Greenhouse Gas Reduction Effect of Solar Energy Systems Applicable to High-Rise Apartment Housing Structures in South Korea

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Abstract: In South Korea, we are aiming for net zero energy use apartment home structures. Since the apartment structure in South Korea is generally a high-rise of 10 or more floors, the types of renewable energy applicable are limited to photovoltaic (PV) panels, solar collectors installed on the wall, or a photovoltaic thermal (PVT) hybrid panel combining both. In this study, the effect of PV, ST (Solar Thermal), and PVT systems on greenhouse gas reduction was analyzed using TRNSYS18. All three systems showed maximum CO₂ reductions at 35° facing south. PV, ST, and PVT showed CO₂ reductions of 67.4, 114.6, and 144.7 kg_CO₂/m²·year, respectively. Compared to those values, when installed on a wall (slope of 90°), CO₂ reduction is about 35–40% less and about 20% less at a slope of 75°. ST and PVT installed on the vertical wall have a greater greenhouse gas reduction effect than the PV installed at the optimal slope of 35°. Since the CO₂ reduction difference among SW, SE, and azimuthal S is within 10%, ST and PVT are recommended for installation on high-rise apartment structure walls or balconies with the azimuthal angle of ±45° with respect to south.

Keywords: solar thermal system; photovoltaic; photovoltaic thermal; CO₂ reduction; energy production; TRNSYS18; high-rise apartment

1. Introduction

In response to the Paris Climate Change Accord for reducing greenhouse gases, South Korea has announced a strategy to expand its new 2030 energy industry [1]. In the energy construction field, standards for reducing greenhouse gases are being strengthened. In particular, Zero Energy Building is to become mandatory for new buildings from 2025 with plans to start in the public sector (2020) and expand to the private sector (2025). Hence, it is essential to introduce renewable energy along with high factor insulation, high performance windows, and heat recovery ventilation systems.

According to South Korea’s national indicator system, the total number of households in the residential sector in 2018 was 19,979,000, of which about 9,550,000 were apartments. A large-scale refurbishment of ≥30-year-old apartment structures has recently been pursued, especially in the Seoul metropolitan area. According to Seoul ordinance, 14% or more of the expected energy consumption per total area of 100,000 m² must be covered by renewable energy sources. South Korean apartments are mostly high-rise structures with more than 10 floors, and the only renewable energy devices that can be applied to high-rise buildings are PV panels or solar collectors installed on walls or balconies [2,3].

PV systems have experienced price reductions and improvements in efficiency through continuous research and development of modules [2]. Moreover, due to solar PV expansion policies in many
countries and even the attainment of grid-parity in some countries, sustained growth is anticipated in the outdoor PV and building Integrated Photovoltaic (BIPV) markets [4–6]. For solar thermal systems, since 2000, attempts have been made mainly in Europe to develop a building-integrated solar collector that can be used as a building exterior material such as a BIPV module [7–9]. Facade-integrated solar collectors in particular have been used in houses in places such as Austria and Germany since the late 1990s [10,11]. Recently, in China, examples of one or two solar collectors on the walls or balconies of apartment houses have become common [12].

The growth of PV supply among renewable energy materials is remarkable both domestically and overseas [13,14]. In South Korea, PV is more widely used for power generation in parking lots and on factory roofs rather than for residential building consumption [15,16]. There are social problems such as some environmental destruction and ESS (Energy Storage System) fires when PV panels are installed in forests and at reservoirs, but it is certain that this is an advantageous method that can send produced energy over long distances. Solar thermal systems, on the other hand, are at a disadvantage for long-distance transportation, and they are more advantageously installed in or near buildings [16]. In general, solar thermal systems are installed on a building rooftop and are widely used for hot water and heating [17–19]. Overseas, BIST (Building Integrated Solar Thermal), which can be installed more flexibly, is being applied as a pilot project [4,20].

PV systems on apartment structures, which account for most building energy consumption, are multiplying in some municipalities, including Seoul. Solar thermal systems have been installed on the roofs of apartment houses and are used as a common heat source but their contribution is insignificant. For greenhouse gas reduction, it is time for more active application to apartment structures, along with redevelopment plans for existing apartments.

In this study, we calculated energy production and CO$_2$ reduction by slope and azimuth when a solar thermal collector, a PV panel, and a PVT hybrid system combining both were installed on a rooftop or outer wall in a South Korean apartment structure [21]. Through this, objective data can be generated to understand and quantify how much greenhouse gas reduction is achieved when the system is introduced in a limited area.

2. Simulation Method and System Modeling

Forms of renewable energy applicable to urban houses, especially high-rise residential structures, are very restricted. With the technology commercialized to date, solar energy is the only relevant solution. The rooftop or roof can be used on the top floor of detached buildings or high-rise apartments, but other households are compelled to use exterior walls. Despite their different uses, both PV and ST systems have become widespread, and PVT hybrid system combining these two has also reached the stage of commercialization [22,23]. Although direct comparison is not easy, we simulated systems consisting of products whose performance and price are the average in South Korea.

In this study, a simulation was performed using TRNSYS18 [24]. This software has been developed for unsteady state simulation of solar energy systems and has been upgraded for about 40 years, and so has been verified for dynamic analysis of ST and PV systems. To simulate with TRNSYS18, set values for the components that make up the actual system must be secured. Since it is not possible to cover all systems in South Korea, the solar thermal collectors and PV and PVT panels of E-MAX System Co., Ltd. which has general performance were simulated. The weather data used for the simulation was TMY2 Seoul, which is in the TRNSYS18 internal library, and the simulation interval was 0.1 h, totaling to 8760 h (one year).

Since the object of this study is solar energy applied to high-rise apartments, installation is restricted. As is well known, solar energy reaches its maximum production of the year when the slope is similar to the local latitude. When installed on the rooftop, the slope is typically low, but installation on the middle floors of the high rise structure is restricted to walls and balconies where panels can be installed vertically or slightly inclined. Slopes were therefore set to 20°, 35°, 75°, and 90°. Southern orientation of solar components is preferred in South Korea, which is located in the northern
hemisphere, but, due to the arrangement of apartments, many are facing west or east. For that reason, we included W, SW, S, SE, and E orientations to see the effects.

In the simulation, the ST system was used for a domestic hot water supply with a heat collection area of 4.18 m². The main components of the system are a flat-plate collector (Type1b) and a heat storage tank (Type60d, 200 L) with a built-in heat exchange coil. The performance of the ST system varies depending on the heat storage tank and the control method regardless of the collector, and, in a previous study [25], the performance of the system shown in Figure 1 was compared through simulations under various conditions. The most basic method is a heat exchange coil arranged only in the lower part of the heat storage tank and a constant flow rate. Contrary to this lower installation of heat exchange coil, our previous studies showed that the upper and side heating of the storage tank is more effective for higher stratification performance [26], as upper heating increases the temperature difference between the top and bottom of the storage tank. In such system, when the solar radiation condition is not strong, it can be seen that operating only the bottom coil or reducing the flow rate improves the solar energy collection efficiency by about 7%. In this study, the simulation was performed with this improved method with lower and upper heating heat storage tank and three-stage flow rate. Table 1 summarizes the specifications of the solar collector, heat storage tank, and pump applied to the simulation.

![Schematic experimental set-up of solar combi-system. 3W.V, three-way valve; S.V, solenoid valve; B.V, bypass valve.](image)

The load pattern and quantity greatly affect the performance of the solar water heater. When the load increases during the daytime, the temperature of the heat storage tank decreases, which leads to an improvement in solar energy collection efficiency. Daily hot water load of 150 L/day, the temperature of 60 °C, and the daily load of Cardinale et al. [27] in Figure 2 were applied. This is a typical usage pattern in a general household, and peak usage is concentrated in the morning and evening. The city water temperature is based on the monthly average value of the temperature at 1.5 m underground as provided by the South Korea Meteorological Administration and is summarized in Table 2.

Simulations for PV systems are relatively simple. Electricity was assumed to be connected to a grid and sent to a power company. A PV component (Type194b) with an inverter was used. This component is appropriate for modeling the electrical performance of monocrystalline, polycrystalline, and thin film photovoltaic panels. Two modules in series with the same area (2.09 m²) as the ST system were set. The performance data of the inverter were based on the default values built in TRNRSYS18, and Table 3 shows the important specifications required for the simulation.
Table 1. Specification of the solar thermal system.

| Component       | Category                  | Unit | Value     |
|-----------------|---------------------------|------|-----------|
| Collector       | Area (Gross)              | m²   | 2.09      |
|                 | Fluid heat capacity       | kJ/kg K | 3.7     |
|                 | Tested flow rate          | kg/s·m² | 0.01835 |
|                 | Intercept efficiency      | -    | 0.6997    |
|                 | Efficiency slope          | W/m²·K | 3.6964   |
|                 | Efficiency curvature      | W/m²·K² | 0.0104   |
| Storage tank    | Volume                    | L    | 200       |
|                 | Height                    | m    | 1.1       |
|                 | Material of heat exchanger| -    | STS 304   |
|                 | Upper heat exchanger      | Diameter × Length | m | 15.8Φ × 5 |
|                 | (smooth tube)             | Height (Inlet, Outlet) | m | 0.962     |
|                 |                         | Height (Inlet, Outlet) | m | 0.881     |
|                 | Lower heat exchanger      | Diameter × Length | m | 15.8Φ × 7 |
|                 | (smooth tube)             | Height (Inlet, Outlet) | m | 0.175     |
|                 |                         | Height (Inlet, Outlet) | m | 0.067     |
| Pump            | Maximum flow rate         | kg/s | 0.073     |
|                 | Maximum power             | W    | 16.7      |

Figure 2. Daily load pattern (Cardinale et al. [27]).

Table 2. Average ground temperature in Seoul.

| Category | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|----------|------|------|------|------|-----|------|------|------|------|------|------|------|
| Temp (°C)| 8.0  | 6.1  | 6.4  | 9.4  | 13.4| 17.2 | 20.9 | 23.4 | 23.2 | 20.7 | 16.6 | 11.7 |

Figure 3 show a schematic diagram of the PVT system. The solar water heater is the same as Figure 1, and the relatively low water temperature is augmented through the auxiliary heater. The electricity produced was connected to the grid in the same way as PV. The configuration of the simulation is the same as that of the ST system except for the PVT component (Type 50d) and the inverter (Type 48b). Type 50d models a combined photovoltaic and thermal (PVT) solar collector by adding a PV module to the standard flat-plate collector. It is available in the default TRNSYS library, can be used with glazed and unglazed modules, and is the most widely used PVT Type. In the case of Type 48b (Inverter), if the battery is fully charged or needs only a taper charge, excess power is either dumped or not collected by turning off parts of the source. The inverter converts the DC power to AC and sends it to the load and/or feeds it back to the utility. For fair comparison, the heat storage tank,
load pattern, and control logic were all set identically. Inverter efficiency was set to 78%, similar to the default value built into the Type 194b used for the PV system. Figure 4 shows the configuration of the TRNSYS18 simulation of the PVT system, and Table 4 shows the specifications of the solar collector at the bottom of the PVT. The PV module of PVT is the same as the one in Table 3.

**Table 3.** Specification of the photovoltaic system (STC: 25 °C, 1 kW/m², Spectrum AM 1.5).

| Category                  | Unit | Value  |
|---------------------------|------|--------|
| Module size               | m²   | 2.09   |
| Open circuit voltage ($V_{oc}$) | V    | 48.8   |
| Short circuit current ($I_{sc}$) | A    | 8.77   |
| Maximum power ($P_{max}$)  | W    | 332.6  |
| Voltage at maximum power ($V_{mpp}$) | V    | 39.6   |
| Current at maximum power ($I_{mpp}$) | A    | 8.41   |
| Fill factor               | %    | 77.7   |
| Module efficiency ($\eta_{C}$) | %    | 15.9   |
| Number of cells           | ea   | 72     |
| Cell size                 | cm²  | 242.7  |

Annual average horizontal solar radiation in South Korea: 4215 MJ/m² [28].

**Figure 3.** Schematic diagram of the PVT system.

**Figure 4.** Composition of the PVT system TRNSYS18 simulation.
Table 4. Specification of the PVT system.

| Collector | Flat Plate Solar Collector |
|-----------|---------------------------|
| Size      | 1042 mm × 2002 mm × 58 mm |
| Area      | Gross Area: 2.09 m², Transmission Area: 1.92 m² |

| Tested flow rate | 0.0385 kg/s |
| Intercept efficiency | 0.5299 |
| Efficiency slope | 4.5752 W/m²·K |
| Efficiency curvature | 0.0206 W/m²·K² |

| Absorber plate | Material: A.I. Plate, Titanium coated aluminum absorber |
|----------------|----------------------------------------------------------|
| Size           | 985 mm × 1948 mm × 0.3 mm |

| Absorptivity | 95.1% |
| Reflectance  | 3.7%  |

| Tube | Material: Copper |
|------|------------------|
| Size | Diameter Φ12.7 mm, Thickness 0.89 mm, Length 23231 mm |

| Operating fluid | 15% Propylene glycol |

| Insulator | Material | Thickness (mm) | Density (kg/m³) | Heat-resisting Temperature (°C) | Thermal Conductivity (W/m·K) |
|-----------|----------|---------------|-----------------|-------------------------------|-------------------------------|
| Side      | EPDM     | 10            | 45              | 409                           | 0.033                         |
| Bottom    | EPDM     | 20            | 45              | 409                           | 0.033                         |

The heat and electricity produced by the PVT module were analyzed using the mathematical algorithm analysis method of TRNSYS 18 Mathematical

\[ Q_{PVT} = A \times F_r \times (S - U_L (T_i - T_d)) \] (1)

Equation (1) is the same as general solar collector formula. The electricity production rate \( P_{PVT} \) and photovoltaic cell efficiency \( \eta_{PVT} \) were calculated using Equations (2) and (3).

\[ P_{PVT} = (\tau \sigma)_{nt} IAM \times G_t \times A \times \eta_{PVT} \] (2)

\[ \eta_{PVT} = \eta_c \times X_t \times X_r \] (3)

As the temperature of the panel rises, the temperature function \( X_t \) decreases, and electricity production decreases. Annual thermal efficiency \( \eta_{th, year} \), electrical efficiency \( \eta_{el, year} \), and solar fraction \( f_{year} \) are as follows.

\[ \eta_{th, year} = \frac{\sum Q_{PVT}}{\sum G_t} \] (4)

\[ \eta_{el, year} = \frac{\sum P_{PVT}}{\sum G_t} \] (5)

\[ f_{year} = \frac{\sum Q_{DHW} - \sum Q_{AUX}}{\sum Q_{DHW}} \] (6)
3. Experimental Results and Discussion

Under the conditions described previously, simulations for PV, ST, and PVT were performed at different slopes (20°, 35°, 75°, and 90°) and azimuthal angles (W, SW, S, SE, and E). From this, we calculated the amount of heat generated by each system, electricity produced, and associated reduction in CO₂ production.

3.1. CO₂ Calculation Method

The amount of CO₂ reduced by use of renewable energy can be calculated by figuring the amount of CO₂ generated when the same amount of heat or electricity is produced on a fossil fuel basis. Since the amount of CO₂ generated depends on the type of fuel, it is reasonable to choose the one that is most often used in apartments. For thermal energy, LNG (Liquefied Natural Gas), which accounts for 71% of heating in the housing sector in South Korea (90% of boiler efficiency, low heating value applied), was used as a reference [15]. In the case of electrical energy, there is an emission factor announced according to the composition of fuel used for power generation by country, and the carbon emission factor of South Korea is 0.1319 kg_C/kWh [29]. This value was applied to calculate the amount of greenhouse gas reduction due to electricity produced by PV. Calories and carbon emissions were calculated based on the data shown in Table 5.

Table 5. The conversion standard of energy units and IPCC carbon factor [16].

| Category (LNG) | Unit | Upper MJ | ×10⁻³ toe | Lower MJ | ×10⁻³ toe | Carbon Emission Factor kg_C/GJ | ton_C/toe |
|---------------|------|---------|-----------|---------|-----------|-------------------------------|-----------|
| Crude oil     | kg   | 44.9    | 10,730    | 1.073   | 42.2      | 10,080                        | 1.008     |
| Gasoline      | L    | 32.6    | 7780      | 0.778   | 30.3      | 7230                          | 0.723     |
| Kerosene oil  | L    | 36.8    | 8790      | 0.879   | 34.3      | 8200                          | 0.820     |
| Diesel oil    | L    | 37.7    | 9010      | 0.901   | 35.3      | 8420                          | 0.842     |
| Natural gas   | kg   | 54.6    | 13,040    | 1.304   | 49.3      | 11,780                        | 1.178     |
| City gas (LNG)| Nm³  | 43.6    | 10,430    | 1.043   | 39.4      | 9420                          | 0.942     |
| City gas (LPG)| Nm³  | 62.8    | 15,000    | 1.500   | 57.7      | 13,780                        | 1.378     |
| Electricity (generation) | kWh | 8.8    | 2110      | 0.211   | 8.8       | 2110                          | 0.211     |
| Electricity (consumption) | kWh | 9.6    | 2300      | 0.230   | 9.6       | 2300                          | 0.230     |

LNG CO₂ emission calculation:

- Ton of oil equivalent (toe) = LNG Conversion (Nm³) × LNG Lower Heating Value (toe/Nm³)
- C emission (ton_C) = Ton of oil equivalent (toe) × LNG Carbon emission factor (ton_C/toe)
- CO₂ emission (ton_CO₂) = (CO₂ (Molar mass 44)/C (Molar mass 12)) × C emission (ton_C)
- Example) 200 MJ energy production in Jan. when slope is 45°. Boiler efficiency 90%, City gas (LNG) LHV Conversion value is 5.64 Nm³
  - Ton of oil equivalent (toe): 5.64 Nm³ × 0.942 × 10⁻³ toe/Nm³ = 5.31 × 10⁻³ toe
  - C emission: 5.31 × 10⁻³ toe × 0.637 ton_C/toe = 3.38 × 10⁻³ ton_C
  - CO₂ emission: (44/12) × 3.38×10⁻³ ton_C = 12.39 × 10⁻³ ton_CO₂
Electrical energy CO\textsubscript{2} emission calculation:

- Carbon (C) emission (kg\_C) = Electrical energy production (kWh) \times \text{Carbon emission factor of electrical energy (kg\_C/kWh)}
- Carbon dioxide (CO\textsubscript{2}) emission (kg\_CO\textsubscript{2}) = (CO\textsubscript{2} (Molar mass 44)/C (Molar mass 12)) \times \text{Carbon emission (kg\_C)}

Example) 10 kWh energy production in Jan. when slope is 45\degree.

- C emission: 10 kWh \times 0.1319 kg\_C/kWh = 1.319 kg\_C \rightarrow 1.4 \times 10^{-3} \text{ ton}_\text{C}
- CO\textsubscript{2} emission: \frac{44}{12} \times 1.319 kg\_C = 4.84 kg\_CO\textsubscript{2} \rightarrow 4.84 \times 10^{-3} \text{ ton}_\text{CO\textsubscript{2}}

3.2. Energy Production and CO\textsubscript{2} Reduction by Slope

Table 6 shows the annual energy production and CO\textsubscript{2} reduction as a result of simulating with the azimuth fixed to the south and at the slope of 20\degree, 35\degree, 75\degree, and 90\degree.

| Category | 20\degree | 35\degree | 75\degree | 90\degree |
|----------|-----------|-----------|-----------|-----------|
| PV       | kWh/m\textsuperscript{2} | 137.4 | 139.4 | 111.9 | 90.9 |
|          | kg\_CO\textsubscript{2}/m\textsuperscript{2} | 66.4 | 67.4 | 54.1 | 44.0 |
|          | Decreasing rate (%) | -1.5 | 0.0 | -19.7 | -34.7 |
| ST       | MJ/m\textsuperscript{2} | 1756.1 | 1846.6 | 1427.8 | 1087.6 |
|          | kg\_CO\textsubscript{2}/m\textsuperscript{2} | 109.0 | 114.6 | 88.6 | 67.5 |
|          | Decreasing rate (%) | -4.9 | 0.0 | -22.7 | -41.1 |
| PVT      | kWh/m\textsuperscript{2} | 170.9 | 173.4 | 136.9 | 107.9 |
|          | MJ/m\textsuperscript{2} | 949.9 | 980.5 | 751.3 | 563.6 |
|          | kg\_CO\textsubscript{2}/m\textsuperscript{2} | 141.6 | 144.7 | 112.8 | 87.2 |
|          | Decreasing rate (%) | -2.1 | 0.0 | -22.0 | -39.8 |

PV, photovoltaic; ST, solar thermal; PVT, photovoltaic thermal.

As expected, PV, ST, and PVT all showed the highest energy production and CO\textsubscript{2} reduction at a slope of 35\degree. The annual solar radiation at 35\degree slope is 4.90 GJ/m\textsuperscript{2} (1.36 MWh/m\textsuperscript{2}), and CO\textsubscript{2} reduction is PV 67.4 kg\_CO\textsubscript{2}/m\textsuperscript{2} (Q\textsubscript{el} = 139.4 kWh/m\textsuperscript{2}, \eta_{el, year} = 10.3%), ST 114.6 kg\_CO\textsubscript{2}/m\textsuperscript{2} (Q\textsubscript{th} = 1846.6 MJ/m\textsuperscript{2}, \eta_{th, year} = 37.8%), PVT 144.7 kg\_CO\textsubscript{2}/m\textsuperscript{2} (Q\textsubscript{th} = 980.5 MJ/m\textsuperscript{2}, Q\textsubscript{el} = 173.4 kWh/m\textsuperscript{2}).

The electrical and solar energy collection efficiencies calculated from Equations (4) and (5) are smaller than the ones commonly known because the total time for the system to operate and produce energy is not very long, and the amount of solar radiation projected at other times is only included in the denominator of Equations (4) and (5).

At the slope of 90\degree installed on the wall, the CO\textsubscript{2} reduction was the smallest, and the values of PV, ST, and PVT were, respectively, 34.7%, 41.1%, and 39.8% lower than at the slope of 35\degree. At a slope of 75\degree, CO\textsubscript{2} reduction is reduced by about 20%. If only installation is possible, 75\degree slope is preferable to 90\degree, which is in close contact with a vertical wall.

Figure 5a shows the results of comparing the electricity production of PV and PVT systems according to tilt angle. Overall, PVT showed about 1.2 times greater production than PV, regardless of the slope. As shown in Equation (3), as the temperature increases, the efficiency modifier \(X_t\) decreases, the efficiency decreases, and consequently electricity production decreases. In the case of PVT, the heat medium lowers the temperature of the PV, so electricity production increases. In Reference [30], PV and PVT efficiency were compared through experiments. Similar to the results of this paper, the electricity production of PV and PVT systems during the day were calculated as 1030 and 1135 Wh, respectively showing that PVT is about 1.1 times greater.
Figure 6 shows the amount of CO2 reduction by azimuth. In all systems, maximum CO2 reduction was at the angle of 35° facing south. At all slopes, the CO2 reduction is greatest in the direction of south (S), followed by southwest (SW), southeast (SE), west (W), and east (E). SW CO2 reduction in ST is slightly less than south, but not significantly. SE generally shows a decrease rate of less than 10% from the south. SW was 0.8% and 3.4% higher than the south at ST slope of 75° and 90°, respectively, but at a negligible level. Note that it is generally better to set up facing west than east, especially for ST.

3.3. Influence of Azimuth

Table 7 summarizes the annual PV, ST, and PVT system energy production and CO2 reduction according to tilt and azimuth. The PV showed maximum values in the southern direction for all slopes, and showed similar results in the southeastern and southwestern directions, which differed little from the southern direction. ST and PVT show generally similar trends. The difference is small, but, for ST, when at slopes of 75° and 90°, heat production was highest when facing southwest.

Figure 5b compares the heat production of the ST and PVT systems. Overall, PVT heat production was half that of ST, regardless of tilt angle. When used separately, the solar collector receives solar radiation directly, which is immediately converted to heat. In the case of PVT system, however, heat production is reduced because solar radiation is indirectly collected using heat of the PV module in the upper part.

Figure 5c compares the amount of CO2 reduction by PV, ST, and PVT systems. Since PVT can produce electricity and heat simultaneously, it showed about 2.1 times greater CO2 reduction than PV. ST reduction was about 1.6 times greater than that of PV.

It is very interesting that the ST installed on a vertical wall has almost the same and PVT has 1.4 times larger greenhouse gas reduction effect than the PV installed at an optimal inclination of 35°. Since this fact is almost without regard for the azimuthal angle, which is discussed below, it can be concluded that, at any slope, the application of ST or PVT is advantageous for reducing CO2 wherever hot water is used.

It should be noted that, due to the nature of the simulation, there is an error from the actual system operation. In the case of PV system, among the various causes of loss, the factor that has the greatest influence on performance is loss due to module temperature, inverter efficiency, and angle of incidence change, which is considered through simulation [31]. However, performance degradation due to aging or natural phenomena such as corrosion, breakage, and soiling is not considered. Especially, as shown in Ref. [32], when the concentration of the fine dust is severe, the amount of power generation decreases by about 17–25% due to the decrease in the amount of solar radiation in the atmosphere and the dust accumulated on the surface of the PV module. In the case of ST system, in a previous study, it was proved that the simulation showed thermal efficiency of 1.1% lower than the experiment.
Table 7. Energy production and CO$_2$ reductions of the PV, ST, and PVT systems according to slopes and azimuths.

| Category | Energy (PV: kWh/m$^2$, ST: MJ/m$^2$) | CO$_2$ Reduction (kg CO$_2$/m$^2$) |
|----------|-----------------------------------|----------------------------------|
|          | 20° | 35° | 75° | 90° | 20° | 35° | 75° | 90° |
| PV       |     |     |     |     |     |     |     |     |
| E        | 118.6 | 111.9 | 83.3 | 70.3 | 57.3 | 54.1 | 40.3 | 34.0 |
| SE       | 131.5 | 131.3 | 102.9 | 85.5 | 63.6 | 63.5 | 49.8 | 41.3 |
| S        | 137.4 | 139.4 | 111.9 | 90.9 | 66.4 | 67.4 | 54.1 | 44.0 |
| SW       | 132.7 | 133.0 | 105.8 | 88.1 | 64.2 | 64.3 | 51.2 | 42.6 |
| W        | 120.2 | 114.3 | 86.4 | 73.0 | 58.1 | 55.3 | 41.8 | 35.3 |
| ST       |     |     |     |     |     |     |     |     |
| E        | 1430.6 | 1377.2 | 942.6 | 701.9 | 701.9 | 88.8 | 85.4 | 58.5 | 43.5 |
| SE       | 1651.6 | 1698.8 | 1297.7 | 984.9 | 1025.2 | 105.4 | 80.5 | 61.1 |
| S        | 1756.1 | 1846.6 | 1427.8 | 1087.6 | 1108.7 | 114.6 | 88.6 | 67.5 |
| SW       | 1707.8 | 1793.8 | 1439.5 | 1125.5 | 114.6 | 111.3 | 89.3 | 69.8 |
| W        | 1506.7 | 1499.0 | 1108.7 | 863.2 | 93.5 | 93.0 | 68.8 | 53.6 |
| PVT      |     |     |     |     |     |     |     |     |
| E        | 144.0 | 788.0 | 130.2 | 734.6 | 461.1 | 62.4 | 338.0 | 118.5 | 108.5 | 68.1 | 51.1 |
| SE       | 162.3 | 897.2 | 159.4 | 900.9 | 655.0 | 93.1 | 488.6 | 134.2 | 133.0 | 97.8 | 75.3 |
| S        | 170.9 | 949.9 | 173.4 | 980.5 | 751.3 | 107.9 | 563.6 | 141.6 | 144.7 | 112.8 | 87.2 |
| SW       | 163.6 | 927.1 | 161.3 | 949.1 | 121.0 | 70.7 | 584.9 | 136.7 | 136.9 | 104.5 | 82.6 |
| W        | 145.7 | 830.9 | 132.6 | 804.8 | 84.9 | 65.4 | 444.6 | 122.0 | 114.0 | 76.3 | 59.2 |

Figure 6. CO$_2$ reduction of the PV, ST, and PVT according to the slopes and the azimuths: (a) photovoltaic; (b) solar thermal; and (c) photovoltaic thermal.

In conclusion, the decreased rates of reduction at SW and SE are within 10% of the value resulting from the azimuth angle S. To maximize the reduction of CO$_2$ in high-rise apartments, ST and PVT are recommended for installation on walls or balconies with an azimuthal angle of S $\pm$ 45°. By exceeding this range, the amount of CO$_2$ reduction drops significantly at all slopes. The shaded area in Figure 6 is therefore recommended.

4. Conclusions

The only renewable energy that can be applied to high-rise apartment structures is a PV panel or solar collector installed on a wall or rooftop, or a PVT hybrid panel combining these two. We analyzed the greenhouse gas reduction effect when a 4.18 m$^2$ solar panel was applied. An annual simulation for PV, ST, and PVT systems was performed using TRNSYS18 with weather data from Seoul. The results are summarized as follows.
1. All three systems showed maximum CO₂ reduction values at 35° facing south, and PV, ST, and PVT showed reductions of 67.4, 114.6, and 144.7 kg_CO₂/m²-year, respectively.

2. If installed on a vertical wall, the CO₂ reduction will decrease by about 35–40% compared to the maximum value, and the reduction will be about 20% less than maximum when installed at a slope of 75°. If it maintains harmony with the building, slightly inclined installation is better than vertical installation.

3. Regardless of the slope and azimuthal angle, ST has 1.6 times and PVT has 2.1 times greater CO₂ reduction than the PV which is most widely used in buildings.

4. It should be noted that ST (almost the same) and PVT (1.4 times) installed on vertical walls have a greater greenhouse gas reduction effect than PV installed at the optimal slope of 35°.

5. Since the decreased rate of CO₂ reduction when installed facing SW and SE is within 10% of the south facing reduction, ST and PVT are recommended for installation on walls or balconies with an azimuthal angle of S ± 45°.

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Nomenclature

- \( Q_{PVT} \): Thermal energy production rate of PVT (W)
- \( Q_d \): Electrical energy production rate of PV (kWh/m²)
- \( Q_{th} \): Thermal energy production of PVT (MJ/m²)
- \( A \): Area of PVT solar collector (m²)
- \( F_r \): Collector heat removal factor
- \( S \): Solar radiation absorbed by a collector (W/m²)
- \( U_L \): Collector overall heat loss coefficient (W/m²·K)
- \( T_i \): PVT inlet temperature (°C)
- \( T_a \): PVT ambient temperature (°C)
- \( P_{PVT} \): Electric energy production rate of PVT (W)
- \( \tau \alpha \): Transmittance-absorptance product of solar collector
- \( IAM \): The incident angle modifier
- \( G_i \): The total radiation incident upon the collector surface (kW/m²)
- \( \eta_{pvt} \): PV cell efficiency of PVT (%)
- \( \eta_c \): PV cell efficiency of PVT at reference condition (%)
- \( X_t \): Efficiency modifier (temperature), STC (1/K)
- \( X_r \): Efficiency modifier (incident radiation), STC (h·m²/kJ)
- \( \eta_{th, year} \): Annual thermal efficiency of PV/PVT (%)
- \( \eta_{el, year} \): Annual electrical efficiency of ST/PVT (%) 
- \( f_{year} \): Annual solar fraction
- \( Q_{DHW} \): Rate of thermal energy required for hot water (W)
- \( Q_{AUX} \): Rate of thermal energy used as auxiliary heater (W)

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