renewable Energy. 2016;93:424-41.

[14] Arabkoohsar A, Machado L, Farzaneh-Gord M, Koury R. Thermo-economic analysis and sizing of a PV plant equipped with a compressed air energy storage system. Renewable Energy. 2015;83:491-509.

[15] Buonomano A, Calise F, Palombo A, Vicidomini M. BIPVT systems for residential applications: An energy and economic analysis for European climates. Applied energy. 2016;184:1411-31.

[16] Arabkoohsar A, Xie G, Wei J, Asok A, Behzadi A, Mahian O. Perspectives and review of photovoltaic-thermal panels in net-zero energy buildings. Journal of

Thermal Analysis and Calorimetry. 2022;147(16):8621-30.
[17] Sartori I, Napolitano A, Voss K. Net zero energy buildings: A consistent definition framework. Energy and buildings. 2012;48:220-32.
[18] Sánchez-Pantoja N, Vidal R, Pastor MC. Aesthetic perception of photovoltaic integration within new proposals for ecological architecture. Sustainable cities and society. 2018;39:203-14.
[19] Shirazi AM, Zomorodian ZS, Tahsildoost M. Techno-economic BIPV evaluation method in urban areas. Renewable Energy. 2019;143:1235-46.
[20] Liu Z, Zhang Y, Yuan X, Liu Y, Xu J, Zhang S, et al. A comprehensive study of feasibility and applicability of building integrated photovoltaic (BIPV) systems in regions with high solar irradiance. Journal of Cleaner Production. 2021;307:127240.
[21] Maghrabie HM, Abdelkareem MA, Al-Alami AH, Ramadan M, Mushtaha E, Wilberforce T, et al. State-of-the-art technologies for building-integrated photovoltaic systems. Buildings. 2021;11(9):383.
[22] Alsema E. Energy payback time and CO2 emissions of PV systems. Practical Handbook of Photovoltaics: Elsevier; 2012. p. 1097-117.
[23] Kumar NM, Sudhakar K, Samykano M. Performance comparison of BAPV and BIPV systems with c-Si, CIS and CdTe photovoltaic technologies under tropical weather conditions. Case Studies in Thermal Engineering. 2019;13:100374.
[24] Jayathissa P, Luzzatto M, Schmidli J, Hofer J, Nagy Z, Schlueter A. Optimising building net energy demand with dynamic BIPV shading. Applied Energy. 2017;202:726-35.
[25] Cuce E, Cuce PM. Tilt angle optimization and passive cooling of building-integrated photovoltaics (BIPVs) for better electrical performance. Arabian Journal for Science and Engineering. 2014;39:8199-207.
[26] Youssef AM, Zhai ZJ, Reffat RM. Generating proper building envelopes for photovoltaics integration with shape grammar theory. Energy and buildings. 2018;158:326-41.
[27] Sui J, Munemoto J. Shape study on a green roof integrated photovoltaic system for Bi–objective optimization of investment value and CO2 emission. Journal of Asian architecture and building engineering. 2007;6(2):307-14.
[28] Samarasinghalage TI, Wijeratne WPU, Yang RJ, Wakefield R. A multi-objective optimization framework for building-integrated PV envelope design balancing energy and cost. Journal of Cleaner Production. 2022;342:130930.
[29] Zeraatpisheh M, Arababadi R, Saffari Pour M. Economic analysis for residential solar PV systems based on different demand charge tariffs. Energies. 2018;11(12):3271.
[30] Gholami H, Røstvik HN. Economic analysis of BIPV systems as a building envelope material for building skins in Europe. Energy. 2020;204:117931.
[31] Sorgato M, Schneider K, Rüther R. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. Renewable Energy. 2018;118:84-98.
[32] Yadav S, and Panda SK (2020) Thermal performance of BIPV system by considering periodic nature of insolation and optimum tilt-angle of PV panel. Renewable Energy 150:136-146.
[33] Ghosh A, Sarmah N, Sundaram S, et al (2019) Numerical studies of thermal comfort for semi-transparent building integrated photovoltaic (BIPV)-vacuum glazing system. Solar Energy 190:608-616.
[34] Miyazaki T, Akisawa A, Kashiwagi T. Energy savings of office buildings by the use of semi-transparent solar cells for windows. Renewable energy. 2005;30(3):281-304.
[35] Olivieri L, Caamaño-Martín E, Moralejo-Vázquez FJ, Martín-Chivelet N, Olivieri F, Neila-Gonzalez FJ. Energy saving potential of semi-transparent photovoltaic elements for building integration. Energy. 2014;76:572-83.
[36] Aguacil S, Lufkin S, Rey E. Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency. Energy and Buildings. 2019;193:15-28.
[37] Nkuissi HJT, Konan FK, Hartiti B, Ndjaka J-M. Toxic materials used in thin film

photovoltaics and their impacts on environment. Reliability and ecological aspects of photovoltaic modules: IntechOpen; 2020.

[38] Yadav S, Panda SK, Hachem-Vermette C. Optimum azimuth and inclination angle of BIPV panel owing to different factors influencing the shadow of adjacent building. Renewable Energy. 2020; 1;162:381-96.

[39] Commercial Reference Buildings. Retrieved from: https://www.energy.gov/eere/buildings/commercial-reference-buildings

[40] Reference Buildings by Building Type: Large office. Retrieved from: https://www.energy.gov/eere/downloads/reference-buildings-building-type-large-office-0

[41] Naderi E, Sajadi B, Naderi E, Bakhti B. Simulation-based performance analysis of residential direct evaporative coolers in four climate regions of Iran. Journal of Building Engineering. 2020 Nov 1;32:101514.

[42] Turkes P, Pluntke C, Helbig R. Thermal conductivity of SnO2 single crystals. Journal of Physics C: Solid State Physics. 1980;13(26):4941.

[43] Neumann H. Lattice vibrational, thermal and mechanical properties of CuInSe2. Solar Cells. 1986;16:399-418.

[44] Wang Y, Tian W, Ren J, Zhu L, Wang Q. Influence of a building's integrated-photovoltaics on heating and cooling loads. Applied energy. 2006;83(9):989-1003.

[45] Chatterjee S, Abhishek K, Mahapatra SS, Datta S, Yadav RK. NSGA-II approach of optimization to study the effects of drilling parameters in AISI-304 stainless steel. Procedia Engineering. 2014;97:78-84.

[46] Ridha HM, Gomes C, Hizam H, Ahmadipour M, Heidari AA, Chen H. Multi-objective optimization and multi-criteria decision-making methods for optimal design of standalone photovoltaic system: A comprehensive review. Renewable and Sustainable Energy Reviews. 2021;135:110202.

[47] Heating ASo, Refrigerating, Engineers A-C, Institute ANS. Thermal environmental conditions for human occupancy: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2004.

[48] Charles KE. Fanger's thermal comfort and draught models. 2003.

[49] Feed-in Tariff (FIT) rates. Retrieved from: https://www.ofgem.gov.uk/publications/feed-tariff-fit-tariff-table-1-april-2019

[50] Ahammad S, Khan AH, Nur TE, Ghose S, editors. A hybrid of 30 KW Solar PV and 30 KW Biomass System for rural electrification in Bangladesh. 2015 3rd International Conference on Green Energy and Technology (ICGET); 2015: IEEE.

[51] Hearps P, McConnell D. Renewable energy technology cost review. Melbourne energy institute technical paper series. 2011.

[52] Phillips PP, Phillips JJ. Return on investment. Handbook of Improving Performance in the Workplace: Volumes 1-3. 2009:823-46.

[53] Knapp K, Jester T. Empirical investigation of the energy payback time for photovoltaic modules. Solar Energy. 2001;71(3):165-72.

[54] Kato K, Hibino T, Komoto K, et al (2001) A life-cycle analysis on thin-film CdS/CdTe PV modules. Solar Energy Materials and Solar Cells, 67(1-4):279-287.

[55] Environmental Impacts. Retrieved from: https://bigladdersoftware.com/epx/docs/8-8/engineering-reference/environmental-impacts.html

[56]Output:EnvironmentalImpactFactors. Retrieved from: https://bigladdersoftware.com/epx/docs/9-1/input-output-reference/input-for-output.html

[57] Naderi E, Sajadi B, Behabadi MA, et al (2020) Multi-objective simulation-based optimization of controlled blind specifications to reduce energy consumption, and thermal and visual discomfort: Case studies in Iran. Building and Environment, 169:106570.

[58] Sin G and Gernaey KV (2009) Improving the Morris method for sensitivity analysis by scaling the elementary effects. Computer Aided Chemical Engineering, 26:925-930