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Annual performance evaluation of thermoelectric generator-assisted building-integrated photovoltaic system with phase change material

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ABSTRACT

Owing to the economic recession due to the Coronavirus disease (COVID-19) pandemic, energy-efficient building retrofitting has been considered as an integrated solution to recover the economy and maintain global greenhouse gas reduction. As part of retrofitting existing building-integrated photovoltaic systems during building renovations, this study evaluated the energy generation potential of a thermoelectric generator-assisted building-integrated photovoltaic system with a phase change material. The combination of a thermoelectric generator and phase change material with photovoltaic systems results in solar cell temperature reduction and additional electricity output owing to the Seebeck effect, increasing the total generated energy from the system. Simulations of the proposed system were performed using MATLAB R2020a, based on transient energy balance equations. The appropriate melting temperature and thickness of the phase change material were derived to maximize the annual electricity generation of the proposed system from simulations of 12 design days in each month. The proposed system with the selected phase change material conditions exhibited a 1.09% annual increase in annual electricity generation of the proposed system from simulations of 12 design days in each month. The proposed system was performed using MATLAB R2020a, based on transient energy balance equations. The appropriate melting temperature and thickness of the phase change material were derived to maximize the annual electricity generation of the proposed system from simulations of 12 design days in each month. The proposed system with the selected phase change material conditions exhibited a 1.09% annual increase in generation output and 0.91%, –1.32%, 2.25%, and 3.16% generation improvements from spring to winter, compared with the building-integrated photovoltaic system alone. Theoretically, the proposed system is expected to generate 4.47% more energy by minimizing the thermal resistance of the system and improving thermoelectric generator performance.

1. Introduction

The coronavirus disease (COVID-19) pandemic has caused an unprecedented impact on global society. In the middle of the COVID-19 pandemic, many countries are facing an economic recession, and the global Gross Domestic Product (GDP) in 2020 indicated the steepest reduction by 5% to the previous year [1,2]. Meanwhile, global greenhouse gas emissions have declined for the first time since 2010, owing to COVID-paralyzed global industries [3]. However, these global greenhouse gas emissions are expected to increase again with industrial activities after the global COVID-19 issue. Therefore, an integrated solution is necessary that can simultaneously recover the global economy and maintain low levels of gas emissions.

The International Energy Agency (IEA) reported that energy efficient building renovation has considerable benefits in this pandemic situation as a measure for economic revival and reducing environmental impact [4]. Energy-efficient building renovation involves enhancing insulation of walls, generating electricity from buildings, and transforming existing buildings into nearly zero-energy buildings. This extensive building renovation policy is expected to cause a large-scale job demand in the market (Fig. 1 (a)). As a result of building retrofitting, cooling and heating energy consumption can be reduced (Fig. 1 (b)), and it is expected that the reduction in greenhouse gas emissions can be maintained.

In energy-efficient building retrofitting, renewable energy generation systems are installed in buildings to reduce the net energy consumption. Among these renewable energy systems, building-integrated photovoltaic (BIPV) systems are the most common generation systems that can be installed at exteriors. When solar radiation enters the semiconductor layers of photovoltaic (PV) systems, a current and voltage are produced from the electromotive force due to the discharged electrons, and electricity is stored in the battery. Recent studies have proposed solar cells with more than 20% and even 26% conversion efficiency [5–7]; however, the theoretical efficiency of single-junction solar cells is limited to approximately 30% [8]. To overcome this efficiency limitation, new technologies (e.g., multijunction solar cells and concentrating solar cells) have been proposed to achieve higher conversion efficiency [9–11].

However, as these novel technologies to enhance the electricity...
generation performance of PV systems have been developed in the laboratory field, available commercialized BIPV modules exhibit a low conversion efficiency of approximately 14% under standard test conditions. In addition, BIPV systems are generally vertically installed on the outer wall of buildings, receiving a smaller amount of solar radiation compared to PV systems with the annual optimal tilt. Thus, the total conversion efficiency of approximately 14% under standard test conditions, available commercialized BIPV modules exhibit a low performance of PV-TEG system. Kraemer et al. (2008) optimized the cutoff temperature (PV-PCM) system, PV-TEG-PCM system or even independent TEG-PCM system, PV-TEG-PCM system or even independent TEG-PCM system without PV generation.

To compensate the low power generation of PV system, a thermoelectric generator (TEG) has been applied to PV systems, converting waste heat from long-wavelength solar radiation into electricity [12]. Firstly, there was basic research to investigate the theoretical performance of PV-TEG system. Kraemer et al. (2008) optimized the cutoff wavelength to increase the integrated PV-TEG system efficiency, which has a 2.44-times higher conversion efficiency compared with the PV-only system [13]. Sark (2011) analyzed the efficiency of a PV-TEG system according to the figure of merit (Z) of a TEG from 0 to 0.01 [1/K], and the results indicated that the PV-TEG system exhibited an 8.9% higher conversion efficiency than the PV system under the given weather conditions (Malaga, Spain) [14]. Zhang et al. (2014) evaluated the generation performance of concentrating PV-TEG systems with solar cells based on four different materials, and the efficiency was improved in all cases [15]. Li et al. (2017) performed exergy analysis of a PV-TEG system under concentrated solar radiation, and the results indicated a higher exergetic efficiency of the integrated system and better electricity-converting performance under a high module temperature, in comparison with those of the sole PV module [16]. Li et al. (2019) optimized the length and dimensions of thermoelectric semiconductor legs to improve the power output of integrated systems [17]. Recent research also has proposed a novel generation system, detaching TEGs from the backside of PV. Zhang et al. (2021) developed a concentrating photovoltaic/thermal (PV/T) system with TEGs which is detached from PV back side. In the system configuration, since cold water from inlet tank and hot water from PVT outlet are placed at each side of TEG, this temperature difference increases power generation from TEG.

Despite of this generation potential of developed systems from previous research, with the good insulation performance of modern buildings [18] and low thermal conductivity of TEG [19], a low overall heat transfer coefficient of building walls causes an unexpected increase in the cell temperature of the BIPV system, reducing power generation [20–22]. In addition, the TEG conversion efficiency is relatively low compared with the PV system [23]. Several studies have shown that applying TEGs can decrease total power generation, compared with using PV modules alone when the solar cell efficiency reduction is larger than the thermoelectric electricity output [15,24,25]. Accordingly, in PV-TEG systems, it is important to avoid reduction of the PV efficiency and increase the TEG efficiency to achieve increased power generation compared with the PV system alone.

In terms of solar cell temperature reduction, phase change material (PCM) is an appropriate cooling source broadly used for PV systems [26, 27]. PCMs absorb solar radiation as a latent heat at a melting temperature, working as a cooling source with a lower temperature than the solar cell temperature [28]. Huang et al. (2006) compared the surface solar cell temperature of a PV-PCM integrated system and found that its temperature was reduced by approximately 30 °C during phase change, compared to a flat plate aluminum [29]. Hasan et al. (2010) compared PV-PCM systems having five different PCMs with the PV system, and the results indicated a 10% improved conversion efficiency with respect to the PV-PCM system and evaluated its 10% improved conversion efficiency with respect to the reference PV system [32]. In recent study of PV-PCM system,
Elsheniti et al. (2020) proposed a simplified model to predict conduction behavior of PCM with significantly high accuracy but short computational time compared with CFD model [33]. As a result, efficiency improvement of PV-PCM system according to different PCM thickness was derived, which indicated that to maximize performance of the system, using appropriate PCM thickness is critical.

Additionally, PCMs release their latent heat after sunset through night cooling; a TEG-PCM combined system can generate continuous electricity not only during daytime but also after sunset, owing to the latent heat released from the PCM. Thus, previous research has proposed

(a) Job creation potential from capital investment

(b) Employment and energy saving potential of building renovations

Fig. 1. Potential of building retrofit [4].
various TEG-PCM with different system concepts as an independent generation system. Tuoi et al. (2020) designed a compact generation system with TEG and PCM, which converts temperature difference between ambient temperature and PCM into electricity, and evaluated its power generation in the chamber with varying air temperature. In the results, the maximum power generation from the experiment was about 0.6 mW. Although the amount of power was small, which shows generation potential compared to the case without PCM [34]. Byron and Jeong (2020) developed a TEG-PCM generation system and the concept was an energy harvesting block, which can be installed in building walls. The experiment was performed according to the wall temperature profiles and the proposed energy harvesting block indicated maximal 0.15 W power output during the daytime phase change of the selected PCM [35]. As a further work, Byron and Jeong (2020) investigated the annual performance of the proposed energy harvesting block. Based on wall surface temperature, seasonal performance indicated that the highest power generation in winter due to the large temperature difference between wall and cold outdoor air [36]. Those results from previous research indicates TEG can continuously generate power when integrated with PCM, which can lead to supply electricity to wireless sensors in buildings [37].

Therefore, there are two main advantages of using a combined PV, TEG, and PCM (PV-TEG-PCM) system: cell temperature reduction and additional generation from the TEG. Cui et al. (2016) integrated a TEG and PCM with a concentrating PV system, and their results showed that approximately 10% of the total generation was improved in the integrated system: 9.8% from PV and 0.2% from TEG [38]. Yin et al. (2019) improved the output power of the PV-TEG-PCM system by improving the thermal conductivity of the PCM through addition of graphite and copper [39]. Darkwa et al. (2019) examined the generation performance of a PV-TEG-PCM system with a micro-encapsulated PCM (MEPCM) board and found a 9.5% improvement in power output compared to the PV-only system [40]. Motiei et al. (2019) evaluated the generation performance of integrated systems according to the melting temperature and thickness, based on the finite difference method, with the results indicating maximum power output at 34–36 °C melting temperature and 115 mm thickness under summer climatic conditions [41]. Naderi et al. (2021) proposed a generation system with different arrangement of components (PV-PCM-TEG) with reflector to increase solar insolation to the system [42]. As a result, the solar cell efficiency was improved by 1.38% with the application of PCM to the backside of photovoltaic. Moreover, the solar cell efficiency improvement was 1.66% in winter, which shows that the system potential is higher in winter than in summer.

Previous studies focused on identifying the generation performance of a PV-TEG-PCM system without combining a generation system with buildings. Thus, analysis of the annual generation performance and design conditions for a TEG-assisted BIPV with a PCM (BIPV-TEG-PCM) is rare. Therefore, it is necessary to evaluate the energy generation potential and thermal behavior of a BIPV-TEG-PCM system under annual outdoor conditions, not constant weather conditions. In this study, a BIPV-TEG-PCM system was assumed to be installed on the exterior of a building. As previous research implied that selecting certain melting temperature and thickness is critical for overall performance of the proposed system, appropriate annual PCM melting temperature and thickness conditions were determined via transient energy generation simulation based on design days. Therefore, the annual power generation performance of the BIPV-TEG-PCM system was evaluated under the selected annual PCM design condition.

2. System overview

The proposed BIPV-TEG-PCM system is shown in Fig. 2. The system comprises a BIPV panel, a series of TEGs, and a casing filled with PCM from the outdoor to the exterior wall. Similar to the existing BIPV system, the proposed system is installed at the exterior of buildings. Fig. 3 (a) shows a conceptual power generation schematic of the proposed system during daytime. When solar radiation reaches the solar cell, solar radiation with energy above the bandgap energy causes an electric potential difference, generating electricity via the PV effect [43] and the solar cell temperature increases owing to the unused radiation, generating waste heat. Then, the temperature difference between the solar cell of high temperature and the other side of the TEG at a low temperature produces an electromotive force that converts this heat transfer to additional electricity via the Seebeck effect [44]. When the PCM reaches its melting temperature, phase change occurs from solid to liquid. The heat flux into the system is accumulated as latent heat, while maintaining the PCM temperature near the melting temperature; therefore, the temperature difference between each side of the TEG can be sustained [41]. This latent heat absorption continues heat transfer from the PV layer to the PCM, increasing the power output from the TEG. Consequently, the PCM prevents solar cell temperature increase.
caused by the TEG installation [25] and maintains heat transfer through the TEG; thus, the PCM works as a cooling source, enhancing power generation in both the PV and TEG.

Fig. 3 (b) presents the nighttime power generation of the system without solar radiation. After sunset, the external surface of the system is mainly cooled by night long-wave radiation and outdoor air (OA) convection heat transfer. Stored sensible and latent heat of the PCM in the daytime is transferred to the solar cell layer through the TEG, and electricity is generated from the TEG during the PCM regeneration process. After the liquid-to-solid phase change, the PCM is ready to absorb daytime heat flux to prevent the generation performance degradation of the solar cell. Consequently, the proposed system can not only generate a major portion of electricity during daytime but can also supply continuous electricity at nighttime. In addition, the PCM works as a cooling source for solar cells, improving power generation performance compared with the sole BIPV system.

The melting temperature and thickness of the selected PCM determine the electricity generation of the system, thus affecting the solar cell temperature of the proposed system [30,41]. A PCM with a low melting temperature facilitates solar cell temperature reduction in the early hours through phase change, while usage of a high-melting temperature PCM results in a higher solar cell temperature before phase change, as in region A (Fig. 4). However, the low-melting temperature PCM prevents solar cell cooling after a full phase change from solid to liquid because of its low thermal conduction coefficient. In the later hours, the high-melting temperature PCM reduces the cell temperature with a later phase change, cooling the solar cell, as in region B. This cell temperature reduction directly increases the PV generation efficiency; thus, selecting the proper melting temperature of the PCM is an important design consideration to generate maximum electricity of the proposed system.

The thickness of the selected PCM also affects the PV power generation performance [31,41]. A thick PCM layer has large sensible and latent heat capacities. This large heat capacity can sustain a low solar cell temperature longer than that sustainable using a thin PCM layer, enhancing the total generated energy of the system. However, a high PCM thickness simultaneously reduces the overall heat transfer coefficient (U-value) of the PCM layer, which decreases the cooling performance of the PCM and electricity generation of the PV. Therefore, to maximize the energy generation of the system, an appropriate PCM thickness should be considered.

The melting temperature of a PCM is determined by its molecular structure; therefore, its thermal properties (e.g., density, conductivity, latent heat, and specific heat) depend on its chemical configuration [45] and the manufacturer’s design [46]. Because commercially available PCMs have different thermal properties, it is difficult to independently identify the effects of the phase change temperature and thickness on the power generation. Therefore, in this study, under the assumption that the PCM thermal properties can be modified to some extent in the production process, energy simulations of the proposed system for 12 design days were conducted on PCMs with the same thermal properties but with different melting temperatures and thicknesses. The melting temperature and thickness ranges were determined to select an appropriate PCM design condition that maximizes energy generation: melting temperature of 5–60 °C and thickness of 10–100 mm.

3. Methodology

3.1. Climatic condition

3.1.1. Design days

To identify the appropriate design conditions for maximizing annual electricity generation, 12 design days were derived that could represent the radiation and climatic conditions from hourly averaged data of each month obtained from IWEC2 (International Weather for Energy Calculation, Version 2) weather data of Seoul, Korea (Fig. 5). Derived hourly climatic data (i.e., direct normal irradiance, diffuse horizontal irradiance, OA temperature, and wind speed) were used for the simulation to evaluate the power generation performance of the proposed system [47].

3.1.2. Radiation transposition model

Because the proposed system is generally attached to the walls of
buildings, beam and diffuse radiation components determine the total solar irradiance to the system [48]. The diffuse radiation component is not affected by the position of the sun under an isotropic sky; however, the beam radiation component toward the proposed system depends on the solar altitude, solar direction, angle, and orientation of the system. Thus, hourly solar irradiance should be modified with the radiation transposition model to estimate the amount of irradiance to the system and its output electricity generation [49].

The total solar irradiance to the system surface is expressed by Eq. (1), assuming that the diffuse radiation is isotropic [50]. Here, the beam radiation component is determined using the direct solar irradiance to the horizontal surface ($I_b$) and geometric factor ($R_b$), while the diffuse component is determined from the diffuse solar irradiance ($I_d$) and the slope of the surface ($\beta$). Because BIPV systems have generally been installed vertically with respect to buildings [51], the surface angle of the proposed system was assumed to be vertical and south-facing to estimate the electricity and produced energy of the system, the system performance owing to the PCM (Eq. (5)) and geometric factor ($R$), while the diffuse component is the horizontal surface (buildings, beam and diffuse radiation components determine the total solar irradiance to the system [48]). The diffuse radiation component is

$$I_{total} = I_b R_b + I_d \left(1 + \frac{\cos \beta}{2}\right)$$  

$$R_b = \frac{\cos \theta}{\cos \beta}$$  

$$\cos \theta = -\sin \delta \cos \gamma + \cos \delta \sin \gamma \cos \omega + \cos \delta \sin \gamma \sin \omega$$  

$$\delta = 23.4 \sin \left(\frac{360 \times 284 + n}{365}\right)$$  

3.2. Thermal model

3.2.1. Proposed system

Because heat transfer through the proposed system can be analyzed by dividing the system into several layers, a one-dimensional energy simulation was performed using MATLAB R2020a [53] with the thermal network (Fig. 6). In each node of the thermal network, transient heat transfer equations were used to evaluate the time-dependent generation performance owing to the PCM (Eq. (5)–(10)), based on the thermal resistances of the layers (Eq. (11)–(18)) (Tables 2 and 3). In addition, to estimate the electricity and produced energy of the system, the system width and length should be determined from the reference PV module size ($1.0 \text{ m} \times 1.6 \text{ m}$) [54,55]. To determine the boundary air temperature, an air conditioning system was assumed to work continuously for the indoor environment, and the target room air temperature was determined according to the recommended thermal comfort range ($T_{th} = 26 \degree C$) [56]. The contact thermal resistance between each layer was neglected.

$$\frac{dT_{gls}}{dt} = \frac{\rho c_p A_{wall}}{R_{wall}} + \frac{T_{wall} - T_{sky}}{R_{sky}} + \frac{T_{OA} - T_{gls}}{R_{OA-gls}} + \frac{T_{T} - T_{sky}}{R_{sky}}$$  

$$\frac{dT_{w}}{dt} = \frac{\tau_{T} A_{wall}}{R_{wall}} + \frac{T_{wall} - T_{w}}{R_{sky}} + \frac{T_{TEG} - T_{sky}}{R_{sky}} - \eta_{T} \frac{T_{T} - T_{cold}}{R_{TEG}}$$  

$$\frac{dT_{doc}}{dt} = \frac{\tau_{DO} A_{wall}}{R_{wall}} + \frac{T_{wall} - T_{doc}}{R_{sky}} + \frac{T_{T} - T_{sky}}{R_{sky}} - \eta_{T} \frac{T_{T} - T_{cold}}{R_{TEG}}$$  

$$\frac{dT_{AL1}}{dt} = \frac{\tau_{AL1} A_{wall}}{R_{wall}} + \frac{T_{wall} - T_{AL1}}{R_{sky}} + \frac{T_{T} - T_{sky}}{R_{sky}} - \eta_{T} \frac{T_{T} - T_{cold}}{R_{TEG}}$$  

$$\frac{dT_{AL2}}{dt} = \frac{\tau_{AL2} A_{wall}}{R_{wall}} + \frac{T_{wall} - T_{AL2}}{R_{sky}} + \frac{T_{T} - T_{sky}}{R_{sky}} - \eta_{T} \frac{T_{T} - T_{cold}}{R_{TEG}}$$  

$$R_{sky-gls} = R_{sky} + \frac{R_{gls}}{2}$$  

$$R_{OA-gls} = R_{OA} + \frac{R_{gls}}{2}$$  

$$R_{0-g} = \frac{R_{0-g}}{2} + \frac{R_{w}}{2}$$  

$$R_{w-TEG} = \frac{R_{w}}{2} + \frac{R_{TEG}}{2}$$

Table 1

| Variable               | Value                          |
|------------------------|--------------------------------|
| Slope of surface ($\beta$) | 90° (Vertically installed)   |
| Latitude ($\phi$)       | 37.5° (Seoul, South Korea)    |
| Surface azimuth angle ($\gamma$) | 0° (South facing)            |
In the glass layer, some short-wave solar radiation is absorbed, and the temperature of the glass changes through long-wave radiation with the sky temperature which is approximated with the equation from a previous study (Eq. (20) [66]).

\[ T_{sky} = 0.0552 \times (T_{OA} + 273.15)^{1.5} - 273.15 \]  

(19)

\[ h_{OA} = 2.8 + 3.0 \times V_{wind} \]  

(20)

### 3.2.3. Solar cell layer

The entire solar cell layer can be assumed to comprise four different layers except the glass cover [60,61]. To evaluate the temperature change in the middle of the solar cell, the total capacity and total conductivity are used, given by Eqs. (21)–(22).

\[ C_{sc} = A_{mod} \left( \rho_{p} \gamma_{sc} \delta_{sc} A_{mod} \right) + \rho_{EVA} \gamma_{EVA} \delta_{EVA} A_{mod} + \rho_{AL} \gamma_{AL} \delta_{AL} A_{mod} + \rho_{Al} \gamma_{Al} \delta_{Al} A_{mod} \]  

(21)

\[ k_{sc} = \frac{A_{mod}}{\frac{\delta_{sc}}{\rho_{p} \gamma_{sc}} + \frac{\delta_{EVA}}{\rho_{EVA} \gamma_{EVA}} + \frac{\delta_{AL}}{\rho_{AL} \gamma_{AL}} + \frac{\delta_{Al}}{\rho_{Al} \gamma_{Al}}} \]  

(22)

### Table 3

**System layers, EVA: Ethylene Vinyl Acetate.**

| Layer          | Material          | Density (\(\rho\)) [\(\text{kg/m}^3\)] | Specific heat (\(c_p\)) [\(\text{J/kg}\)] | Conductivity (\(k\)) [\(\text{W/m-K}\)] | Thickness (\(d\)) [\(\text{m}\)] | References |
|----------------|-------------------|----------------------------------------|----------------------------------------|----------------------------------------|---------------------------------|------------|
| Glass layer    | Glass             | 3000                                   | 500                                    | 1.8                                    | 0.003                           | [57,58]    |
| Solar cell layer| Solar cell        | 2330                                   | 677                                    | 148                                    | 0.000225                        | [57,59,60] |
|                | EVA               | 960                                    | 2090                                   | 0.35                                   | 0.0005                          | [59,60]    |
|                | Aluminum sheet    | 2700                                   | 910                                    | 205                                    | 0.00001                         | [61,62]    |
|                | Tedlar            | 1200                                   | 1250                                   | 0.2                                    | 0.0001                          | [57,59]    |
| TEG layer      | TEG               | 92.74                                  | 798.4                                  | 0.92                                   | 0.004                           | [63]       |
| PCM layer      | Front/back aluminum casing | 2700                            | 910                                    | 205                                    | 0.0005                          | [61,62]    |
|                | Solid MEPCM       | 829                                    | 1789                                   | 0.382                                  | Parametric variable             | [63]       |
|                | Liquid MEPCM      | 819                                    | 2153                                   | 0.203                                  |                                 |            |
When solar radiation enters the solar cell layer, the solar cell converts the radiation into electric power via the PV effect. This generated power can be calculated using the PV efficiency under standard test conditions (STCs) and the corresponding temperature [66]. As the solar cell temperature increases, the inner electric resistance of the PV module increases [67], decreasing the power generation efficiency determined by the PV module performance in Eq. (23). In the simulation, the PV efficiency under STC and the temperature coefficient were determined ($\eta_{PV} = 0.14$, $\eta_T = -0.0043$), considering the efficiency of a commercial PV panel [68]. The power output from the PV can be estimated using Eq. (24), based on irradiance into the module, area of the module, and conversion efficiency.

$$P_{sc} = I_{AM0} \eta_{AM} \eta_{AM0}$$  \hspace{1cm} (24)

### 3.2.4. Thermoelectric generator

The TEG of the system converts conduction heat transfer from the solar cell layer to the PCM layer into electric power. The maximum efficiency of the TEG can be determined using the dimensionless figure of merit (ZT) of the selected material [19] [25]. Generally, Bi$_2$Te$_3$ is the most common material used for TEGs; the ZT value in the proposed system was assumed to be 1 [14], considering ZT values from previous studies on thermoelectric module applications [69–73]. According to the obtained conversion efficiency, the lumped output power from the TEG layer was estimated via Eq. (26).

$$\eta_{TEG} = \left(1 - \frac{T_{cold}}{T_{hot}} + 273.15\right) \times \left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{\sqrt{1 + ZT}}{273.15}}\right)$$  \hspace{1cm} (25)

$$P_{TEG} = \eta_{TEG} \dot{Q}_{loss} = \eta_{TEG} \times A_{mod} \frac{T_{hot} - T_{cold}}{R_{TEG}}$$  \hspace{1cm} (26)

### 3.2.5. Phase-change material layer

In general, the commonly used PCM causes problems in the PCM casing because the PCM can easily flow out of the casing. In the proposed system, MEPCM particles were applied in the system to prevent unintentional temperature variance of solar cells and leakage [74]. Particle-type MEPCM has a rare effect owing to natural convection [75], and only heat-type MEPCM was considered in the heat transfer equations.

During the phase change process from solid to liquid, the thermal properties (e.g., heat capacity, conductivity, and density) of the PCM change. The behavior of thermal properties during phase change was analyzed using the effectiveness heat capacity method, considering the latent heat of the selected PCM as the equivalent heat capacity [76]. The thermal conductivity and density of the PCM change depending on the second-order liquid fraction function (Eq. (27)–(28)). The heat capacity of the PCM is defined by its latent heat capacity (Eq. (29)–(31)), depending on the delta function, which describes the distribution of latent heat during the phase change process [77].

In this research, MEPCM which consists of the hexadecane (C$_{16}$H$_{34}$), was filled in the PCM casing, and the latent heat of the selected MEPCM and the melting temperature range were determined from Wang and Niu [63] ($L_p = 196.000\text{ J/kg}$) and Darkwa et al. [40] ($\Delta T = 6^\circ\text{C}$). The coefficients of the polynomial equation (Eq. (31)) were derived from the following boundary conditions:

$$k(T) = k_0 + (k_1 - k_0)f(T)$$  \hspace{1cm} (27)

$$\rho(T) = \rho_0 + (\rho_1 - \rho_0)f(T)$$  \hspace{1cm} (28)

$$c_p(T) = c_{p0} + (c_{p1} - c_{p0})f(T) + L_{PCM}D(T)$$  \hspace{1cm} (29)

$$f(T) = \frac{\sum_{i=0}^{n} a_i T^i}{\sum_{i=0}^{n} a_i T^i}$$  \hspace{1cm} (30)

$$D(T) = \frac{\left[T(T) - T_{cold}\right]}{\left[T(T) - T_{hot}\right]}$$  \hspace{1cm} (31)

$$f(T) = f(T_s) = f^*(T_s)$$  \hspace{1cm} (32)

### 3.2.6. Reference system

To compare the proposed system with the reference case, a BIPV system was selected as the reference system. In the reference system, only the PV module was installed on the exterior wall. The solar cell temperature was determined from the transient heat transfer equations (Eq. (23)–(35)). According to the obtained solar cell temperature, the conversion efficiency and generated power were calculated using only the BIPV system (Eq. (23)–(24)).

$$\frac{dT_{Sc}}{dt} = \frac{I_{AM0}A_{Sc}}{R_{tot}A_{Sc}} + \frac{T_{Sc} - T_{hot}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}}$$  \hspace{1cm} (33)

$$\frac{dT_{Sc}}{dt} = \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}} + \frac{T_{sc} - T_{cold}}{R_{sc}A_{Sc}}$$  \hspace{1cm} (34)

$$R_{sc}A_{Sc} = \frac{R_{sc}}{2} + R_{wall}$$  \hspace{1cm} (35)

Because there are no clear design guidelines for the PCM properties of the proposed system, it is necessary to identify the appropriate melting temperature and thickness of the PCM to maximize power generation. In this study, the following simulations of 12 design days were first implemented with various PCM conditions, as in Section 4.1: melting temperature of 5–60 °C and thickness of 10–100 mm, without thermal property change. Then, the annual power generation potential of the proposed system was evaluated according to the derived PCM condition in the following sections.

### 4. Results

#### 4.1. Appropriate annual PCM design conditions

From the simulations for 12 design days, to select the PCM design condition expected to create the most amount of energy, the generated energy of the proposed system was summarized according to PV generation, TEG generation, and total generation (Eq. (36)–(39)).

$$E_{PV} = \sum_{design\ days}\left(\int P_{PV} dt\right)$$  \hspace{1cm} (36)

$$E_{TEG,daytime} = \sum_{design\ days}\left(\int P_{TEG,daytime} dt\right)$$  \hspace{1cm} (37)

$$E_{TEG,nighttime} = \sum_{design\ days}\left(\int P_{TEG,nighttime} dt\right)$$  \hspace{1cm} (38)

$$E_{net} = \sum_{design\ days}\left(\int (P_{PV} + P_{TEG}) dt\right)$$  \hspace{1cm} (39)

Fig. 7 shows the total energy produced from the PV during the 12 design days. As the thickness of the PCM increases, the power generation increases accordingly; however, if the thickness increases beyond a certain degree, the power generation decreases. This is because a thin PCM has small sensible and latent heat capacities owing to its thickness, causing a solar cell temperature increase without a time-lag effect. Meanwhile, a highly thick PCM increases the heat transfer resistance as the conduction resistance increases, which decreases the cooling effect.
of the PCM for the solar cell.

If the melting temperature is too high, the PCM layer cannot undergo a full phase change process, which reduces the cooling effect from phase change. However, when the melting temperature is too low, the phase change process ends too early; thus, the PCM cannot work as a cooling source after the middle of the day. This is because the PCM temperature cannot be sustained after the phase change. According to the summarized generation result (Fig. 7), the PCM with a specific melting temperature range (30–45°C) facilitates high energy generation. This is because the total generation energy depends mostly on design days with high radiation (spring to summer), and an appropriate melting temperature condition for these seasons results in high generation performance.

Fig. 8 (a) shows the generated energy from the TEG in the daytime with solar radiation and the nighttime without solar radiation. The TEG power generation increase depends on the heat flux from the temperature difference between the hot and cold sides. A thin PCM cannot sustain a temperature difference for a long period due to its small heat capacity, reducing heat flux through the TEG and power generation. However, an excessively thick PCM also increases thermal resistance to the PCM layer, reducing the total heat transfer between the solar cell and PCM layer as well as the power generation. Therefore, under extremely high melting temperatures, the PCM cannot undergo phase change, reducing the time the temperature difference is maintained between the solar cell and PCM layer. For very low melting temperatures, the hot-side temperature is too low during the phase change process, reducing the energy generation efficiency of TEG.

The maximum generated energy at nighttime (Fig. 8 (b)) is indicated at a slightly higher melting temperature, compared with the daytime results (Fig. 8 (a)). In the PCM with a high melting temperature, a phase change occurs at a late time of the day, which is disadvantageous in maintaining the temperature difference between both sides during the daytime; however, it is possible to obtain a higher TEG power generation efficiency due to the rather high temperature of the hot side of the TEG after the sunset.

Fig. 9 indicates the total generated energy from the PV and TEG for the 12 design days. The maximum generation output is indicated at the melting temperature of 35°C and thickness of 30 mm. This design condition was determined from the heat absorption capacity and thermal resistance between the solar cell and the PCM.

4.2. Annual energy generation

From the energy summary of the design days shown in Fig. 9, the appropriate annual PCM design conditions indicating the greatest generation improvement could be derived: melting temperature of 35°C and thickness of 30 mm. According to the PCM design conditions, a yearly energy generation simulation of the proposed system was performed, and the results were compared with those of the reference system. The daily solar cell temperature and power generation profile were introduced for approximately four days in each season. The annual total energy generation was evaluated according to season and according to the total generation.

Fig. 10 shows the solar cell temperature of the proposed system and the reference system during the middle of each season in the annual simulation. Solar cell temperature reduction was maintained for 77%,
Fig. 10. Daily cell temperature reduction, OA: outside air.

Fig. 11. Daily power generation.
31%, 55%, and 70% of the daytime for the spring to winter days. During early hours, there is a solar cell temperature reduction of the proposed system compared with the reference system, indicating a slight improvement of the solar cell efficiency of the proposed system. With the cooling effect from the PCM phase change, this cell temperature was maintained lower than that of the BIPV system until late afternoon. Afterward, the solar cell temperature of the BIPV system decreased slowly owing to the higher heat capacity of the proposed system with the PCM than the BIPV system alone, which caused the hot side and cold side temperatures to reverse, generating additional electricity from the TEG. Furthermore, long-term solar cell temperature reduction occurred in spring, autumn, and winter; however, on summer days, the selected PCM of the proposed system could not regenerate into the solid state because of the high OA temperature. Thus, the solar cell temperature of the proposed system is even higher than that of the reference system for a longer period, as the selected PCM cannot effectively absorb the solar irradiance (Fig. 10 (b)). This solar cell temperature increase can result in a slight decrease in annual energy generation with low solar cell conversion efficiency.

Owing to the improved conversion efficiency of the solar cell with temperature reduction, the proposed system also produces a higher PV power output during daytime, compared with the BIPV system (Fig. 11). Moreover, the TEG generates additional electricity with an increase in solar radiation and the nighttime temperature difference between each TEG side. With improved solar cell conversion efficiency and additional electricity generation, the proposed system has improved annual energy generation, as described in the following section. Although the days of spring, autumn, and winter exhibited higher PV power outputs in the peak generation hour, the summer day exhibited lower PV generation, compared with those in the reference system at 12:00 (Fig. 11 (b)). Thus, it is expected that the energy generated by the proposed system may be lower than that of the reference system in summer.

Regarding the seasonal generation comparison shown in Fig. 12 (a), the proposed system demonstrated 0.91%, 1.32%, 2.25%, and 3.16% improved energy generation performances in the spring, summer, autumn, and winter, respectively, compared with the reference system. In most seasons, the energy output of the proposed system was higher than that of the reference with the temperature reduction of the PCM at early times in the days and additional TEG generation.

However, especially in summer, the total energy from the proposed system was lower than that of the reference system. Fig. 12 (b) indicates monthly energy generation improvement of the proposed system according to various OA temperature conditions. The improvement ratio and monthly average OA temperature shows negative relationship, which means that the generation performance of the proposed system can be inferior than that of the reference system under the high OA temperature condition. As previously mentioned, this is because the high OA temperature of summer reduced heat transfer from the PCM to surroundings in the nighttime, delaying the PCM regeneration process. Continuous exposure to these high OA temperature makes that the PCM
was not fully regenerated and could not act as a passive cooling source with phase change. Thus, the not fully regenerated liquid-state PCM only raises the thermal resistance of the backside of PV panel, which increases the solar cell temperature and reduces the temperature difference between the sides of the TEG. This causes a reduction in the power conversion efficiency of PV and TEG during summer, resulting in the lower produced energy from the proposed system than the reference system.

Fig. 13 shows the summarized annual energy generation of the proposed system. The proposed system produced 197.39 kWh of energy from a 1.6 m$^2$ system module, indicating 1.09% increased generation compared with the reference system: 0.18% from TEG and 0.91% from PV. This low generation improvement was due to the energy output decrease in the summer as described above, although the average energy output improvement rate was 2.11% in spring, autumn, and winter.

5. Discussions

The total generation improvement of the proposed system compared with the BIPV system was approximately 1% in the performed simulation (Fig. 13). There are two reasons for this low improvement while combining BIPV, TEG, and PCM.

The first reason is the low generation performance of the TEG. The power conversion efficiency of a TEG depends on its figure of merit ($ZT$), which is theoretically defined by Eq. (40), where $\sigma$, $S$, and $k$ are the electrical conductivity, Seebeck coefficient, and thermal conductivity, respectively. In the simulations, the $ZT$ value of the TEG was assumed to be 1.0, considering the general performance of commercialized TEGs [78], which still exhibit low performance under ideal conditions. If the $ZT$ value increases with an increase in $S$, the system generation performance can be improved. The theoretical ideal TEG conversion efficiency can be assumed to be the efficiency of the Carnot engine as $ZT \rightarrow \infty$ (Eq. (41)).

$$ZT = \frac{\sigma S T}{k}$$  \hspace{1cm} (40)

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{cold}} + 273.15}{T_{\text{hot}} + 273.15}$$  \hspace{1cm} (41)

Additionally, there is no component such as a fin or heat pipe in the PCM casing to improve the heat transfer rate from the solar cell to the PCM. The thermal equation based on thermal resistance can be described with the overall heat coefficient and heat transfer area. In the given system schematic, there was no additional area to increase heat transfer for the PCM, causing high thermal resistance from the casing to the PCM ($R_{\text{AL-PCM}}$). A high thermal resistance decreases the solar cell temperature reduction performance of the PCM, as well as the temperature difference between the sides of the TEG, which results in decreased PV and TEG power outputs. Thus, if a fin/heat pipe is used to increase the heat transfer area and the coefficient ($UA$) is applied to the proposed system, both the PV and TEG generation outputs can be improved (Eq. (42) [79]). Assuming that an ideal fin/heat pipe design is used, the thermal resistance ($R_{\text{AL-PCM}}$) can be nearly zero with an ideal large heat transfer coefficient and area.

$$\dot{Q}_{\text{PCM}} = UA(T_{\text{AL}} - T_{\text{PCM}}) = \frac{T_{\text{AL}} - T_{\text{PCM}}}{R_{\text{AL-PCM}}}$$  \hspace{1cm} (42)

Therefore, the ideal generation potential of the proposed system can be evaluated under the assumption of ideal TEG generation performance and minimal thermal resistance ($\dot{Q}_{\text{TEG}} = \eta_{\text{Carnot}} R_{\text{AL-PCM}} \approx 0$). Fig. 14 shows the ideal annual energy generation potential with the same melting temperature and PCM thickness condition ($T_{\text{melt}} = 35^\circ \text{C}, D_{\text{pcm}} = 30 \text{ mm}$) as those corresponding to the previous result. The ideal proposed system generates 204.0 kWh from a system module, compared with the reference system. This result indicates that the ideal improvement potential is approximately 4.47% when combining TEG and PCM compared with the BIPV system alone. Although the proposed system with current performance can only improve the annual energy generation by approximately 1%, it is expected that the generation performance of the proposed system can be further increased with additional studies to decrease the thermal resistance to the PCM layer and improve the TEG generation performance. In addition, because the theoretical generation potential was derived under a selected PCM melting temperature and thickness condition, there is a limit to the amount of latent heat that can be stored. Thus, this generation potential can be improved by minimizing the thermal resistance if a larger PCM volume is employed.

6. Conclusion

The IEA report states that building renovation policies have significant economic resilience and environmental benefits, which can be used to recover from the economic damage due to the COVID-19 crisis. In this study, a thermoelectric generator-assisted building-integrated photovoltaic system with a phase change material (BIPV-TEG-PCM system) was proposed to improve the energy-generating efficiency of the existing building-integrated photovoltaic system. The proposed system has two main advantages: reduction in solar cell temperature with the cooling
effect from the phase change material and additional electricity generation from the thermoelectric generator. The energy generation of the proposed system was compared with that of the existing system. The simulations were performed for a single south-facing system module based on transient energy balance equations using MATLAB R2020a. Appropriate annual melting temperature and thickness design of the phase change material were analyzed for design days from each month, and then, the annual energy generation performance was evaluated.

According to the simulation results, the proposed system generated 1.09% (0.18% from thermoelectric generator and 0.91% from photovoltaic) more energy than the sole building-integrated photovoltaic system. Furthermore, regarding seasonal generation, it was revealed that the proposed system generated 0.91% more energy in spring, –1.32% in summer, 2.25% in autumn, and 3.16% in winter, compared with the reference system. The reason of efficiency reduction in summer was resulted from the fact that PCM was not regenerated enough due to the high outdoor air condition, so that PCM was not able to absorb solar insolation.

Although the additional energy generation of the proposed system was small, the produced energy could be increased by improving the figure of merit (ZT) value of the thermoelectric generator as well as reducing the thermal resistance to the phase change material. Under the ideal design condition, the proposed system generated 4.47% more energy than the reference system. To achieve this ideal energy generation potential, further research should be conducted on the thermoelectric generator performance improvement and incorporation of heat sink designs such as fin and heat pipes into the phase change material casing.

Credit author statement

Jinyoung Ko: Conceptualization, Methodology, Data curation, Writing original draft preparation. Jae-Weon Jeong: Supervision, Validation, Reviewing and Editing.

Declaration of competing interest

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

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