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Article

Energy Efficiency Indicators for Assessing Construction Systems Storing Renewable Energy: Application to Phase Change Material-Bearing Façades

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Abstract: Assessing the performance or energy efficiency of a single construction element by itself is often a futile exercise. That is not the case, however, when an element is designed, among others, to improve building energy performance by harnessing renewable energy in a process that requires a source of external energy. Harnessing renewable energy is acquiring growing interest in Mediterranean climates as a strategy for reducing the energy consumed by buildings. When such reduction is oriented to lowering demand, the strategy consists in reducing the building's energy needs with the use of construction elements able to passively absorb, dissipate, or accumulate energy. When reduction is pursued through M&E services, renewable energy enhances building performance. The efficiency of construction systems that use renewable energy but require a supplementary power supply to operate can be assessed by likening these systems to regenerative heat exchangers built into the building. The indicators needed for this purpose are particularly useful for designers, for they can be used to compare the efficiency or performance to deliver an optimal design for each building. This article proposes a series of indicators developed to that end and describes their application to façades bearing phase change materials (PCMs).

Keywords: energy efficiency; renewable energy; regenerative heat exchangers; phase change materials (PCMs); indicators

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1. Introduction

Lowering the amount of energy needed to maintain indoor thermal comfort is an objective shared by all advanced societies, driven both by rising energy costs and environmental considerations such as the reduction of carbon footprint.

Building consumption levels cannot be lowered to under certain thresholds with strategies based solely on insulation or ventilation control. Renewable energies and natural sinks are also needed. The timing of the demand for renewable energies is at odds with the timing of supply, however. One of the most promising techniques for solving that mismatch is the storage of thermal energy.

Many papers have been published on thermal energy storage (TES) systems. Dinçer and Rosen [1] studied such systems in general, contending that they induce energy savings through the use of renewables. Storage may involve the sensible heat absorbed by or from building construction elements, water, or rocks, or the latent heat in PCMs, capitalizing on the high enthalpy attendant upon phase changes. The use of PCMs in building construction has been studied by Mehling and Cabeza [2] and more recently by other authors [3–6].

A broad spectrum of PCMs is available. Cabeza *et al.* [7] compiled and classified a full list, analyzing the requirements, problems, and solutions for their use in buildings. Assessment of their performance calls for suitable simulation methods. Any number of articles have been written on simulation, most dealing with detailed methods [8–15].

In another vein, while solar energy may be passively absorbed and harnessed via construction systems in buildings or the environment as a means of obtaining cost-free cooling, this approach often requires an external source of energy; classical examples are Trombe walls and other derived structures that preheat outdoor air for ventilation.

Assessment of the performance of these systems calls for a series of indicators to aid design and provide information on their integration in the building. If the aim is for the building to absorb, exchange, or accumulate energy, designers must have suitable tools for assessing system operation. In the case of PCMs, such indicators must ensure the accurate quantification of the amount of material needed and the operating conditions for each application in keeping with specific building use and the potential of the climate where it is sited.

These indicators constitute an innovation in the field of building energy given the technology involved, although benchmarking is generally accepted as a useful endeavor. The regenerative efficiency indicator or the use factor of the amount of energy stored is one of the parameters most relevant to the design of regenerative heat exchangers (also known as regenerators), for instance [16,17]. Some papers [18,19] on efficiency describe simplified methods derived from detailed methods for calculating indicators from energy accumulation system design parameters.

The indicators defined in this article are generally applicable to any construction element in a building's envelope or interior that harnesses renewable energy. They were developed specifically for PCM-bearing façades, however, and are adapted to analyzing night-time cooling. Their development forms part of the first author's Ph.D. dissertation.

2. Phase Change Material (PCM)-Bearing Façade

The suitability of using PCMs in ventilated façades was studied under a research project entitled MECLIDE. The aim was to develop PCM-based night-time cooling solutions able to meet a significant fraction of a building's cooling needs and identify the circumstances under which residential needs could be fully covered [20–23].

The PCM-bearing façade studied here comprises three parts: an outer element, an air chamber housing the PCM-bearing fins, and an inner element or wall. A plan view diagram of the façade is shown in Figure 1.

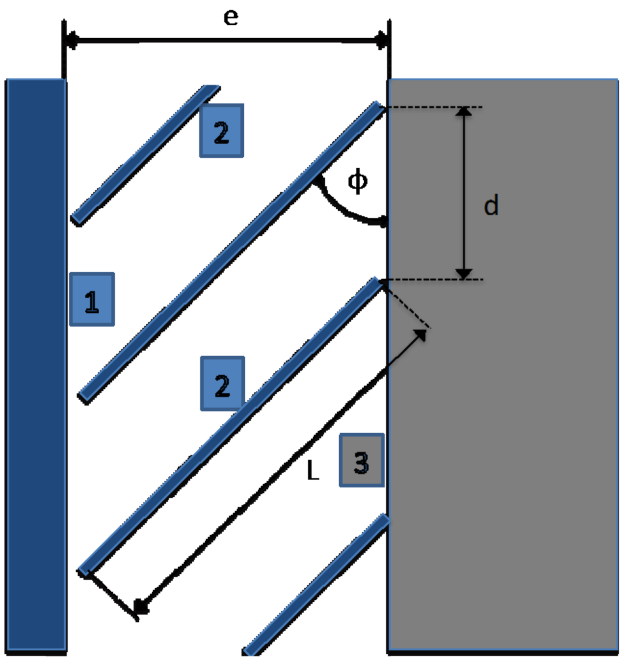


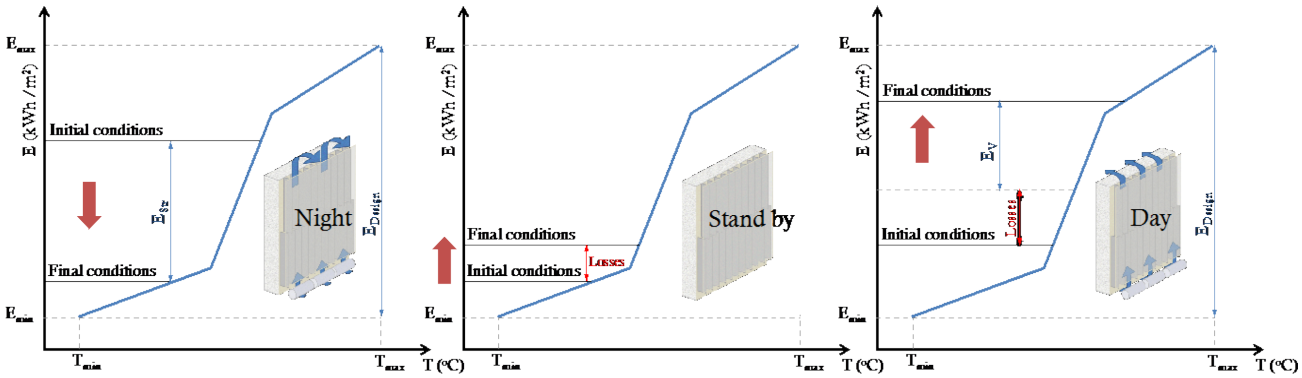
Figure 1. Façade diagram: plan view: (**1**) Outer element; (**2**) the fins; and (**3**) the inner element.

The vertical air chamber runs along the entire façade. The rectangular membranes forming the fins bear PCMs. Air flows upward in the chamber.

During the night the outdoor air circulates through the chamber, cooling the PCM fins. During the day the warm indoor air melts the PCMs and flows back into the building at a cooler temperature. Demand starts when the exterior air temperature is higher than 26 °C and continues until the outlet air temperature from the chamber exceeds T_{max} = 25 °C.

Consequently, as discussed in a later section on indicators, the building is dually impacted by the chamber. On the one hand, it is cooled by the ventilation system during the day, using the cooling power accumulated during the night in the PCMs, and on the other it benefits from the thermal barrier formed.

Façade operation is illustrated in Figure 2. Its operating range foreseeably lies between the maximum and minimum temperatures defined, T_{min} = 15 °C and T_{max} = 25 °C. The orientation considered is south. Façade daily operation is shown in Figure 3.



(**a**) (**b**) (**c**)

Figure 2. Façade operation: (**a**) Storage; (**b**) Standby; (**c**) Release.

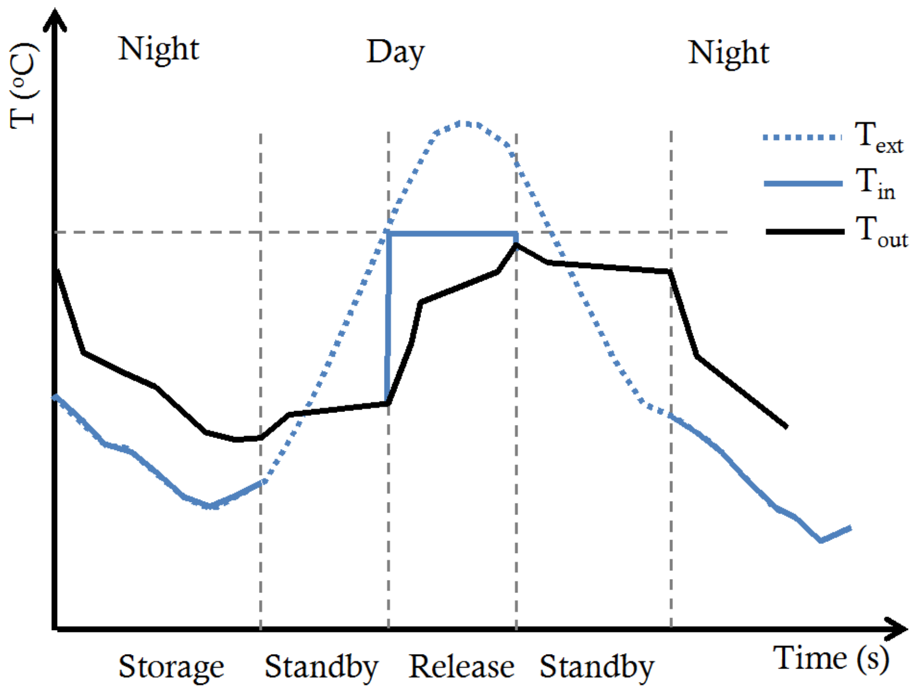


Figure 3. Daily façade operation temperatures.

The façade described acts as a cooling and a thermal stabilization element. The larger the number of energy storage and release cycles, the greater is façade efficiency.

Elements of this type depend directly on climate and the building's energy needs. If the element is used for cooling, energy can only be released if it was previously stored. By the same token, its operation is only effective if the energy released is needed. In other words, weather conditions must be appropriate for operation, with cool nights and warm days, as is normally the case in Mediterranean summers.

PCMs are characterized in terms of effective heat capacity *vs.* temperature. This simplification of material (RT 22, Rubitherm, Berlin, Germany) behavior is sufficiently accurate according to the model proposed [24] (Figure 4).

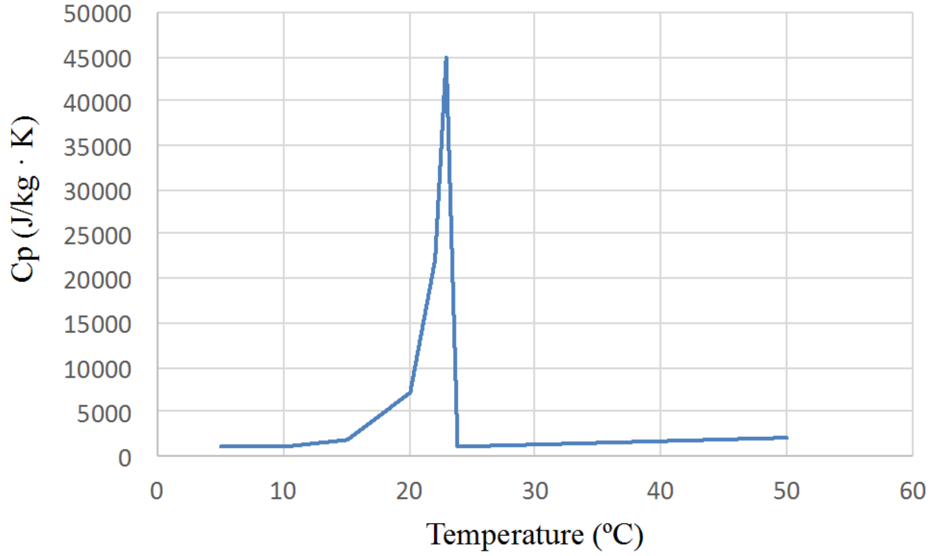


Figure 4. Effective heat capacity.

3. Description of Indicators Proposed

As noted earlier, the indicators are generally applicable to other construction systems. Nonetheless, the façade described above is used here as an example to facilitate discussion.

The first indicator defined, the global efficiency indicator, determines the amount of energy actually delivered by a system relative to the energy needed.

3.1. Global Building Efficiency (GBE) Indicator

Global building efficiency (*GBE*) is designed to provide insight into system behavior as part of a building.

It is defined as the ratio of the energy saved in a building attributable to the installation of a PCM-based façade (ΔD) to the energy needed to achieve such savings (C'vent).

The *GBE* indicator may be analyzed in terms of energy demand, independently of HVAC systems:

$$GBE = \frac{\Delta D}{C'_{\text{vent}}} \tag{1}$$

3.2. Global Façade Efficiency (GFE) Indicator

The performance of façades or other elements bearing PCMs depends primarily on climate, façade orientation, and the building's cooling load. Such performance can be analyzed independently of the building, *i.e.*, likening it to a renewable air conditioning system.

Global façade efficiency (*GFE*) is defined as the ratio between the variation in energy consumption attained by installing PCMs in the façade and the energy consumed in the process. As an indicator separate from the building, it affords no information on energy savings. The difference is related both to daytime ventilation (free night-time cooling) and the thermal barrier formed by the air chamber in the façade. Evaluating this indicator calls for a model that can be simplified by dividing the façade into sections:

$$GFE = \frac{E_V + E_C}{C_{vent}} \tag{2}$$

where E_V is the energy delivered during the day for cooling and E_c is the difference between heat loss in the inner-most wall with and without PCM. Fan energy consumption (C_{vent}) may differ in *GBE* and *GFE*, although both indicators are similar to coefficient of performance (COP) and provide a measure of a façade's thermal performance. E_v and E_C are calculated with the equation described in Section 4.2.

3.3. Partial Indicators

The further factors of Equation (3) can be defined to analyze façade behavior, all of them being non-dimensional, namely the ventilation factor, f_V, and the chamber factor, f_c (Figure 5):

$$f_V = \frac{E_V}{E_{Design}}\ ;\ f_C = \frac{E_C}{E_{Design}} \tag{3}$$

GFE can therefore be expressed as follows:

$$GFE = \frac{E_{Design}}{C_{vent}}(f_V + f_C) \tag{4}$$

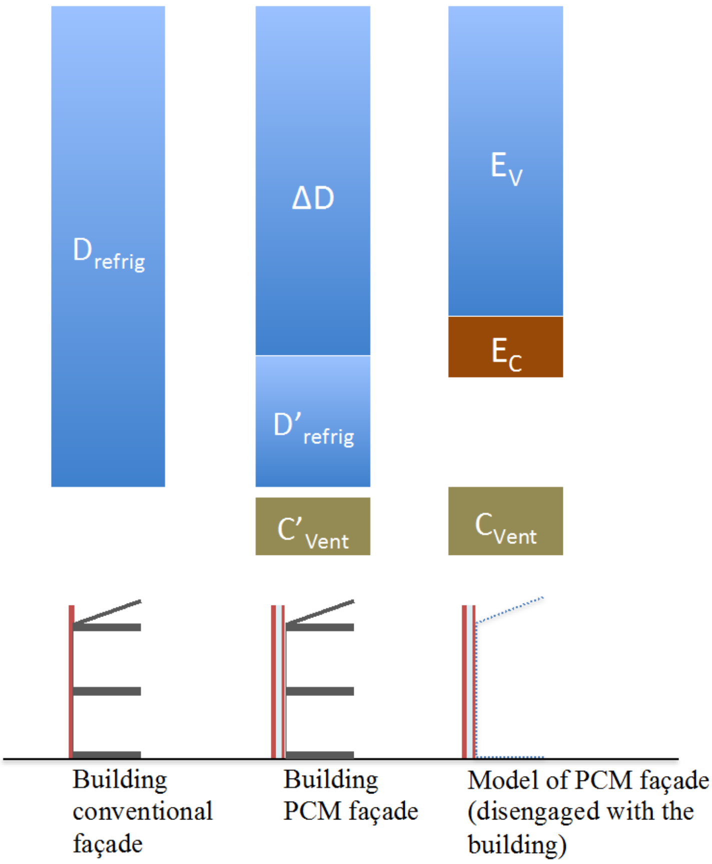


Figure 5. Façade energy diagram. PCM: phase change materials.

For the intents and purposes of design, an installation factor Equation (5), f_{I}, and a design factor, f_{D}, can also be defined. The installation factor is the ratio between actual fan consumption and consumption, assuming operation under design conditions:

$$f_{\mathrm{I}} = \frac{C_{\mathrm{vent}}}{C_{\mathrm{vent.Design}}} \tag{5}$$

Lastly, the design factor is:

$$f_{\mathrm{D}} = \frac{E_{\mathrm{Design}}}{C_{\mathrm{vent.Design}}} \tag{6}$$

This factor, which depends exclusively on design conditions, is the ratio between the theoretical renewable energy stored by the system and theoretical consumption.

GFE can therefore be expressed as follows:

$$GFE = f_{\mathrm{D}} \cdot \frac{f_{\mathrm{V}} + f_{\mathrm{C}}}{f_{\mathrm{I}}} \tag{7}$$

After analyzing system performance independently of the building (*GFE*), a suitable tool can be used to define a factor to link *GBE* and *GFE*, thereby integrating the system into the building to optimize design.

3.4. Supplementary Indicators

Supplementary indicators can be used to analyze how energy is stored and released.

As noted above, maximum storage capacity depends on the amount of PCM in the system and element inertia. This storage capacity cannot be exceeded, but neither does it need to be activated in all cycles. For the system to store energy, energy must have been previously released, just as for energy to be released, it must have been previously stored.

Partial indicators can be defined to separately analyze the developments affecting storage and release. If the study is confined to the system's main purpose, namely ventilation, the following non-dimensional indicators can be defined:

$$f_{\mathrm{V}} = \frac{E_{\mathrm{V}}}{E_{\mathrm{Design}}} = \frac{E_{\mathrm{V}}}{E_{\mathrm{V.Max}}} \cdot \frac{E_{\mathrm{V.Max}}}{E_{\mathrm{Str}}} \cdot \frac{E_{\mathrm{Str}}}{E_{\mathrm{Str.Max}}} \cdot \frac{E_{\mathrm{Str.Max}}}{E_{\mathrm{Design}}} = f_{\mathrm{U}} \cdot f_{\mathrm{B}} \cdot f_{\mathrm{RS}} \cdot f_{\mathrm{DS}} \tag{8}$$

where: f_{U} is the use factor or the ratio between the ventilation energy delivered and the maximum transferrable energy; f_{B} is the balance factor or the ratio between the maximum transferrable energy and the energy stored by the system; f_{RS} is the real storage factor or the ratio between the energy stored and the maximum storable energy; and f_{DS} is the design storage factor or the ratio between the maximum storable energy and the design energy.

A detailed study of these factors is useful for understanding façade behavior. The aforementioned indicators are designed to study the façade system as a cooling element, although as general factors they can be adapted to other elements and redefined for application to heating. These indicators can be combined or can be estimated and used as weighting factors.

4. Estimates and Models

4.1. Estimates

Construction systems that absorb renewable energy can be likened to regenerators. Regenerative heat exchangers operate by extracting thermal energy from a hot fluid and conveying it to a matrix. In a second cycle the energy stored in the matrix is released to a cold fluid. The similarity to storage systems is obvious. Models often use two non-dimensional parameters to characterize this process; Λ and Π in Equation (10):

$$\Lambda = \frac{hc \cdot A}{\dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}}} \; ; \; \Pi = \frac{hc \cdot A\left(P - \frac{L}{v}\right)}{m_{\mathrm{m}} \cdot C_{\mathrm{m}}} \tag{9}$$

where hc is the convective heat transfer coefficient; A is area; $\dot{m}_{\mathrm{f}}$ is the mass air flow rate; C_{f} is the heat capacity of the air; P is period; L is length; v is air speed; m_{m} is matrix mass; and C_{m} is matrix heat capacity. These parameters are extremely useful for analyzing the results, particularly for Λ.

Regenerative heat efficiency can be calculated from the inlet and exit air temperatures during storage and consumption:

$$\eta = \frac{T_{\mathrm{out}} - T_{\mathrm{in}}}{T_{\mathrm{PCM}} - T_{\mathrm{in}}} \tag{10}$$

As losses have a heavier impact on consumption than on storage, efficiency is more stable in the latter and can be calculated theoretically.

Moreover, regenerator efficiency varies with time because the temperatures involved are not constant.

Façades may be likened to regenerators and studied using parameters Λ and Π, modifying the definition of Π as in Equation (11). Here the term L/P is regarded as negligible and hence dropped and C_m is not constant:

$$\Pi = \frac{hc \cdot A \cdot \tau}{m_{\mathrm{PCM}} \cdot \dfrac{\lambda}{T_{\mathrm{PCM}} - T_{\mathrm{in}}}} \tag{11}$$

where τ and λ are storage time and latent heat, respectively.

4.2. Models

A number of simulation models were developed to study the façade described. A detailed model calibrated with empirical tests was described by Ruiz-Pardo *et al.* [21]. In his Ph.D. thesis, Tenorio [25] developed two simplified models, one based on an analogy with electricity and the other on the direct estimation of performance as a regenerator.

In the first simplified model, the façade is divided into three sections, representing the indoor and outdoor walls with three resistors and two capacitors each. Any combination of building elements can be simulated with this scheme.

Radiation between the inner surfaces inside the air chamber and PCM-bearing fins is factored into the model. Radiation heat transfer between inner surfaces inside the air chamber is neglected in light of the distance involved and the existence of PCM fins in the chamber. Radiation heat transfer among the

PCM-bearing fins is likewise neglected. In contrast, the model includes convection heat transfer between all surfaces and the air (Figure 6).

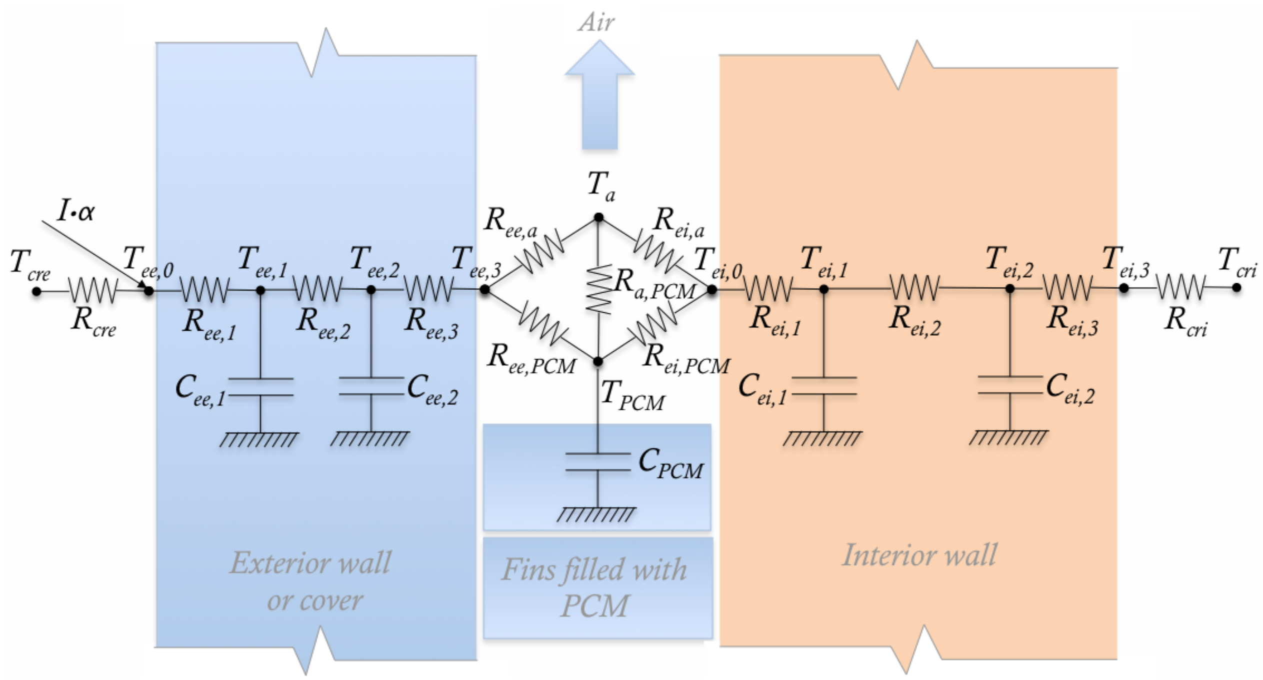


Figure 6. Simplified model.

Air temperature is calculated from the energy balance in each section. Certain simplifications were adopted for the model, including the assumption of a constant temperature in each section and of a uniform temperature in the fins, as well as the use of the average of the inlet and exit air temperatures in each section. PCMs were characterized in terms of effective thermal capacity *vs.* temperature.

Variables used in indicators can be calculated from the simplified model with the following equations:

$$E_{\mathrm{V}} = \int_{\tau} \dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}} \left(T_{\mathrm{out}}(t) - T_{\mathrm{in}}(t)\right) \mathrm{d}t \tag{12}$$

$$E_{\mathrm{Str}} = \int_{\tau} \dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}} \left(T_{\mathrm{out}}(t) - T_{\mathrm{in}}(t)\right) \mathrm{d}t \tag{13}$$

$$E_{\mathrm{façade}} = m_{\mathrm{PCM}} \cdot \lambda + \int m_{\mathrm{façade}} \cdot Cp\ (T + 273)\ \mathrm{d}T \tag{14}$$

$$E_{\mathrm{V.max}} = E_{\mathrm{Max}} - E_{\mathrm{façade\ (initial\ release\ conditions)}} \tag{15}$$

$$E_{\mathrm{Str.max}} = E_{\mathrm{Max}} - E_{\mathrm{façade\ (final\ storage\ conditions)}} \tag{16}$$

$$E_{\mathrm{Design}} = m_{\mathrm{PCM}} \cdot \lambda + \int m_{\mathrm{facade}} \cdot Cp\ (T_{\max} - T_{\min})\ \mathrm{d}T \approx m_{\mathrm{PCM}} \cdot \lambda \tag{17}$$

E_{C} is the difference between heat loss in the inner-most wall with and without PCM, therefore can be calculated using an overlapping model without PCM, in the same conditions.

The model was calibrated against experimental data and the more detailed model described in [23] to very satisfactory results. The correlation coefficients obtained are given in Table 1.

Table 1. Correlation coefficients between simplified model, experimental data and detailed simulation.

Correlated with	T_{out}	T_{PCM} (Section 1)	T_{PCM} (Section 2)	T_{PCM} (Section 3)
Experimental data	0.987	0.989	0.977	0.973
Detailed model	0.988	0.986	0.970	0.978

In the second simplified model, system behavior was assessed for theoretical efficiency by solving the following four-equation system:

Air:

$$T_{\text{out}}(t) - T_{\text{in}}(t) = [T_{\text{PCM}} - T_{\text{in}}(t)](1 - \mathrm{e}^{-h \cdot A(t)/\dot{m} \cdot Cp}) \tag{18}$$

PCM:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{Q(t)}{\lambda} = \frac{\dot{m} \cdot Cp \cdot (T_{\text{PCM}} - T_{\text{in}}(t))}{\lambda} \cdot (1 - \mathrm{e}^{-h \cdot A(t)/\dot{m} \cdot Cp}) \tag{19}$$

Change in effective area exposed to the phase change:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = \frac{A_0}{M_0} \cdot \frac{\mathrm{d}M}{\mathrm{d}t} \tag{20}$$

Efficiency:

$$\eta = \frac{\int_\tau \big(T_{\text{out}}(t) - T_{\text{in}}(t)\big)\mathrm{d}t}{\int_\tau \big(T_{\text{PCM}} - T_{\text{in}}(t)\big)\mathrm{d}t} \tag{21}$$

In façades, the value of Λ generally ranges from 0 to 5. The η values estimated with the model are shown in Figure 7.

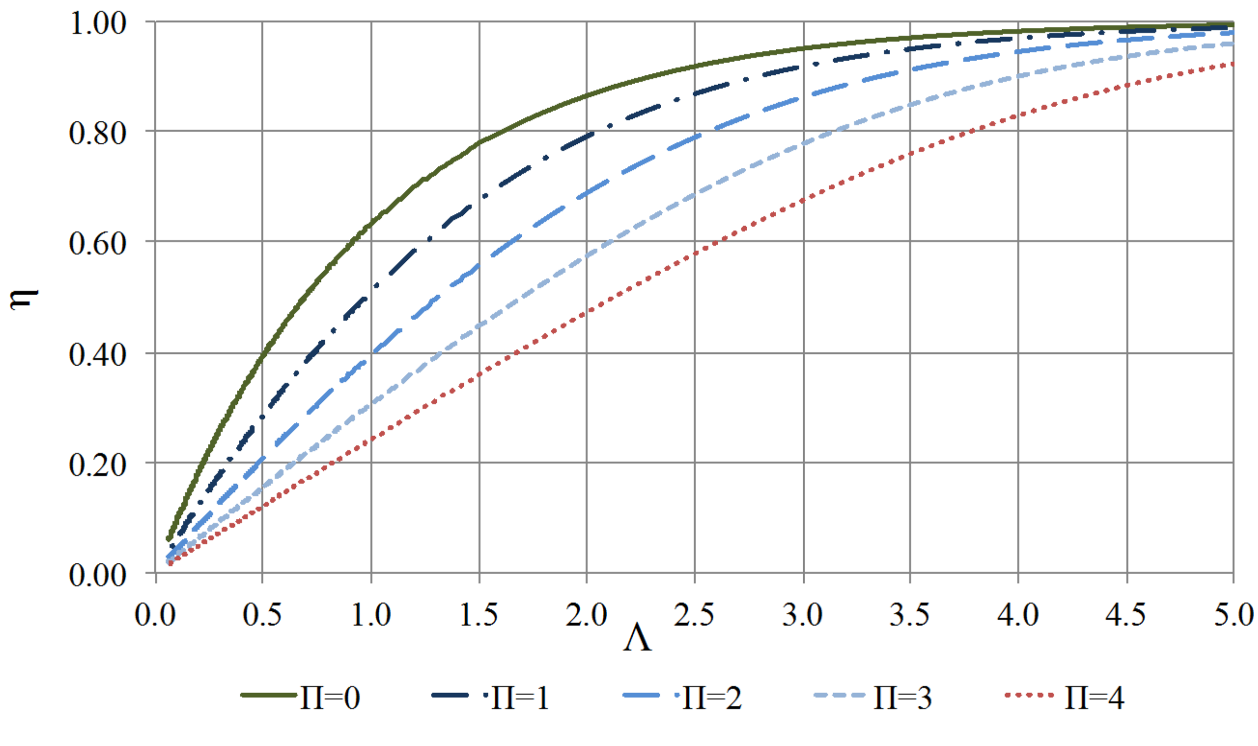


Figure 7. Regenerator efficiency.

5. Discussion

Tenorio [25] ran the first model described for a number of configurations of PCM-bearing façades to study the functional dependence of the indicators on variations in the basic variables (insulation, mass, weather, amount of PCM, and air speed).

The variations in the indicators observed with variations in the weather and the amount of PCM are discussed here by way of example. The figures below illustrate the utility of indicators in determining façade performance. They compare performance of a standard façade with 70 kg/m^2 of PCM in different climates and the same façade in Madrid with PCM contents ranging from 10 kg/m^2 to 100 kg/m^2.

Figure 8 shows the results of the simulation for several climates in Spain, Figure 9 shows the variation with different amounts of PCM, and Figure 10 shows the ventilation energy delivered in July and August.

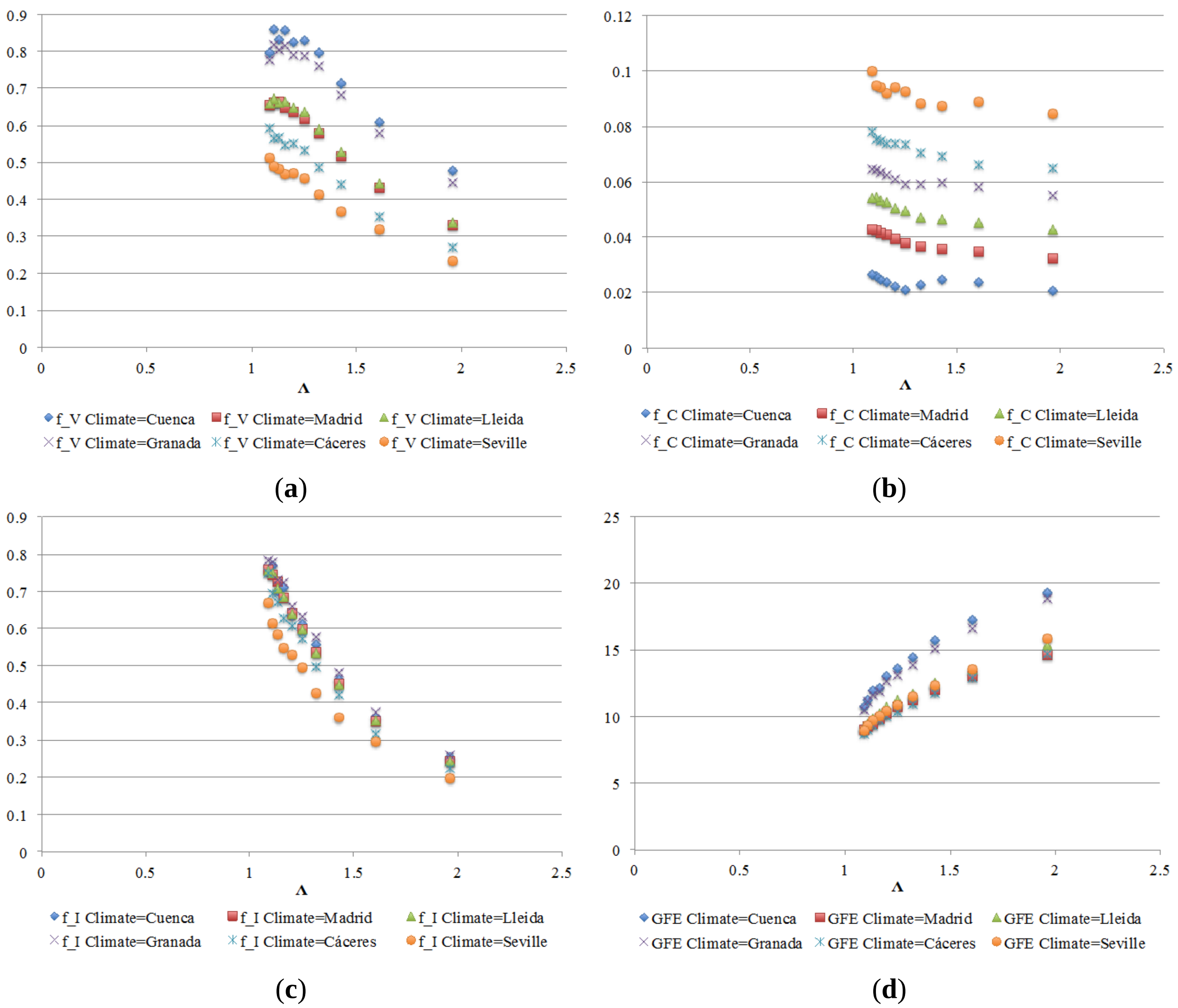


Figure 8. Indicators in different climates: (**a**) f_V; (**b**) f_C; (**c**) f_I; (**d**) *GFE*.

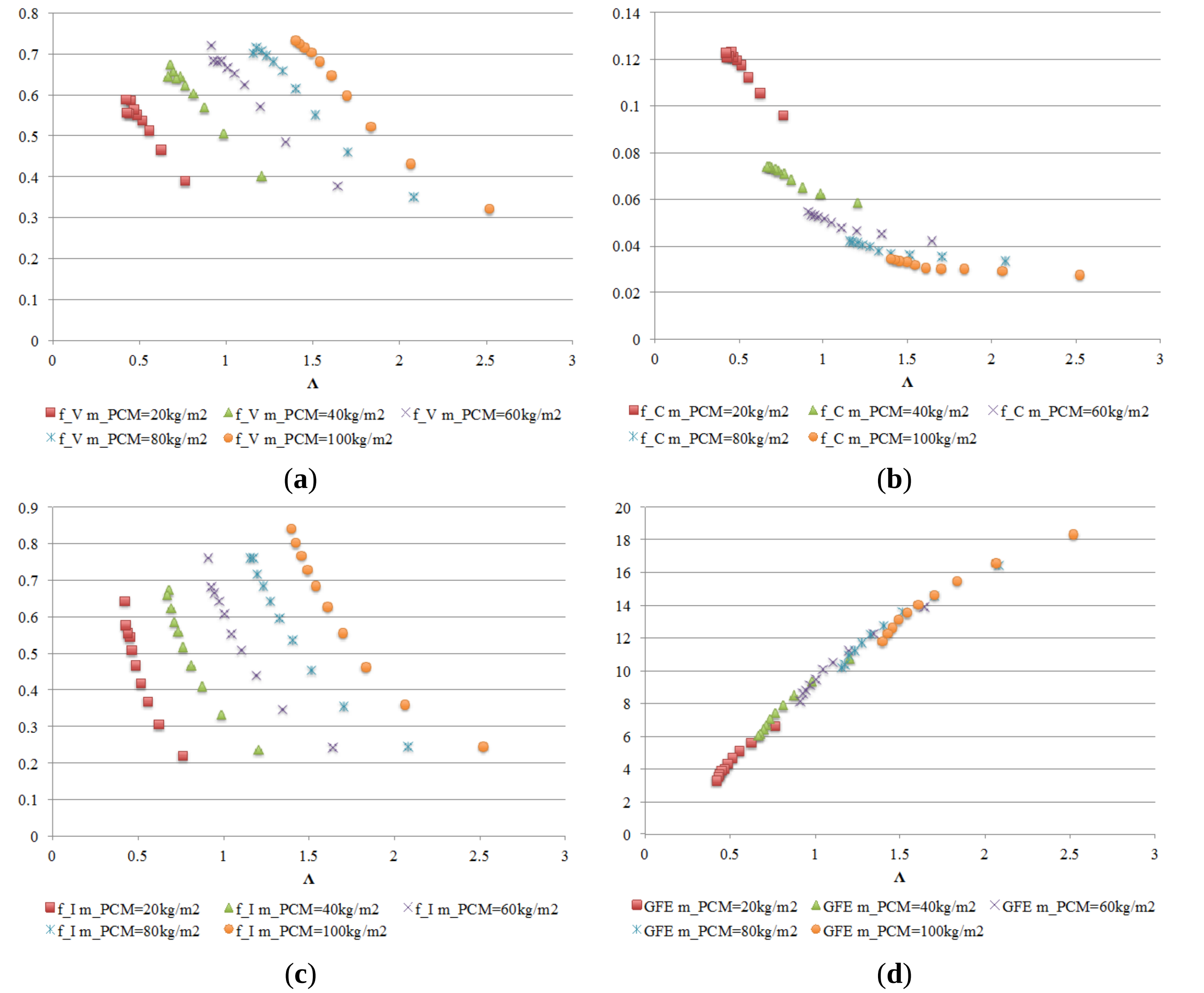


Figure 9. Indicators for different amounts of PCM: (**a**) f_V; (**b**) f_C; (**c**) f_I; (**d**) *GFE*.

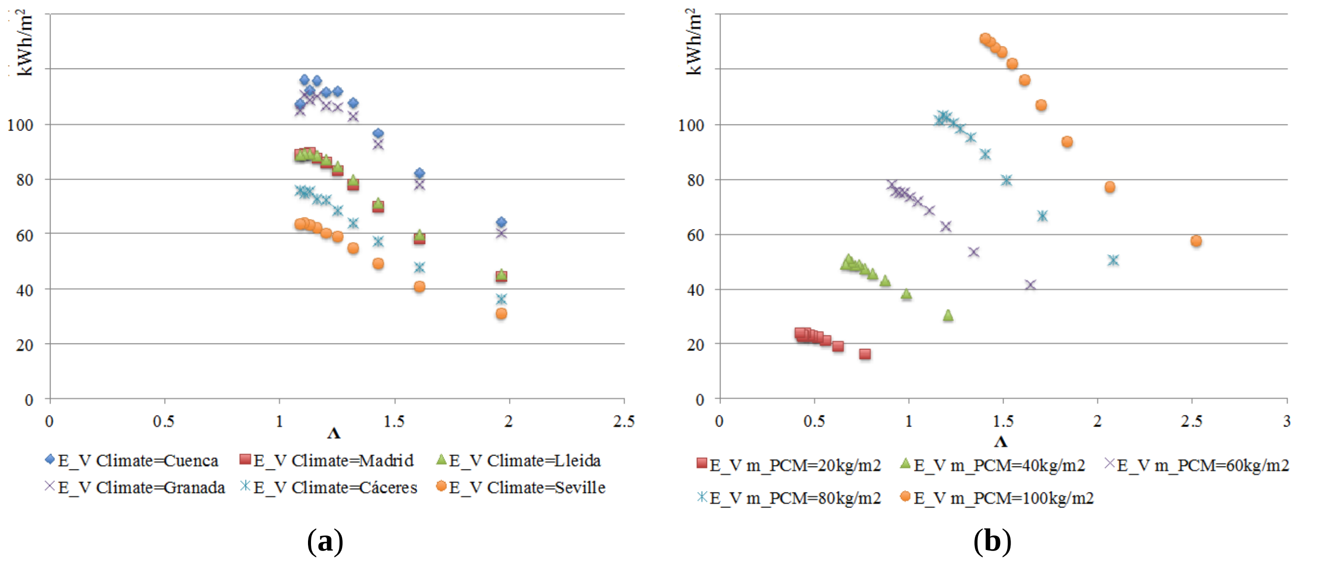


Figure 10. Ventilation energy delivered in July and August: (**a**) different climates; (**b**) different amounts of PCM.

Similarly, an analysis of supplementary indicators $f_U \cdot f_B \cdot f_{RS} \cdot f_{DS}$ for different façade configurations in different climates revealed the following:

- Use factor f_U provides information on the use of energy in the system and fewer losses. A high f_U value means efficient release with fewer losses; efficiency can be improved with façade insulation and the speed of release.
- Balance factor f_B compares release capacity to storage capacity. A high f_B value implies small loss during inactivity. This factor depends (inversely) on the maximum temperatures (greatest loss) and speed of release and directly on the outer insulation.
- Real storage factor f_{RS} reflects operation during storage. A high f_{RS} means good storage performance. It depends directly on the maximum and minimum temperatures, but more on the high temperatures, and on speed of release and insulation.
- Design storage factor f_{DS} provides information on cooling potential relative to climate. A high f_{DS} is symptomatic of design suited to the climate at issue. It depends directly on minimum temperatures and storage speed, and, inversely, on the amount of PCM. It is affected slightly, likewise inversely, by inertia.
- Façade performance can also be estimated with the theoretical model (second simplified model) using non-dimensional parameters Λ and Π.
- The energy stored in an air medium can be calculated from the following expressions in Equations (22)–(24):

$$E_{\mathrm{Str}} = \int_{\tau} \dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}} \left(T_{\mathrm{out}}(t) - T_{\mathrm{in}}(t)\right) \mathrm{d}t \tag{22}$$

$$E_{\mathrm{Str}} = \dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}} \, \frac{\int_{\tau}\left(T_{\mathrm{out}}(t) - T_{\mathrm{in}}(t)\right)\mathrm{d}t}{\int_{\tau}\left(T_{\mathrm{PCM}} - T_{\mathrm{in}}(t)\right)\mathrm{d}t} \int_{\tau}\left(T_{\mathrm{PCM}}(t) - T_{\mathrm{in}}(t)\right)\mathrm{d}t \tag{23}$$

$$E_{\mathrm{Str}} = \dot{m}_{\mathrm{f}} \cdot C_{\mathrm{f}} \cdot \eta \cdot CCP \tag{24}$$

where *CCP* is climate cooling potential (Kh) in degree-hours over a given night-time storage period.

While as a rule $E_V < E_{Str}$, where Λ is not overly small it may be regarded as roughly similar and used to estimate f_V.

The advantage of the method is that it can be used to estimate façade behavior from the perspective of regenerator efficiency and to obtain Λ and Π, which define the main variables. The amount of PCM, air speed, and energy delivered can consequently be predesigned to the climate in question.

Comparison with a regenerator and the theoretical values defined are only valid for highly insulated façades; otherwise, losses distort the results. Nonetheless, as the above example shows, the difference is not large.

Both the simulations and the theoretical values showed that the façade behaved much like a regenerator. Note that the Π values ranged from 0.8 to 2.1 in this approach.

Figure 11 shows the energy stored and released (kWh/m^2) in July and August in façades with different amounts of PCM. The figure also shows the energy stored as estimated from η and *CCP*.

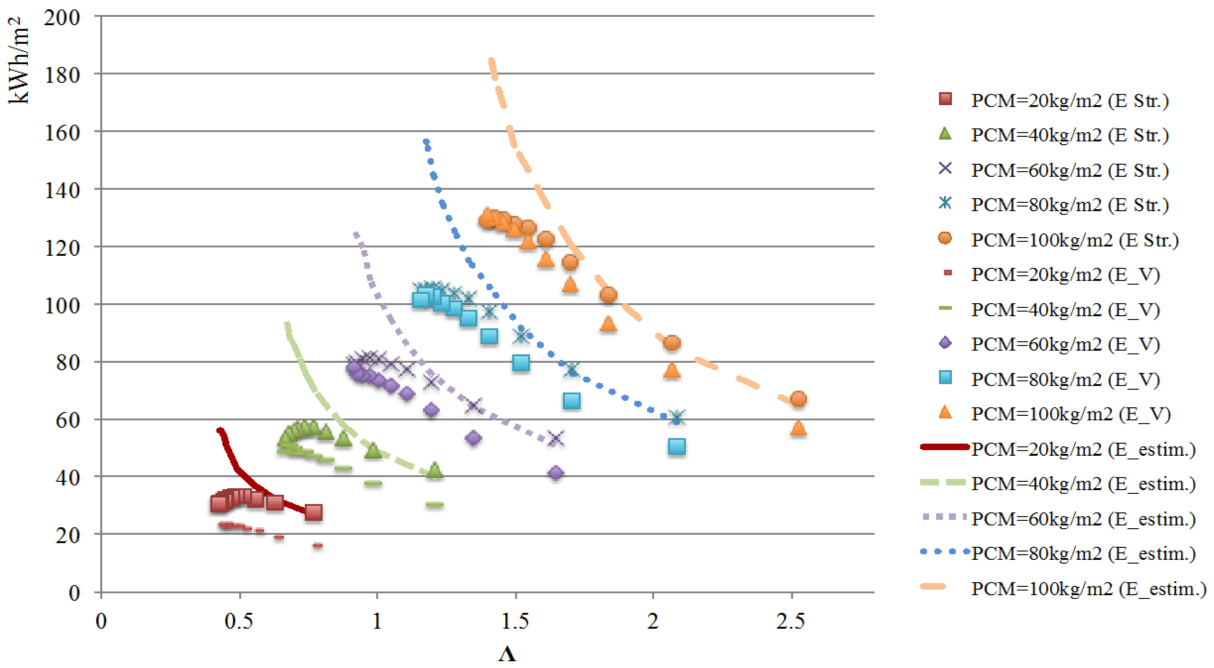
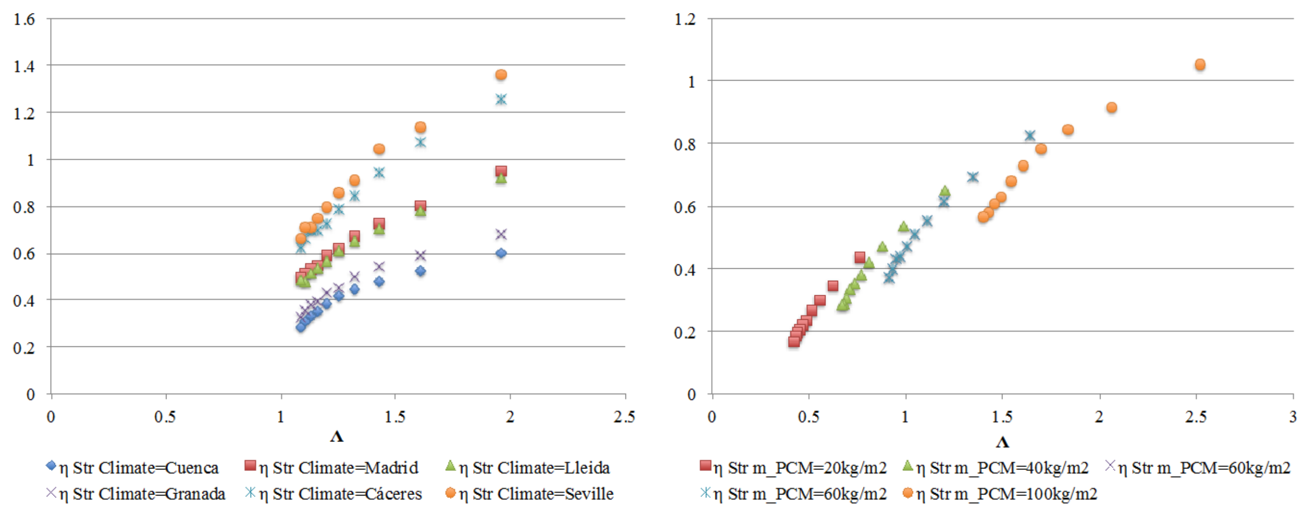


Figure 11. Energy stored, energy delivered for ventilation, and estimated energy storage in July and August.

As the figure shows, PCM-bearing ventilated façades can deliver substantial amounts of renewable energy for use in air conditioning.

System behavior as a heat exchanger merits comment. In the simulation, at high values of Λ, which denote low air speed, η normally fluctuates around 1 (Figure 12). That *GFE* and η increase with the amount of PCM is another finding of interest. While *GFE* is greater in cold climates, heat exchanger efficiency, η, is higher in warm climates. The reason is that façades perform better when the cooling potential is high (cold nights), even if regenerator use is less intense. Values of η greater than 1 mean that the façade is active in both the latent and the sensible ranges because of the mass from the indoor wall, which is more relevant in warm than in cold climates.



(**a**) (**b**)

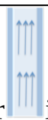
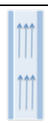
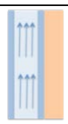
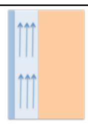
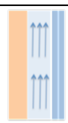
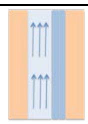
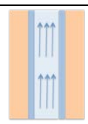
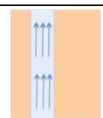
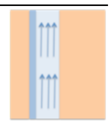
Figure 12. Efficiency as a regenerator: (**a**) different climates; (**b**) different amounts of PCM.

The results of applying the model to different façade configurations (Table 2) are given in Table 3. The drawings in the table represent the insulation, the ventilation chamber, and the masonry wall typical of construction in Spain, as appropriate. The example is based on Madrid's climate and a PCM content of 60 kg/m^2.

Table 2. Façade configurations.

Case	Configuration
Case 1	Lightweight outer element, lightweight inner element
Case 2	Lightweight outer element, heavy inner element with insulation on the chamber side
Case 3	Lightweight outer element, heavy inner wall
Case 4	Heavy outer element, lightweight inner element
Case 5	Heavy outer heavy element, heavy inner element with insulation on the chamber side
Case 6	Heavy outer element with insulation on the chamber side, heavy inner element with insulation on the chamber side
Case 7	Heavy outer element, heavy inner wall
Case 8	Heavy outer element with insulation on the chamber side, heavy inner wall

Table 3. Results obtained in different façade configurations.

Case	1	2	3	4	5	6	7	8
outer  inner								
f_U Use factor	0.91	0.92	0.92	0.91	0.91	0.98	0.9	0.97
f_B Balance factor	0.99	1	0.97	1.1	1.1	1.08	1.03	1.04
f_{RS} Real storage factor	0.82	0.82	0.82	0.73	0.73	0.76	0.76	0.78
f_{DS} Design storage factor	0.84	0.84	0.83	0.84	0.84	0.85	0.83	0.84
f_V Ventilation factor	0.62	0.63	0.61	0.61	0.61	0.68	0.59	0.66
f_C Chamber factor	0.12	0.1	0.17	0.02	0.02	0.11	0.09	0.19
f_I Installation factor	0.54	0.54	0.54	0.53	0.54	0.54	0.55	0.55
f_D Design factor	7.54	7.54	7.87	7.95	7.95	7.54	8.28	7.87
GFE Global façade efficiency indicator	10.38	10.16	11.26	9.31	9.23	11	10.32	12.24

A yearly performance graph for one of the façades (case 1) is reproduced in Figure 13, by way of illustration. The thermal stabilization afforded by the façade is clearly visible.

As noted, climate is a key factor in this type of systems. The ability to estimate the amount of energy available for use is directly related to *CCP* in degree-hours (Kh), which can be readily calculated for a given climate and prevailing conditions.

Figure 14 contains a temperature diagram for the cities where the studies were conducted. The horizontal lines represent the time of day from 0:00 to 24:00 and the vertical lines (from top down) the days of the year. The diagrams stand as proof of the substantial cooling power that can be derived from the thermal sink comprising the low night-time summer temperatures.

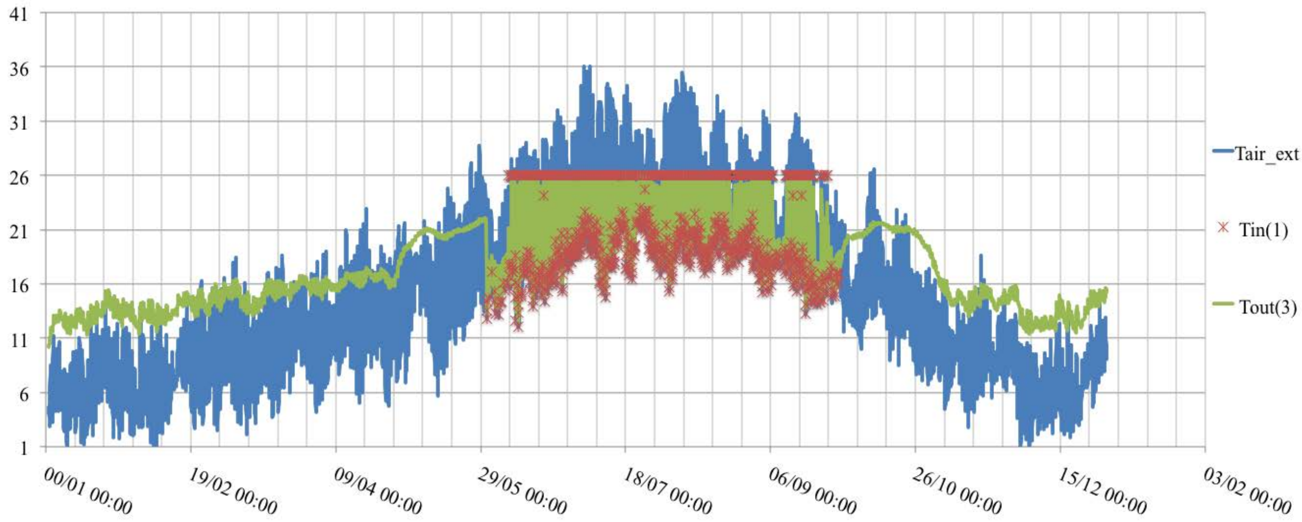


Figure 13. Façade temperatures over a 12-month period.

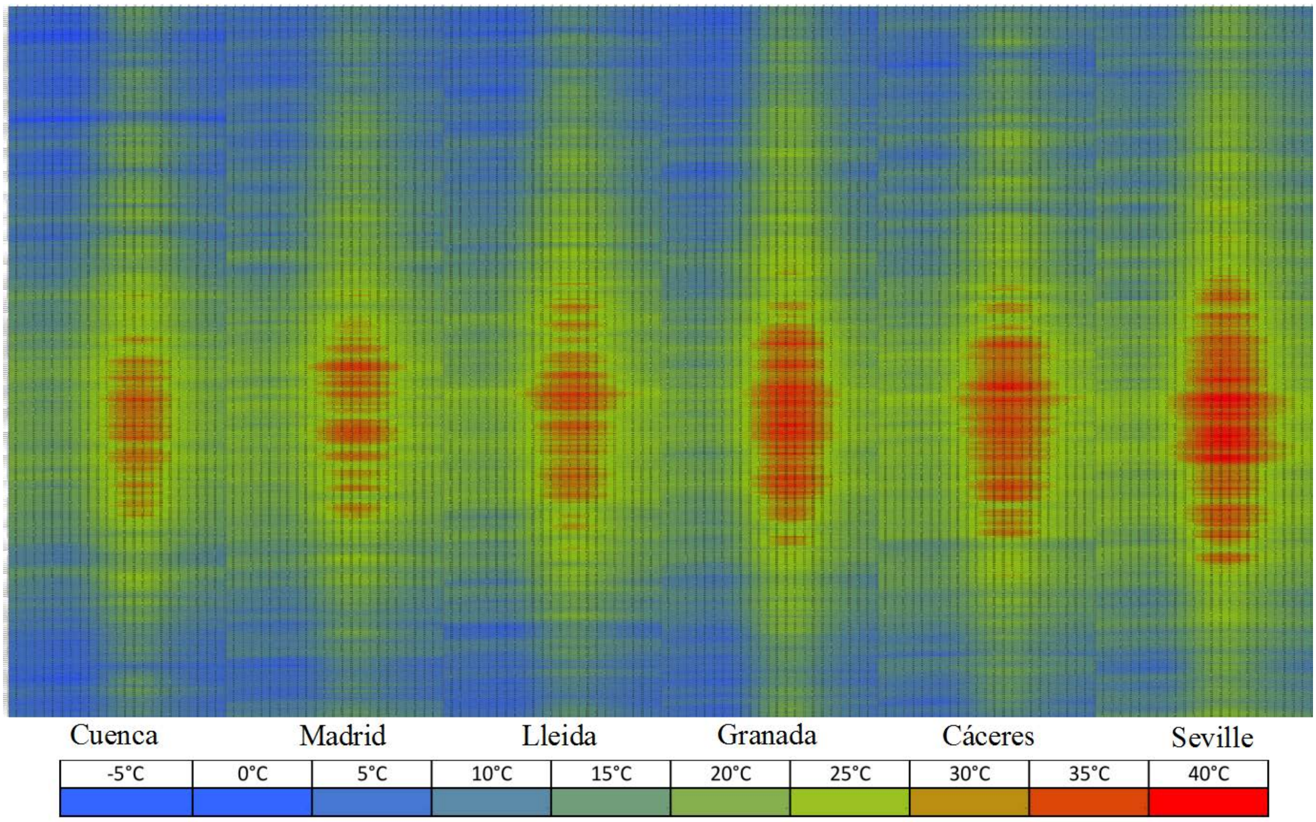


Figure 14. Hourly temperatures in the cities studied over a one-year period.

Climate potential can be fairly simply assessed from the following expression, which depends on the phase change temperature:

$$CCP = \int_{\tau} \left(T_{\mathrm{PCM}}(t) - T_{\mathrm{in}}(t)\right) \mathrm{d}t \tag{25}$$

Given the hourly temperatures for a climate, its *CCP* can be estimated for a specific phase change temperature. The findings for 22 °C in the climates selected are given in Table 4.

Table 4. Climate cooling potential (*CCP*) values for selected climates.

CCP **(Kh Degree-Hours)**	**June**	**July**	**August**	**September**
Cuenca	3324	1695	1714	3255
Madrid	1960	646	709	1909
Lleida	1757	746	714	1854
Granada	2311	1307	1302	2281
Cáceres	1520	427	432	801
Seville	1120	445	378	698

Insight into the natural cooling power that can be drawn from energy stored during the night can be obtained by comparing those values to the degree-hours of cooling in the respective climates. The data in Table 5, provided by way of indication only, were calculated for a temperature of 26 °C.

Table 5. Degree-hours of cooling in selected climates.

Degree-hours of cooling	**June**	**July**	**August**	**September**
Cuenca	84	827	707	222
Madrid	248	973	832	209
Lleida	350	1175	868	318
Granada	682	1652	1533	699
Cáceres	651	1712	1415	798
Seville	925	2201	2126	1081

Note that the storage potential in Cuenca is very high compared to its cooling needs. Madrid and Lleida yield similar values, although the summer is warmer in the latter. Granada has high cooling potential as well as high cooling needs. Cáceres and Seville exhibit much lower potential than needs, particularly in July and August.

6. Conclusions

Ventilated facades containing PCMs have been shown to help reduce buildings' energy consumption, contributing to energy savings. Spain's climate is particularly well adapted to reducing or eliminating energy consumption for air conditioning by deploying the cooling power stored overnight in PCMs.

The suitability of system design depends on needs-driven efficiency. Indicators furnish the information on performance required to analyze and compare different solutions. They may also be used to standardize technical specifications. In simplified models, non-dimensional parameters such as defined for regenerators (Λ and Π) stabilize the results and facilitate their analysis by condensing all the basic variables in a single value.

Likening PCM storage to regenerator behavior is a useful approach to capitalize fully on climate potential. Regenerator efficiency contributes to global system efficiency.

Preliminary estimates and simplified modeling are useful for determining system behavior, for by saving on calculation time they optimize the design of new solutions.

As the findings show, very high façade efficiency values are obtained for both lightweight and heavy elements.

Cooling potential is very high in continental climates and high in temperate Mediterranean climates.

Solutions should be designed in keeping with the aims pursued respecting the amount and duration of energy release, while energy storage depends upon the potential available.

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Author Contributions

These authors contributed equally to this work. José A. Tenorio introduced the idea of indicators and wrote the draft; José Sánchez-Ramos and Álvaro Ruiz-Pardo worked in the second simplified model and in detailed model; Servando Álvarez contributed in concepts, managed and supervised the research works and Luisa Cabeza managed also the research and provided experimental issues. All of them have together contributed in developing the ideas, improving the manuscript, and they have read as well as approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

CCP	Climate cooling potential
COP	Coefficient of performance
C'_{vent}	Fans energy consumption in the operation of the façade
C_{vent}	Theoretical fans energy consumption in the operation of the façade (without building)
$C_{vent.Design}$	Fans energy consumption assuming operation under design conditions
C_f	Heat capacity of the air
C_m	Matrix mass capacity
C_p	Heat capacity of the façade
ΔD	Theoretical energy saved in a building attributable to the installation of a PCM façade
E_{Design}	Energy stored in the façade due to increase temperature between T_{min} and T_{max}
E_v	Energy delivered for cooling in a period of time
E_C	Energy saved attributable to the PCM façade as thermal barrier
E_{Str}	Energy stored
f_B	Balance factor
f_C	Chamber factor
f_D	Design factor
f_{DS}	Design storage factor
f_I	Design factor related to fans consumption
f_U	Use factor
f_{RS}	Real storage factor

f_V	Ventilation factor
GBE	Global building efficiency indicator
GFE	Global façade efficiency indicator
hc	Convective heat transfer coefficient
L	Length (regenerative heat exchangers)
λ	PCM latent heat
Λ	Reduced length (regenerative heat exchangers)
$\dot{m}_f$	Mass air flow rate
$m_{façade}$	Façade mass
m_m	PCM mass
m_{PCM}	Matrix mass (regenerative heat exchangers)
η	Efficiency (regenerative heat exchangers)
P	Period (regenerative heat exchangers)
Π	Reduced period (regenerative heat exchangers)
T_{in}	Inlet air temperature
T_{min}	Minimum temperature range defined in the air chamber
T_{max}	Maximum temperature range defined in the air chamber
T_{out}	Outlet air temperature
T_{PCM}	Phase change temperature
τ	Storage time (regenerative heat exchangers)
v	Air speed (regenerative heat exchangers)

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