A novel active building envelope with reversed heat flow control through coupled solar photovoltaic-thermoelectric-battery systems

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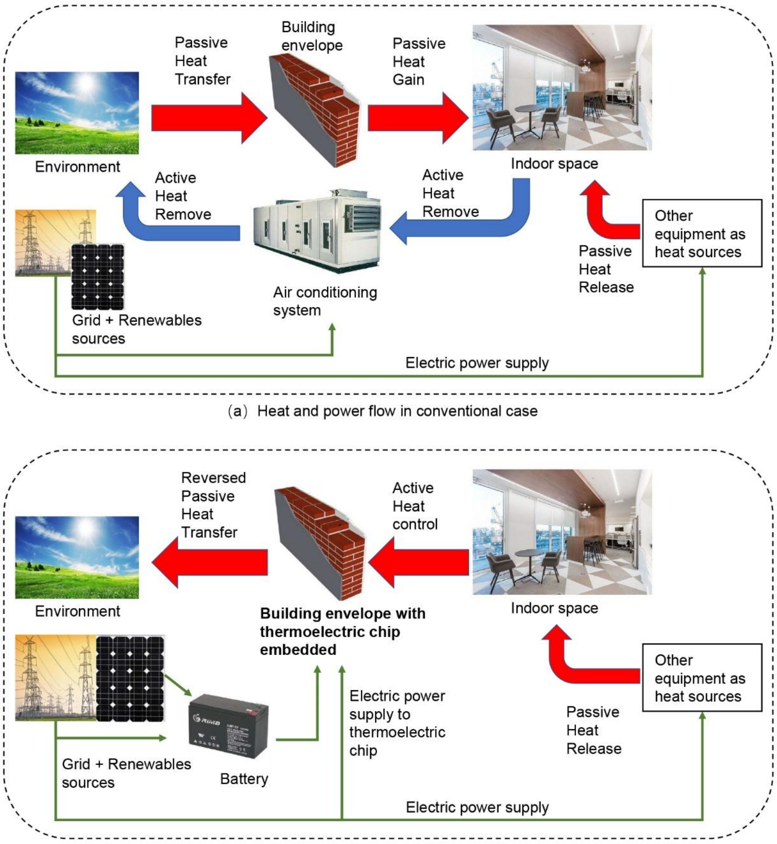
Highlights

- A new concept of building envelope can achieve reversed heat flow
- Energy flow control model is established for realizing the concept
- Energy analysis is performed for five types of systems under the framework
- The join of battery can enhance performance and reduce power abandon

Graphical abstract



(a) Heat and power flow in conventional case

(b) A new concept of Heat and power flow control

Abstract

Heat transmit between ambient and indoor space passively through building envelope. This heat flow intensity can be reduced by using insulations and eliminated by conventional air conditioner, which causes huge amount of energy. In this study, a new concept is proposed for a new active building envelope system that can realize heat gain/loss control and in some senses the conventional air conditioner system could be saved, because it is shown that the building envelope itself could be an air conditioner. It should be specially noted that, we can set parameter Q_w in this system to determine how much extra thermal energy you want from the new building envelope. It is based on the combination of photovoltaic (PV), thermoelectric modules (TEM), energy storage and control algorithms. Five types of systems, namely PV+TE (S1), Grid+TE (S2), PV+Grid+TE (S3), PV+Battery+TE (S4) and PV+Grid+Battery+TE (S5) are studied. It is found that in all the five systems, there is a typical optimum setting of thermal load for each one of them with minimum annual power consumption.

keywords: Net zero energy building; Photovoltaic; Thermoelectric chip; Heat flux control; Battery storage

1. Introduction

1.1. Background

Building energy consumption takes the biggest proportion among all sectors. It was reported that global buildings contributed to 30–40% of the final energy consumption and emitted 40% of total CO_2 in direct or indirect paths [1]. A question was raised: "*What if buildings can afford the energy bill by themselves*?" Then the concept of zero energy building was proposed and it shoulder the duty to create a sustainable development scheme in building sector [2].

The ZEB/NZEB is a promising but also a tough goal for both energy and indoor environment aspect [3]. What is the standard for ZEB/NZEB [4]? However, there is no unified standard for ZEB across nations but they shared something in core [5]. In EU, it is called as nearly ZEB [6], while net ZEB in the US [7], zero emission building in Australia [8]. Although various terms or similar concepts are used, their anticipated goals are the same that buildings should reduce fossil fuel consumption as much as possible, and make full use of renewable energy to enhance building energy-saving potential. It can be conceived that an ideal ZEB or full ZEB can support itself with no need of conventional energy sources.

1.2. Literature survey

Discussing what ZEB is and how ZEB should be is helpful as a guide but not enough. The technologies to realize ZEB or NZEB matters [9]. Feng et al. [10] conducted a case-study-driven review on 34 different NZEBs. In terms of the concrete technologies, the advanced building envelope, HVAC, lighting, and renewable energy sources are analyzed for different cases in hot and humid regions. It is learned that many buildings obeyed current codes for NZEB and achieved pretty low U-value of the wall or glazing façade [11]. This can reduce undesired heat gain which cuts HVAC energy consumption for the extra heat removal. While most studies are for residential buildings, Bandeiras et al. [12] discussed some issues about definition, net-metering, and evaluation of net zero energy in industrial/commercial buildings.

There are three major approaches for the advanced NZEBs as summarized by Li et al. [13]: *(Approach 1) minimizing building energy demands* [14], *(Approach 2)* *improving on-site renewable energy supplies* [15], and *(Approach 3) load matching among the on-site energy supply side and energy use end*.

(Approach 1:) The most common method minimizing building energy demand is to enhance thermal performance of building envelopes or adopting HVAC system with higher energy efficiency [16]. Increasing thermal resistance through insulation[17] [18], enhancing thermal stability through PCM [19], are common and effective means for lowering thermal load of buildings as passive design. And some active technologies [20] such as thermoelectric wall [21], or water flow window [22], are also contributing novel solutions for NZEBs. Li et al. [13] emphasized the importance of building envelope and its role in NZEB by analyzing examples like wall thermal insulation[23], window glazing, and green roof [24]. Shin et al. [25] analyzed the difference between renovated and non-renovated NZEB in a US army base. The renovation is conducted mainly for improving the thermal insulation of building envelope including lowering solar heat gain coefficient (SHGC) of the glazing. Usually the life cycle cost analysis can be a critical tool for the performance evaluation of NZEBs with advanced building envelope systems like low-energy window glazing and the better thermal insulation adoption [26]. And many aspects including global cost and thermal comfort should be concerned [27].

(Approach 2:) Solar energy is the most suitable as well as widely adopted renewable energy source for NZEB. It is noticed that most of studies related to NZEB discussed the important role of BIPV [28,29] or BIPV/T [30]. In order to analyze the uncertainties, multi factors in technical, economic, environmental, and social dimensions are all should be involved in the optimization of NZEBs. Karunathilake et al. [31] proposed a framework to support net-zero development, and finally suggested the combination of ground source heat pump from geothermal energy source and PV from solar energy source is an optimal option for multi-unit residential buildings. Wu and Skye [32] concluded PV+HVAC with air source heat pump has the lowest cost across different regions. Considering the impact of local climate conditions on the choice for renewable energy sources for NZEB, Harkouss et al. [33] compared six different renewable energy sources in cooling dominant, heating dominant and mixed climate zone. The simulation results offered a specific suggestion for NZEB in each climate zone. Moreover, solar collector integrated envelope [34] is also a good of solar energy application for ZEBs.

(Approach 3:) Advanced control algorithms and management strategies consider vast aspects, which should be key to optimal coordination between power supply and demand side, or the load match issue between grid and renewable energy sources. The NZEB is not asking off-line from grid entirely but requiring NZEB to generate as much power energy as it uses over a given period [35]. This explain its name as "net". Tumminia et al. [35] introduced environmental factors impact when analyzing the problem of NZEB with the angle of CO_2 emission and sustainable development. Considering the multiple complex factors of climate conditions [36], government subsidies and uncertainty of renewable energy systems, Sun et al. [37] proposed a heuristic optimization method for the grid-interactive NZEBs which outperform the benchmarked case based a case study of the Hong Kong Zero Carbon Building.

1.3. Objective of this study

The above only listed a very limited representative studies in those three aspects towards NZEBs. There is much more literature or many on-going projects devoting to new advancements. But few considered that those three paths can be in one single system for NZEB, namely an advanced building envelope system which can take full use of renewable energy to lower building energy demand and even provide additional cooling/heating energy for indoor space.

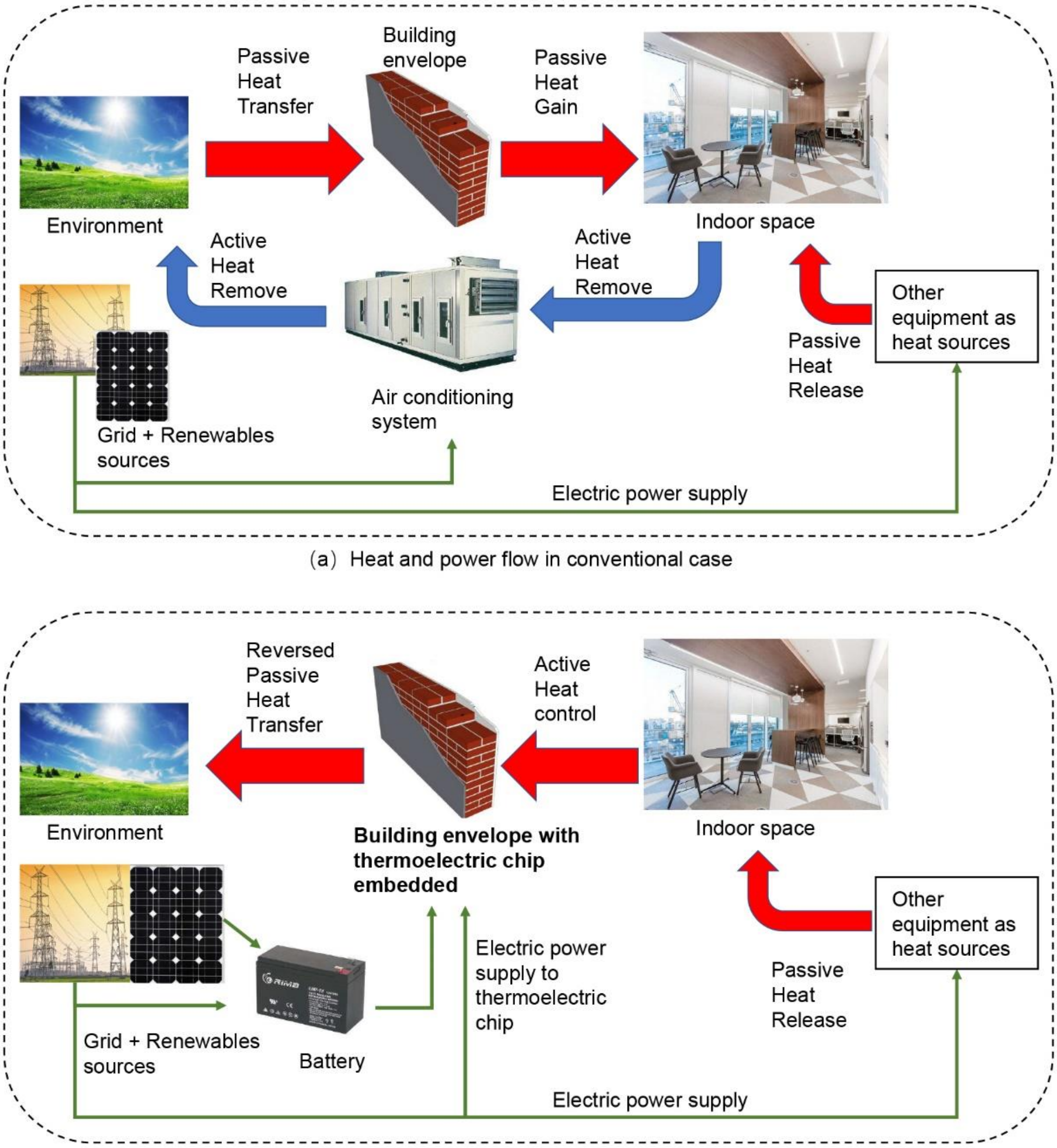
Therefore, this study aims to achieve net zero energy in buildings by integrating the three pathways in one single system. The main novelty and contribution of this study:

- a new system along with its operation control mechanism is presented not only for zero heat gain/loss of building envelope, but also undertaking partial heating/cooling load in different seasons; therefore, the building envelope can relieve some burden from air conditioner system;
- the overall energy performance of the system is concerned, and investigated to access a complete understanding on its functionality for different system configurations.

The rest of the paper is arranged as follows. **Section 2** introduces system concept and function. **Section 3** introduces system structure and models which will serve some important tools for investigations. **Section 4** will provide energy analysis method for which the **Section 5** gives a final summary and some valuable findings.

2. System concept and function

This is a new concept proposed here based on our previous investigation on a kind of photovoltaic thermoelectric wall system [38]. In the previous study [38], we only proved a kind of building envelope can realize zero heat gain/heat loss as an initial step towards NZEBs, but here we move in a further step, and try to prove the system can be evolved to shield heat flux from ambient, making true value of solar energy locally, and offsetting part of thermal energy demand of indoor space simultaneously. There is an illustrative description of the proposed idea by comparing conventional building (Fig.1a), and the new concept (Fig.1b) in the case of summer condition as an example.



(a) Heat and power flow in conventional case

(b) A new concept of Heat and power flow control

Fig.1 Illustration on (a) conventional buildings that can only passively received heat gain from ambient through building envelope, (b) the new concept in summer condition as an example can realize a reverse heat flux through thermoelectric chip powered by PV.

As Fig.1a depicted, in summer for example, the thermal energy flows into indoor space through building envelope. No matter how well insulation works, heat gain is inevitable. In order to keep indoor thermal comfort, air conditioning is required to remove the heat out of indoor space and back to ambient with power input from grid. This process will cause huge energy consumption. Conventionally, renewable energy sources are added such as PV system, which can save much energy from grid. However, the proposed envelope system in Fig.1b perhaps can change the path entirely. The core element in it is a co-working system of solar PV and thermoelectric chips. The thermoelectric chips can be triggered by the electric power from PV power generation, battery or the grid to remove heat gain in summer. By using renewable energy sources, with assistance of energy storage and very limited power from the grid, the building envelope itself will not pass the heat into indoor space, but in addition, it can offer additional cooling energy to offset the heat generated by some other heat sources indoor. On the contrary, it can minimize the heat lost through itself and even assist in heating in winter. If this concept can be realized, the installation capacity of air conditioner (AC) could be hugely reduced and the NZEB, or even positive energy building (PEB) [39] can be achieved. The remaining question is how to determine the suitable configuration and control strategy of the system, which will be explained in the next section in details.

3. Systems and Models

3.1. System structure

The basic system structure is shown in **Fig.2**. It is named as building integrated photovoltaic thermoelectric wall (BIPVTE) system. TEMs are attached onto the backside of a vertical placed radiant panel. Insulation was used to prevent energy loss through this panel. TEMs are powered by PV but after modification, the power can also be provided by battery, grid or both. There is an air gap between insulation and PV panel which will be open in summer for heat dissipation and close in winter for improved insulation.

The system parameters we used to build experimental rig are listed in **Table1**. It should be noted that this is only the original prototype. In order to realize the new function mentioned in the Introduction, some additional power source and control methods should be added. Thus, other four types are also proposed and investigated for comparison including Grid+TE (S2), PV+Grid+TE (S3), PV+battery+TE (S4), and PV+Grid+Battery+TE (S5). The power flow and control are different among them but their heat transfer behaviors follow that of the PV+TE type, which will be explained in details along with system models in Section 3.2.

Table 1

System parameters of BIPVTE system

Parameters	Values
The cold side thermal resistance, R_c in cooling mode	0.1 K/W
The hot side thermal resistance, R_h in cooling mode	0.7 K/W
The cold side thermal resistance, R_c in heating mode	0.5 K/W
The hot side thermal resistance, R_h in heating mode	0.09 K/W
Seebeck coefficient, α	0.05 V K^{-1}
Thermal conductivity of TEM, K_{TEM}	0.51 W/K
Electrical resistance of TEM, R_{TEM}	2.236 Ω
Dimension of aluminum panel	1580mm×810mm
The thermal conductivity of the aluminum, λ_{Al}	230 W/m·K
The thickness of aluminum panel, δ_{Al}	0.002 m
The density of insulation, ρ_{Al}	30 kg/m^3
The thermal conductivity of the insulation, λ_{ins}	0.05 W/m·K
The specific heat capacity of insulation, C_{ins}	500 J/kg K
The thickness of insulation, d_{ins}	0.04 m
The contract thermal resistance, R_{cont}	0.1 m^2 K/W
The height of air duct, H	0.81 m
The thickness of air duct, d_f	0.25 m
The density of PV panel, ρ_{PV}	2300 kg/m^3
The specific heat capacity of PV panel, C_{PV}	800 J/kg K
The thickness of PV panel, d_{PV}	0.045 m
The area ratio parameter, x	0.91

3.2. System model

3.2.1. PV+TE

The system model actually is coupled by heat flow model (**Fig.2a**) and power flow model (Fig.2b). The two major parts are coupled by the system electric current. The electric power and current used by heat flow model are just from the obtained system power P_{sys} and current I_{sys} from the power flow model. Guided by **Fig.2**, the details of models are explained as follows.

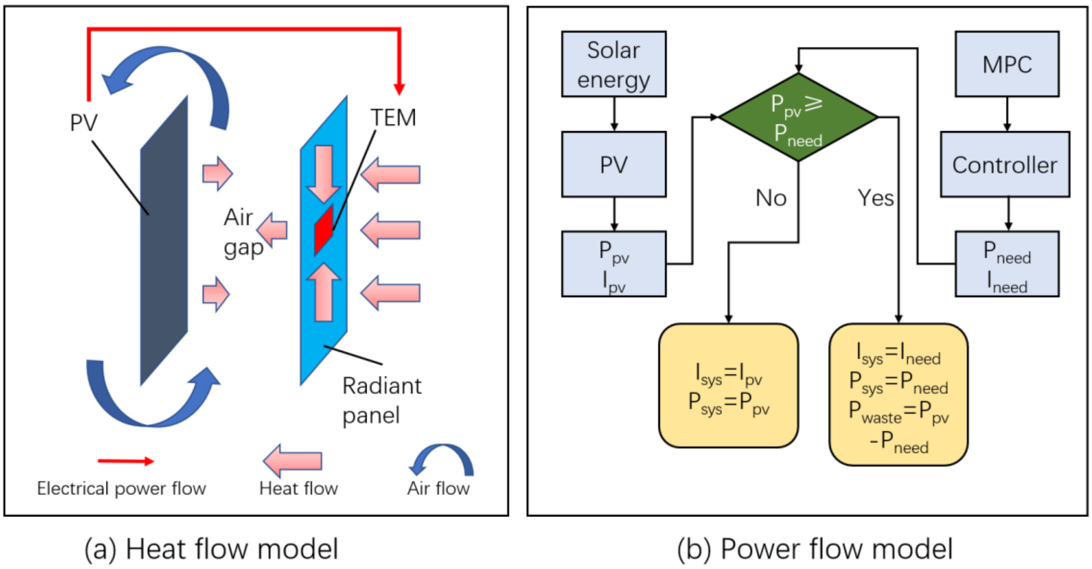


Fig.2 System model for (a) heat flow and (b) power flow of PV+TE.

(a) Heat flow model:

In this part we should assume the system working current and power from PV are already obtained. Then the TEMs will either cool or heat the radiant panel which depends on the current direction. An accurate and effective analytical model was built in our previous study [40], which will be adopted here directly.

Based on the previous study, the dynamic and non-uniform temperature field of internal surface of wall can be simulated by Eq.(1) [40], with two parameters calculation by Eq.(2) and Eq.(3), where T is the temperature at any place on the surface of the aluminium panel (K); R_c is the thermal resistance between the cold side of TEM and the surface of aluminium panel (K/W); T_{in} is indoor air temperature (K); T_{mrt} is the area-weighted average radiant temperature from other surfaces in the room (K); δ_{Al} is the thickness of aluminium panel (m); a is the thermal diffusivity coefficient of aluminium (m^2/s); r_i is the distance between the calculation point and one real heat source and four another virtual heat sources in method of mirror (m); N is the superposition number; Δt is time step series (s). And the parameters h_c, h_r, h_{cont} are respectively convective heat coefficient, radiative heat coefficient and heat transfer coefficient for thermal contact.

$$T^{(\tau+1)}=\left\{\begin{array}{l}\left\{\sum_{j=1}^{N}\left[\frac{q_s^{(\tau-j+1)}}{4\pi\lambda_{Al}}\sum_{i=0}^{m}\int_{(j-1)\times\Delta t}^{j\times\Delta t}\frac{1}{t}\exp\left(-\frac{r_i^2}{4at}-\omega^2 at\right)dt\right]\right\}\\+\frac{h_cT_{in}+h_{cont}T_{b2}+h_rT_{mrt}}{h_c+h_{cont}+h_r}\end{array}\right\} \quad (1)$$

$$\omega=\sqrt{\frac{h_c+h_r+h_{cont}}{\lambda_{Al}\delta_{Al}}} \quad (2)$$

$$q_s=\frac{(\xi_1-1)T_1+\xi_2}{R_c\delta_{\mathrm{Al}}} \quad (3)$$

The parameters ξ_1 and ξ_2 are given by Eq.(4) and Eq.(5) [40], where α is Seebeck coefficient of TEM; K_{TEM} is the heat conductivity of TEM; R is electric resistance of TEM; T_{f} is the air temperature in the air duct; and I is the working current for each TEM.

$$\xi_1=\frac{\frac{1}{R_cK_{TEM}}\left(\frac{1-\alpha IR_h}{R_hK_{TEM}}+1\right)}{\left(\frac{1+\alpha IR_c}{R_cK_{TEM}}+1\right)\left(\frac{1-\alpha IR_h}{R_hK_{TEM}}+1\right)-1} \quad (4)$$

$$\xi_2=\frac{\frac{I^2R}{2K_{TEM}}\left(\frac{1-\alpha IR_h}{R_hK_{TEM}}+1\right)+\left(\frac{T_f+\frac{1}{2}I^2RR_h}{R_hK_{TEM}}\right)}{\left(\frac{1+\alpha IR_c}{R_cK_{TEM}}+1\right)\left(\frac{1-\alpha IR_h}{R_hK_{TEM}}+1\right)-1} \quad (5)$$

Besides the dynamic and non-uniform heat transfer in TE and radiant panel, the rest components of insulation board, air duct and the PV panel, are modeled by using state-space model [21], which are expressed and solved in an efficient matrix form of Eq.(6) [21]. The vector **X** in Eq.(6) is [T_{PV}, T_{f}, T_{b1}, T_{b2}] and the input vector **u** is [$G_{\mathrm{t}}\alpha_{\mathrm{PV}}$-$P_{\mathrm{sys}}/A_{\mathrm{pv}}$, T_{out}, T_{h}, T_{Al}]. The matrix **E** is 4×4 identity matrix. The coefficient matrix **A** and **B** is derived and reformed based on heat transfer equations of insulation board, air duct and the PV panel.

$$\mathbf{X}_{\tau+h}=e^{\mathbf{A}\cdot h}\mathbf{X}_{\tau}+\left(\mathbf{\Gamma}_1-\mathbf{\Gamma}_2\right)\mathbf{u}_t+\mathbf{\Gamma}_2\mathbf{u}_{\tau+h} \quad (6)$$

$$\mathbf{\Gamma}_1=\mathbf{A}^{-1}\left(e^{\mathbf{A}\cdot h}-\mathbf{E}\right)\mathbf{B} \quad (7)$$

$$\mathbf{\Gamma}_2 = \mathbf{A}^{-1}\left(\frac{\mathbf{\Gamma}_1}{h} - \mathbf{B}\right) \quad (8)$$

(b) Power flow model:

In this part, two tasks are to be addressed (**Fig.2b**). One is accurate calculation of PV power output based on received solar radiation and ambient temperature. Another is to determine the power demanded by the system with model predictive control (MPC).

The power output of PV module is modeled by an equivalent electric circuit and its I-V equation (Eq.(9)) where I_{PV} and V_{pv} are the electric current and voltage output generated by PV module. In addition, there are five important parameters: I_{ph} is the photo current (A); I_0 is the diode saturation current (A); R_s is the series resistance (Ω); R_p is the parallel resistance (Ω); $V_{th} = N_s KT/q$ is the diode thermal voltage. And N_s is the number of solar cells in series; K is Boltzmann's constant (-1.380653×10^{-23} J/K); q is the absolute value of electron's charge ($-1.60217646\times10^{-19}$ C); T is the temperature of the junction (K); n_0 ranging from 1 to 2, is the diode ideality factor.

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{n_0 V_{th}}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_p} \quad (9)$$

The values of five parameters in Eq.(9) are dynamically changed with solar irradiance and cell temperature. Those parameters under general conditions can be calculated by using the five parameters under standard testing condition (STC: 1000W/m^2 and 25°C) and applying some extension formulas [41].

The Eq.(9) is an implicit function with current and voltage which cannot be solved directly by common functions. In this study, combining *I-V* equation (9) with Ohm's law $V=I\times R_{load}$, the output current and voltage can be calculated by Lambert-W function solution for an explicit expression [42], as presented by Eq.(10). The parameter R_{TEM} refers to the total resistance of TE modules. And the five parameters under STC are: I_{ph} = 5.13806 (A); $I_0 = 1.35845\times10^{-7}$ (A); R_s = 0.454354 (Ω); R_p = 1852.48 (Ω); n_0 = 1.37594.

$$\begin{cases} I_{PV} = \dfrac{(I_{ph} + I_0)R_p}{R_{TEM} + R_s + R_p} - \dfrac{V_{th}}{R_{TEM} + R_s} W[X] \\ X = \dfrac{(R_{TEM} + R_s)I_0 R_p}{(R_{TEM} + R_s + R_p)V_{th}} \exp\left[\dfrac{(I_{ph} + I_0)(R_{TEM} + R_s)R_p}{(R_{TEM} + R_s + R_p)V_{th}}\right] \end{cases} \quad (10)$$

By obtaining the I_{pv} and P_{pv}, the power provided by PV can be obtained. Next, in the power flow model, it is also required to find out how much the system demand is for a certain requirement.

In this study, it is assumed that the BIPVTE can provide additional thermal energy Q_w for indoor space. Note that Q_w is a setting parameter of the envelope system which can change according to indoor requirements. The basic case is set Q_w as zero and it means zero heat flux through the envelope system. If $Q_w > 0$, then this positive-heat-flux scenario can provide additional cooling in summer or heating in winter by the wall rather than AC. The mission of MPC is to find a suitable working current I_{need} for TE wall to generate Q_w under the indoor and outdoor thermal conditions. The searching of I_{need} can be expressed as the Eq.(11). The function f is an abstractive representative of heat flow model. The Q_{in} refers to the instant heat flux through the internal surface of BIPVTE wall, a positive value of whom indicates indoor heat gain while a negative one represents indoor heat lose. The upper script "t" means the current time node. The T_{Al} indicates the internal surface temperature of BIPVTE wall. The searching of minimum and maximum of I_{need} are set as -5 and 5 (A) in the model. The control of the system is to make Q_{in} approach Q_w as much as possible with available PV power. Note that Q_w is always not negative while the sign of Q_{in} changes with the actual operation of the system. In order to facilitate understanding and also for convenient computer programming, the parameter named "hx" is used to denote winter (hx = 1) or summer (hx = -1).

$$\begin{cases} \min\left\{Q_{in}^{t} \times hx - Q_{w}\right\} \\ Q_{in}^{t} = h_{r}(T_{Al}^{t} - T_{mrt}^{t}) + h_{c}(T_{Al}^{t} - T_{in}^{t}) \\ T_{Al}^{t} = f\left(T_{in}^{t}, T_{out}^{t}, G_{tv}^{t}, T_{m}^{t}, I_{need}^{t}\right) \\ I_{\min} \le I_{need}^{t} \le I_{\max} \end{cases} \tag{11}$$

Once the I_{need} and P_{need} are obtained, as shown in Fig.3b, by judging the value of P_{pv} and P_{need}, two choices are to be made. It is worth mentioning that when P_{pv} exceeds the demand, excessive power will be wasted, because in most cases, the selling power to grid is not allowed.

3.2.2. Grid+TE

The Grid+TE type is only powered by the grid rather than instant PV generation when compared with the PV+TE type. It is applicable to the areas with no abundant solar energy, and also serves as a reference case for comparison where no renewable energies are utilized in the system. The schematic of this model is shown in **Fig.3**. The heat flow and power flow models of PV+TE can still adopted in this scenario by only eliminating the PV generation part.

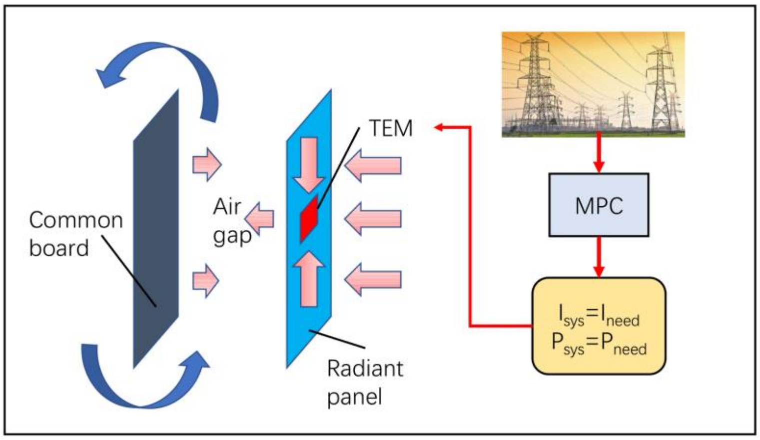


Fig.3 System model for Grid+TE mode.

3.2.3. PV+Grid+TE

It is clear that both PV+TE and Grid+TE have their own shortcomings by nature. In PV+TE case, there are always some times in which PV output is not available or qualified. In Grid+TE case, although the demand can be met at each time node, zero renewable energy is utilized. So, the combination of PV, Grid with TE in this case could have a potentially better performance.

Fig.4 depicts the function of PV+Grid+TE scenario. The involvement of grid can make power demand can be met all the time. The basic principle of this type of system is to use as much solar energy as possible. And also, the wasted PV power is inevitable since selling power to grid is neglected in this study and also not allowed in most of real situations. The heat flow and power flow model can still be used here with only minor modification on the power supply source.

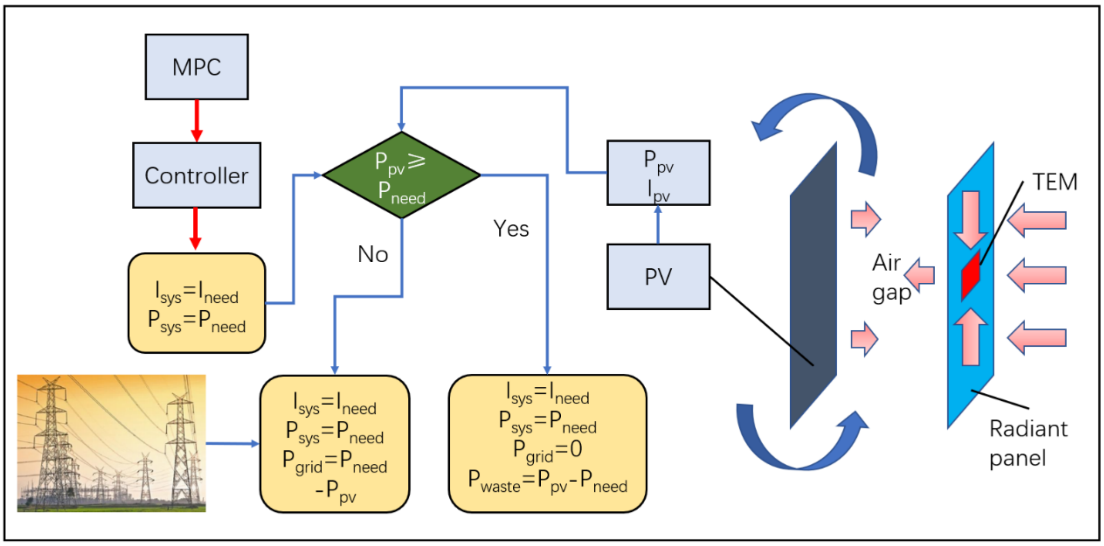


Fig.4 System model for PV+Grid+TE scenario

3.2.4. PV+battery+TE

As the above cases denoted, the wasted PV power always happen during operation. The introduction of energy storage like battery can make full use of those wasted PV power that are reused for TE wall. Therefore, both the PV and battery are power source for TE wall to realize heat flux control.

The basic logic is to use PV power output first. If it is excessive, battery can store the power. If it is not sufficient, battery can afford the rest. If it is still not enough to meet the demand for P_{need}, TE wall failed to control the heat flux Q_w as expected. The basic control flow is given in **Fig.5**. In the charging condition, the charging power should be the minimum value among [$(P_{pv}$-$P_{need})$*y_c, $(soc_{max}$ - $soc_1)$*Q_{batt}, P_{cmax}], where y_c is charging efficiency of battery; SOC is the state of charging of battery; Q_{batt} is the power capacity of battery (Wh); and P_{cmax} is the maximum limit of charging rate of battery (W). The similar process is also for discharging situation when PV power is not enough for the requirement. Those battery related parameters used in this model are listed in **Table 2**.

Table 2

Battery model parameters

Variable	value
Q_{batt} (Wh)	3000

P_{cmin}, P_{cmax} (W)	1000
SOC_{min}, SOC_{max}	0.15, 0.95
y_c, y_d	0.9

It should be mentioned that in discharging situation, it is possible to happen that the power provided by both PV and battery is still insufficient for the system to remove heat gain/loss. Then the power $P_{pv}+P_d*y_d$ is all the system can get. Under this condition, the system working current is the solution of Eq.(12), where m is the number of TEM connected in series; ΔT is the temperature difference between cold and hot side of TEM. The explicit solution is given in Eq.(13).

$$P_{sys} = I_{sys}^2 R_{tem} m / 2 + \alpha m \Delta T I_{sys} \quad (12)$$

$$I_{sys} = \frac{-\alpha m \Delta T + \sqrt{(\alpha m \Delta T)^2 + 2 R_{tem} m P_{sys}}}{R_{tem} m} \quad (13)$$

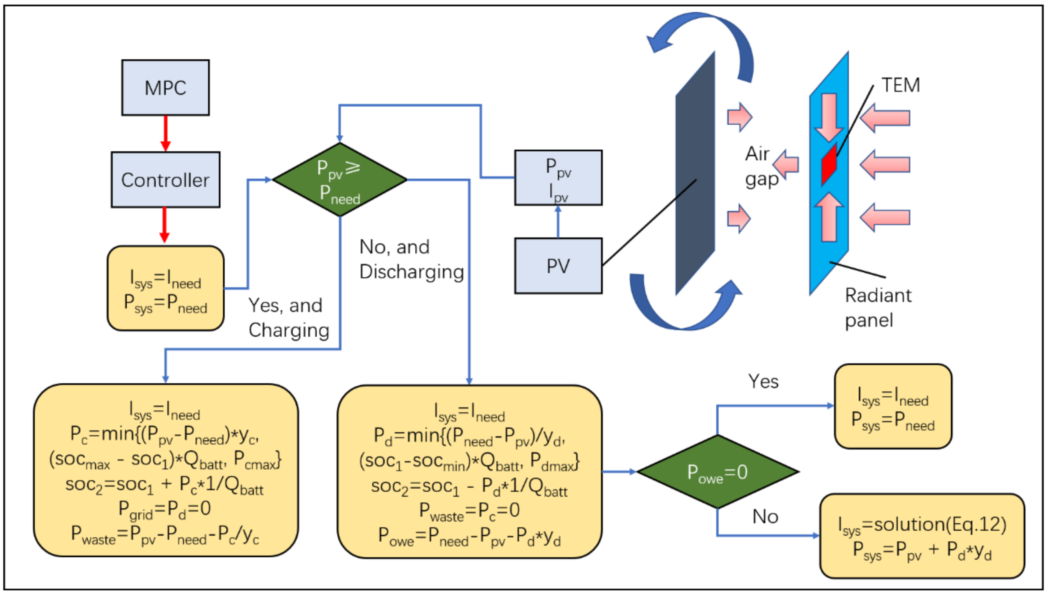


Fig.5 System model for PV+Battery+TE scenario.

3.2.5. PV+Grid+battery+TE

The PV+Battery+TE in **Fig.5**, still has the chance to encounter power shortage. The connection to grid simply makes the finial type as **Fig.6** exhibited. Through this way, the system may achieve even better energy performance. It should be noticed that in both **Fig.5** and **Fig.6**, there still has a chance wasting some part of PV power energy if the output by PV is far beyond the need and the battery can take. The majority content in PV+Battery+TE and PV+Grid+Battery+TE system are similar in function. The battery parameters in **Table 2** are also used in this model.

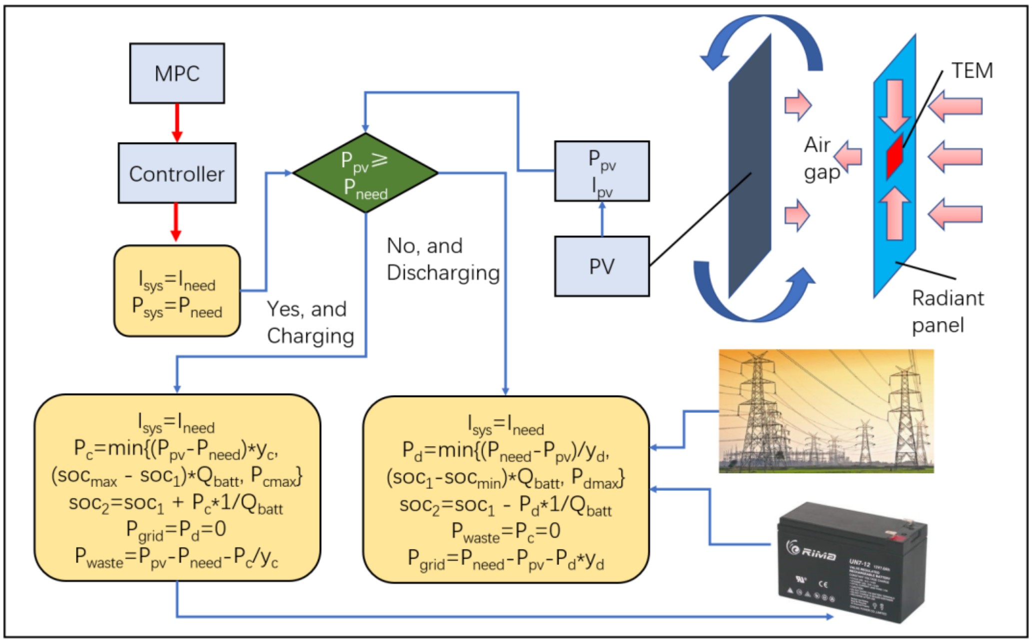


Fig.6 System model for PV+Grid+Battery+TE scenario.

3.3. Reference system model

In order to conduct comparison study or calculate some performance indexes, a benchmark or reference should be provided. Based on the fairness of comparison, in this study, the reference system is chosen as the original BIPVTE wall system but the input working current is zero, which means this reference system cannot use electric power to trigger TEMs and cannot manipulate heat flux through the wall. This design can ensure that this reference system has identical physical structure.

As for the model of reference system, the models proposed in Eq.(1)-(3) are still valid. But the parameters in Eq.(4)-(5) should be revised into Eq.(14)-(15) by simply setting the working current I_{sys} equals zero. The power flow also is zero in this reference model since PV is not working here.

$$\xi_1' = \frac{\frac{1}{R_c K_{TEM}}\left(\frac{1}{R_h K_{TEM}}+1\right)}{\left(\frac{1}{R_c K_{TEM}}+1\right)\left(\frac{1}{R_h K_{TEM}}+1\right)-1} \tag{14}$$

$$\xi_2' = \frac{T_f}{\left(\frac{R_h}{R_c}+1\right)\left(1+R_h K_{TEM}\right)-R_h K_{TEM}} \tag{15}$$

4. Energy analysis method

4.1. Method description

In this study, a new concept of building envelope system is proposed that can not only shield heat flux from or to outer environment according to seasons or indoor requirements, but also can undertake the role to share burden of indoor HVAC system. Its energy performance is a key in the system analysis, especially with five different system structures proposed waiting for evaluation and comparisons. Besides that, we may learn from other literature that energy should not be sole index. Therefore, the method of economic and environmental analysis along with energy analysis are given here, to present a comprehensive study.

First, the internal surface temperature of the wall T_w and hourly intake heat flux Q_{in} through the envelope system. The calculation of Q_{in} is given in Eq.(11) and the value of T_w equals the average temperature on the panel, namely T_{Al} in Eq.(11).

Second, it is very important to know how much power P_e is cost for the operation of BIPVTE. This index is slightly different for each system structure. In all, there are two routines counting for power consumption: one is power from grid and another is a calculated power consumption that is used by HVAC to remove undesired heat gain/loss.

To help understand the calculation process, a simple example is given. It is assumed that Q_w is anticipated to be 10W/m^2, but BIPVTE wall can only make it as 4W/m^2 due to some reasons (The proposed system cannot handle the entire heat flux, mainly because of insufficient solar power input and thus insufficient PV power output if PV is the only power source to the system). In this case, the HVAC system will take the extra 6W/m^2 by using power, that is the value of 6 divided by COP (coefficient of performance) of HVAC. The COP of HVAC is set as 2.8 in winter and 2.6 in summer.

In order to facilitate understanding and for convenient computer programming, the parameter named "hx" is used to denote winter (hx=1) or summer (hx=-1). Then the calculations of P_e for S1 to S5 are shown in **Fig.8**. It should be noted the parameter *A* means the area of internal surface of wall. By doing so, only power consumption per unit square meter is used for evaluations. Some other detailed explanations for each system (S1 to S5) are provided in **Fig.7**. A detailed example explanation for the function and evaluation is provided in **Appendix A**.

In addition, in order to clear showcase the hourly variation of system power consumption within a year-round simulation, a kind of data treatment using accumulated power consumption over the past time is adopted. And considering in some cases, part of PV power will be wasted if no battery is used or the battery is full. This part of waste energy is also recorded for later analysis.

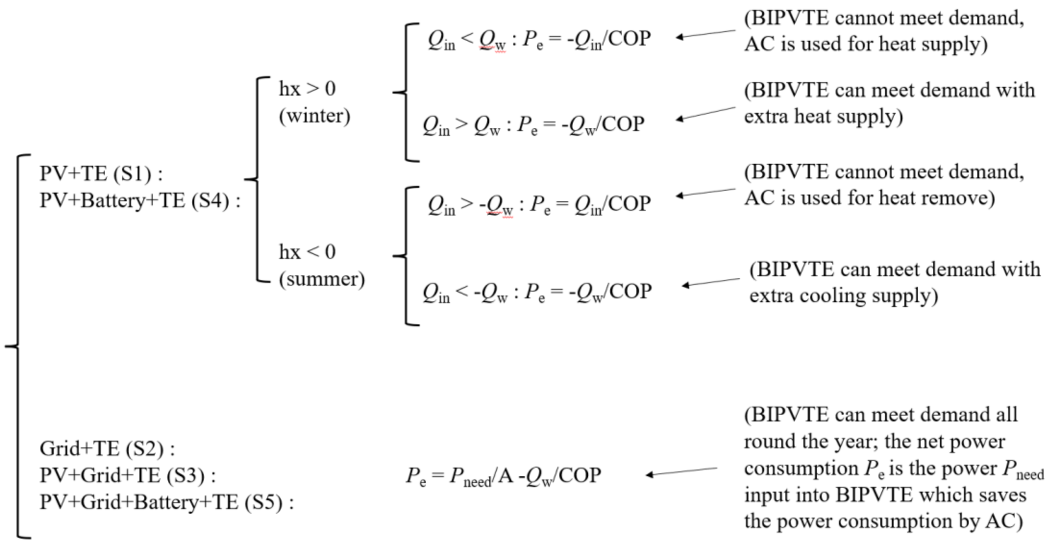


Fig.7 Calculation method for power consumption of the wall.

4.2. Notes

There are several notes to be made for the simulations or the application of the system models:

1) The proposed model is very flexible according to our previous tests and evaluations. By simply changing the working current from *I* into -*I*, the BIPVTE can shift from cooling mode into heating mode. Even by setting the current as zero, the model still can function properly. Accordingly, the only modification of the models is

replacing the contact thermal resistance in cooling model R_c with that in heating model R_h in Eq.(3), for the change from cooling mode to heating mode.

2) Most of studies carried out simulation or analysis by evaluating the energy saving with the unit of kWh. Since the case study may vary in different situations, in this study, all the indices for energy performance are transformed into kWh/m^2 or W/m^2 in unit, which can offer a better and justified results, not only for the analysis included in this study, but also better for comparison with many other studies.

3) In order to check the model validity, an experimental rig was built and a series of experimental measurements were conducted for BIPVTE wall system. In our previous study on net zero energy building [38], the proposed model was verified through comparison with experimental data in both summer and winter conditions, which can ensure the model accuracy and validity.

4) It is claimed that although the model is very flexible, some issues should be paid attention for the sake of model applications. First, the number of TEM chip is ten with each five in a series connection. This means the value of parameter m is five in Eq.(12). If there is a different design layout of TEM chip on the radiant panel, this value should be updated by the designer. Second, the insulation used in the model is assumed as in an ideal condition that can provide adiabatic boundaries. In real application, this may be slightly different which depends on the insulation materials used.

5) All the mathematical models and corresponding control algorithm are written in a home-developed computer program based on open-source programming language.

5. Results and discussions

We noticed that there is too much power from PV wasted, and the BIPVTE may offer additional heating/cooling energy as **Fig.1b** envisioned. In this sub-section, those five systems S1 to S5 are set to reach this goal with different Q_w values. This is going to test if this aim can be realized and if the cost to this aim is fair or not. In the following analysis, the system parameters and climate data are the same with the last section. And the typical meteorological year (TMY) in a representative city of hot summer and cold winter zone, Wuhan, is chosen as the model inputs (data source: EnergyPlus weather data: https://energyplus.net/weather).

5.1. PV+TE

In order to better showcase the changes brought by $Q_w \neq 0$, the results for Q_w equals 0, 10, 20, 30 W/m^2 are compared. In **Fig.8a** and **Fig.8b**, the internal surface temperature and hourly heat gain/loss of wall under various Q_w are compared. In this winter condition, if the weather condition is a sunny day, the system can fully ensure the heat flux as set values and the internal surface temperature is 18℃, 19℃, 20℃ and 21℃ with one-degree increasement under Q_w = 0, 10, 20, 30 W/m^2. But if the weather condition is not feasible, all four cases behave the same.

In summer month, as **Fig.8c** and **Fig.8d** shows, at daytime of summer, the PV should have enough power to stimulate TEMs to provide required cooling energy. There is a sharp temperature increase at night due to power shortage. And also if the weather condition is not feasible, all four curves overlapped. Those results can roughly show the PV+TE system can only realize required Q_w when PV power is qualified. The uncertainty of this system is high.

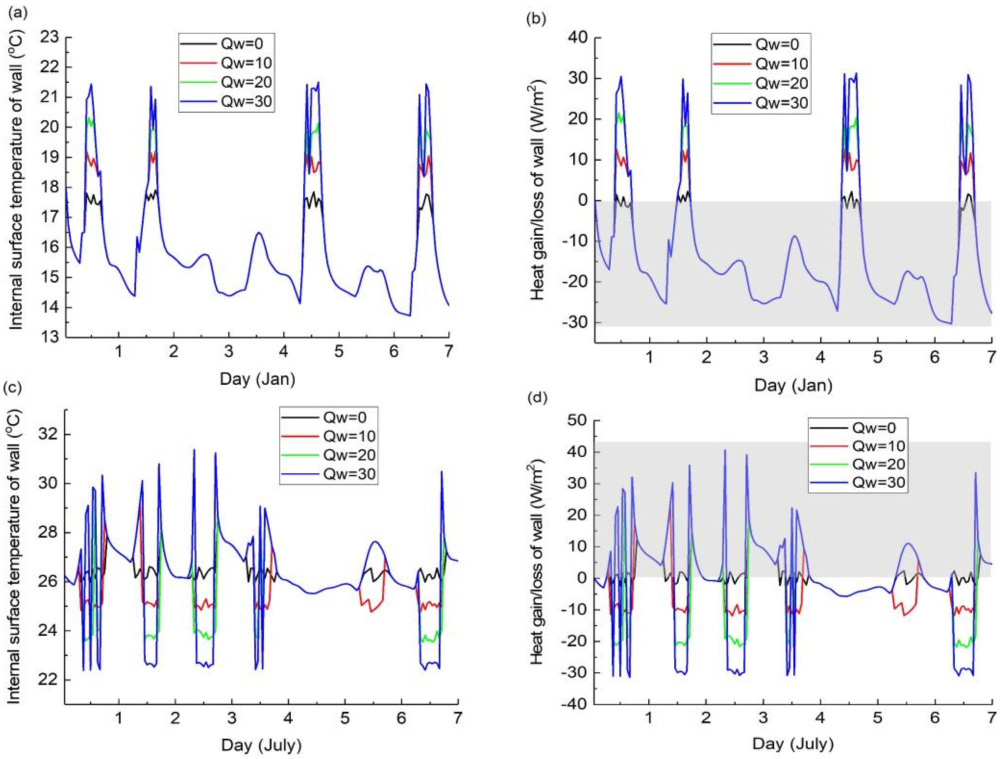


Fig.8 Hourly internal surface and heat gain/loss of PV+TE wall in a typical week of winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th) under various Q_w settings. [*The gray area in the figure means this part of heat gain in summer and heat loss in winter must be undertaken by air conditioner*].

5.2. Grid+TE

The simulations are performed for Grid+TE system under various Q_w settings. From the results of internal surface temperature and heat gain/loss of wall in both winter and summer, all the requirements are met in good order (**Fig.9**). In winter, the wall can provide extra heating and in summer the extra cooling for indoor space, despite of some weak fluctuations. There is no concerned about power consumption from AC to remove heat gain/loss of wall like conventional wall systems. All the power consumption is used to commission Grid+TE system with different demand of Q_w.

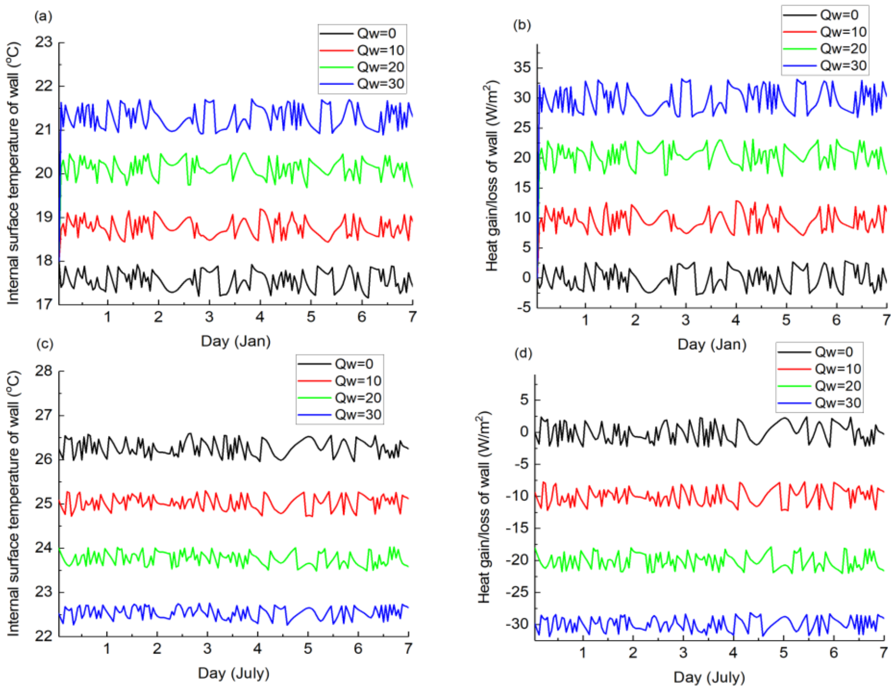


Fig.9 Hourly internal surface and heat gain/loss of Grid+TE wall in a typical week of winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th) under various Q_w settings.

5.3. PV+Grid+TE

The prototype of PV+Grid+TE is also received with energy analysis. Because the grid is included, the surface temperatures and heat flux are fully controlled and the results should be identical as **Fig.9**. So, it is not repeatedly shown here. The energy performance of this type is focused on its hourly power consumption and wastes. The results in a typical week of winter and summer are presented in **Fig.10**.

In winter, it is found that if weather condition is good, for example, the day 1, 2, 5 and 7, the PV can provide enough power and realize the required Q_w, which lead to negative power consumption (means energy saving instead). But at night or solar energy is not enough at day 3, 4 and 6, power must be used from grid and the value is larger with higher Q_w demand. At the same time, when the Q_w is as high as 30W/m^2, no power from PV will be wasted in this week.

In summer, the system energetic behaves different. The reason behind is the enough solar energy in summer. Zero-heat-flux is requested, then the power consumption curve could also be zero in Fig.11c. And when the higher Q_w is asked for, the BIPVTE can share much more burden from AC system, and thus saving more energy.

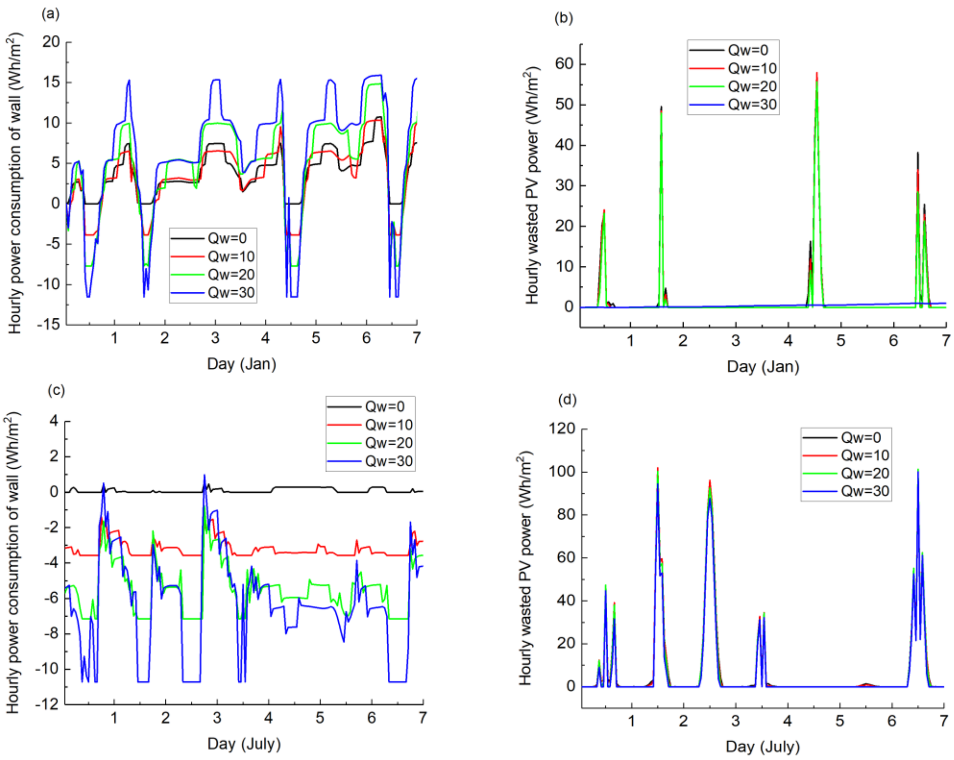


Fig.10 Hourly power consumption and wasted PV power of PV+Grid+TE wall in a typical week of winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th) under various Q_w settings.

5.4. PV+Battery+TE

As for the PV+Battery+TE type, the temperature and heat flux in **Fig.11** show that both in winter and summer, the requirements can be met except for some very rare chance that PV or battery is unable to provide required power for TEMs. This caused some very sharp drops or peaks here.

The involvement of battery makes this type of system different from the previous ones. In the first week of Jan in winter (**Fig.12**), the SOC curve is going down all the way and the slope is sharper with higher Q_w values. While in summer, the SOC is always kept as a flat curve or just with small floats. When Q_w is lower than 20W/m^2, the battery is always in full state.

The year-round variation of SOC under various Q_w values is shown in **Fig.13**. When Q_w is low, the SOC only decreases in winter season. With a higher Q_w, those SOC curves are becoming shorter which means the power in battery is frequently used and hugely consumed.

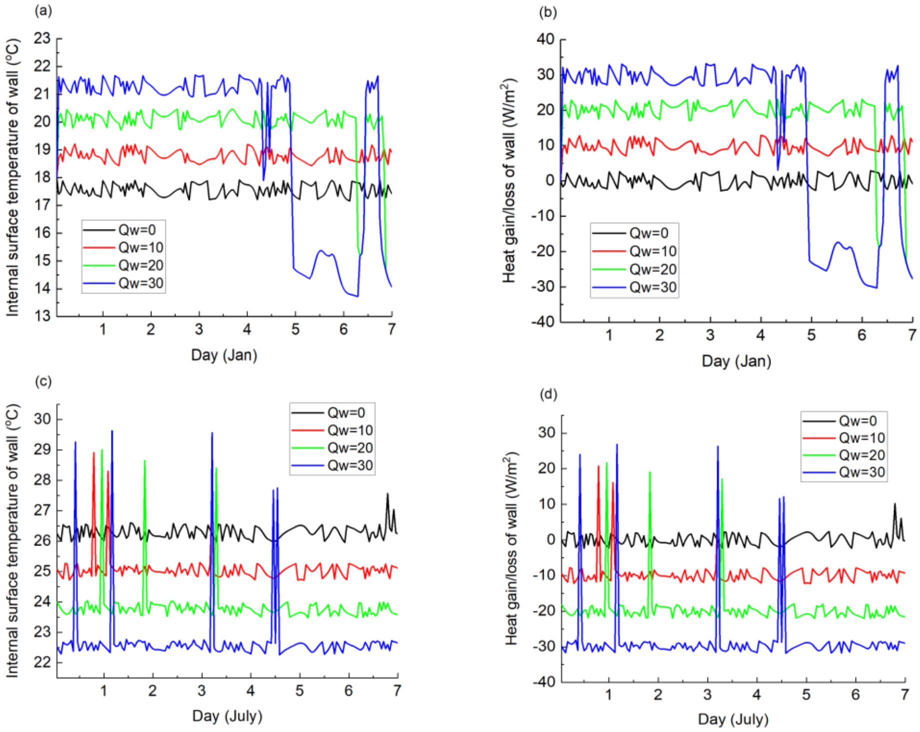


Fig.11 Hourly internal surface and heat gain/loss of PV+Battery+TE wall in a typical week of winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th) under various Q_w settings.

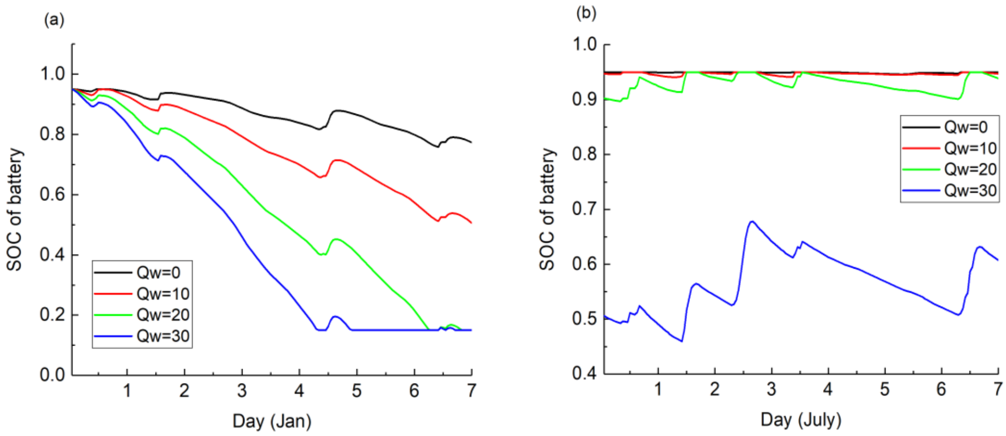


Fig.12 The SOC of battery in winter or summer condition under various Q_w settings.

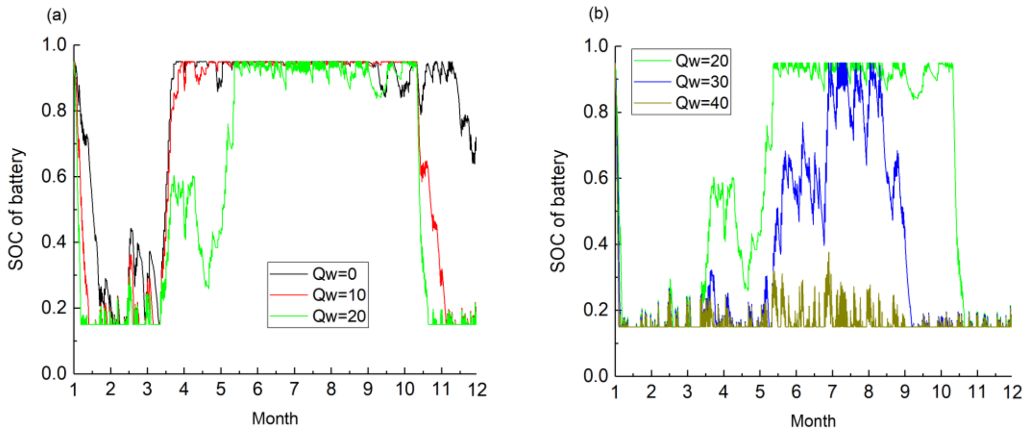


Fig.13 The SOC of battery throughout the operation year under various Q_w settings.

5.5. PV+Grid+Battery+TE

In this system, also because the involvement of power grid, the Q_w can be satisfied all the time. **Fig.14** shows the hourly power consumption and waste in winter and summer. It is found that power variation becomes much less complex.

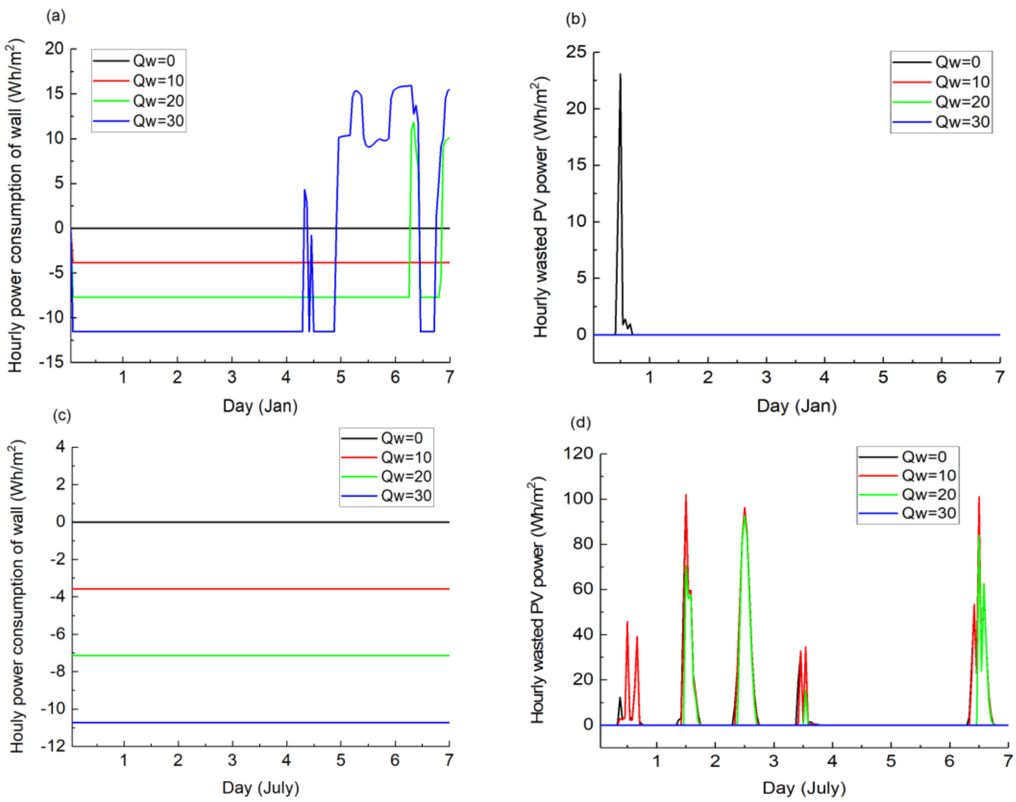


Fig.14 Hourly power consumption and wasted PV power of PV+Grid+Battery+TE wall in a typical week of winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th)

under various Q_w settings.

For the case with Q_w=0 W/m^2 and Q_w =10 W/m^2, the power curves are completely flat. This means by using PV and electric storage of battery, the system can perform well. When the value of Q_w is increased to 20 or 30 W/m^2, for most of the time, the power consumption is negative that means energy saving. But only some very few moments, the curve is above zero line. And at the same time, the PV power waste is improved greatly. This means the solar energy has been fully used.

While in summer condition, the power consumption are all negative flat curves for all the cases. The PV power is excessive and the volume of battery cannot take any more power which lead to some part of power waste. But from **Fig.14d**, it is also observed that when Q_w raised to 30 W/m^2, even in summer, the power waste can be solved and at the same time, as **Fig.14c** shown, the energy saving intensity is noticeable.

5.5. Energy performance comparison across different systems

In order to facilitate the features of the proposed concept and performance of different systems, a cross comparison is made in **Fig.15**. There are two settings of Q_w in the comparison.

It is clear for "zero heat flux" setting, the power consumption and PV power abandon are in a descendant order from S1 to S5. By using PV and grid as power source, using battery as power storage, coupled with control algorithm, the building envelope system can save about 40 kWh/m^2 for air conditioner and the PV power abandon is much lower for unit area of the wall.

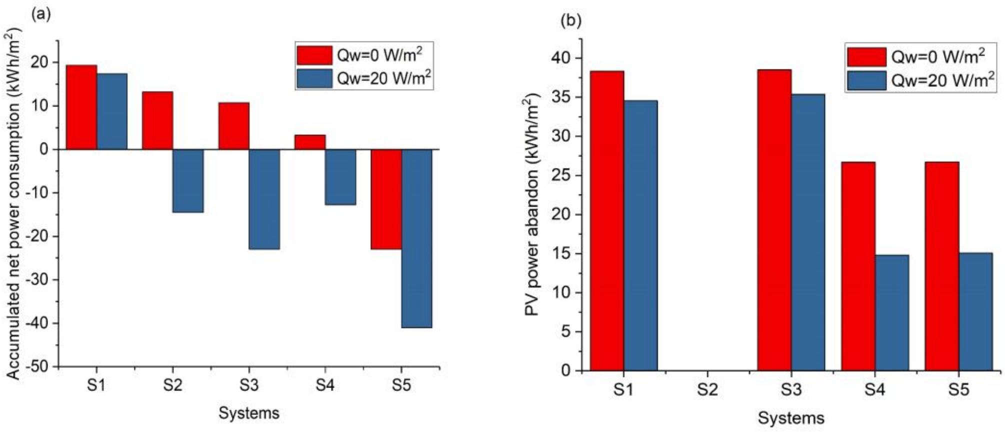


Fig.15 The comparison of net power consumption and PV power abandon among five systems in annual operation.

If a “positive heat flux” setting is assigned to the system, their behavior becomes different. Except for S1 (PV+TE), the rest systems can all achieve negative net power consumption for air conditioner. And compared with “zero heat flux” scenario, the PV power abandon is reduced in a further step. This means that renewable energy is making full usage and the energy efficiency is enhanced noticeably.

5.6. Application related discussions

The control is the core and its implementation are very important in engineering application. Considering that there are five different systems discussed in the study, their control realizations are discussed respectively.

PV+TE (S1): This system proposes a direct connection between solar PV cell and TE modules and no particular control is designed for it. Actually, the S1 is a self-controlled system. The higher solar radiation will promote PV power output at noon time and it may be lower in the early morning or late afternoon. But this self-controlled system may not be matching with the heat flow control, which is also shown in the numerical analysis.

Grid+TE (S2): This system does not use renewable sources but from power grid. The control in this system can be implemented by a power regulator that can adjust the input direct electric flow into the TE module based on the required inward heat flow of the wall. And the regulation magnitude is calculated by MPC algorithm.

PV+Grid+TE (S3): This system has a similar control procedure as the S2 system. But in application, the algorithm should firstly evaluate the PV power output is sufficient or not. The grid in this system is a supplement.

PV+Battery+TE (S4): The controller in this system should undertake two roles. One side is to satisfy the instant heat flow demand of the wall and another side is for extra power charging or discharging to or from the battery. This can make the system working at part of night time.

PV+Grid+Battery+TE (S5): This system complexity is the highest and it require three aspects of control that is required in S2 to S4.

In terms of application issues, there are two aspects to be noted. One is for new buildings. The proposed system could be manufactured as a building component in pre-fabrication. This can make the wall module as a mature product with standard performance and indexes. Another is for refurbishment of old buildings. Because it must be deeply integrated into the wall structure, it cannot be integrated directly. But the building should first remove the window and it can be installed within window frame.

6. Conclusions

In this study, an idea is put forward to turn building envelope into a multi-function component that can shield heat flux from outside while providing additional heating/cooling energy to indoor space. Through this new concept, not only the thermal load from building envelope can be waived, but also the conventional air conditioning system can be designed with smaller capacity. Huge energy saving and investment saving could be realized. This idea is to be realized based on a building integrated photovoltaic thermoelectric wall (BIPVTE) system. There are five different porotypes as PV+TE (S1), Grid+TE (S2), PV+Grid+TE (S3), PV+Battery+TE (S4) and PV+Grid+Battery+TE (S5).

The building envelope can be served as an air conditioner to fulfill additional task of providing cooling/heating. Those five systems behave so different. All the grid connected system can maintain the extra thermal flux Q_w as set value. In all the five systems, there is a typical optimum setting of Q_w for each one of them with minimum annual power consumption. Except for the PV+TE system, the rest can realize accumulated negative power consumption in a year-round operation. By increasing the value setting of Q_w, it can help with power consumption of PV, but it is only in the system of PV+Battery+TE and PV+Grid+Battery+TE that can realize a substantial reduction of power waste, mainly due to battery.

Appendix. A. Example illustration of system function and evaluation

A simple example explanation is given for a full understanding of the calculation proposed in **Fig.7**. It is assumed that there is a thermal load Q_w = 10W/m^2 to be undertaken by the building envelope. It means that the wall itself should provide additional cooling in summer and heating in winter by the intensity of 10W/m^2. There are five important power related parameters in the calculation flow in **Fig.7** and they are listed in **Table.A1** by example with explanations. The following table gives the reaction of each system for this goal and the way how power consumption is calculated.

This reaction of system depends on the actual heat gain/loss Q_{in} although the system has tried its best to meet the demand.

Table. A1

Parameters	Meanings	Example: PV+TE system	Example: Grid+TE system
Q_w	The requested cooling/heating flow rate assigned to the building envelope system (W/m^2)	We ask the envelope should provide 10 (W/m^2) cooling in summer and heating in winter.	
Q_{in}	The closest cooling/heating flow rate currently the system can provide (W/m^2)	Only winter condition is taken in example. Because the power source is PV, it cannot provide power at night or the power is insufficient at some time. If it is at winter night, Q_{in} is a negative value and assumed as -10 (W/m^2); and if solar radiation is not enough, Q_{in} may be 6 (W/m^2) which lower than Q_w. If the condition is good, Q_{in} can be larger than Q_w, for example 20 (W/m^2).	Because this system is always connected to the power grid, it can meet the demand all the time by using TE cooling or heating. So, $Q_{in} = Q_w$ all the way.
COP	The coefficient of performance of air conditioner	The COP of HVAC is set as 2.6 in winter and 2.8 in summer	
P_{grid}	Power used by TEM from power grid	None	Assuming 7 W.
P_e	The power consumption by air conditioner	Following the example for the value of Q_{in}:	The system can meet the demand all the time by

		If Q_{in} is -10 (W/m^2), then this part of heat loss has to be supplied by AC. So, P_e = -(-10)/COP. If Q_{in} is 6 W/m^2, then this means some part of AC power is saved and this saved power is P_e = -6/COP. If Q_{in} is 20 (W/m^2), the system exceeds the request, but only the requested thermal load is certified. So, P_e = 10/COP.	connecting to the grid. The pure power consumption by AC included power consumption by TEM by using source of the grid and the power saved for AC. Therefore, the net power consumption of AC becomes: 7/A – 10/COP.

Declaration of Competing Interest

None

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