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

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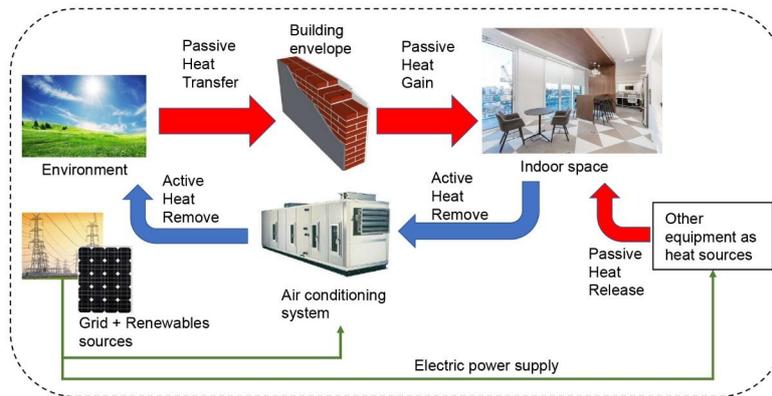
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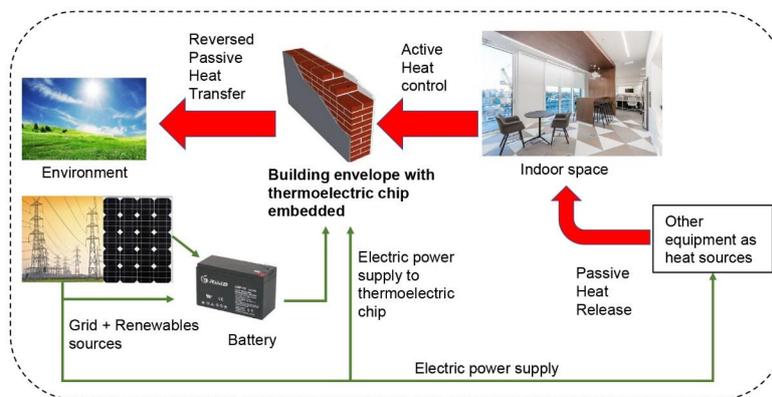
17 **Highlights**

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

1 Graphical abstract



(a) Heat and power flow in conventional case



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

2

3 Abstract

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

17

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

3 **1. Introduction**

4 **1.1. Background**

5 Building energy consumption takes the biggest proportion among all sectors. It
6 was reported that global buildings contributed to 30–40% of the final energy
7 consumption and emitted 40% of total CO₂ in direct or indirect paths [1]. A question
8 was raised: “*What if buildings can afford the energy bill by themselves?*” Then the
9 concept of zero energy building was proposed and it shoulder the duty to create a
10 sustainable development scheme in building sector [2].

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

20 **1.2. Literature survey**

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

31 There are three major approaches for the advanced NZEBs as summarized by Li
32 et al. [13]: (*Approach 1*) minimizing building energy demands [14], (*Approach 2*)

1 *improving on-site renewable energy supplies* [15], and *(Approach 3) load matching*
2 *among the on-site energy supply side and energy use end.*

3 (Approach 1:) The most common method minimizing building energy demand is
4 to enhance thermal performance of building envelopes or adopting HVAC system with
5 higher energy efficiency [16]. Increasing thermal resistance through insulation[17] [18],
6 enhancing thermal stability through PCM [19], are common and effective means for
7 lowering thermal load of buildings as passive design. And some active technologies
8 [20] such as thermoelectric wall [21], or water flow window [22], are also contributing
9 novel solutions for NZEBs. Li et al. [13] emphasized the importance of building
10 envelope and its role in NZEB by analyzing examples like wall thermal insulation[23],
11 window glazing, and green roof [24]. Shin et al. [25] analyzed the difference between
12 renovated and non-renovated NZEB in a US army base. The renovation is conducted
13 mainly for improving the thermal insulation of building envelope including lowering
14 solar heat gain coefficient (SHGC) of the glazing. Usually the life cycle cost analysis
15 can be a critical tool for the performance evaluation of NZEBs with advanced building
16 envelope systems like low-energy window glazing and the better thermal insulation
17 adoption [26]. And many aspects including global cost and thermal comfort should be
18 concerned [27].

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

34 (Approach 3:) Advanced control algorithms and management strategies consider

1 vast aspects, which should be key to optimal coordination between power supply and
2 demand side, or the load match issue between grid and renewable energy sources. The
3 NZEB is not asking off-line from grid entirely but requiring NZEB to generate as much
4 power energy as it uses over a given period [35]. This explain its name as “net”.
5 Tumminia et al. [35] introduced environmental factors impact when analyzing the
6 problem of NZEB with the angle of CO₂ emission and sustainable development.
7 Considering the multiple complex factors of climate conditions [36], government
8 subsidies and uncertainty of renewable energy systems, Sun et al. [37] proposed a
9 heuristic optimization method for the grid-interactive NZEBs which outperform the
10 benchmarked case based a case study of the Hong Kong Zero Carbon Building.

11 **1.3. Objective of this study**

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

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

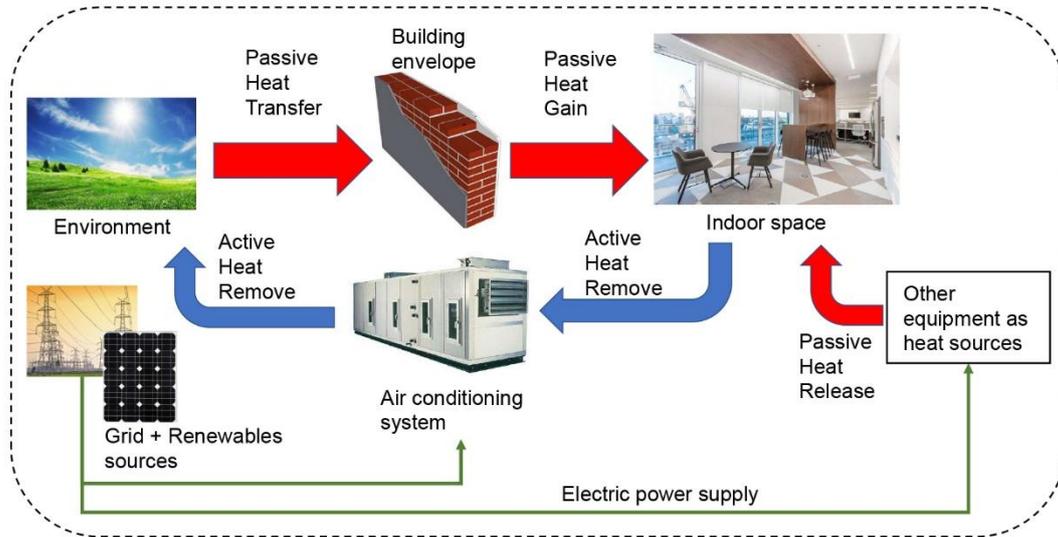
- 21 ■ a new system along with its operation control mechanism is presented not only
22 for zero heat gain/loss of building envelope, but also undertaking partial
23 heating/cooling load in different seasons; therefore, the building envelope can
24 relieve some burden from air conditioner system;
- 25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

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

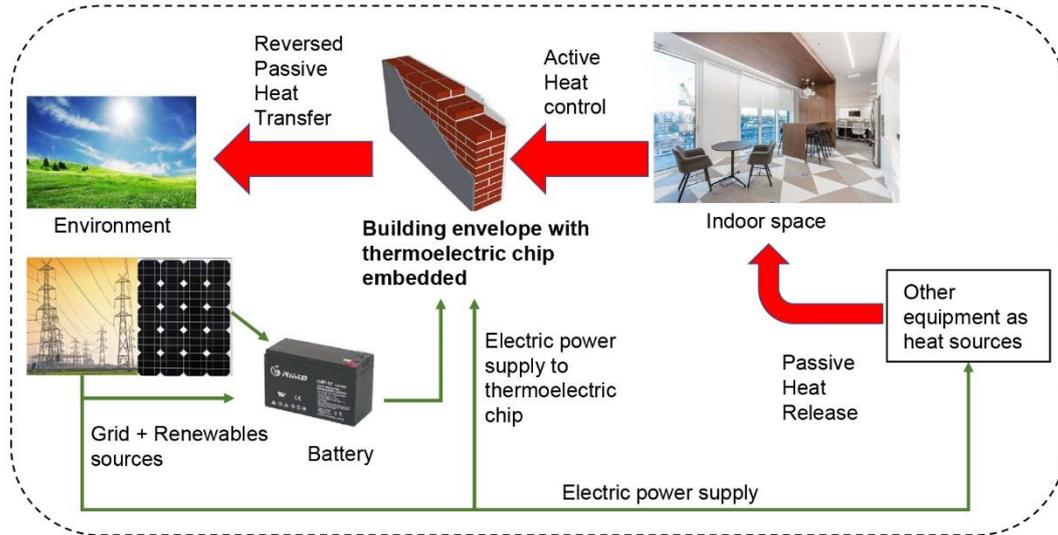
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1 **2. System concept and function**

2 This is a new concept proposed here based on our previous investigation on a kind
3 of photovoltaic thermoelectric wall system [38]. In the previous study [38], we only
4 proved a kind of building envelope can realize zero heat gain/heat loss as an initial step
5 towards NZEBs, but here we move in a further step, and try to prove the system can be
6 evolved to shield heat flux from ambient, making true value of solar energy locally, and
7 offsetting part of thermal energy demand of indoor space simultaneously. There is an
8 illustrative description of the proposed idea by comparing conventional building
9 (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

10

11 **Fig.1** Illustration on (a) conventional buildings that can only passively received heat
12 gain from ambient through building envelope, (b) the new concept in summer

1 condition as an example can realize a reverse heat flux through thermoelectric chip
2 powered by PV.

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

21

22 **3. Systems and Models**

23 **3.1. System structure**

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

31 The system parameters we used to build experimental rig are listed in **Table1**. It
32 should be noted that this is only the original prototype. In order to realize the new
33 function mentioned in the Introduction, some additional power source and control

1 methods should be added. Thus, other four types are also proposed and investigated for
 2 comparison including Grid+TE (S2), PV+Grid+TE (S3), PV+battery+TE (S4), and
 3 PV+Grid+Battery+TE (S5). The power flow and control are different among them but
 4 their heat transfer behaviors follow that of the PV+TE type, which will be explained in
 5 details along with system models in Section 3.2.

6 **Table 1**

7 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

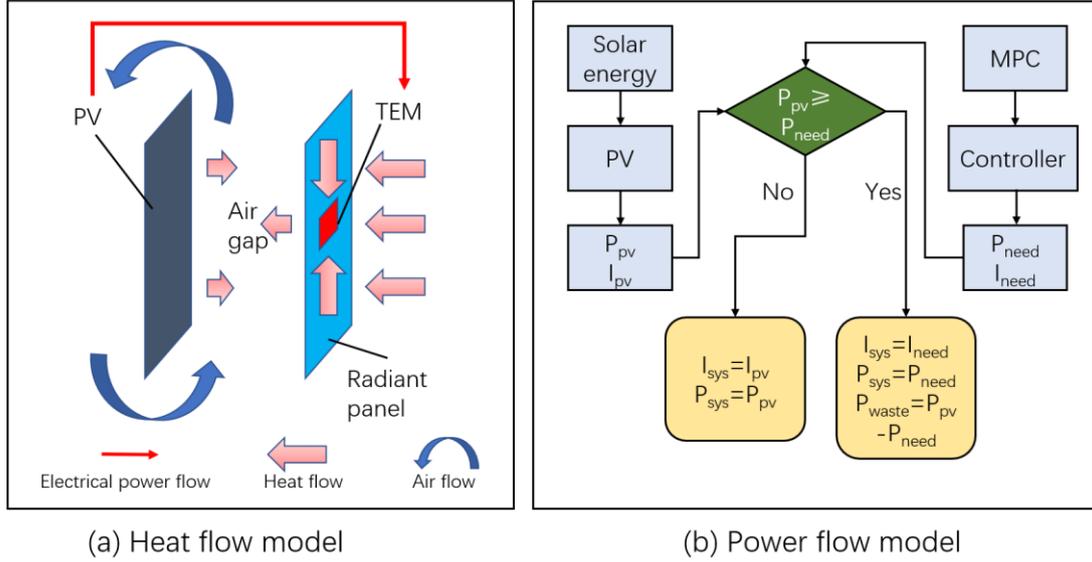
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9 **3.2. System model**

10 **3.2.1. PV+TE**

11 The system model actually is coupled by heat flow model (**Fig.2a**) and power flow
 12 model (Fig.2b). The two major parts are coupled by the system electric current. The

1 electric power and current used by heat flow model are just from the obtained system
 2 power P_{sys} and current I_{sys} from the power flow model. Guided by **Fig.2**, the details of
 3 models are explained as follows.



4

5

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

6

(a) Heat flow model:

7

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.

10

11

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.

22

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

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

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

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

$$8 \quad \xi_1 = \frac{\frac{1}{R_c K_{TEM}} \left(\frac{1 - \alpha I R_h}{R_h K_{TEM}} + 1 \right)}{\left(\frac{1 + \alpha I R_c}{R_c K_{TEM}} + 1 \right) \left(\frac{1 - \alpha I R_h}{R_h K_{TEM}} + 1 \right) - 1} \quad (4)$$

$$9 \quad \xi_2 = \frac{\frac{I^2 R}{2 K_{TEM}} \left(\frac{1 - \alpha I R_h}{R_h K_{TEM}} + 1 \right) + \left(\frac{T_f + \frac{1}{2} I^2 R R_h}{R_h K_{TEM}} \right)}{\left(\frac{1 + \alpha I R_c}{R_c K_{TEM}} + 1 \right) \left(\frac{1 - \alpha I R_h}{R_h K_{TEM}} + 1 \right) - 1} \quad (5)$$

10 Besides the dynamic and non-uniform heat transfer in TE and radiant panel, the
11 rest components of insulation board, air duct and the PV panel, are modeled by using
12 state-space model [21], which are expressed and solved in an efficient matrix form of
13 Eq.(6) [21]. The vector \mathbf{X} in Eq.(6) is $[T_{PV}, T_f, T_{b1}, T_{b2}]$ and the input vector \mathbf{u} is $[G_t \alpha_{PV}$
14 $P_{sys}/A_{pv}, T_{out}, T_h, T_{Al}]$. The matrix \mathbf{E} is 4×4 identity matrix. The coefficient matrix \mathbf{A}
15 and \mathbf{B} is derived and reformed based on heat transfer equations of insulation board, air
16 duct and the PV panel.

$$17 \quad \mathbf{X}_{\tau+h} = e^{\mathbf{A}h} \mathbf{X}_{\tau} + (\mathbf{\Gamma}_1 - \mathbf{\Gamma}_2) \mathbf{u}_{\tau} + \mathbf{\Gamma}_2 \mathbf{u}_{\tau+h} \quad (6)$$

$$18 \quad \mathbf{\Gamma}_1 = \mathbf{A}^{-1} (e^{\mathbf{A}h} - \mathbf{E}) \mathbf{B} \quad (7)$$

$$\Gamma_2 = \mathbf{A}^{-1} \left(\frac{\Gamma_1}{h} - \mathbf{B} \right) \quad (8)$$

2

3 (b) Power flow model:

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

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

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

16 The values of five parameters in Eq.(9) are dynamically changed with solar
17 irradiance and cell temperature. Those parameters under general conditions can be
18 calculated by using the five parameters under standard testing condition (STC:
19 1000W/m^2 and 25°C) and applying some extension formulas [41].

20 The Eq.(9) is an implicit function with current and voltage which cannot be solved
21 directly by common functions. In this study, combining I-V equation (9) with Ohm's
22 law $V=I \times R_{load}$, the output current and voltage can be calculated by Lambert-W function
23 solution for an explicit expression [42], as presented by Eq.(10). The parameter R_{TEM}
24 refers to the total resistance of TE modules. And the five parameters under STC are: I_{ph}
25 = 5.13806 (A); $I_0 = 1.35845 \times 10^{-7}$ (A); $R_s = 0.454354$ (Ω); $R_p = 1852.48$ (Ω); $n_0 =$
26 1.37594.

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

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

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

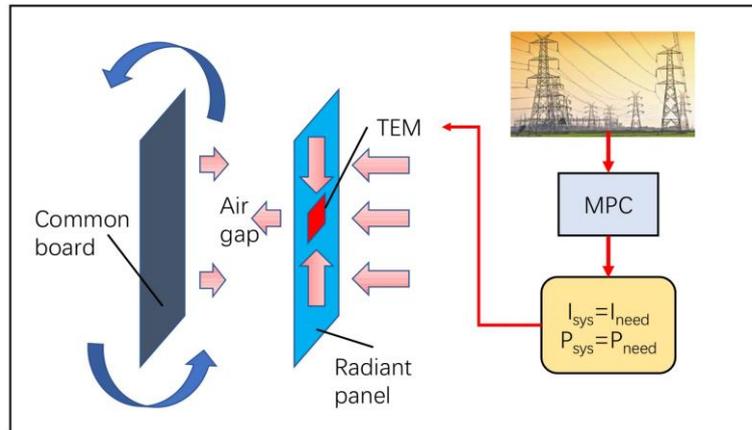
$$\begin{cases} \min \{ Q_{in}^t \times hx - Q_w \} \\ Q_{in}^t = h_r (T_{Al}^t - T_{mrt}^t) + h_c (T_{Al}^t - T_{in}^t) \\ T_{Al}^t = f (T_{in}^t, T_{out}^t, G_{iv}^t, T_m^t, I_{need}^t) \\ I_{\min} \leq I_{need}^t \leq I_{\max} \end{cases} \quad (11)$$

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

27 3.2.2. Grid+TE

28 The Grid+TE type is only powered by the grid rather than instant PV generation
 29 when compared with the PV+TE type. It is applicable to the areas with no abundant
 30 solar energy, and also serves as a reference case for comparison where no renewable

1 energies are utilized in the system. The schematic of this model is shown in **Fig.3**. The
 2 heat flow and power flow models of PV+TE can still adopted in this scenario by only
 3 eliminating the PV generation part.



4

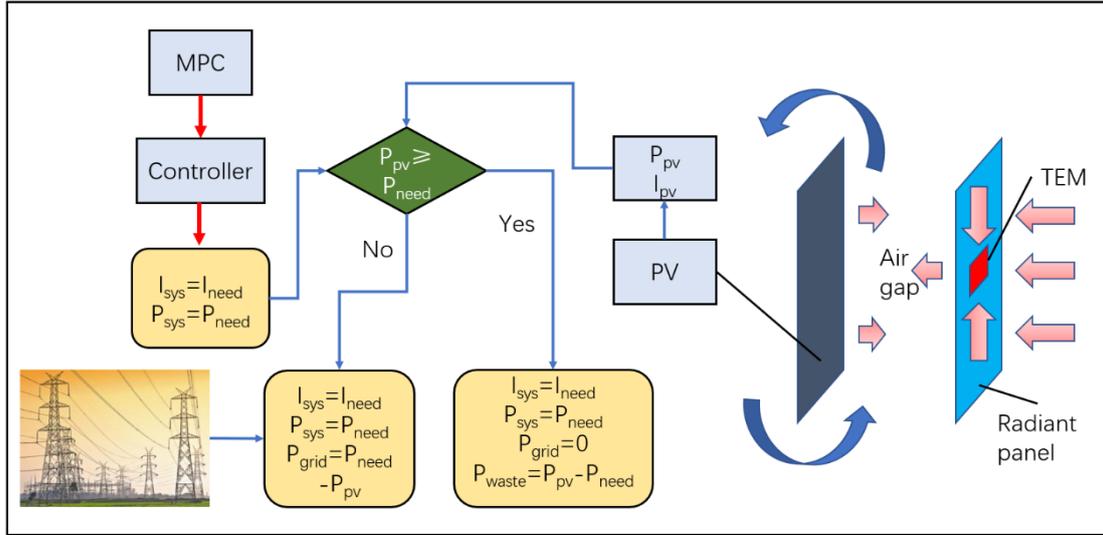
Fig.3 System model for Grid+TE mode.

5

6 **3.2.3. PV+Grid+TE**

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

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



1

2

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

3 **3.2.4. PV+battery+TE**

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

8 The basic logic is to use PV power output first. If it is excessive, battery can store
 9 the power. If it is not sufficient, battery can afford the rest. If it is still not enough to
 10 meet the demand for P_{need} , TE wall failed to control the heat flux Q_w as expected. The
 11 basic control flow is given in **Fig.5**. In the charging condition, the charging power
 12 should be the minimum value among $[(P_{pv}-P_{need}) \cdot \eta_c, (SOC_{max} - SOC_1) \cdot Q_{batt}, P_{cmax}]$, where
 13 η_c is charging efficiency of battery; SOC is the state of charging of battery; Q_{batt} is the
 14 power capacity of battery (Wh); and P_{cmax} is the maximum limit of charging rate of
 15 battery (W). The similar process is also for discharging situation when PV power is not
 16 enough for the requirement. Those battery related parameters used in this model are
 17 listed in **Table 2**.

18 **Table 2**

19 Battery model parameters

Variable	value
Q_{batt} (Wh)	3000

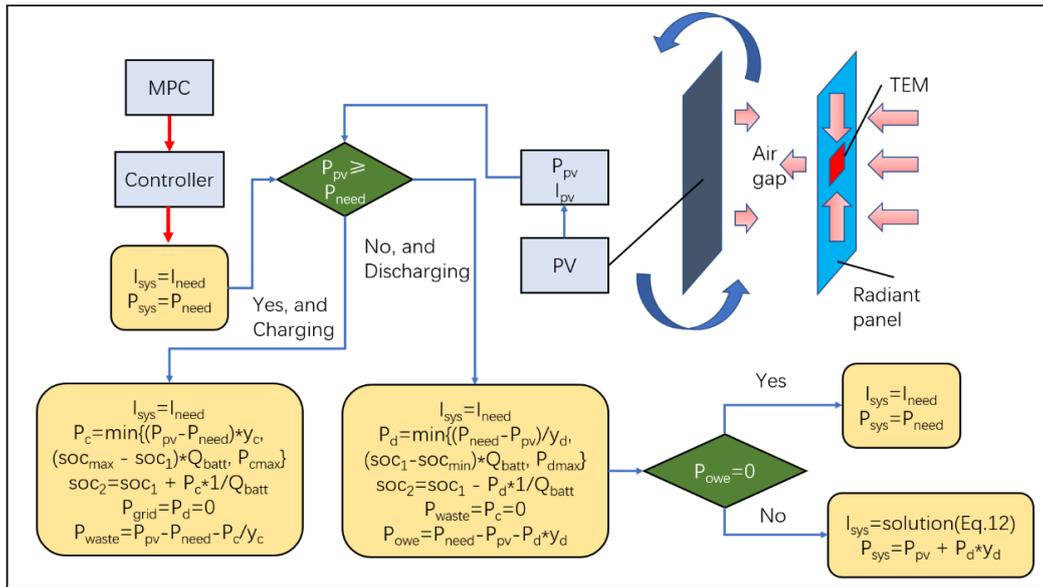
P_{cmin}, P_{cmax} (W)	1000
SOC_{min}, SOC_{max}	0.15, 0.95
y_c, y_d	0.9

1

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

$$8 \quad P_{sys} = I_{sys}^2 R_{tem} m / 2 + \alpha m \Delta T I_{sys} \quad (12)$$

$$9 \quad I_{sys} = \frac{-\alpha m \Delta T + \sqrt{(\alpha m \Delta T)^2 + 2 R_{tem} m P_{sys}}}{R_{tem} m} \quad (13)$$



10

11

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

12

13 3.2.5. PV+Grid+battery+TE

14

15

The PV+Battery+TE in **Fig.5**, still has the chance to encounter power shortage. The connection to grid simply makes the final type as **Fig.6** exhibited. Through this

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

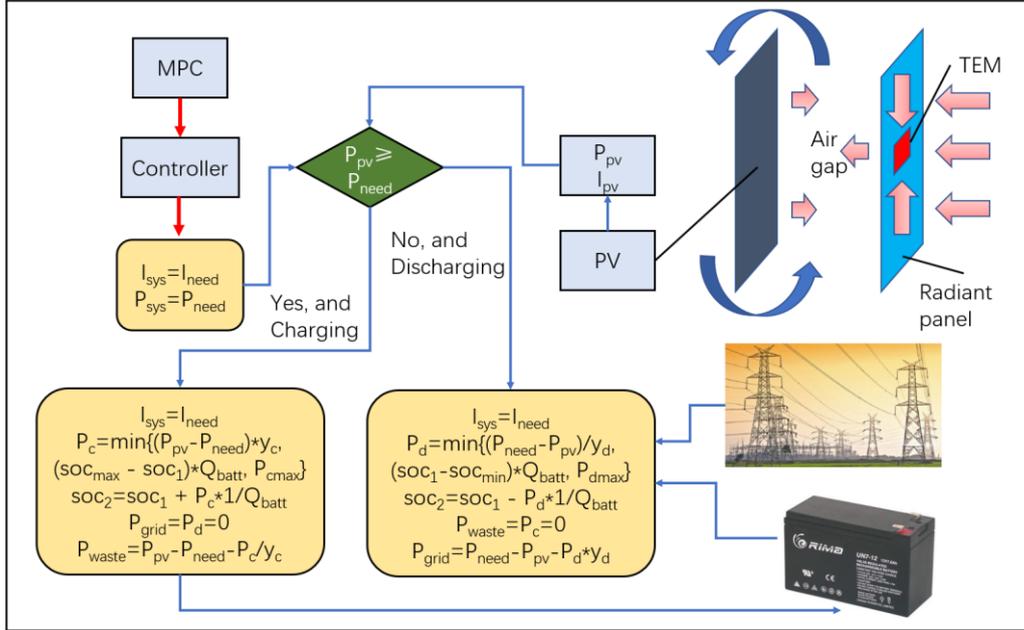


Fig.6 System model for PV+Grid+Battery+TE scenario.

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.

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

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

3

4 Energy analysis method

4.1 Method description

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

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

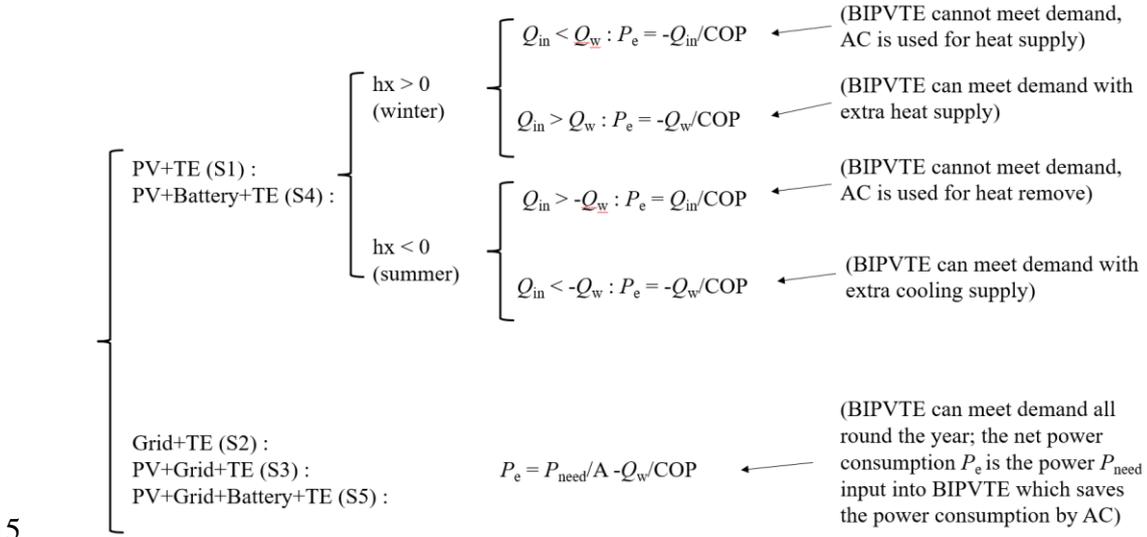
17 Second, it is very important to know how much power P_e is cost for the operation
 18 of BIPVTE. This index is slightly different for each system structure. In all, there are
 19 two routines counting for power consumption: one is power from grid and another is a
 20 calculated power consumption that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

22 To help understand the calculation process, a simple example is given. It is
 23 assumed that Q_w is anticipated to be $10W/m^2$, but BIPVTE wall can only make it as
 24 $4W/m^2$ due to some reasons (The proposed system cannot handle the entire heat flux,
 25 mainly because of insufficient solar power input and thus insufficient PV power output
 26 if PV is the only power source to the system). In this case, the HVAC system will take

1 the extra $6\text{W}/\text{m}^2$ by using power, that is the value of 6 divided by COP (coefficient of
 2 performance) of HVAC. The COP of HVAC is set as 2.8 in winter and 2.6 in summer.

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

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



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

17 **4.2. Notes**

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

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

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

3 2) Most of studies carried out simulation or analysis by evaluating the energy saving
4 with the unit of kWh. Since the case study may vary in different situations, in this
5 study, all the indices for energy performance are transformed into kWh/m² or W/m²
6 in unit, which can offer a better and justified results, not only for the analysis
7 included in this study, but also better for comparison with many other studies.

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

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

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

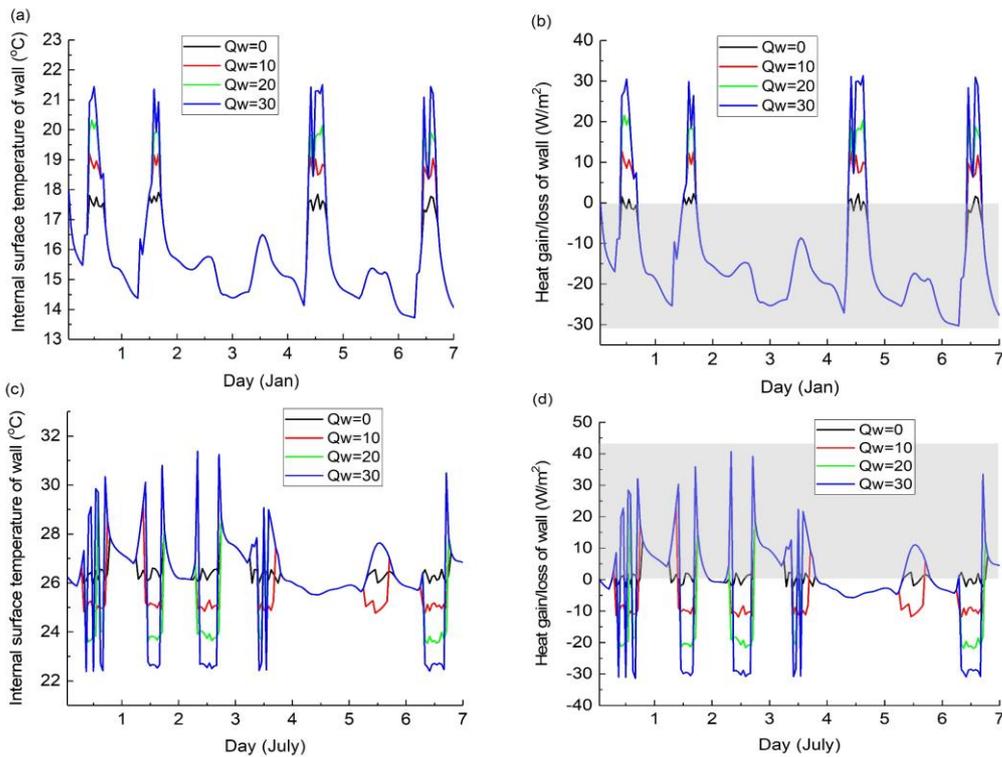
24 5. Results and discussions

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

1 **5.1. PV+TE**

2 In order to better showcase the changes brought by $Q_w \neq 0$, the results for Q_w equals
 3 0, 10, 20, 30 W/m^2 are compared. In **Fig.8a** and **Fig.8b**, the internal surface temperature
 4 and hourly heat gain/loss of wall under various Q_w are compared. In this winter
 5 condition, if the weather condition is a sunny day, the system can fully ensure the heat
 6 flux as set values and the internal surface temperature is 18°C, 19°C, 20°C and 21°C
 7 with one-degree increasement under $Q_w = 0, 10, 20, 30 \text{ W/m}^2$. But if the weather
 8 condition is not feasible, all four cases behave the same.

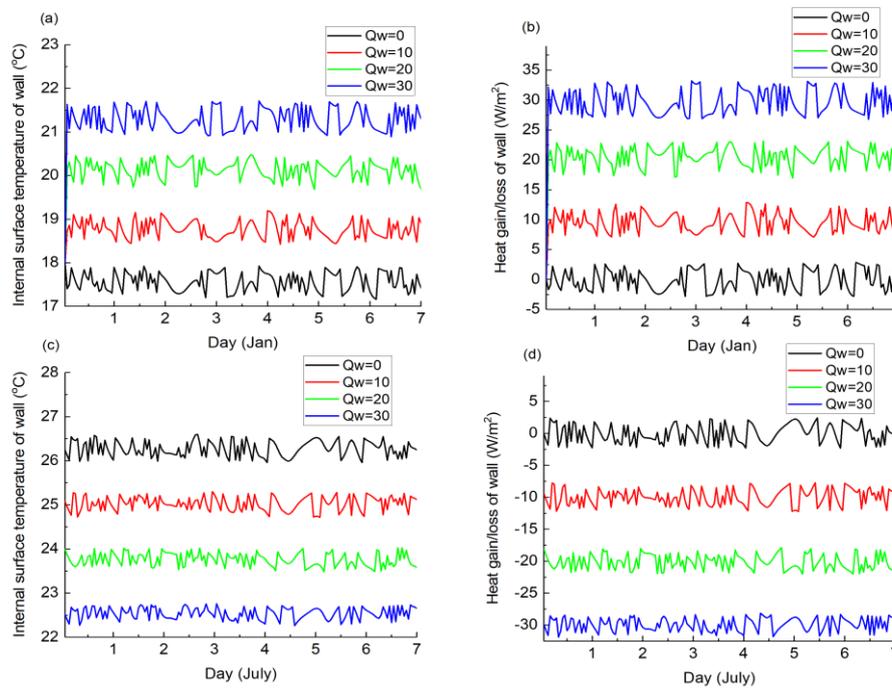
9 In summer month, as **Fig.8c** and **Fig.8d** shows, at daytime of summer, the PV
 10 should have enough power to stimulate TEMs to provide required cooling energy.
 11 There is a sharp temperature increase at night due to power shortage. And also if the
 12 weather condition is not feasible, all four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



15
 16 **Fig.8** Hourly internal surface and heat gain/loss of PV+TE wall in a typical week of
 17 winter (Jan 1st to Jan 7th) and summer (July 1st to July 7th) under various Q_w settings.
 18 [The gray area in the figure means this part of heat gain in summer and heat loss in
 19 winter must be undertaken by air conditioner].

1 5.2. Grid+TE

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



9

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

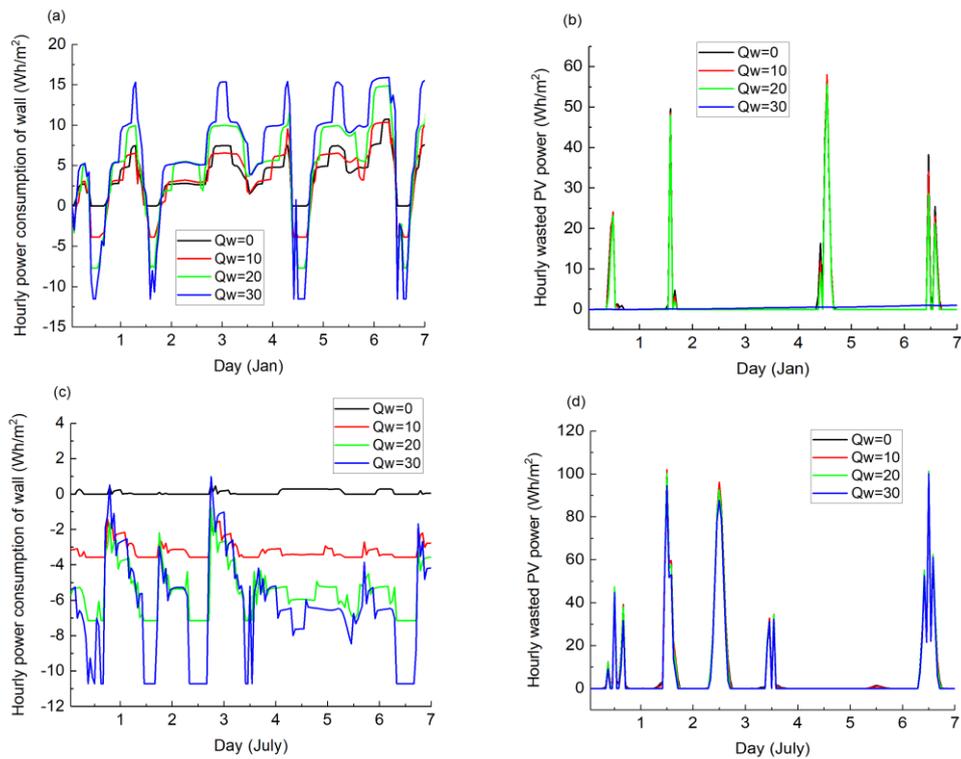
12 5.3. PV+Grid+TE

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

18 In winter, it is found that if weather condition is good, for example, the day 1, 2,
19 5 and 7, the PV can provide enough power and realize the required Q_w , which lead to
20 negative power consumption (means energy saving instead). But at night or solar

1 energy is not enough at day 3, 4 and 6, power must be used from grid and the value is
 2 larger with higher Q_w demand. At the same time, when the Q_w is as high as 30W/m^2 ,
 3 no power from PV will be wasted in this week.

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



9

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

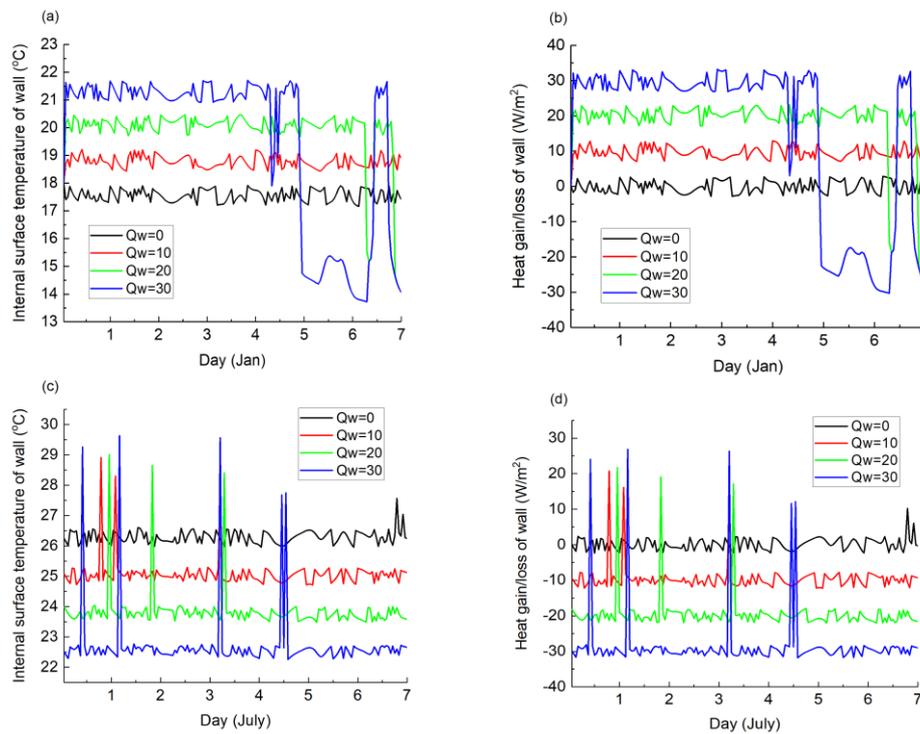
13 5.4. PV+Battery+TE

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

18 The involvement of battery makes this type of system different from the previous
 19 ones. In the first week of Jan in winter (**Fig.12**), the SOC curve is going down all the

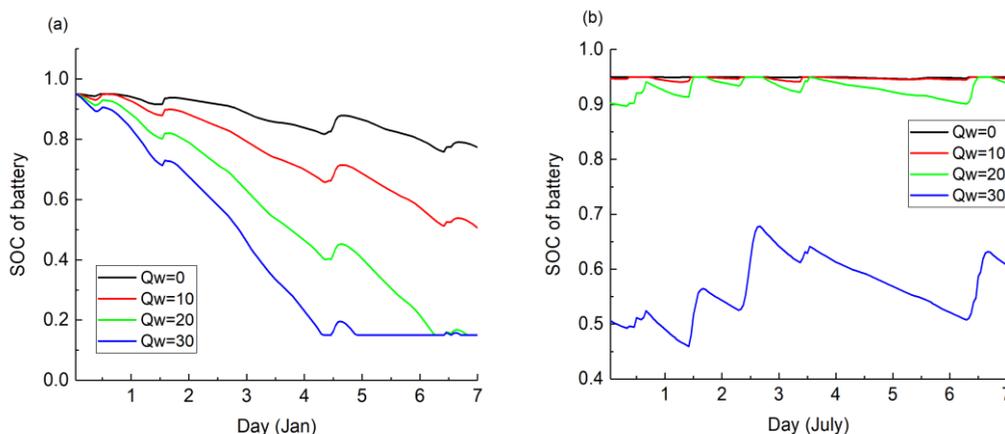
1 way and the slope is sharper with higher Q_w values. While in summer, the SOC is
 2 always kept as a flat curve or just with small floats. When Q_w is lower than 20W/m^2 ,
 3 the battery is always in full state.

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



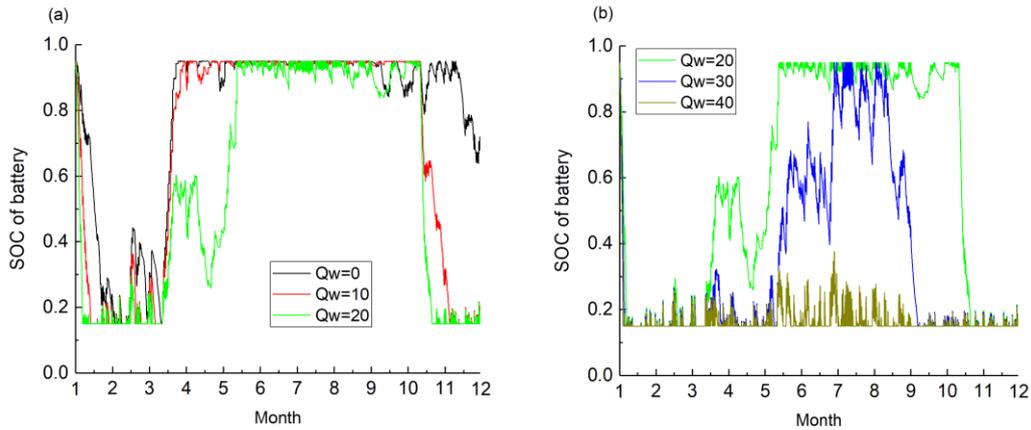
8

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



12

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

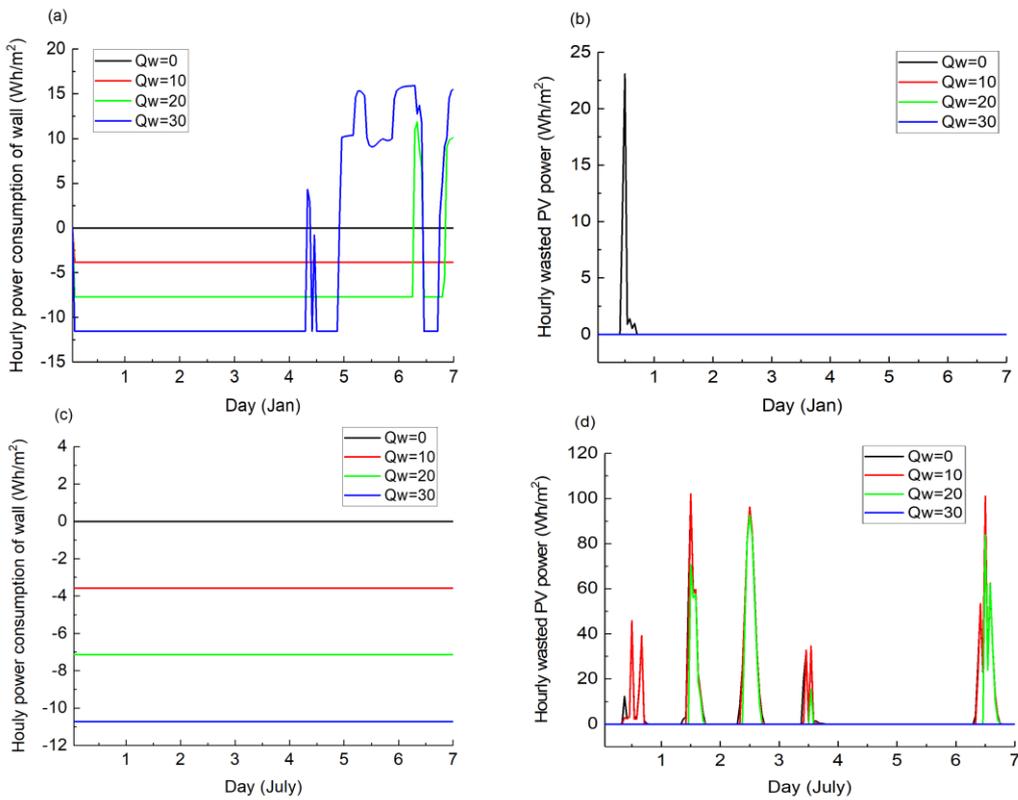


2

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

4 **5.5. PV+Grid+Battery+TE**

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



8

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

1 under various Q_w settings.

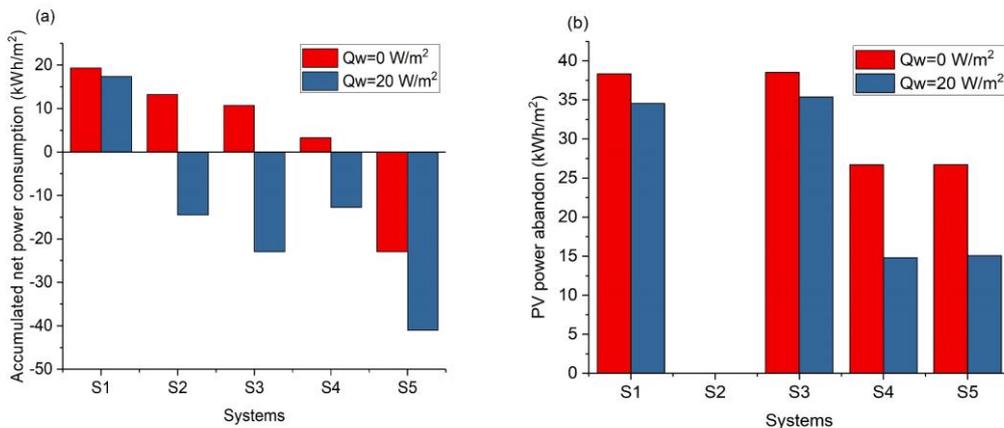
2 For the case with $Q_w=0 \text{ W/m}^2$ and $Q_w=10 \text{ W/m}^2$, the power curves are completely
3 flat. This means by using PV and electric storage of battery, the system can perform
4 well. When the value of Q_w is increased to 20 or 30 W/m^2 , for most of the time, the
5 power consumption is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

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

13 5.5. Energy performance comparison across different systems

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

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



22

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

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

6 **5.6. Application related discussions**

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

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

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

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

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

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

29 In terms of application issues, there are two aspects to be noted. One is for new
30 buildings. The proposed system could be manufactured as a building component in pre-
31 fabrication. This can make the wall module as a mature product with standard
32 performance and indexes. Another is for refurbishment of old buildings. Because it

1 must be deeply integrated into the wall structure, it cannot be integrated directly. But
2 the building should first remove the window and it can be installed within window
3 frame.

5 **6. Conclusions**

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

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

25 **Appendix. A. Example illustration of system function and evaluation**

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

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

3

4 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

		<p>If Q_{in} is -10 (W/m^2), then this part of heat loss has to be supplied by AC. So, $P_e = -(-10)/COP$.</p> <p>If Q_{in} is 6 W/m^2, then this means some part of AC power is saved and this saved power is $P_e = -6/COP$.</p> <p>If Q_{in} is 20 (W/m^2), the system exceeds the request, but only the requested thermal load is certified. So, $P_e = 10/COP$.</p>	<p>connecting to the grid.</p> <p>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: $7/A - 10/COP$.</p>
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1

2

3 Declaration of Competing Interest

4 None

5

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