# Thermal and Lighting Energy Benefits of Photovoltaic Glass in an Architecture Studio

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# Thermal and lighting energy benefits of photovoltaic glass in an architecture studio

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***Abstract*— Buildings are responsible for 40% of the total energy consumption, which is critical for global warming. Thus, our buildings are expected to be renovated following the zero-energy building (ZEB) strategies. In the context of ZEB strategies, renewable energy sources are crucial. It is necessary to understand their role in a nearly-ZEB for future scenarios. This research aims to find out the thermal, daylight, and energy performance of thin-film amorphous-silicon (a-Si) photovoltaic (PV) glass on an architecture studio of an education building at Izmir Institute of Technology (IZTECH) Campus in Izmir, Turkey. Simulation modeling and field measurements have become the methods applied in three scenarios to test the benefits of such a PV glass in terms of thermal and lighting energy consumption and comfort levels. Scenarios included a-Si thin-film modules in three transmittance values modeled in existing windows. Research findings propose that PV glasses have the potential to balance the room's lighting loads in a range between 15.1-and 20.3%. They improved occupant thermal and visual comfort by preventing overheating and glare risks. They also decreased cooling loads. However, an essential development could not be achieved in reducing heating loads since new PV glasses absorb less heat due to a lower g-value.**

***Keywords*— *daylight performance, solar energy, thermal performance, thin-film photovoltaics, zero-energy buildings***

## I. Introduction

According to European Union (EU), the population of cities will continue to increase, and by 2050, 66% of the World's population will be living in the cities. Thus, cities will need more buildings. This will increase energy demand since buildings are responsible for 40% of total energy consumption [1]. The uncontrolled energy consumption of buildings significantly accelerates global warming [2]. Therefore, in the context of the EU's 2050 targets for climate change, our buildings are expected to be designed following the zero-energy building (ZEB) strategies. According to the EU, one significant factor for ZEBs is to use renewable energy sources (RES) [3]. In the context of renewable energy sources, photovoltaic (PV) technology takes a great responsibility [4]. PV systems absorb solar energy to produce electrical energy. As a new type, building-integrated photovoltaics (BIPV) are introduced to the market lately. Rather than a separate system far from the building, BIPVs are directly attached to building surfaces (i.e., roof, window, shading element, etc.) to supply some of the buildings' energy demand. As a very recent development, thin-film solar cells have been introduced to the market. When thin-film solar cells are applied as photovoltaics, they produce energy and allow daylight to enter the building. According to one study, semi-transparent photovoltaic glazing has reduced energy consumption by 43.4%, 66%, 48.8%, and 35% in four climatic zones [5]. PV glass improved the building's overall performance and comfort for occupants. Another study assessed different types of PV solar cells and their energy performance. Results show that the a-Si PV module performed better compared to other cell types and it improves energy saving of heating and cooling loads [6].

This study aims to test the use of a Low-E PV glass in an architecture studio at the Izmir Institute of Technology (IZTECH) Campus in Izmir, Turkey. The study aims to understand the PV glass's potential for building's overall performance and explore the advantages of PV technology in heating, cooling, and lighting loads together with visual and thermal comfort.

## II. Method

### *A. Study Design*

Firstly, the architecture studio is monitored for one week. According to monitoring results, a calibration procedure is conducted on simulation models. Then, the study includes testing the base case model's daylight and energy performance through simulation software; analyzing three Low-E PV glass modules of OnyxSolar © [7], in which the transmittance of solar cells is changed as 10%, 20%, and 30% respectively (Table 4); calculating electrical energy of PVs and lighting energy load; then matching whether the PV glasses are advantageous in terms of balancing the lighting energy consumption monthly and yearly. The simulation engine calculates heating and cooling loads. Those are discussed together with occupant thermal comfort in the case room. The effect of PV glass on occupant visual comfort is also analyzed in the study.

### *B. Case Building*

The architecture studio is located in the 3-story-high-faculty building in Izmir Institute of Technology (IZTECH) Campus on the west side of Turkey, on the coast of the Aegean Sea. Its coordinates are 38.32 N, 26.63 S, and its sea elevation is 77m. Due to the closeness to the Aegean Sea, the city's climate is classified as a Mediterranean climate with hot and dry for summers and warm and rainy for winters, according to Köppen-Geiger Climate Classification [8]. The architecture studio (Fig. 1) is 4m in height, located on the 1st floor, facing south and east, with dimensions of 11.8x17.8m (Fig. 1).

Fig. 1. Location of the building on the aerial photograph and case room.

### C. Experimental Setting

Data loggers conduct monitoring of temperature, relative humidity, and illuminance for one week and at 10-minute intervals. Datalogger can collect data on temperature, RH, and illuminance simultaneously. Two data loggers are attached to the interior and exterior surfaces of the studio. The outside datalogger is placed on the exterior window wall where direct sun and rain cannot reach. The inside datalogger is placed on the interior wall surface (Fig. 2). The two data loggers are located next to each other, attached to surfaces vertically, 1.5 m above the floor, and facing South. Around 20-30 people have occupied the case room for 8 hours a day. It is ventilated naturally. In the case room, students' computers are used throughout the daytime and may be a potential heat gain source. There is a VRF HVAC system for the heating and cooling of the whole building beside toilets throughout the year. No curtains are used in the building. Measurements started on the 30th of November 2021 at 1:00 p.m.

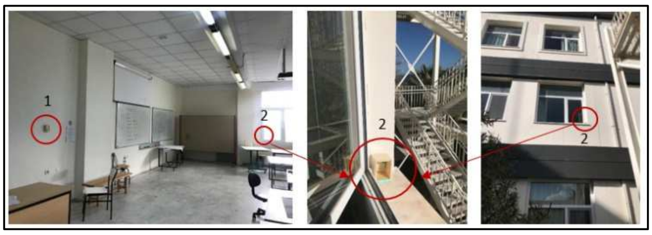



Fig. 2. Photos of inner and outer climate data loggers (1: indoor, 2: outdoor).

### D. Simulation Models

Simulation models are generated on Rhino/Grasshopper environment for daylight, thermal, and energy performance analysis. Monitored climate data is imported to the Izmir weather file for climate-based sensitive calculations. Grasshopper plug-in Honeybee v1.3.0. is used with Radiance to analyze the room's daylight performance annually. Material specifications are introduced to the system as in Table 1. Daylight performance is calculated and evaluated on a grid with a height from the floor of 0.75m. The distance between measuring sensor points is defined as 0.6m. Outputs are illuminance (lux) and spatial Daylight Autonomy (sDA). Daylight Autonomy (DA) performs annually with a task-illuminance-based metric for a room's daylight performance. Recently, it is also called spatial Daylight Autonomy (sDA) by IES. sDA is defined as "the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year" by IES [9]. This analysis type is beneficial for identifying proper illumination on a work plane during the year.

The energy simulation model is similarly modeled on Rhino/Grasshopper environment. Grasshopper plug-ins Honeybee, EnergyPlus, and OpenStudio are used for energy and thermal performance analysis. Several decisions are introduced to the system as input for proper calculations. All the schedules can be seen in Table 2. The building is naturally ventilated during the year according to a temperature schedule. Different schedules are assigned to different room types. The building is used between 9 a.m. and 5 p.m. Computers are defined as potential heat gain sources in the studios since they are plugged into the batteries. They are only used in architecture studios when the students occupy them. When there are no students in the building, no electrical equipment is used. The building is an average tight building. Infiltration is defined as 0.0004 $m^3/s$ per $m^2$ façade. Infiltration levels kept constant throughout the year. Surrounding building blocks and trees are modeled, and their shading effect is included in energy calculations. Their materials are also set for sensitive analysis. Throughout the study, heating, cooling, and lighting loads are analyzed in terms of the energy performance of the building.

TABLE I. DATA INPUT DETAILS FOR DAYLIGHT SIMULATION MODEL

| **Building Element** | **Data Input** | |
|---|---|---|
| | ***Material*** | ***Specifications Subhead*** |
| Floor | White polished marble | Rho 65% |
| Ceiling | Gypsum board | Rho 80% |
| Walls | White matt paint | Rho 60% |
| Windows | Double glazing | Transmittance 75% |

TABLE II. DATA INPUT DETAILS AND SCHEDULES FOR ENERGY SIMULATION MODEL

| | **Building Area** | | | | |
|---|---|---|---|---|---|
| **Base Program** | | ***Large class*** | ***Small class*** | ***Corridor*** | ***WC*** |
| People | People/area | 0.17 | 0.17 | 0.17 | 0.18 |
| | Occupancy | Mon-Fri 9:00-18:00 | Mon-Fri 9:00-18:00 | Mon-Fri 9:00-18:00 | Mon-Fri 9:00-18:00 |
| Elect. Equip. | Watts/area | 1.42 | 1.42 | - | - |
| | Schedule | Mon-Fri 9:00-18:00 | Mon-Fri 9:00-18:00 | - | - |
| Doors | Schedule | Closed | Closed | Closed | Closed |
| Natural Vent. | Min. indoor temperature (°C) | 21 | 21 | 21 | 21 |
| | Max. indoor temperature (°C) | 30 | 30 | 30 | 30 |
| Infiltration | Flow/ exterior surface area | 0.0004 | 0.0004 | 0.0004 | 0.0004 |
| Condition | HVAC | VRF | VRF | VRF | - |
| Heating/ Cooling Setpoint | Degree (°C) | 21/24 | 21/24 | 21/24 | - |

*E. Calibration*

Calibration needs to be evaluated to understand whether the simulation model and actual conditions correlate with each other. ASHRAE Guideline 14-2002 is used for this procedure [10]. This study conducted calibration according to indoor simulated and monitored data temperature values. "Typically, models are declared to be calibrated if they produce MBEs within ±10% and CV(RMSE)s within ±30% when using hourly data" is given as a guideline [10]. Two different error ratios are calculated as MBEs and CV(RMSE)s, and they are analyzed if they are in the acceptable range.

## III. Results

*A. Measurement Results*

The monitoring process is conducted between the 30th of November at 1:00 p.m. and the 7th of December at 1:00 p.m. for temperature, relative humidity, and illuminance level at every 10 minutes for indoor and outdoor environments (Fig. 3). The average outdoor temperature is calculated as 15.2˚C. It is recorded as 19.6°C as the highest and 8.8°C as the lowest value. Average relative humidity (RH) is defined as 68.5%. The highest and lowest relative humidity values are 88.12% and 40.5%, respectively. The average outdoor illuminance level is measured as 3832 lux, including nighttime. The highest and lowest values are calculated as 32.280 lux and 3.9 lux, respectively. The lowest value refers to nighttime. While defining the daytime, 8:10 a.m.-06:00 p.m. are taken as the interval. According to these, when the temperature drops, there achieved an increase in relative humidity and a decrease in illuminance value. For the indoor environment, the average indoor temperature is calculated as 23.4˚C. It is recorded as 24.9˚C as the highest and 22˚C as the lowest. Average RH is calculated as 50.5%. The highest and lowest relative humidities are 58.4% and 38.6%, respectively. The average indoor illuminance level is measured 167.64 lux, including the nighttime. The highest and lowest values are calculated as 1028 lux and 3.9 lux. Since the building is continuously heated, there is not a big fluctuation in temperatures. However, there are still obtained changes in RH values. Therefore, temperature and RH are not as correlated as in outdoor monitoring. Besides nighttime, average illuminance level is 212.9 lux (Table 3).

TABLE III. Monitored Data on Highest/Lowest Temperature and Relative Humidity

| Env. | Monitored Data | | | | |
|---|---|---|---|---|---|
| | ***Data*** | ***Date*** | ***Temp (˚C)*** | ***RH (%)*** | ***Illuminance (lux)*** |
| Outdoor | Hottest hour | 6.12.21, 3:30 p.m. | 19.6 | 67.6 | 2400 |
| | Coldest hour | 2.12.21, 1:00 a.m. | 8.8 | 64 | 3.9 |
| | Highest RH | 6.12.21, 7:00 p.m. | 16.1 | 88.1 | 3.9 |
| | Lowest RH | 30.11.21 1:00 p.m. | 18 | 40.5 | 32.280 |
| | Average | - | 15.2 | 68.5 | 3832 |
| Indoor | Hottest hour | 06.12.21 9:10 a.m. | 24.9 | 51.7 | 350 |
| | Coldest hour | 02.12.21 9:00 a.m. | 22 | 42.7 | 240.5 |
| | Highest RH | 06.12.21 8:30 p.m. | 23.2 | 58.4 | 303.5 |
| | Lowest RH (%) | 01.12.21 6:30 a.m. | 22.1 | 38.6 | 145.8 |
| | Average | - | 23.4 | 50.5 | 212.9 |

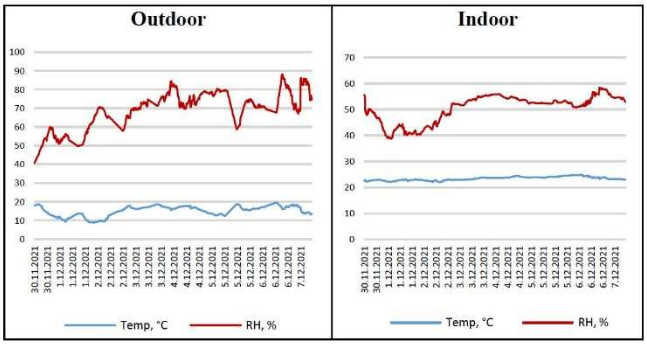


Fig. 3. Indoor and outdoor monitored data of temperature, relative humidity.

*B. Calibration Results*

Calibration is conducted according to monitored indoor temperature results. Two types of error ratios, MBEs and CV(RMSE)s, are calculated as 8.57% and -7.6%, respectively, using ASHRAE Guideline 14-2002 [10]. They are both calculated in the acceptable range but higher than expected. There are no high fluctuations in indoor simulated and monitored temperature. This may be due to the continuously heated classroom during the monitoring period. The second calibration model changes natural ventilation and HVAC schedules to increase the simulated indoor temperature. The highest and lowest indoor air temperature scheduled for natural ventilation are changed to 26°C and 22°C, respectively. The HVAC system's heating setpoint is increased to 23°C. The difference between the average monitored and simulated temperature is decreased by 0.9°C. The lowest and highest temperature difference between simulated and monitored indoor temperature is calculated as 0 and 2.92°C. CV(RMSE) and MBE are calculated as 6.3 and -3.78, respectively. These are calculated lower than previous results. When the results are compared with the first model, indoor simulated and monitored temperatures are calculated closer to each other (Fig. 4).

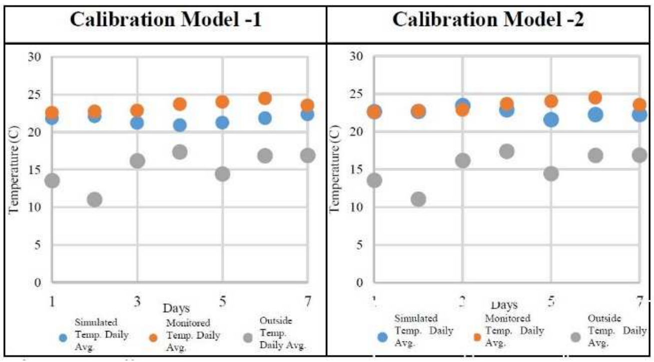


Fig. 4. Daily average temperatures per two calibration models: simulated/monitored indoor temperatures and outdoor temperatures.

*C. Base Case Results*

Daylight performance is evaluated based on Spatial Daylight Autonomy (sDA). sDA is a climate-based method for daylight performance. In classrooms, 500 lux and above illumination is required. Below 300 lux illumination is defined as unacceptable [11]. In this study, the threshold sDA value is defined as sDA500, 50% ⩾ 75%, which means that in 50% of the total period in 75% of the analysis zone, sDA offers a 500-lux illumination. sDA500,50% ⩾ 55% is also defined as nominally acceptable. sDA500, 50% ⩽ 55% is insufficient. In 50% of total analysis period, sDA offers a 500-lux daylight illumination in 59.1% of the analysis zone.

TABLE IV. SPECIFICATIONS OF PHOTOVOLTAIC GLASS MODULES [7]

| Thickness/ Configuration | Glass Properties | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Transmittance (%)* | *U-value ($W/m^2K$)* | *G-value (%)* | *Peak power (Wp)* | *Open-circuit voltage (V)* | *Short-circuit current (A)* | *The voltage at nominal power (V)* | *Current at nominal power (A)* | *Temp. coefficient of $P_{mpp}$ (%/°C)* | *Temp. coefficient of $V_{oc}$ (%/°C)* |
| 6T+3.2+6T/12 Air/6T Low-E | 30 | 1.6 | 17 | 28 | 47 | 0.74 | 32 | 0.63 | -0.19 | -0.28 |
| | 20 | | 12 | 34 | | 0.93 | | 0.76 | | |
| | 10 | | 9 | 40 | | 1.11 | | 0.90 | | |

Although it is nominally acceptable; it is not at the desired level. In the studio, there are very bright and very dark areas. Thus, the homogenous distribution of daylight is not achieved. To evaluate the glaring risk of the studio, a threshold of 2000 lux is also defined. According to the results, a minimum of 2000 lux illumination is available in 13.6% of the analysis zone in 50% of the total analysis period. The aim is to decrease glare risks and increase the illuminance of poor daylit areas (Fig. 5).

Heating, cooling, and lighting loads are calculated annually for energy calculations. Heating and cooling loads are calculated by EnergyPlus and OpenStudio of Honeybee for the whole building. Lighting load is calculated manually for only the case room according to some equations (1:2). According to this calculation method, two annual lighting loads are calculated. One of them is operated for a clear sky with sun, while the other one is for an overcast sky.

(a) (b)

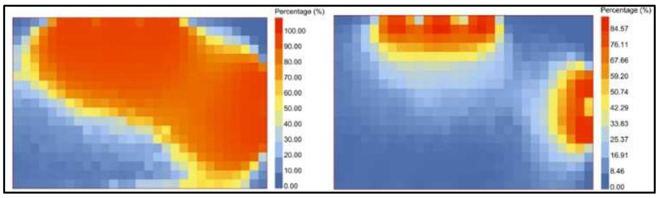


Fig. 5. (a) Annual daylight autonomy results according to 500 lux threshold (b) Annual daylight autonomy results according to 2000 lux threshold.

*Daily Energy Consumption = luminaire power x luminaire number x operating hours* (1)

*Seasonal Energy Consumption = daily energy consumption x 60 (days)* (2)

Point-in-time grid-based simulations are conducted for two different sky components on the 21st of March, June, December, and 23rd of September. Simulations are performed for various periods as 8:00 a.m., 10:00 a.m., 12:00 p.m., 3:00 p.m., 6:00 p.m., and 8:00 p.m. Studio is used by students, including nightshift on spring and winter seasons. It is used between 9 a.m-and 6 p.m. during the summer and fall seasons. Areas that do not meet 300 lux thresholds are defined, and artificial lights are applied there. According to the results, annual lighting loads are calculated as 2453 and 3730 kWh on a clear sky with sun and overcast sky conditions, respectively. A VRF system is used to heat and cool spaces beside toilets in the entire building. According to the results, the building's annual heating and cooling loads are calculated as 7.909.507 kWh and 1.114.731 kWh, respectively (Fig. 6). For the case room, time is not comfortable according to simple ASHRAE 55-2004 Standards with winter clothes, summer clothes, and winter or summer clothes are calculated as 877, 1278.5, and 94.75 hours respectively. Heat gain from HVAC zone equipment sensible heating, people, electricity equipment, windows, and infiltration is calculated as 1.494.734 kWh, 5388 kWh, 608 kWh, 11.472 kWh 329.363 kWh, respectively. Heat loss from HVAC zone equipment sensible cooling, windows, infiltration, opaque surface conduction, and other heat removal is calculated as 335.808 kWh, 2750 kWh, 1.501.512 kWh, and 3.972.254 kWh, respectively.

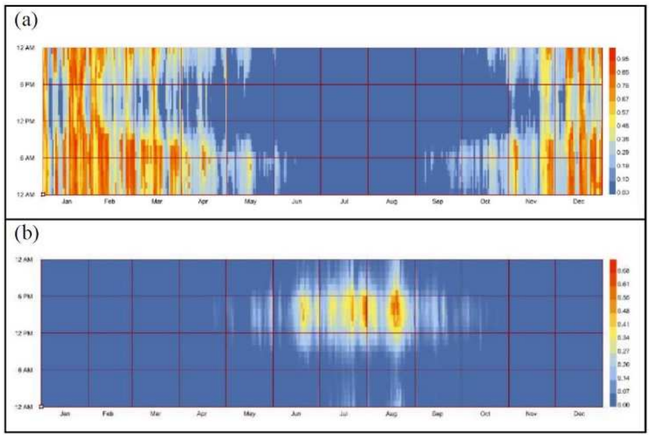


Fig. 6. (a) Hourly energy consumption for heating of whole building (b) Hourly energy consumption for cooling the whole building.

## D. Scenario Results

According to daylighting results, in 50% of the total analysis period, 500 lux illumination was found available in 28.8%, 17.6%, and 7% of the analysis zone for 30%, 20%, and 10% transmittance PV glass, respectively (Fig. 7). According to energy generation results, the lowest transparent (i.e., 10%) PV glass produced the highest electricity while the highest transparent one (i.e., 30%) generated the lowest electrical energy. In the case room, there are three windows on the east façade and two on the South. Windows on the same façade have equal energy production results.

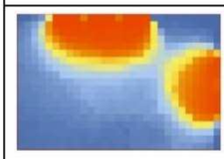
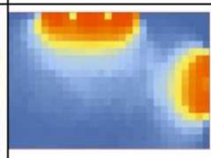
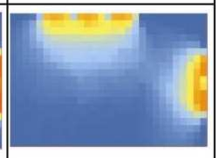
| PV glass transmittance (%) | | |
|---|---|---|
| 30 | 20 | 10 |
|  |  |  |
| sDA 500,50% (%) | sDA 500,50% (%) | sDA 500,50% (%) |
| 28.8 | 17.6 | 7 |

Fig. 7. The studio's annual daylight autonomy results in different transmittance a-Si thin-film photovoltaic modules.

For 30% transmittance modules, total AC power for a whole year is calculated as 108 kWh and 148.5 kWh per window on East and South, respectively. Annual energy production is noted as 620.9 kWh. kWh. For 20% transmittance modules, total AC power for a whole year is calculated as 130.2 kWh and 178.9 kWh per window on east and South. Annual energy production is noted as 748.4 kWh. For 10% transmittance modules, total AC power for a whole year is calculated as 154 kWh and 211.5 kWh per window on east and South (Fig. 8).

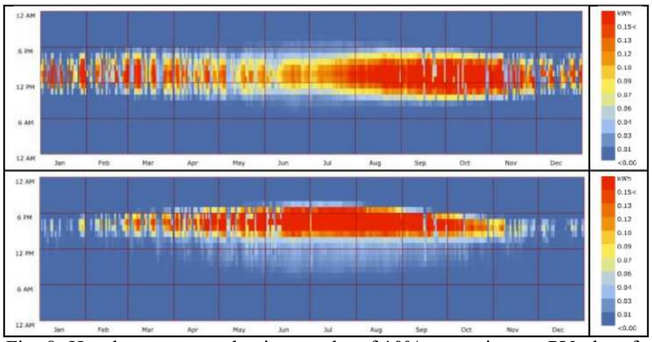


Fig. 8. Hourly energy production results of 10% transmittance PV glass for South and East façades, respectively.

Annual energy production is noted as 884.9 kWh. Since PV modules created a difference in illuminance level, the studio's lighting load is also changed. As the lowest and highest, the lighting load range is calculated as 3509-4106 kWh, 3997-4210 kWh, and 4354-4417 kWh for 30%, 20%, and 10% transmittance PV modules, respectively (Table 6). PV glass energy generation during winter is calculated as 54 kWh, 65 kWh, and 76.9 kWh for 30%, 20%, and 10% glass transmittance, respectively. This is calculated as 140.8 kWh, 169.7 kWh, and 200.7 kWh in the spring season. It is 241.3 kWh, 290.8 kWh, and 343.8 kWh in summer. Lastly, it is noted as 182 kWh, 219.4 kWh, and 259.4 kWh in the fall season. (Table 5). In terms of thermal performance analysis, annual indoor air temperatures are analyzed. The average yearly indoor temperature is calculated as 22.57°C, 22.8°C, 22.3°C), and 26.6(C for 10%, 20%, 30% transmittance PV glass, and base case.

TABLE VI. SEASONAL LIGHTING LOAD AND PV ENERGY GENERATION COMPARISON

| Season | Data Input | | | |
|---|---|---|---|---|
| | *Total lowest and highest lighting load (kWh)* | *Electrical energy generation from PV (kWh)* | | |
| | | 30% T. | 20% T. | 10% T. |
| Winter | 1178-1514 | 54 | 65 | 76.9 |
| Spring | 1067-1413 | 140.8 | 169.7 | 200.7 |
| Summer | 97-360 | 241.3 | 290.8 | 343.8 |
| Fall | 109-441 | 182 | 219.4 | 259.4 |

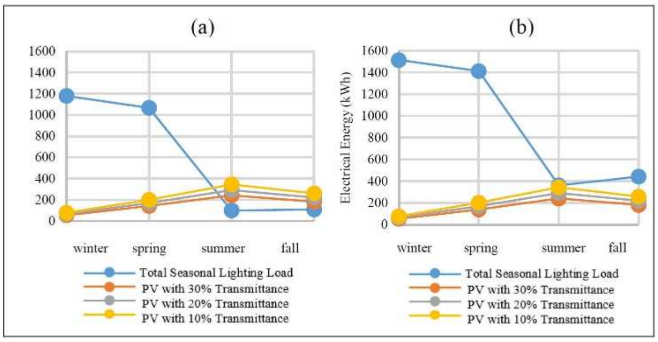



Fig. 9. a) Seasonal lighting load under a clear sky with sun condition and PV energy generation comparison (b) Seasonal lighting load under overcast sky condition and PV energy generation comparison.

## IV. DISCUSSION

The paper presents a comprehensive analysis of three a-Si thin-film solar cells due to their transmittance. Solar PV glasses are modeled 90˚ vertically to the South and east facades and tested in terms of energy, thermal, and daylight performance. The main conclusions are listed below:

- Regarding energy generation, less transparent solar cells provide a higher amount of electricity generation. The 10% transmittance PV glass produced the highest and the 30% one provided the lowest energy. To obtain higher energy production, less transparent Low-E PV glass is better to prefer. When the annual energy production is analyzed, all the tested PV glasses generate higher energy on the south-facing façade than on the other facades. Orientation becomes the key consideration in installing these systems.

TABLE V. OVERALL ENERGY AND DAYLIGHTING DATA

| Energy Data | | Transmittance (%) | | |
|---|---|---|---|---|
| | *Case model* | *30* | *20* | *10* |
| Whole building heating end use (kWh) | 7909507 | 7910341 | 7911702 | 7912563 |
| Whole building cooling end-use (kWh) | 1114731 | 1097786 | 1094508 | 1092536 |
| Case room annual lighting load range (kWh) | 2453-3730 | 3509-4106 | 3997-4210 | 4354-4417 |
| Time not comfortable for winter, summer and both clothes (hour) | 877<br>1278.5<br>94.7 | 465.7<br>1411.5<br>96.3 | 410.2,<br>1456.5<br>98 | 386.7<br>1494.7<br>102 |
| Time setpoint not met during heating (hour) | 2060 | 2075 | 2079 | 2081 |
| HVAC zone equipment sensible air heating (kWh) | 1494734 | 1496123 | 1496400 | 1496678 |
| Heat gain from people (kWh) | 5388 | 5416 | 5416 | 5416 |
| Heat gain from electricity equipment (kWh) | 608 | 608 | 608 | 608 |
| Heat gain from windows (kWh) | 11472 | 2944 | 2047 | 1511 |
| Heat gain from infiltration (kWh) | 329363 | 329391 | 329391 | 329391 |
| HVAC zone equipment sensible air cooling (kWh) | 335808 | 332752 | 332447 | 332280 |
| Windows heat removal (kWh) | 2750 | 1555 | 1608 | 1647 |
| Infiltration heat removal (kWh) | 1501512 | 1499317 | 1499039 | 1499095 |
| Opaque surface conduction heat removal (kWh) | 3972254 | 3166692 | 3055580 | 2958079 |
| Peak Heating Sensible Heat Gain Components: HVAC zone sensible air heating (kW) | February 3rd, 1299 | February 3rd, 1299 | February 3rd, 1299 | February 3rd, 1299 |
| PV energy generation (kWh) | - | 620.9 | 748.4 | 884.9 |
| Power output per window (kWh) | - | East: 108<br>South: 148.5 | East: 130.2<br>South: 178.9 | East: 153.9<br>South: 211.5 |
| sDA500,50% | 59.1 | 28.8 | 17.6 | 7 |

- Regarding daylight performance, less transparent PV glasses worsened the room's daylight performance and increased lighting loads. They block most of the amount of daylight entering the space. Their application in north-oriented areas may cause some problems since no direct sunlight reaches the surface of the PV glass. The case studio showed us that the possible largest windows could benefit daylight performance when less transparent PV glasses are used. In this study, the total window area is 28.8 $m^2$ which is relatively narrow and unable to transmit daylight to the back parts of the room. Thus, PV glasses did not perform at the desired level. On the other hand, another benefit is their potential to eliminate glare risks and provide visual comfort mainly.

- The annual energy generated by PV glasses covered the room's annual lighting loads between 15.1-and 20.3%. Although the lighting load increases with less transmittance, electrical energy increases relatively. This may make less transparent glasses preferable in this sense. In summer, the energy generation of PV glass is the highest. It covers at least 67% of the seasonal lighting loads of the case room. Under a clear sky with sun conditions, PV glasses cover all seasonal lighting loads. In the fall season, electrical energy generation is lower than in summer but higher than in other seasons. Under overcast sky conditions, it covers at least 41.2% of the seasonal lighting load. It covers all the lighting load under the clear sky with sun conditions. In the spring season, the lighting load increases significantly. Still, PV glass covers at least 10% of the seasonal lighting load. Under a clear sky with sun conditions, PV glasses can cover 18.7% of the seasonal lighting load. The lowest energy generation is provided in the winter season. PV glasses provide only 3.5% of the seasonal lighting load. Under a clear sky with sun conditions, they can cover up to 6.5%.

- Selected Low-E PV glass has lower u-value, g-value, and transmittance. A lower u-value means better insulation, decreasing the heating loads in mostly heated buildings. A lower g-value absorbs less heat. Heat gain through windows decreased significantly in PV scenarios. This increases the building's heating load and decreases the cooling load. The selected Low-E PV glasses can be preferred in hot climate areas with high solar radiation to reduce the cooling loads of buildings. Applying them on the South, east, and west-oriented facades is better to generate more electrical energy and decrease the cooling load. During the winter and spring seasons, the electrical energy generation of PV glass is the lowest, and energy consumption for heating is the highest. Most of the consumed energy belongs to these seasons. In summer and fall, heating energy consumption is the lowest. The building is cooled mainly, but the energy used to cool it is relatively significantly lower than the one used to heat it. In these seasons, the energy generation of PV glass is highest. The lowest generation and highest savings are achieved.

- After PV glasses implementation, indoor air temperatures are decreased. Besides, annual thermally uncomfortable hours are reduced by 12.3%, 12.6%, and 11.9% for 30%, 20%, and 10% transmittance. The simulation engine calculates this according to ASHRAE standards using indoor air temperatures. Since Low-E PV glasses decrease indoor air temperatures, they better benefit in cooling-dominated regions.

- The seasons that generate the closest electrical energy are summer and fall. Sun has a more direct angle in summer. Therefore, it may not be able to hit the window surface for some hours. Still, more energy is generated in that season. During the hours when the sun hits the window surface, the solar cells heat more, resulting in more energy generation. All PV glasses generate more energy than the energy used for lighting load in the summer and fall seasons under a clear sky with sun conditions. It is worth mentioning that energy generation increases in the spring, summer, and fall. In these seasons, the lighting load is also significantly decreased.

- A small scale of PV glass is applied on a low-rise building, but when PV glass applications in larger-scale buildings are examined, payback times vary between 3.7-16 years, and an internal rate of return between 5-29.3% is noted [12]. They may be seen as profitable in high-rise buildings.

## V. Conclusion

This study displays that PV glass has great potential to reduce glare problems and cooling loads while improving occupant thermal comfort. Designing/optimizing the window area, location, and orientation together with room geometry will reveal their potential to balance the energy generated by PV and electrical lighting consumption.

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