Evaluation of annual performance for building-integrated photovoltaics based on 2-terminal perovskite/silicon tandem cells under realistic conditions

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Abstract
The authors optimized the thickness of the layers in the 1.67-eV-bandgap-perovskite sub-cell of a 2-terminal perovskite/silicon monolithic tandem solar cell under standard test conditions to get the current matching between the top and the bottom sub-cells. Based on that optimized structure of the tandem cell, we characterized, calculated, and analyzed the annual output energy and the annual efficiency of the tandem cells on the facades and the rooftop of buildings under realistic conditions composed of module temperature, realistic illumination irradiance, and incident angle directly measured in Gifu, Japan in 2015. Consequently, the obtained annual output energy is 279.52, 238.89, 129.99, and 115.21 kWh/m² with the corresponding annual efficiency of 22.42%, 19.70%, 10.50%, and 9.19% for the tandem solar cells mounted on the rooftop, the south, east, and west facades of the buildings, respectively. Thus, the rooftop and the south face of the buildings are the preferred directions for the BIPV application to gain higher energy.

KEYWORDS
actual irradiance, BIPV, GenPro4, incident angle, perovskite, tandem

1 | INTRODUCTION
A perovskite/silicon monolithic tandem solar cell is a promising candidate for increasing the photovoltaic (PV) cell’s efficiency and reducing PV energy costs. Its top and bottom cells are electrically connected in series through a tunnel recombination junction (TRJ). Compared with a 4-terminal perovskite/silicon tandem cell, a 2-terminal tandem cell has only one top transparent electrode, which lowers manufacturing costs resulting in less parasitic absorption in non-active layers. That is the reason why the 2-terminal tandem cell has a high practical potential of photon conversion efficiency.

Building-integrated photovoltaics (BIPV) is considered an emerging PV application. The PV, which replaces the traditional building parts such as roof, especially window, and wall, generates power for the buildings and prevents the buildings from the adverse external environmental factors, such as temperature, moisture, dust, and wind, simultaneously produces comfortable indoor environment. So far, many kinds of materials for solar cells were utilized for BIPV application, such as crystalline silicon, cadmium telluride,
perovskite,
dye-sensitized,
quantum dot, and organic-polymer.
Some works were researched on the energy yield harvested by the tandem solar cells.\textsuperscript{9–12} Besides, a few publications presented the energy yield of perovskite single-junction under realistic conditions with actual outdoor data.\textsuperscript{13,14} However, their solar cell performances are still limited. Furthermore, no publications have reported the annual BIPV yield based on the tandem cell technology under realistic conditions. As mentioned above, the 2-terminal tandem solar cell can be a high potential candidate in terms of efficiency for BIPV. To apply the 2-terminal tandem solar cell to BIPV effectively, it is worth determining and optimizing the 2-terminal tandem cell structure, especially the tandem solar cell orientation on the facades of buildings and assessing the impact of realistic factors composed of temperature, solar illumination irradiance, and the angle of incident light on the tandem performance. Typically, the 2-terminal perovskite/silicon heterojunction (SHJ) monolithic tandem solar cell was simulated and optimized numerically under the AM 1.5 G spectrum\textsuperscript{15} with the direction of the sunlight perpendicular to the solar cell at a room temperature of 300 K (standard test conditions). However, the realistic solar illumination irradiance, its incident angle to the solar cells, the solar module temperature changes over time, depending on the sun’s orientation, the solar cell’s installation direction, and the atmospheric properties. Therefore, the monthly, and annual solar cell yields are significantly influenced and varied.

In this study, we use a MATLAB-based GenPro4 program to numerically maximize the photocurrent density of a 2-terminal perovskite/SHJ monolithic tandem solar cell under the standard test conditions (AM 1.5G, 1000 W/m\textsuperscript{2}, room temperature) by adjusting the thickness of all layers in the 1.67-eV-bandgap-perovskite top cell.\textsuperscript{16} It is known that the perovskite top cell’s optimal bandgap energy in conjunction with Si bottom cells is in a range of 1.65–1.7 eV.\textsuperscript{12} However, Aydin et al. revealed that the ideal perovskite bandgap in the 2-terminal perovskite/c-Si tandem cell for the outdoor performance at operational temperatures of more than 55°C should be less than 1.68 eV.\textsuperscript{17} Due to the lack of experimental complex refractive index data (n, k) of various perovskite bandgap, we decided to utilize the perovskite bandgap of 1.67 eV for the simulations in this study. Then, the tandem solar cell’s electrical characteristics composed of open-circuit voltage (\(V_{oc}\)), fill factor (FF), and efficiency (\(\eta\)) are extracted based on an electrical simulation method. This study also evaluates the effect of illumination irradiance, incident angle, and solar module temperature on tandem performance. Significantly, the authors calculate the annual output energy, the annual efficiency of the 2-terminal tandem cells on the rooftop, the south, east, and west facades of the buildings under the realistic conditions (temperature, realistic spectral illumination, and incident angle) in Gifu (the latitude of 35.42° N, the longitude of 136.76° E), which is almost a center location of Japan. Finally, this study assesses and discusses the 2-terminal tandem cell’s applicability to BIPV.

### 2 | DEVICE STRUCTURE AND SIMULATION METHODOLOGY

#### 2.1 | Structure of a 2-terminal perovskite/SHJ tandem solar cell

The 2-terminal perovskite/SHJ tandem monolithic solar cell structure in this study is illustrated in Figure 1A. The tandem structure consists of two top (perovskite) and bottom (SHJ) solar sub-cells connected in series via a middle TRJ layer. The design of the perovskite top cell consists of a lithium fluoride (LiF) antireflective coating (ARC), an indium tin oxide (ITO) front contact, an electron transport titanium oxide (TiO\textsubscript{2}), a 1.67-eV-bandgap-perovskite absorber, and a hole transport contact layer.
and p⁺ doped a-Si:H layers, the n-type crystalline silicon (c-Si) absorber (wafer), i and p⁺ doped a-Si:H layers, and a silver (Ag) rear contact. The TRJ layer, which is based on the TRJ model of thin-film silicon tandem solar cells, consists of p-type hydrogenated microcrystalline silicon oxide (p-μc-Si₁₋ₓ Oₓ:H) and a-Si:H(n). Note that all interfaces in our simulations were considered to be optically flat, which does not scatter any sunlight. The p-i-n device architecture for the tandem solar cells is currently the regular structure. However, this study studied the n-i-p device architecture because it has the advantage of much thinner electron-selective contacts, leading to less parasitic absorption, hence higher photocurrent densities (J_ph). This point was briefly summarized and presented in the literature.

### 2.2 Optical simulation method

The 2-terminal tandem cell structure is optically simulated and optimized with the GenPro4 program based on the extended net-radiation method. The J_ph values of different layers are estimated according to the following equation:

\[
J_{ph,i} = -q \int_{350\text{nm}}^{1200\text{nm}} A_i(\lambda) \Phi(\lambda) d(\lambda),
\]

where q, A_i, \Phi, and \lambda are the electron charge, the absorption spectrum of the ith layer, photon flux, and wavelength, respectively.

The J_ph of the tandem cell is a minimal value between two J_ph values in the top and bottom absorbers due to the current matching condition in the monolithic tandem solar cell. In this study, we maximized the J_ph of the tandem cell by adjusting the layers’ thickness of the perovskite sub-cell, while the thickness of all layers in the SHJ sub-cell was kept constant, as depicted in Figure 1A. Also, we utilized the particle swarm algorithm, which is integrated with the MATLAB Global Optimization Toolbox to perform the optimization. The boundary conditions of layer thicknesses used for the optimization are listed in Table 1. The optimization goal is to minimize the current mismatching value expressed by the following equation:

\[
J_{mis} = |J_{ph} - J_{top} - J_{bottom}|.
\] (2)

The refractive index, extinction coefficient (n, k) data and absorption coefficient spectra of all the materials in the 2-terminal perovskite/SHJ tandem solar cell are taken from literature: LiF, ITO, TiO₂, 1.67-eV-perovskite, Spiro-OMeTAD, p-μc-Si₁₋ₓ Oₓ:H, p⁺ a-Si:H, a-Si:H(i), c-Si, n⁺ a-Si:H (see Figure S1).

In this study, we also took the angle of incident light into account for the GenPro4-based optical simulation processes. Thereby, the incident angles are divided into 30 angular intervals (from interval 1: 1° to interval 30: 87°–90°). A from-0°-to-87° range of the incident angle are examined in our simulations since the incident light can be completely reflected with the incident angle more than 87°.

### 2.3 Electrical simulation method

The solar cell’s J-V curve could be generated by an equivalent electrical circuit based on the parameters of a current source characterized by a photo-current density J_ph, a diode with ideality factor (n_i) characterized by saturation current density (J₀), and series (R_s) and shunt (R_sh) resistances. If the above parameters are provided as the input data, the solar cell’s electrical characteristics composed of V_oc, FF, maximum power (P_max), and η will be calculated by the single-diode equation. The parameters of n_i, J₀, R_s, and R_sh, which were fitted and extracted from the experimental solar cell’s J-V curves in the 2-terminal perovskite/SHJ tandem solar cells reported by Al-Ashouri et al. in recent literature were

| Layer          | Minimum thickness (nm) | Maximum thickness (nm) | Optimum thickness (nm) |
|---------------|------------------------|------------------------|------------------------|
| LiF           | 80                     | 130                    | 100                    |
| ITO           | 80                     | 100                    | 82                     |
| TiO₂          | 10                     | 30                     | 10                     |
| Perovskite    | 400                    | 700                    | 689                    |
| Spiro-OMeTAD  | 10                     | 50                     | 14                     |
| p-μc-Si₁₋ₓ Oₓ:H | 30                     | 80                     | 76                     |

TABLE 1 The boundary conditions and the obtained optimum values of layer thicknesses of the perovskite cell in the optimization procedure by the particle swarm algorithm.
utilized as the input parameters in our simulation. The tandem cells’ corresponding fitted characteristics were estimated as shown in the Supporting Information. Their report presented a monolithic 1.68-eV-bandgap-perovskite/c-Si tandem cell configuration that has achieved an efficiency of 29.15%. In our simulations, the 1.67-eV-bandgap-perovskite top and c-Si bottom sub-cells’ values of $R_{sh}$, $R_s$, and $n_{tp}$ were assumed to be similar to that in the above report. The values of the input parameters utilized in this study are listed in Table 3. Herein, the $R_s$ value (3.834 $\Omega$cm$^2$) of the bottom sub-cell in the tandem cell is considerably high because it is composed of the $R_s$ values in the single SHJ cell and the TRJ (see Figure S2 and Table S1). The $J_0$ values were estimated by Equation (11) of Supporting Information from the $J_0$ values of the above report. The temperature dependence of $J_0$ is shown in Figure S3A.

The $V_{oc}$ values of the top and bottom sub-cells are given as the following equation:

$$V_{oc} = \frac{n_{tp}kT}{q} \ln \left( \frac{J_{sc}}{J_0} + 1 \right), \tag{3}$$

where $k$ is the Boltzmann constant and short-circuit current density ($J_{sc}$) of the tandem cell is attributed to be equal to $J_{ph}$, taken from our optical simulation result. The tandem cell $V_{oc}$ is the sum of the $V_{oc}$ values in the two sub-cells.

The FF values of the two sub-cells are estimated by Equation (4), as proven in the electrical simulation method of the Supporting Information:

$$FF = FF_0 \left( 1 - r_s - \frac{1}{r_{sh}} \right), \tag{4}$$

where $FF_0$, $r_s$, and $r_{sh}$ are the fill factor without additional charge transport losses estimated by an empirical expression,30 normalized series resistance, normalized shunt resistance, respectively. These parameters are described in Supporting Information in detail.

The $P_{max}$ and $\eta$ values can be attained by the following equation:

$$P_{max} = FF \times J_{sc} \times V_{oc}; \quad \eta = \frac{P_{max}}{P_{illumin}}, \tag{5}$$

where $P_{illumin}$ is the solar illumination irradiance.

In this study, the solar module temperature dependence of bandgap ($E_g$), $J_0$ of the perovskite and SHJ solar cells were also considered to estimate the tandem solar cell performance. Thereby, the $E_g$ values of the perovskite and c-Si absorbers are estimated by the Tauc formula with their temperature coefficients of $E_g$ ($dE_g/dT$) taken from literature17,31 (see Supporting Information). The temperature dependence of $E_g$ within a various range of 300–360 K is illustrated in Figure S3B. The perovskite $E_g$ value increases linearly within a temperature range of solar cell operation,17,32 while the c-Si $E_g$ values decrease linearly versus temperature.33,34 In our simulations of the temperature dependence of the $J_{sc}$, the optical parameters of the perovskite and c-Si absorbers taking into account the temperature dependence of the $E_g$ values were generated by shifting their original optical parameters34,25 into the blue and red wavelengths, respectively (see Figure S4). Thereby, the tandem cell $J_{sc}$ values dependent on temperature were simulated optically.

### 2.4 Numerical simulation and calculation under the realistic conditions

The angle of the incident light toward the solar cell plane depends on time, date, the cell location (latitude and longitude), the cell orientation (tilt angle, azimuth angle), as shown in Figure 1B. The sunlight’s incident angle toward the solar cell plane is between the incident light and the solar cell plane’s perpendicular direction. The tilt and azimuth angles are the angles between the solar cell plane and horizontal, and due north, respectively.35 In this study, we consider the realistic illumination irradiance toward the solar cells on the rooftop (tilt angle of 0°, any azimuth angle), the south (tilt angle of 90°, azimuth angle of 180°), east (90°, 90°), and west (90°, 270°) facades of buildings in Gifu, Japan, as shown in Figure 1C. The north facade is not mentioned due to little sunlight toward this orientation. For the solar panels on the rooftop, the tilt angle of the solar panels is essential to make the sun perpendicular to them, producing the maximum output energy. The optimum tilt angle of solar panels depends on the geographical location and seasons of the year. In this case, the solar cells’ directions (east, west, south, north) have to be considered, leading to the more complex simulations. Therefore, we performed simple simulations for the rooftop cells installed horizontally in this study, although their output energy may be higher in reality. In this study, the incident light’s angle toward the solar cell plane on the rooftop, the south, east, and west facades in Gifu of Japan (the latitude of 35.42° N, the longitude of 136.76° E) were taken from the website pvlighthouse.com, as shown in Figure S5. Therein, the black areas in this figure illustrate the angles that are not in the examined interval from 0° to 87°.

As shown in Figure S6, the input data of the realistic illumination irradiance was experimentally measured in Gifu, Japan, in 2015. The measurement was supported and performed by a 2015-year project of the New Energy and Industrial Technology Development Organization (NEDO)
of Japan. Note that at one time, the realistic illumination irradiances that come to the solar cell are simultaneously the same in all directions. Therefore, the input irradiances used in simulations for those directions are equal. Herein, the black areas are the times without sunlight illumination to solar cells. Meanwhile, the module temperature depends closely on the heating effect of the solar illumination irradiance and ambient temperature, the cooling effect of wind velocity, and direction. The module temperature values in different directions, as shown in Figure S7, were calculated by a model for the insulated BIPV modules based on the c-Si wafer, as described in SI in detail. The black areas, shown in Figure S7, are temperature regions that do not need to be considered in this study. The numerical simulations were performed under the simultaneous input data of the angle of the incident light, the module temperature, and the realistic illumination irradiance in a daytime range from 6 to 18 o’clock with a time interval of 1 h. Consequently, we calculated the monthly and annual output energy and efficiency of the 2-terminal tandem solar cell in all directions.

The value of the tandem $P_{\text{out}}(t)$ at a certain time in a year is calculated by the following equation:

$$P_{\text{out}}(t) = P_{\text{illum}}(t) \times \eta(t),$$

(6)

where $P_{\text{illum}}(t)$, and $\eta(t)$ are the illumination irradiance and the efficiency at a specific time of a day, respectively.

The monthly illumination energy ($E_{\text{illum,monthly}}$) of the sunlight and monthly output energy ($E_{\text{out,monthly}}$) of the tandem solar cell on a specific day could be obtained by Equation (7), while the monthly efficiency ($\eta_{\text{monthly}}$) is calculated by Equation (8):

$$E_{\text{illum,monthly}} = \int_{1}^{12} P_{\text{illum}}(t) dt; E_{\text{out,monthly}} = \int_{1}^{12} P_{\text{out}}(t) dt,$$

(7)

$$\eta_{\text{monthly}} = E_{\text{out,monthly}} / E_{\text{illum,monthly}}.$$

(8)

The annual output energy ($E_{\text{out,annual}}$) and the annual efficiency $\eta_{\text{annual}}$ of the tandem solar cell are estimated by Equations (9) and (10):

$$E_{\text{annual,illum}} = \sum_{t=1}^{12} E_{\text{monthly,illum}}(t); E_{\text{annual,out}} = \sum_{t=1}^{12} E_{\text{monthly,out}}(t),$$

(9)

$$\eta_{\text{annual}} = E_{\text{annual,out}} / E_{\text{annual,illum}}.$$

(10)

where $E_{\text{annual,illum}}$ is the annual illumination energy.

3 | RESULTS AND DISCUSSIONS

3.1 | Dependence of $J_{\text{ph}}$ on irradiance and incident angle

According to the optical optimization, we obtained the optimal thicknesses of 100, 82, 10, 689, 14, and 76 nm for the LiF, ITO, TiO$_2$, perovskite, spiro-OmεTAD, and p-μc-Si$_{1-x}$O$_x$H layers (Table 1). Figure 2A shows the absorption profile of the optimized 2-terminal perovskite/SHJ tandem solar cell structures. With such a 2-terminal tandem structure, we attained the optimal tandem $J_{\text{ph}}$ of 19.49 mA/cm$^2$. The reflective loss and the total parasitic absorption loss occurring in the other layers are 5.98 and 1.45 (1.40 by ITO) mA/cm$^2$, respectively.

The $J_{\text{ph}}$ values of the perovskite top and SHJ bottom cells are stable for incident angular ranges of 0°–27° and 0°–57°, and then start decreasing for the incident angles of above 27° and above 57°, respectively (Figure 2B). The decrease of the $J_{\text{ph}}$ values versus the incident angle increase in the perovskite top and SHJ bottom cells is due to the elevated reflective loss. The larger incident angle makes the reflective loss more significant. Furthermore, the perovskite top cell is located on the front side of the tandem cell, and the refractive index of the sub-cell layers is lower than that in the SHJ cell (see Figure S1). According to the Fresnel equations, the top cell’s reflective loss is higher than on the bottom cell. Therefore, the different decrease of the $J_{\text{ph}}$ values between the two sub-cells leads to the current mismatching when the incident angle is higher than 27°. Thus, the $J_{\text{ph}}$ of the tandem cell is lower for the higher incident angles.

We observed that the mismatching phenomenon (red color in Figure 2C) occurs seriously in an angular incident range of around 57°–69° but not in an angular incident range 69°–87° under irradiance in a range of 800–1000 W/m$^2$ (Figure 2C). This is because the optical losses due to the reflection for both top and bottom sub-cells are largest in the angular incident range of 69°–87° (see Figure 2D), leading to the low different of $J_{\text{ph,top}}$ and $J_{\text{ph,bottom}}$ values. Also, according to Figure 2C, the matching requirement (in the blue color area) should be performed under the conditions of the incident angle below 27° for high irradiance or the incident angle below 57° for low irradiance. However, the tandem $J_{\text{ph}}$ value is low under the low irradiance. As shown in Figure 2E, the high tandem $J_{\text{ph}}$, thus, should be obtained under the irradiance in the range of 800–1000 W/m$^2$ with incident angles below 69°. This is consistent with low reflective loss also with incident angles below 69° as observed in Figure 2D.
3.2 Dependence of the tandem performance on irradiance, incident angle and module temperature

We calculated the top, bottom, and tandem solar cells’ electrical characteristics under standard test conditions, as listed in Table 2. Thus, our optimal 2-terminal perovskite/SHJ monolithic tandem cell structure could attain the η value of 29.19%. The temperature dependences of the performance in the top, bottom, and tandem cells were examined by varying the temperature in a 300–360 K range, as shown in Figure 3A–D). Their $J_{sc}$, $V_{oc}$, FF, and η values decrease linearly with the temperature increase. The decreases in the $J_{sc}$ ($dJ_{sc}/dT$), $V_{oc}$ ($dV_{oc}/dT$), FF ($dFF/dT$), and η ($d\eta/dT$) of the tandem cell fitted are $-0.0089$ (mA/cm$^2$/K), $-0.0029$ (V/K), $-0.0519$ (%/K), and $-0.0753$ (%/K), respectively. Hence, we calculated the relative temperature coefficient (TC) normalized by η at 300 K of the tandem η of $-0.25$ (%/K) (the calculation method is presented in Supporting Information). This TC value is in good agreement with the experimental result in a recent report.\textsuperscript{17} Notably, the current mismatch between the top and bottom cells is considered the cause of enhancing the tandem TC. Hence, to minimize the tandem TC value, the perovskite $E_g$ needs to be optimized to obtain the current matching condition at the highest module temperature (Table 3).

The systematic decrease of the tandem $J_{sc}$, $V_{oc}$, FF, and η with temperature for each incident angle is also shown in Figure 3E–H. Besides, we observed that the tandem FF is almost constant with incident angle, except for the high incident angle of 81°–87°. Meanwhile, the tandem η decreases from 29.19% to 3.03% with the temperature because the longer-wavelength-photons are absorbed additionally ($E_g$ red-shifting). Therefore, the current mismatch occurs in the tandem cell as temperature increases, leading to the decrease of the tandem $J_{sc}$. The decrease in the tandem $J_{sc}$ with temperature was demonstrated experimentally.\textsuperscript{17} Notably, the current mismatch between the top and bottom cells is considered the cause of enhancing the tandem TC. Hence, to minimize the tandem TC value, the perovskite $E_g$ needs to be optimized to obtain the current matching condition at the highest module temperature (Table 3).

| TABLE 2 | Input parameters used in the electrical simulations |
| Parameters | Top cell | Bottom cell |
| Temperature (K) | 300 | 300 |
| $n_D$ | 1.26 | 1.15 |
| $J_0$ (mA/cm$^2$) | $2.68 \times 10^{-15}$ | $8.11 \times 10^{-10}$ |
| $R_{sh}$ (Ωcm$^2$) | 1170 | 8900 |
| $R_s$ (Ωcm$^2$) | 1.067 | 3.834 |
incident angle in a range of 0°–87°. However, the tandem \( \eta \) is most significantly dropped (around from 22.65% to 3.03%) with the incident angle of above 72° for the temperature of 300 K and the lower incident angle of above 69° for the temperature of 360 K. Thus, the high incident angle combined with the temperature increase causes more severe reduction of the tandem \( \eta \). Also, we characterized the dependence of the tandem

| TABLE 3 | Simulated characteristic parameters of the solar cells |
|----------|---------------------------------|
|          | Top cell | Bottom cell | Tandem |
| \( J_{sc} \) (mA/cm\(^2\)) | 19.49    | 19.49       | 19.49 |
| \( V_{oc} \) (V)       | 1.19     | 0.71        | 1.90  |
| FF (%)   | 81.67    | 74.07       | 78.83 |
| \( \eta \) (%)        | 18.94    | 10.25       | 29.19 |

FIGURE 3 Dependence of tandem performance on temperature (a–d), the constraint of temperature and incident angle (e–h) under the fixed irradiance of 1000 W/m\(^2\), and the constraint of temperature and irradiance (i–l) with the incident light perpendicular to the solar cell plane.
performance for simultaneous changes in temperature and irradiance (Figure 3I–L). The tandem performance increase systematically under the irradiance range of 200–1000 W/m² at each temperature. We could obtain the tandem $\eta$ of around 28.18%–29.19% at the temperature of 335–300 K and the irradiance of 400–1000 W/m². Summarily, the tandem solar cells work well under these following conditions: the incident angle of below 72°, the temperature of 335–300 K, and the irradiance of 400–1000 W/m².

### 3.3 | Annual output energy in the 2-terminal perovskite/SHJ tandem solar cells

Figure 4 shows the efficiency ($\eta(t)$) over time in a year obtained by the 2-terminal perovskite/SHJ tandem solar cells mounted on the rooftop, the south, east, and west facades. The black areas illustrate the nonworking area of the solar cells, mainly caused by no illumination or too weak illumination, and too high incident angles. This study assumes that an effective working area of the solar cell is with an efficiency around from 20%. Accordingly, the solar cells mounted on the east and west facades effectively work from 8 o’clock to 11 o’clock and from 13 o’clock to 16 o’clock, respectively. The effectively working areas for these solar cells expand from 7 o’clock (even from 6 o’clock) to 8 o’clock and from 16 o’clock to 17 o’clock in the middle-year months. This depends on the sunrise and sunset times and incident angles for each direction.

Meanwhile, the solar cells mounted on the rooftop could work all day from 8 o’clock to 16 o’clock, especially from 6 o’clock to 17 o’clock in the middle-year months. The solar cells mounted on the south facade also could mainly work from 8 o’clock to 16 o’clock in a day. Their working areas expand from 7 o’clock to 17 o’clock in the February-to-March and August-to-October months. However, the solar cells in this direction work inefficiently in the middle-year months from April to July. This is because the incident angles for this direction are too high in these months. The highest $\eta(t)$ values, which reach 27.10, 28.20, 28.20, and 28.20% for the solar cells mounted on the rooftop and the east, south, and west facades, respectively, have not reached the optimal efficiency of 29.19% under the standard test condition. This is due to the constraint of the realistic conditions of the incident angle, the illumination irradiance, and the solar module temperature, which are different from the standard test condition for solar cells.

As shown in Figure 5, the tandem $P_{\text{out}}(t)$ values reach the highest values around noontime for the rooftop and the south facade, from 8 o’clock to 10 o’clock for the east facade, and from 13 o’clock to 15 o’clock for the west facade. The highest $P_{\text{out}}(t)$ value the tandem solar cell obtains is 236, 235, 206, and 222 W/m² for the rooftop, the south, east, and west facades, respectively. The highest $P_{\text{out}}(t)$ values are incompatible with the above highest $\eta(t)$ values because the highest $P_{\text{out}}(t)$ and $\eta(t)$ values happen at different times. Note that a $P_{\text{out}}(t)$ value in a certain time mainly depends on the corresponding illumination irradiance. In reality, the highest illumination irradiance appears around noontime, leading to the highest $P_{\text{out}}(t)$ values for the rooftop and the south facade more than that for the east and west facades.

In addition, the $P_{\text{out}}(t)$ value for the rooftop is high and stable in almost all months, while that for the south facade is unstable and low in the middle months from...
April to August. Therefore, the rooftop is assumed a more effective working direction compared with the other directions. While the roof and south-mounted tandem cells could operate all daytime, the tandem cells work in the morning for the east facade and in the afternoon for the west facade. This is a vast disadvantage if the tandem solar cells are mounted on these facades of buildings.

Figure 6A illustrates the $E_{\text{monthly, illum}}(t)$ of the incident light and the tandem solar cell's $E_{\text{monthly, out}}(t)$ on the rooftop, the south, east, and west facades in a year. As usual, the sunlight's $E_{\text{monthly, illum}}(t)$ values in clear sky conditions should be higher in the mid-year months (sunny months) and lower in the other months. In reality, the $E_{\text{monthly, illum}}(t)$, which significantly depends on the weather conditions (rainy, cloudy, and foggy), irregularly appears independent on the months of the year. This is the critical factor to correctly estimate the actual performance of the annual tandem solar cells.

As mentioned above, the tandem solar cells on the rooftop have the high and stable $\eta(t)$ and $P_{\text{out}}(t)$ values in almost all months of a year, so the tandem $E_{\text{monthly, out}}(t)$ values for this direction are stable and higher than that for the other directions. The highest and lowest $E_{\text{monthly, out}}(t)$ values are 33.06 kWh/m² in May and 12.85 kWh/m² in November, respectively. Meanwhile, the tandem $E_{\text{monthly, out}}(t)$ values for the south facade are more severely affected by the incident angles in several months from April to August, leading to the low tandem $E_{\text{monthly, out}}(t)$ in these months. The highest and lowest $E_{\text{monthly, out}}(t)$ attained for the south facade is 27.42 kWh/m² in March, and 11.96 kWh/m² in June. The tandem solar cells could obtain the maximum $E_{\text{monthly, out}}(t)$ of 14.83 kWh/m² for the east facade and 13.81 kWh/m² for the west facade in May, while the minimum $E_{\text{monthly, out}}(t)$ are around 6.82 and 4.68 kWh/m² for the east and west facades in January, respectively. The similar performance behavior of the tandem solar
cells for each direction was also presented through their $\eta_{\text{monthly}}$ values in Figure 6B.

Figure 6C shows the obtained tandem $E_{\text{annual, out}}$ of 279.52, 238.89, 129.99, and 115.21 kWh/m$^2$ for the rooftop, the south, east, and west facades, respectively. Thus, the rooftop is still the best orientation for the tandem solar cell’s operation in tandem performance. The $E_{\text{annual, out}}$ obtained from this direction is 1.17, 2.15, and 2.43 times more than from the south, east, and west facades. The $E_{\text{annual, out}}$ attained from the tandem cells mounted on the south facade is 1.84 and 2.07 times more than from the east and west facades, respectively. Hence, this direction is assumed the most preferred facade of buildings for the BIPV application. The corresponding $\eta_{\text{annual}}$ values of the tandem solar cell are 22.42, 19.70, 10.50, and 9.19% for the rooftop, the south, east, and west facades, respectively. The $\eta_{\text{annual}}$ values harvested by the tandem cells for the rooftop and the south facade are much more than those for the east and west facades. This finding is because the tandem solar cells could work all day for the rooftop and the south facade, while they only work in the morning or the afternoon for the east and west facades. This also confirms that the building’s rooftop and south facade are superior in BIPV application.

4 | CONCLUSIONS

This study utilized the combination of the optical and electrical simulations to optimize the 2-terminal monolithic perovskite/SHJ tandem solar cell with the perovskite bandgap of 1.67 eV under standard test conditions. With such a structure, the best efficiency attained is 29.19%. This study also clarified the tandem solar cell performance’s dependence on the current mismatch on module temperature, solar illumination irradiance, and the sunlight’s incident angles toward solar cells. We assume that the tandem solar cells could work well in terms of these conditions: the incident angle of below 72°, the temperature of 300–335 K, and the irradiance of 400–1000 W/m$^2$. The perovskite $E_g$ should be optimized at the highest module temperature to restrict the tandem performance’s temperature dependence. Also, this study presented the model to estimate the 2-terminal perovskite/SHJ tandem solar cell’s annual output energy under realistic conditions composed of solar illumination irradiance, incident angle, and module temperature. Our 2-terminal monolithic perovskite/SHJ tandem solar cell configuration could get the annual output energy of 279.52, 238.89, 129.99, and 115.21 kWh/m$^2$ for the tandem solar cell on the rooftop, the south, east, and west facades of buildings, respectively. This confirms the superiority of the rooftop and the south facade of the buildings in terms of PCE in BIPV application in Gifu, Japan. Thus, this model allows us to determine the best direction for a specific solar cell configuration in the BIPV application.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

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