SUPPLEMENTARY INFORMATION

# Passive heating and cooling of photovoltaic greenhouses including thermochromic materials

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**Table S1.** Electrical and mechanical characteristics of the PV modules used to build the cubic structures called PV cubes.

| Technology | c-Si | a-Si:H | CdTe | OPV |
|---|---|---|---|---|
| Manufacturer | Atersa | EPS | First Solar | Infinity PV |
| Model | SHS 100 | EPS 80S 24 | FS 397 PLUS | customised |
| $P_{nom}$ [W] | 100 | 80 | 97.5 | 16 |
| $V_{mpp}$ [V] | 18.1 | 34.33 | 46.3 | 330 |
| $I_{mpp}$ [A] | 5.56 | 2.33 | 2.11 | 0.05 |
| $V_{oc}$ [V] | 22.2 | 43.83 | 58.6 | 400 |
| $I_{sc}$ [A] | 5.93 | 2.51 | 2.29 | 0.07 |
| FF | 0.76 | 0.73 | 0.73 | 0.59 |
| Active Area [$m^2$] | 0.70 | 0.67 | 0.71 | 0.55 |
| PCE [%] | 14 | 12 | 14 | 3 |
| Length [mm] | 1200 | 1205 | 1200 | 1200 |
| Width [mm] | 670 | 605 | 600 | 600 |
| Thickness (frame not included) [mm] | 4.5 | 6.8 | 6.8 | 12 |
| Weight [kg] | 8.2 | 12 | 12 | 2.0 |
| Frame (F) \| No Frame (NF) | F | F | NF | NF |
| Encapsulation | Glass-Tedlar | Glass-Glass | Glass-Glass | Polycarbonate |

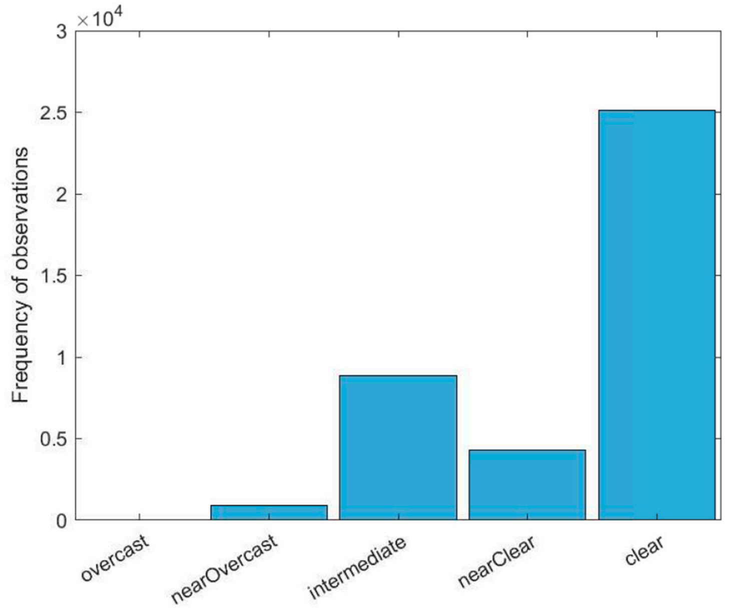


**Figure S1**. Histogram of the sky type according to Igawa et al. [Ref. 27 in main text] classification for the period under analysis (two years, from July 2017 to July 2019).

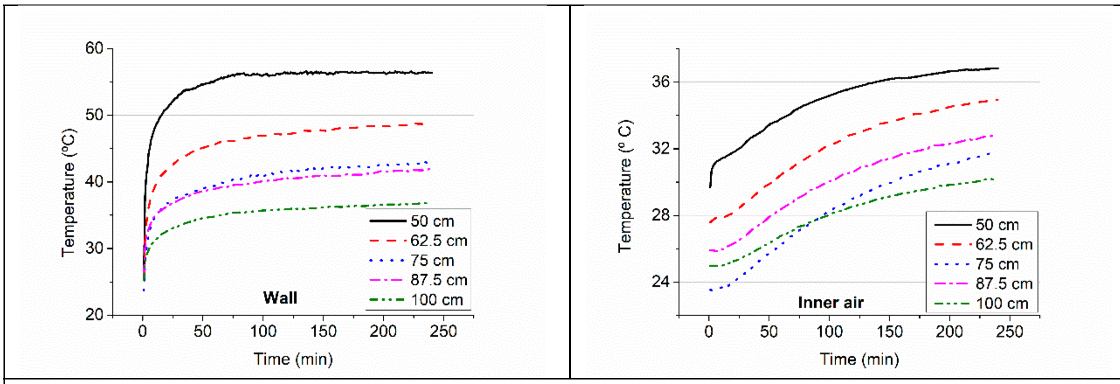


**Figure S2.** Evolution of (left) outer wall temperature and (right) inner air temperature as a function of spotlight distance (i.e. irradiance). (Data shown in the figure correspond to white colored wood. Similar exponential evolutions, not shown explicitly for all cases for the sake of clarity, were found for the rest of materials).

**Table S2**. Fitting parameters for equations $T(t) = T_{sta} - \Delta T e^{-\frac{t}{\tau}}$ corresponding to internal air temperature evolution.

| | 50 cm | 62.5 cm | 75 cm | 87.5 cm | 100 cm |
|---|---|---|---|---|---|
| | | | Inner air | | |
| | | | Brick-black | | |
| $r^2$ | 0.997 | 0.997 | 0.999 | 0.997 | 0.996 |
| $T_{sta}$ | 48.297 | 41.037 | 40.344 | 37.720 | 35.635 |
| $\Delta T$ | 26.297 | 19.037 | 18.344 | 15.720 | 13.635 |
| $\tau$ | 87.210 | 110.792 | 99.027 | 107.281 | 98.134 |
| | | | Brick-white | | |
| $r^2$ | 0.997 | 0.997 | 0.997 | 0.996 | 0.996 |
| $T_{sta}$ | 39.279 | 37.218 | 34.250 | 35.138 | 33.859 |
| $\Delta T$ | 17.279 | 15.218 | 12.250 | 13.138 | 11.859 |
| $\tau$ | 124.070 | 122.604 | 99.273 | 186.157 | 176.663 |
| | | | Wood-black | | |
| $r^2$ | 0.996 | 0.996 | 0.998 | 0.998 | 0.997 |
| $T_{sta}$ | 45.444 | 40.945 | 37.563 | 36.799 | 33.716 |
| $\Delta T$ | 23.444 | 18.945 | 15.563 | 14.799 | 11.716 |
| $\tau$ | 93.555 | 133.622 | 99.929 | 81.607 | 77.573 |
| | | | Wood- white | | |
| $r^2$ | 0.997 | 0.996 | 0.998 | 0.997 | 0.996 |
| $T_{sta}$ | 37.308 | 36.610 | 34.191 | 34.645 | 31.786 |
| $\Delta T$ | 15.308 | 14.610 | 12.191 | 12.645 | 9.786 |
| $\tau$ | 86.175 | 131.236 | 153.460 | 141.649 | 150.042 |
| | | | Plasterboard-black | | |
| $r^2$ | 0.998 | 1.000 | 0.997 | 1.000 | 0.999 |
| $T_{sta}$ | 51.726 | 44.122 | 40.090 | 38.985 | 36.519 |
| $\Delta T$ | 29.726 | 22.122 | 18.090 | 16.985 | 14.519 |
| $\tau$ | 63.675 | 68.856 | 63.333 | 73.245 | 82.751 |
| | | | Plasterboard-white | | |
| $r^2$ | 0.997 | 1.000 | 0.999 | 0.999 | 0.985 |
| $T_{sta}$ | 43.481 | 38.284 | 35.026 | 35.642 | 32.728 |
| $\Delta T$ | 21.481 | 16.284 | 13.026 | 13.642 | 10.728 |
| $\tau$ | 56.961 | 99.531 | 94.628 | 113.442 | 53.926 |
| | | | Glass-black | | |
| $r^2$ | 0.997 | 1.000 | 0.999 | 1.000 | 0.999 |
| $T_{sta}$ | 54.850 | 45.637 | 41.852 | 40.072 | 37.242 |
| $\Delta T$ | 32.850 | 23.637 | 19.852 | 18.072 | 15.242 |
| $\tau$ | 52.538 | 73.973 | 88.253 | 87.001 | 61.614 |

| Glass-white | | | | | |
|---|---|---|---|---|---|
| $r^2$ | 0.999 | 0.979 | 0.999 | 0.995 | 0.999 |
| $T_{sta}$ | 45.824 | 41.232 | 36.996 | 36.995 | 34.426 |
| $\Delta T$ | 23.824 | 19.232 | 14.996 | 14.995 | 12.426 |
| $\tau$ | 52.822 | 33.567 | 89.936 | 61.182 | 103.673 |

* Regression coefficients were rounded to the third significant figure. Where the fourth figure is higher, regression coefficient appears as 1.000, which obviously does not correspond to a perfect fitting.

**Table S3**. Fitting parameters for equations $T(t) = T_{sta} + \Delta \mathrm{T} e^{-\frac{t}{\tau}}$ corresponding to front external wall temperature evolutions.

| | 50 cm | 62.5 cm | 75 cm | 87.5 cm | 100 cm |
|---|---|---|---|---|---|
| | | | Front wall | | |
| $r^2$ | 0.987 | 0.984 | 0.982 | 0.926 | 0.993 |
| $T_{sta}$ | 70.214 | 55.914 | 54.013 | 45.690 | 44.435 |
| $\Delta T$ | 48.214 | 33.914 | 32.013 | 23.690 | 22.435 |
| $\tau$ | 19.745 | 32.160 | 36.940 | 19.585 | 29.295 |
| | | | Brick-white | | |
| $r^2$ | 0.982 | 0.979 | 0.986 | 0.991 | 0.989 |
| $T_{sta}$ | 52.083 | 46.254 | 41.233 | 38.508 | 36.938 |
| $\Delta T$ | 30.083 | 24.254 | 19.233 | 16.508 | 14.938 |
| $\tau$ | 44.463 | 39.736 | 31.509 | 60.371 | 55.632 |
| | | | Wood-black | | |
| $r^2$ | 0.697 | 0.924 | 0.975 | 0.954 | 0.970 |
| $T_{sta}$ | 68.579 | 57.573 | 52.560 | 51.147 | 45.227 |
| $\Delta T$ | 46.579 | 35.573 | 30.560 | 29.147 | 23.227 |
| $\tau$ | 12.182 | 21.474 | 16.188 | 17.307 | 18.440 |
| | | | Wood- white | | |
| $r^2$ | 0.921 | 0.928 | 0.925 | 0.934 | 0.956 |
| $T_{sta}$ | 56.142 | 47.928 | 42.619 | 41.337 | 36.396 |
| $\Delta T$ | 34.142 | 25.928 | 20.619 | 19.337 | 14.396 |
| $\tau$ | 13.708 | 27.833 | 43.141 | 42.996 | 35.460 |
| | | | Plasterboard-black | | |
| $r^2$ | 0.884 | 0.969 | 0.965 | 0.874 | 0.937 |
| $T_{sta}$ | 73.940 | 58.094 | 49.862 | 47.600 | 44.599 |
| $\Delta T$ | 51.940 | 36.094 | 27.862 | 25.600 | 22.599 |
| $\tau$ | 13.311 | 14.888 | 12.509 | 19.593 | 23.748 |
| | | | Plasterboard-white | | |
| $r^2$ | 0.942 | 0.867 | 0.925 | 0.957 | 0.945 |
| $T_{sta}$ | 62.243 | 44.779 | 41.595 | 40.579 | 37.718 |
| $\Delta T$ | 40.243 | 22.779 | 19.595 | 18.579 | 15.718 |
| $\tau$ | 12.122 | 25.810 | 37.883 | 37.885 | 13.642 |
| | | | Glass-black | | |
| $r^2$ | 0.989 | 0.990 | 0.967 | 0.987 | 0.997 |
| $T_{sta}$ | 72.515 | 55.712 | 50.772 | 47.977 | 43.116 |
| $\Delta T$ | 50.515 | 33.712 | 28.772 | 25.977 | 21.116 |
| $\tau$ | 18.077 | 25.449 | 39.697 | 34.313 | 19.403 |

| Glass-white | | | | | |
|---|---|---|---|---|---|
| $r^2$ | 0.984 | 0.997 | 0.990 | 0.985 | 0.987 |
| $T_{sta}$ | 54.774 | 45.866 | 41.199 | 40.861 | 37.228 |
| $\Delta T$ | 32.774 | 23.866 | 19.199 | 18.861 | 15.228 |
| $\tau$ | 21.615 | 19.275 | 45.539 | 23.604 | 49.823 |

**Table S4.** Linear fitting values of inner air and front wall temperatures vs. irradiance, for the four different materials tested and the two corresponding colorations.

| | Inner air | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Brick-black | Brick-white | Wood-black | Wood-white | Plasterboard-black | Plasterboard-white | Glass-black | Glass-white |
| $r^2$ | 0.978 | 0.975 | 0.963 | 0.835 | 0.978 | 0.967 | 0.978 | 0.982 |
| Slope | 0.020 | 0.009 | 0.019 | 0.009 | 0.024 | 0.016 | 0.029 | 0.018 |
| $T_0$ | 31.010 | 31.954 | 30.029 | 31.073 | 31.811 | 29.826 | 30.312 | 31.177 |
| | Front wall | | | | | | | |
| $r^2$ | 0.988 | 0.962 | 0.967 | 0.957 | 0.984 | 0.917 | 0.968 | 0.975 |
| Slope | 0.044 | 0.024 | 0.037 | 0.034 | 0.047 | 0.038 | 0.047 | 0.027 |
| $T_0$ | 33.318 | 32.192 | 37.619 | 30.723 | 33.955 | 28.730 | 31.571 | 32.084 |

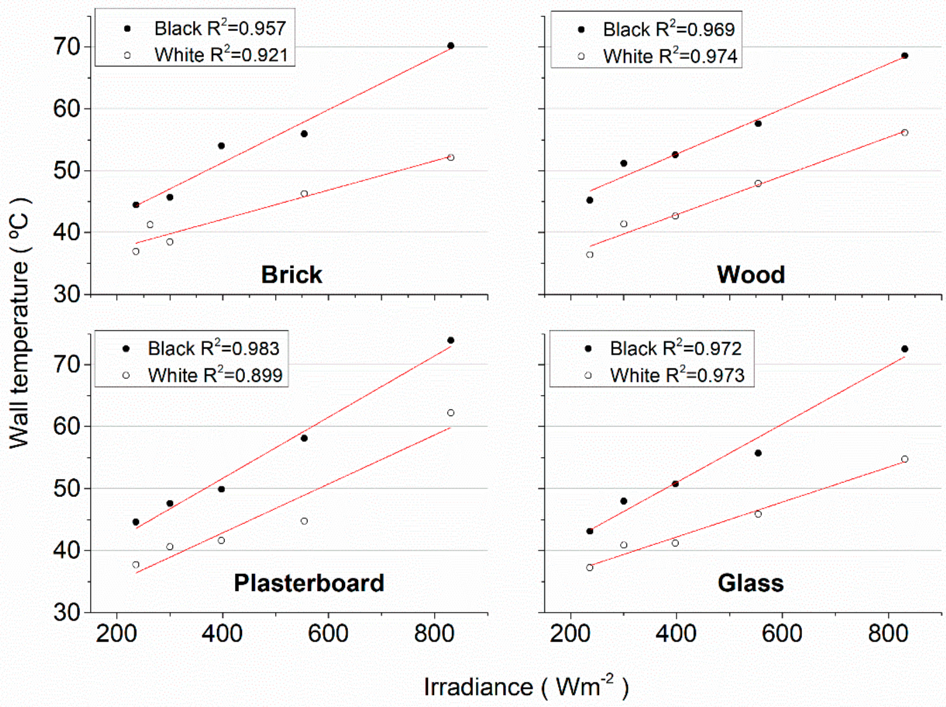


**Figure S3**. Stationary temperature of the front wall in the chromic box (brick, wood, plasterboard and glass) vs. incident irradiance. Plots show the different values obtained when the materials were painted in white or black.

*Modelling of thermal response under stationary or variable irradiance conditions*

To simulate the temperature evolutions in our test box, we used a simple 1-D transient heat conduction finite difference model, with a mesh composed of eight nodes, as shown in the following scheme:

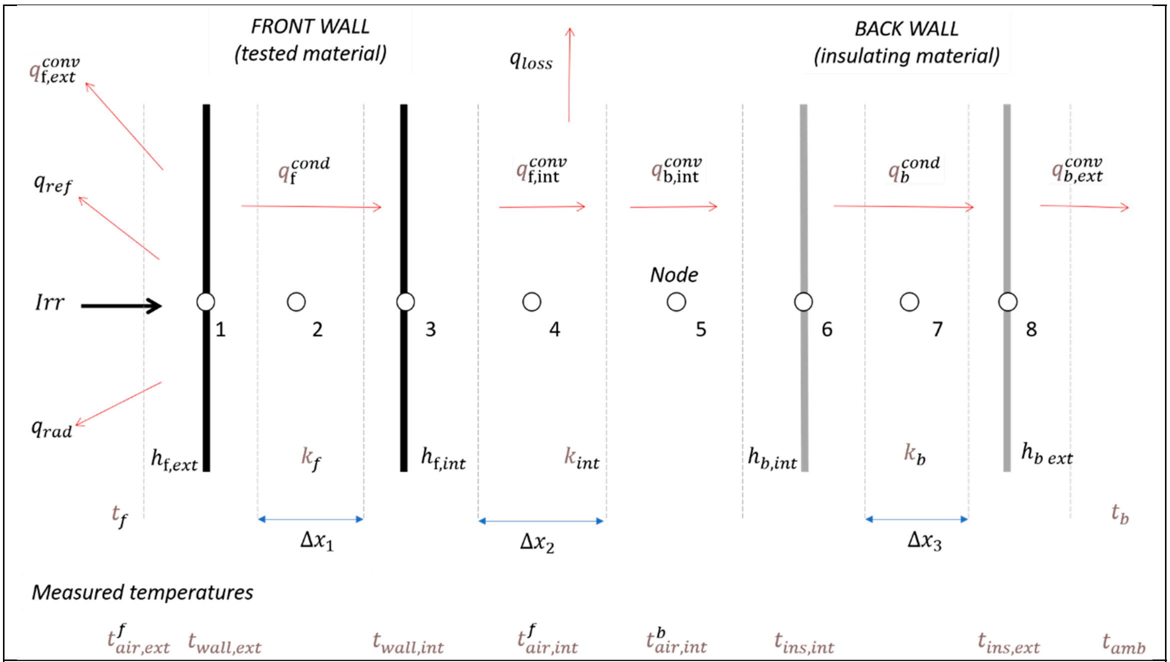


**Figure S4**. Scheme of the proposed 1-D mesh and the parameters included in the transient heat conduction finite difference model.

Experimental temperature values available were:

$t^{f}_{air,ext}$- Front fluid temperature (air) close to the irradiated front wall.

$t_{wall,ext}$- Front wall (tested material) external temperature.

$t_{wall,int}$- Front wall (tested material) internal temperature.

$t^{f}_{air,int}$- Inner air temperature in the front half box volume.

$t^{b}_{air,int}$- Inner air temperature in the back half box volume.

$t_{ins,int}$- Back wall (insulating material) internal temperature.

$t_{ins,ext}$- Back wall (insulating material) external temperature.

$t_{amb}$- air ambient temperature.

**Table S5.** Optical and thermal values used for each material

| | Reflectance | $C_p$ / $Jkg^{-1}K^{-1}$ | ρ /$kgm^{-3}$ | Wall thickness /cm | k /$Wm^{-1}K^{-1}$ |
|---|---|---|---|---|---|
| Brick, white | 0.424 | 840[a] | 1602[b] | 5.00 | 0.69[a] |
| Brick, black | 0.022 | | | | |
| Wood, white | 0.483 | 2800[a] | 430[a] | 2.70 | 0.11[a] |
| Wood, black | 0.019 | | | | |
| Plasterboard, white | 0.373 | 840[a] | 1440[a] | 1.75 | 0.18[c] |
| Plasterboard, black | 0.025 | | | | |
| Glass, white | 0.426 | 840[b] | 2700[b] | 1.75 | 0.76[b] |
| Glass, black | 0.024 | | | | |
| Glass Wool, back wall | | 840[d] | 40[d] | 2.50 | 0.04[b] |

[a] From "Heat transfer". J. P. Holman.(10th ed.) (2010)

[b] From "Heat transfer" A. J. Chapman (4th ed.) (1984)

[c] From "Manual técnico Pladur" www.pladur.es (2020)
[d] From "Rockwool: Firesafe insulation" (2020)
http://download.rockwool.es/media/111580/catalogo%20industria.pdf

Reflectance values (R) and wall thickness ($\Delta x_1$, $\Delta x_3$) were measured, while $C_p$ (specific heat capacity), ρ (density) and k (thermal conductivity) values were obtained from the references listed in the table. The rest of parameters and/or values were calculated/defined as follows:

*Front wall (tested material)*

$Irr$ – Irradiance

$q_{ref}$ – Reflected heat flux, defined as $q_{ref} = R\ Irr$ , being R the reflectance of the tested material

$q_{inc}$ – Incident heat flux, defined as $q_{inc} = Irr - q_{ref}$

$q_{f,ext}^{conv}$ – Exterior convective heat flux (convection between ambient air and front wall), calculated as $q_{f,ext}^{conv} = h_{f,ext}(t_{wall,ext} - t_{air,ext}^{f}\ )$

$q_{rad}$ – Net radiative heat flux, calculated as $q_{rad} = \varepsilon_f \sigma T_{wall,ext}^4 - \varepsilon_{amb} \sigma T_{amb}^4$ , difference between radiated heat flux of the tested wall material and the incident radiated heat flux from ambient. For the sake of simplicity values of ε were considered 0.9 in all cases. $T_{wall,ext}^4$ and $T_{amb}^4$ were obtained from the stationary experimental values of $t_{wall,ext}$ and $t_{amb}$ expressed in Kelvin. σ=5.67x10 $^{-8}$ W/m$^{-2}$ K (Stefan-Boltzmann constant).

$t_f$ - Front fluid temperature (air). Obtained from the experimentally measured stationary values of $t^f_{air,ext}$

$h_{f,ext}$- Exterior heat transfer coefficient (convection between ambient air and front wall). This coefficient was calculated as $h_{f,ext} = \frac{5}{4}\frac{NuK_f}{\Delta y}$ a corrected average coefficient corresponding to a vertical wall submitted to a constant incident heat flux. In that expression, Nusselt number was obtained as $Nu = 0.6\,(Gr^*Pr)^{0.2}$ , where $Pr$ stands for Prandtl number and $Gr^*$stands for a modified Grashoff number calculated as $Gr^* = \frac{g\beta q_{inc}\Delta y^4}{k_{air}\nu^2}$ , being g= gravitational acceleration, 9.8 $ms^{-2}$; $\beta = \frac{1}{T}$ , fluid expansion coefficient , $q_{inc}$=incident heat flux as defined above; Δy= height of the wall, 0.36 m; ν=fluid kinematic viscosity, $k_{air}$= fluid thermal conductivity. Fluid parameters (air) were evaluated at $t_m = \frac{t_{wall,ext}+t^f_{air,ext}}{2}$ .

$q_f^{cond}$ – Front wall conductive heat flux, calculated as $q_f^{cond} = Irr - q_{ref} - q_{f,ext}^{conv} - q_{rad}$

$k_f$ - Front wall thermal conductivity

$\Delta x_i$ – Nodal spacing, with $\Delta x_1 = \frac{d_1}{2}, \Delta x_2 = \frac{d_2}{3}, \Delta x_3 = \frac{d_3}{2}$, and $d_i$ thickness of the corresponding element ($d_1$=wall thickness, $d_2$=inner space thickness, $d_3$=insulating wall thickness).

$q_{f,int}^{conv}$ – Interior convective heat flux (convection between inner air and front wall), equaled to $q_f^{cond}$

$h_{f,int}$- Interior heat transfer coefficient (convection between inner air and front wall). This coefficient was calculated as $h_{f,int} = \frac{q_{f,int}^{conv}}{t_{wall,int}-t^f_{air,int}}$

$k_{int}$- inner air thermal conductivity

*Back wall (insulating material)*

$k_b$ - back wall thermal conductivity

$q_b^{cond}$ - Front wall conductive heat flux, calculated as $q_b^{cond} = \frac{k_b}{d_3}(t_{ins,int} - t_{ins,ext})$

$q_{b,int}^{conv}$ – Interior convective heat flux (convection between inner air and back wall), equaled to $q_b^{cond}$

$h_{b,int}$- Interior heat transfer coefficient (convection between inner air and back wall). This coefficient was calculated as $h_{b,int} = \frac{q_{b,int}^{conv}}{t^b_{air,int}-t_{ins,int}}$

$q_{b,ext}^{conv}$ – Exterior convective heat flux (convection between back wall and ambient air), equaled to $q_b^{cond}$

$h_{b,ext}$- Exterior heat transfer coefficient (convection between back wall and ambient air). This coefficient was calculated as $h_{b,ext} = \frac{q_{b,ext}^{conv}}{t_{ins,ext} - t_{amb}}$

$q_{loss}$ - heat flux loss through the rest of box walls. It was estimated as $q_{loss} = nq_{b,ext}^{conv}$, with n=4 (number of walls)

Resulting equations for each node were as follows:

$$t_1' = t_1[1 - 2Fo_f(1 + Bi_{f,ext})] + 2Fo_f[\, t_2 + Bi_{f,ext}t_f + (q_{inc} - q_{rad})\frac{\Delta x_1}{k_f}]$$

$$t_2' = t_1(1 - 2Fo_f) + Fo_f\,(t_3 + t_1)$$

$$t_3' = t_3[1 - 2Fo_f(1 + Bi_{f,int})] + 2Fo_f \quad (t_2 + Bi_{f,int}t_4)$$

$$t_4' = t_4[1 - Fo_f(Bi_{f,int} + Bi_{b,int})] + Fo_f(\, Bi_{f,int}t_3 + Bi_{b,int}t_5 + q_{loss}\frac{\Delta x_2}{k_{int}})$$

$$t_5' = t_5[1 - Fo_f(Bi_{f,int} + Bi_{b,int})] + Fo_f(\, Bi_{f,int}t_4 + Bi_{b,int}t_6)$$

$$t_6' = t_6[1 - 2Fo_b(1 + Bi_{b,int})] + 2Fo_b \quad (t_7 + Bi_{b,int}t_5)$$

$$t_7' = t_7(1 - 2Fo_b) + Fo_b\,(t_6 + t_8)$$

$$t_8' = t_8[1 - 2Fo_b(1 + Bi_{b,ext})] + 2Fo_b \quad (t_7 + Bi_{b,ext}t_b)$$

Where

$$Bi_{f,ext} = \frac{h_{f,ext}\Delta x_1}{k_f}$$

$$Bi_{f,int} = \frac{h_{f,int}\Delta x_1}{k_f}$$

$$Fo_f = \frac{\alpha_f \Delta\tau}{\Delta x_1^2}$$

$$Bi_{b,int} = \frac{h_{b,int}\Delta x_3}{k_b}$$

$$Fo_b = \frac{\alpha_b \Delta\tau}{\Delta x_3^2}$$

$$Bi_{b,ext} = \frac{h_{b,ext}\Delta x_3}{k_b}$$

**Table S6.** Average values of heat transfer values of the materials as modified when using white or black paint.

| | $h_{f,ext}$ /$Wm^{-2}K^{-1}$ | $h_{f,int}$ / $Wm^{-2}K^{-1}$ | $h_{b,ext}$ / $Wm^{-2}K^{-1}$ | $h_{b,\,int}$ / $Wm^{-2}K^{-1}$ |
|---|---|---|---|---|
| Brick, white | 5.53 | 12.03 | 3.03 | 8.39 |
| Brick, black | 6.37 | 9.39 | 4.48 | 10.06 |
| Wood, white | 5.56 | 7.15 | 2.80 | 5.09 |
| Wood, black | 6.32 | 8.04 | 4.07 | 5.92 |
| Plasterboard, white | 5.80 | 11.37 | 3.97 | 8.63 |
| Plasterboard, black | 6.47 | 7.43 | 4.94 | 12.03 |
| Glass, white | 5.24 | 18.83 | 3.78 | 4.67 |
| Glass, black | 6.46 | 8.20 | 4.89 | 5.97 |

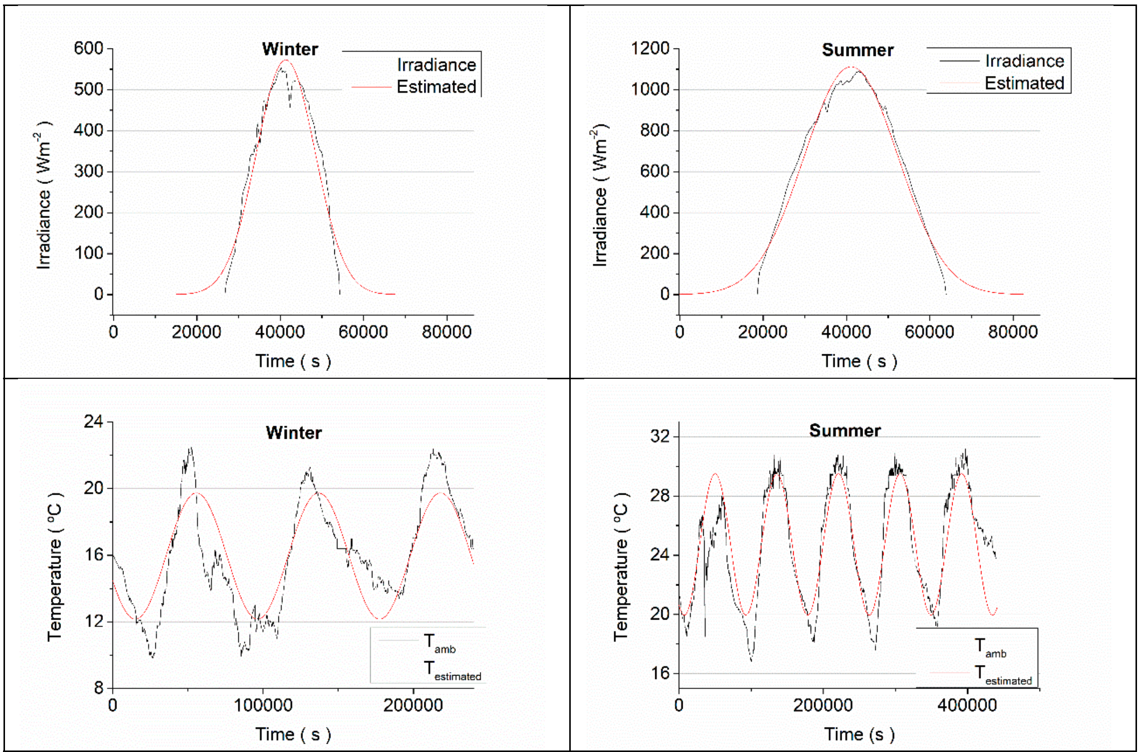


**Figure S5.** (Up) Measured and estimated irradiance of two representative days in winter and summer.

(Down) Measured and estimated ambient temperature of two representative days in winter and summer.