Impacts of Roof-top Solar Photovoltaic Modules on Building Energy Performance: Case Study of a Residence in HCM City, Vietnam

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Abstract. Vietnam is considered a country with high solar potential and solar irradiation is comparable to most countries in the region. However, high density solar project in areas causes overload state of transmission grid system and some plants wouldn’t operate at full design capacity. Therefore, roof-top solar PV projects in provinces and cities, which have large potential of solar irradiation, are promoted to reduce pressure on power supply. Besides, roof-top solar would be also affordable for home and business owners and communities by helping households halve electricity bills and gain energy efficiency. In this paper, we investigate case study of a residential building in HCM city, Vietnam for analysing impacts of roof-top solar photovoltaic modules on energy performance. The results showed not only the potential photovoltaic power, but also the reduction of roof heat transfer. In consequence, the building cooling load and total energy consumption are significantly reduced thanks to Roof-top PV installation. On the other hand, the reduction of solar incident on the building roof keeps cooling roof surface (outer and inner) and improves thermal comfort of attic space. Our research objective is to quantify indirect benefit of Roof-top PV on energy efficiency and to provide ideas for further researches.

1. Introduction
Vietnam is considered a country with high solar potential and solar irradiation is comparable to most countries in the region. Indeed, solar energy intensity is scientifically estimated an average of 4-5 kWh/m²/day in Southern, Central and some parts of Northern Vietnam (totalling up to 1,460-1,825 kWh/m²/year), especially average peak up to 5.5 kWh/m²/day in some Southern regions (totalling up to 2000 kWh/m²/year) [1]. Following a report of EVN (Electricity of Vietnam), after 2 years of implementing the Prime Minister’s Decision 11/2017 about selling electricity of solar power projects at fixed price, 141 projects of 365 registered solar farms have been added to master plans (total capacity of over 14,000 MWp). However, high density solar project in areas (such as Ninh Thuan, Binh Thuan, Khanh Hoa, Dak Lak and Binh Phuoc provinces) causes overload state of transmission grid system and some plants wouldn’t operate at full design capacity [2]. Therefore, roof-top solar PV projects in provinces and cities, which have large potential of solar irradiation, are promoted to reduce pressure on power supply. On the other hand, roof-top solar would be also affordable for home and business owners and communities by helping households halve electricity bills and gain energy efficiency.

Among demands of energy urban use, heating, ventilation and air conditioning (HVAC) are the main load in residential and non-residential buildings. In some poor insulated building, most of solar irradiation heat enters through the roof. Thus, building with Roof-top PV installation not only gains
benefits from PV power supply, but also reduces cooling load in sunny or hot climates by roof-top shading. Following a research on effect of roof-top solar photovoltaic systems on roof heat transfer in San Diego, California [3], PV covered roof through simulation could reduce up to 38% of annual cooling load and leads to energy savings and/or human comfort. Another research in India about impact of roof-top PV solar modules on building cooling load [4] investigated dual role of roof-top PV system in electricity generation and reduction of building cooling load due to shading. The simulated energy required for cooling load has been decreased 73%-90% after installing PV system. However, there are still few studies of this research on evaluation of power supply and thermal performance [5]. In Vietnam, most people concentrate to optimize design and power supply of Roof-top PV system for electricity generation, self-consumption [6] or power grid connected [7]. Studies on building energy performance, which includes PV power supply, their impacts of roof shading and human comfort, must be processed for assessing overall benefit of roof-top PV modules.

In this paper, we investigate case study of a residential building in HCM city, Vietnam for analysing impacts of roof-top solar photovoltaic modules on energy performance. The building model represents typical low-income apartment and household buildings which are normally constructed with poor insulated roof and occupies large area in city. Our case study has been simulated in Design Builder (Energy Plus core) with and without PV. Through daily simulation of one-year period, beside benefit of PV power supply, the effect of PV panels shading as double roof on reduction of cooling load and energy consumption have been assessed. Then, to analyse influence on thermal comfort, hourly simulation of summer typical week was realized for calculating roof solar incident, surface roof temperature and Fanger PMV. Our research objective is to quantify indirect benefit of roof-top PV on energy efficiency and to provide ideas for further research in this field.

2. Methodology

2.1. Case-study

In the framework of this research, our case study is illustrated from Lo Gom condominium located along Tan Hoa canal in District 6, HCM city, Vietnam (Figure 1). This building is a social housing project designed for poor households supported by Belgium government with the copyright belong to T3-Architecture and Villes en Transition [8]. Because of limited budget, the design hasn’t concentrated to improve the construction insulation, but has provided a significant improvement to living quality in bio-climatic comfort through passive design. Especially, the building roof is double ventilated roof with an air gap which prevents direct solar irradiation to lower roof and allow the circulated air to transfer heat of upper roof to the environment.

![Figure 1. Lo Gom condominium](source: T3-Architecture)

Without passive design solution, this building represents typical social residence and household buildings with poor insulation of building envelope. In fact, these buildings are usually in small and medium size (GFA under 2500 m² floor area) to be covered by QCVN09:2017/BXD (Vietnam...
Building Energy Efficiency Code), but they outnumbered high-rise and commercial buildings with large area occupied in provinces and cities. In our case study, we reuse the building shape and the upper roof is replaced by roof-top solar photovoltaic modules. Then, the building energy performance will be analysed with and without roof-top PV installation.

2.2. Building model

The building model consists 3 blocks, which have been built in simulation software (Design Builder), with 3 to 4 storeys in height, 69 apartments and 7 grocery stores. The site orientation is southwest and the weather data is extracted from Tan Son Nhat International Airport weather station (climate.onebuilding.org). The corridors and circulation area of the building are simplified as shading component in energy model. All apartments have 1 door and 2 windows opposite to each other with 0.5m overhang (Figure 2). For each block, solar PV panels are supposed to cover whole roof area and provide overhang as upper roof design of Lo Gom condominium (Figure 3).

![Figure 2. Plan of an apartment in building model](image)

![Figure 3. Building model in Design Builder](image)

| Table 1. Building model configuration in Design Builder |
| --- |
| **Category** | **Property** | **Parameter** |
| External walls | Burned bricks | 220 mm thickness, U-Value = 2.11 W/m²-K |
| Flat roof | Reinforced concrete | 120 mm thickness, U-Value = 4.045 W/m²-K |
| PV panels | Solar collector | Efficiency: 15% fixed |
| | | Tilt angle: 7° |
| | | PV area of block A: 594 m² |
| | | PV area of block B: 907.5 m² |
| | | PV area of block C: 495 m² |
| HVAC | Package terminal air conditioner | Cooling COP: 3.0 fixed |
| Lighting | Fluorescent compact | Normalized LPD: 5 W/m²-100lux |
| | Apartment space | TM59_3-BedLivingKitchen Template |
| | | 0.0188 people/m² |
| | | Cooling setpoint: 25°C, Cooling setback: 28°C |
| Activity | Grocery stores | Small Shop Template |
| | | 0.1169 people/m² |
| | | Cooling setpoint: 23°C, Cooling setback: 28°C |
| WC | Domestic bathroom template | 0.0187 people/m² |
| | No air conditioned |
The external wall of building model is configured to burned brick and the lower roof is mostly made of reinforced concrete. This is indeed popular construction of dwelling buildings in Vietnam. For equipment, all room is air conditioned and lighting is fluorescent compact. Activities and operational schedule are consulted from activity template of simulation software which based on ASHARE 90.1. The detail of building model configuration has been shown in Table 1.

3. Simulation results and analysis

Through the software simulation mechanism, the building model is converted to IDF file and transferred to EnergyPlus calculation core, developed by US Department of Energy (energyplus.net). This calculation engine allows calculating cooling load and annual energy consumption of whole building with and without roof-top PV installation. The solar incident and thermal comfort of roof space could also be investigated from output data to assess overall impacts of roof-top solar photovoltaic modules.

3.1. Cooling load and annual energy consumption

The cooling load is amount of heat energy that would need to be removed from the space to maintain the temperature in an acceptable range following setpoint and setback temperature. The building envelope, internal gains, solar irradiation and outdoor ambient temperature are the main factors which mostly affect. For cooling design, the peak load is referred to determine the capacity of mechanical cooling equipment required. Thus, the first simulation was set up for the hottest summer day with high solar irradiation under local weather condition.

HCM city is located between tropic and equator, so the solar radiation comes mainly to the roof from vertical position. Due to poor insulation of reinforced concrete, without shading, the building roof is heated under direct solar radiation and large amount of heat is transferred to attic space. Figure 4 shows that heat transfer through roof was much reduced from 107.12 to 13.91 kW-peak thanks to the shading of roof-top PV modules. In consequence, the total cooling load was significantly reduced up to 100 kW-peak (Figure 5). Because of residential activity, the cooling demand starts from 14h30 which made the peak load is situated at that moment.

To assess the impacts of roof-top PV on annual energy consumption, the second simulation was set up for one-year period. In Table 2, we can observe benefits of roof-top PV on building energy performance. The photovoltaic power represents direct benefit which provides up to 565 MWh per year, more than building energy demand. For the indirect benefit, the energy saving is 11.9% of total energy consumption, corresponding to 18.4% of total cooling energy consumption of the case without roof-top PV installation.
Table 2. Comparison of simulation results with and without roof-top PV installation

|                                | without roof-top PV | with roof-top PV | reduction |
|--------------------------------|---------------------|-----------------|-----------|
| Total building cooling load    | 530.13              | 430.98          | 18.7%     |
| (kW-peak)                      |                     |                 |           |
| Total attic spaces cooling     | 242.16              | 143.74          | 40.6%     |
| load (kW-peak)                 |                     |                 |           |
| Total building energy          | 317993.28           | 280192.84       | 11.9%     |
| consumption (kWh)              |                     |                 |           |
| Total building cooling         | 199736.15           | 163005.29       | 18.4%     |
| energy consumption (kWh)       |                     |                 |           |
| Photovoltaic power             | 0                   | 564972.712      | -         |
| (kWh)                          |                     |                 |           |

3.2. Solar incident and thermal comfort

3.2.1. Solar incident

In the tropical climate area like HCM city, a major part of the energy use is for the cooling. The heat balance simulation shows the solar incident on the building envelop particularly on the roof is the main cause of the roof surface’s temperature both inside and outside of the building.

![Solar incident on the building envelope without (a) and with (b) roof-top PV installation at noon](image)

The simulation’s results of a typical summer day (Figure 6) showed that at noon the building with roof-top PV has almost no solar incident on the roof as it is shaded by the PV panel on top. Without the roof-top PV, the building receives maximum amount of solar incident (900 W/m²) on its roof. Besides, solar incident also causes the increase of the external roof surface’s temperature (Figure 7). The graph shows that in the case that has Roof-top PV, the temperature of the roof and façades of the building is similar while without roof-top PV, the temperature of the roof can raise up to 50°C which is 10°C higher than the façade’s temperature at noon time.

![External surface temperature without (a) and with (b) roof-top PV installation at noon](image)
Obviously, the roof-top PV panels can do twice benefits to the building itself. It can generate the electricity but also can prevent the solar incident falling on the roof as such keeping the roof surface’s temperature as low as the facades’ temperature at any time of the day. It is good for the thermal comfort of the spaces inside the building which is explained in detail in the following part.

3.2.2. Thermal comfort

The thermal comfort is one of the key elements for evaluating the building’s indoor environmental quality. There are six primary factors that directly affect the thermal comfort which in turn are air temperature, radiant temperature, humidity, wind speed, clothing and metabolic rate (human factors). In this research, we only focus on the first fours factors (environmental factors) as they are influenced by the outside conditions. The human factors such as clothing assumed as 0.5 clo (0.155 m²·K/W) for a general summer clothing and metabolic is 1 met (58.2 W/m²).

Predicted Mean Vote (PMV) model, the most recognized thermal comfort model, is used to analyse the thermal comfort for the conditioned spaces of the building. This model is developed by P.O.Fanger using heat balance equation in 1970. It has seven points scale from (-3) to (+3) equivalent to the thermal sensation from very cold to very hot. PMV equal to zero is representing thermal neutrality. Fanger also developed another equation to relate PMV to the Predicted Percentage of Dissatisfied (PPD). ASHRAE Standard 55-2017 uses PMV model to set the requirements for indoor thermal conditions. It requires that at least 80% of occupant be satisfied.

A room on the 4th floor of Block A is chosen for the thermal comfort analysis. This room is underneath the roof so we can easily see the impact of the roof-top PV to room’s indoor conditions. The simulation is carried out for a typical weather summer day. The results show some remarkable benefits of the building with roof-top PV over it without roof-top PV as follows:

- **Solar incident vs roof surface temperature**: as explained in previous section that the solar incident causes the increase of the roof’s temperature significantly. Figure 8 shows that with roof-top PV panel, the external roof surface’s temperature is decreased from 50.33°C (at 2pm) to 31.29°C (at 4pm). Similarly, the internal roof surface’s temperature is decreased from 38.68°C (at 5pm) to 28.82 °C (at 5pm). From this, we also see the time lag of both cases in thermal conductivity (at peak) through the roof which is composed of reinforced concrete and plaster layers. The internal roof surface’s temperature has impact to the thermal comfort as it is part of the radiant temperature which is discussed below.

- **Indoor temperatures vs Outdoor temperature**: Figure 9 shows the air, radiant and operative temperature in relation to the outdoor temperature. The radiant temperature is, defined by Wikipedia, the amount of radiant heat transfer from a surface. The radiant of a room is the mean radiant
temperature of all the its surfaces including walls, floor and ceiling. The operative temperature also called “equivalent temperature” or “effective temperature” is defined as the average mean radiant and ambient air temperature, weighted by their respective heat transfer coefficients. In a simplest form, it is the average of the air temperature and radiant temperature. As can be seen in Figure 9, in both cases with and without roof-top PV, the indoor temperature is always below the outdoor temperature. However, with roof-top PV, there is a smaller difference (max 3°C at 4pm) between the room’s air temperature and the mean radiant temperature while in the case without roof-top PV, the difference temperature can go up to 5.5°C at 5pm. The vertical air temperature difference also called “thermal stratification” that results in the air temperature at the head level being higher than at the ankle level may cause thermal discomfort. ASHRAE Standard 55 recommends that the difference not be greater than 3°C for seated occupants or 4°C for standing occupants.

![Figure 9. Solar incident vs roof surface temperature without (a) and with (b) roof-top PV installation](image)

- **Relative humidity**: Figure 10 shows the relative humidity in the building that has roof-top PV is higher than the case without roof-top PV. It is understandable as the higher the air temperature the more vapor water can be store. Therefore, with same amount of water vapor in the air, the higher air temperature has lower relative humidity.

![Figure 10. Relative humidity](image)

- **Thermal comfort**: the comfort zone is defined by the combination of the six parameters mentioned above for which the PMV is within the recommended limits (-0.5<PMV<+0.5). As shown on Figure 11, the building with roof-top PV has the PMV value varied from 0.51 (at 10 pm) to 1.31 (at 2pm) and without roof-top PV this value is lower and varies from 0.63 (at 11pm) to 2.05 (at 2 pm). It can be concluded that the roof-top PV panel has contributed at some degree to maintain the thermal comfort for the occupied spaces underneath. However, to secure the thermal comfort, we need to keep the
PMV value within range by adjusting the room’s setpoint accordingly to the outside conditions. It is necessary in the daytime.

- **Wind speed**: in the room that is cooling by the air conditioner, all the doors and windows are closed. The wind speed therefore is very small so that it is not considered in this case.

### 4. Conclusions

This paper has introduced our first assessments about impacts of roof-top solar photovoltaic modules on building energy performance in Vietnam, through a case study of a social apartment in HCM city. The results showed not only the potential photovoltaic power, but also the reduction of roof heat transfer. In consequence, the building cooling load and total energy consumption are significantly reduced thanks to roof-top PV installation. On the other hand, the reduction of solar incident on the building roof keeps cooling roof surface (outer and inner) and improving thermal comfort of attic space. For perspective, we will deeply study on each impact of solar panels to building energy performance and to power grid. Furthermore, our research will also contribute to the economic analysis on feasibilities of investment and life cycle cost of roof-top PV installation in Vietnam.

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