

THERMODYNAMIC LIMITS OF THE USE OF PCM SIMULTANEOUSLY IN PHOTOVOLTAIC MODULES AND IN BUILDING

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ABSTRACT: The paper quantifies the thermodynamic limits on the energy and exergy use that would result from the use of PCM in photovoltaic BIPV modules versus not using PCM, by limiting module temperature to 298 K and the thermal energy use in buildings according to a set of hypotheses. The results obtained have been extended to six different climates. The results show that the maximum use of PCM depends heavily on the climate, therefore in hot climates as Seville, Cairo and Nairobi, the improvements in energy efficiency are very important (multiplied from 6 to 9 times), while in cold climates as London and Helsinki, the improvements are not that significant (multiplied from 1.5 to 2 times). The exergetic efficiency improvements range of about 5% for all climates, due to the low operating temperature of the PCM. These materials requirements are significant, ranging between 31 and 193 kg/m², with thicknesses between 3.9 and 24.2 cm/m².

Keywords: Photovoltaic, BIPV, PCM, phase change materials.

1 INTRODUCTION

The temperature reached by a PV module depends on multiple variables. For crystalline silicon solar cells, photovoltaic (PV) temperature elevation reduces solar to electrical energy conversion efficiency by 0.4–0.5 %K⁻¹ [1].

The use of latent heat stored and released in the solid–liquid transition of phase change materials (PCM), replacing or augmenting the sensible heat storage, has been repeatedly proposed [2]. Different types of materials were used, notably of the paraffin and salt hydrate families, and recently combined with graphite as a method to increase heat transfer [3]. It has been also discussed, the possibilities of using PCMs as an energy storage system in solar domestic hot water [4] and renewable energies in general [5].

One of the possible ways of limiting the temperature increase of the photovoltaic module is using phase change materials, PCMs [6]. The use of PCMs only to limit the photovoltaic module temperature in a passive way Analyzed and has been proven experimentally by different authors and it has proven to be an effective means of limiting temperature rise in photovoltaic modules, but the mass of PCM required is very high, in an order of 100-200 kg/m² for a phase change temperature of 298 K. [7].

PCMs use in construction, applied to both active and passive systems is performed with the main objective of stabilizing the temperature inside the building, being the main drawback to ensure the compliance of the heating-cooling cycle to stabilize the material temperature, being the most widely used microencapsulation technology[8]. On the other hand, in buildings, in many locations thermal energy at temperatures not too high is required (heating, ventilation and hot water). [9].

However, its use is not sufficiently studied for the concurrent use in photovoltaic and building. Therefore, lowering the temperature of the module and the simultaneous use of the waste heat released by the module are two aspects that would improve the utilization of solar radiation.

One way that may be considered is the use of phase change materials disposed on the module which would be placed it in the building envelope in contact with the interior [10] [11]

2 OBJECTIVE

This work quantifies the maximum improvement in energy and exergy efficiency, in both the PV installation and the building, to preheat hot water or thermal comfort, with and without PCM limiting the panel temperature to 298 K and according to very specific study hypotheses.

The results obtained have been extended to 6 different climates: Seville (Spain), Helsinki (Finland), London (UK), Cairo (Egypt), Nairobi (Kenya) and Sydney (Australia).

3 HYPOTHESIS

For the realization of this work we have made the following assumptions:

- It will prioritize the use of PCMs in the PV installation rather than on their use in construction. This means that the system design and sizing is done based on the requirements of the PV installation, being the excess energy of the cooling of the modules, the one used later for the building.

- The phase change temperature of the PCM is 298 K. since this value is within a level of comfort temperature in the building and there are PCM with these characteristics available in the market.

- The PCM used in the analysis has a density of 800 kg/m³, a thermal conductivity of 0.21 W/m·K, Cp = 1.8 kJ/kg·K and a phase change enthalpy of 200 kJ/kg.

- Climate data of the indicated cities were extracted from the database METEONORM v6.0 (Global Meteorological Database for Engineers, Planners and Education).

It has been utilized hourly data of:

- Annual hourly global tilted irradiance (W/m²) (with an inclination equal to the latitude of the location and orientated to the Ecuador)

- Annual hourly ambient temperature (°C)
- Annual hourly wind speed (m/s)
- Annual hourly sky temperature (°C).
- The photovoltaic module is monocrystalline silicon with temperature power coefficient of 0.48% / K.

- It is assumed that all heat transfer mechanisms between the PCM material and the photovoltaic module are ideal. Consequently, it is assumed that the union PCM-PV module behaves thermally as a single element, that is to say that both will be in thermal equilibrium at all times.

- All the energy extracted from the PCM material is the maximum that may be available to use in the building. Systems harnessing this energy will be the maximum available to introduce the corresponding losses in the heat transfer process.

- The set PCM-PV module will contain that quantity of PCM that the situation in which the temperature of the PCM exceeds its temperature (298 K) would never occur. This implies that the material, once reached the set point temperature by the union PCM-PV module, will be permanently in phase change.

-The energy consumption of auxiliary systems used for the forced recovery of the latent heat accumulated in the PCM and for the control system installation is despised.

4 METHODOLOGY

With the stated hypothesis and data the following variables have been calculated:

4.1 Monthly hourly average temperature of the PV module ($T_{p,hm}$)

Time monthly average temperature reached by the surface of the photovoltaic module (°C) has been obtained according to the expression [12]:

$$T_{p,hm} = T_{a,hm} + \omega \cdot \left(\frac{0.32}{8.91 + 2.0V_{v,hm}} \right) \cdot I_{hm}$$

where:

$T_{p,hm}$: Monthly hourly average temperature of the PV module (°C)

$T_{a,hm}$: Monthly hourly average ambient temperature (°C)

$V_{v,hm}$: Monthly hourly average wind speed (m/s)

I_{hm} : Monthly hourly average global tilted irradiance (W/m^2)

ω : Coefficient of mounting: According to mounting: 1; 1.8 and 2.4.

4.2 Monthly hourly average electricity, monthly daily average electricity and yearly average electricity at the PV module output without PCM ($E_{e,hm}$, $E_{e,dm}$ y E_e).

$E_{e,hm}$, obtained from the expression

$$E_{e,hm} = \int P_{e,hm} dt$$

where $P_{e,hm}$ is the average electric power in

each time 'h' on the month 'm' generated by the PV module without PCM given by the expression:

$$P_{e,hm} = \eta_p I_{hm} \left[1 - \beta_{ref} \left(T_{a,hm} + \omega \frac{0.32}{8.91 + 2.0V_{v,hm}} I_{hm} - 25 \right) \right]$$

where:

P_e : Monthly hourly average electric power at the PV module output without PCM (W/m^2)

η_p : Efficiency of the PV module

I_{hm} : Monthly hourly average global tilted irradiance (W/m^2)

$T_{a,hm}$: Monthly hourly average ambient temperature (°C)

ω : Coefficient of mounting: It has been taken: 2.4 for mounting on cover.

$V_{v,hm}$: Monthly hourly average wind speed (m/s)

β_{ref} : Correction coefficient of the module efficiency due to temperature (°C⁻¹).

$E_{e,dm}$ has been obtained from the expression:

$$E_{e,dm} = \sum_{h=1}^{h=24} E_{e,hm}$$

To calculate the average annual power generated by the photovoltaic module without PCM it has been used the equation

$$E_e = \sum_{m=1}^{m=12} E_{e,dm} \cdot n_m$$

n_m : Numbers of days of the month m

4.3 Monthly hourly average net electricity, monthly daily average net electricity and the yearly average net electricity at the PV module output with PCM incorporated ($E_{e,hm}^{PCM}$, $E_{e,dm}^{PCM}$ y E_e^{PCM}).

$E_{e,hm}^{PCM}$ is measured in Wh/m^2 and is given from the expression:

$$E_{e,hm}^{PCM} = \int P_{e,hm}^{PCM} dt$$

where $P_{e,hm}^{PCM}$ is the average electric power in each time 'h' on the month 'm' generated by the PV module with PCM incorporated given by the expression:

$$P_{e,hm}^{PCM} = \eta_p I_{hm} \left[1 - \beta_{ref} (T_k - 25) \right] = \eta_p I_{hm}$$

where:

$P_{e,hm}^{PCM}$: Monthly hourly average electric power at the PV module output with PCM (W/m^2)

η_p : Efficiency of the PV module in standard conditions.

I_{hm} : Monthly hourly average global tilted irradiance (W/m^2)

T_k : Set point temperature (°C)

4.4 Increase of the monthly hourly average net electricity, monthly daily average net electricity and the yearly

average net electricity produced by the PV module due to the PCM ($\Delta E_{e,hm}$, $\Delta E_{e,dm}$ y ΔE_e).

The increase of the monthly hourly average net electricity at the PV module output due to the PCM is measured in Wh/m² and calculated through the expression:

$$\Delta E_{e,hm} = E_{e,hm}^{PCM} - E_{e,hm}$$

It may be noted that in some cases, negative values of ΔE_e are obtained. This happens because in cold climates, the ambient temperature is below the set point temperature during all or part of the day.

To calculate the monthly daily average net electricity at the PV module output due to the PCM it is used the equation:

$$\Delta E_{e,dm} = \sum_{h=1}^{h=24} \Delta E_{e,hm}$$

To calculate the yearly average net electricity at the PV module output due to the PCM it is used the equation:

$$\Delta E_e = \sum_{m=1}^{m=12} \Delta E_{e,dm} \cdot n_m$$

4.5 Decrease of the monthly hourly average net electricity, monthly daily average net electricity and monthly yearly average net electricity produced by the PV module due to the PCM ($\nabla E_{e,hm}$, $\nabla E_{e,dm}$ y ∇E_e).

The decrease of the monthly hourly average net electricity at the PV module output due to the PCM $\nabla E_{e,hm}$, is measured in Wh/m² and calculated through the expressions

$$\begin{aligned} \nabla E_{e,hm} &= E_{e,hm} - E_{e,hm}^{PCM}, & \text{if } T_{p,hm} < T_k \\ \nabla E_{e,hm} &= 0, & \text{if } T_{p,hm} \geq T_k \end{aligned}$$

To calculate the decrease of the monthly daily average net electricity at the PV module output due to the PCM $\nabla E_{e,dm}$, it is used the equation

$$\nabla E_{e,dm} = \sum_{h=1}^{h=24} \nabla E_{e,hm}$$

To calculate the decrease of the yearly average net electricity at the PV module output due to the PCM, ∇E_e , it is used the equation

$$\nabla E_e = \sum_{m=1}^{m=12} \nabla E_{e,dm} \cdot n_m$$

4.5 Maximum increase of the monthly hourly average net electricity, monthly average net electricity and the yearly average net electricity produced by the PV module due to the PCM ($\Delta E_{e,hm}^{\max}$, $\Delta E_{e,dm}^{\max}$ y ΔE_e^{\max})

The maximum increase of the monthly hourly average net electricity at the PV module output due

to the PCM $\Delta E_{e,hm}^{\max}$, is measured in Wh/m² and calculated through the expressions

$$\begin{aligned} \Delta E_{e,hm}^{\max} &= E_{e,hm}^{PCM} - E_{e,hm} & \text{if } T_{p,hm} \geq T_k \\ \Delta E_{e,hm}^{\max} &= 0 & \text{if } T_{p,hm} < T_k \end{aligned}$$

To calculate the maximum increase of the monthly daily average net electricity at the PV module output due to the PCM $\Delta E_{e,dm}^{\max}$ it is used the equation

$$\Delta E_{e,dm}^{\max} = \sum_{h=1}^{h=24} \Delta E_{e,hm}^{\max}$$

To calculate the maximum increase of the yearly average net electricity at the PV module output due to the PCM, ΔE_e incorporated, it is used the equation

$$\Delta E_e^{\max} = \sum_{m=1}^{m=12} \Delta E_{e,dm}^{\max} \cdot n_m$$

4.6 Monthly hourly average maximum thermal energy, monthly daily maximum thermal energy and the yearly maximum thermal energy available for the building ($E_{v,hm}$, $E_{v,m}$ y E_v) is calculated with the equation

$$E_{v,hm} = I_{hm} - E_{i,hm}$$

where:

I_{hm} : Monthly hourly average global tilted radiation (Wh/m²)

E_i : Monthly hourly average incident energy on the PV module necessary for not to exceed the set point temperature (Wh/m²). It is obtained through the equation

$$E_{i,hm} = \int P_{i,hm} dt$$

Being $P_{i,hm}$ the monthly hourly average global tilted irradiance that has to reach the surface of the PV module for not to exceed the set point temperature (Wh/m²). It is calculated through the next expression where it is derived in terms of the other variables, known them all, since the $T_{p,hm}$ has been set to T_k .

$$T_{p,hm} = \frac{P_{i,hm}/2 + (2.8 + 3.0V_{v,hm} + 0.93h_{rd,hm}) \cdot T_{a,hm}}{2.8 + 3.0V_{v,hm} + h_{rd,hm}}$$

4.7 Monthly daily average mass of PCM per unit area ($M_{pcm,dm}$) and PCM required mass per unit area (M_{pcm}).

The monthly daily average mass of PCM per unit area is calculated through the equation:

$$M_{pcm,dm} = \frac{E_{v,dm}}{\Delta H / 3600}$$

where:

ΔH : PCM phase change enthalpy (kJ/kg)

The PCM required mass per unit area is equivalent to the worst month in terms of evacuated heat at the photovoltaic module.

4.8 Monthly daily average PCM thickness ($e_{pcm, dm}$) and required PCM thickness (e_{pcm})

The following expressions are obtained:

$$e_{pcm, dm} = \frac{M_{pcm, dm}}{100 \cdot \rho}$$

$$e_{pcm} = \max(e_{pcm, dm})$$

where:

ρ : PCM density (kg/m³). Is multiplied by the constant value of "100" to convert the units into centimeters.

4.9 Increase of collection surface equivalent to the use of the PCM (ΔS_p)

Indicates the percentage of collection surface that would be necessary to expand to produce the same increase in net annual average power that occurs due to the PCM.

$$\Delta S_p = \frac{\Delta E_e - \nabla E_e}{E_e} \times 100$$

where:

ΔE_e : Increase net annual average power produced by PV modules due to the inclusion of PCM (Wh/m²)

E_e : Annual average electrical power at the output of the PV modules without PCM (Wh/m²)

4.10 Energetic and exergetic annual average efficiency of the process without PCM (η_e , η_{ex}) and with PCM (η_e^{pcm} , η_{ex}^{pcm}).

Annual average energetic efficiency with PCM, η_e^{pcm} , and without PCM, η_e , is measured in %, and is determined by the equations:

$$\eta_e = \frac{E_e}{\tau \alpha G} \times 100$$

$$\eta_e^{pcm} = \frac{E_e^{pcm} + E_v^{pcm}}{\tau \alpha G} \times 100$$

where:

τ : PV module thermal transmittance

α : PV module thermal absorptivity

G : Annual global tilted radiation over the tilted surface of the PV module (Wh/m²).

$$G = \sum_{m=1}^{m=12} G_{dm} \cdot n_m$$

where:

$$G_{dm} = \sum_{h=1}^{h=24} G_{hm}$$

where:

G_{hm} : Number of days of the month 'm' (Wh/m²)

G_{dm} : Monthly daily average global tilted irradiance over the tilted surface of the PV module (Wh/m²)

n_m : Number of days of the month 'm'

The percentage increase energy efficiency by introducing the PCM, $\Delta \eta_e$, comes from the equation:

$$\Delta \eta_e = \eta_e^{pcm} - \eta_e$$

The annual average exergetic efficiency with PCM, η_{ex}^{pcm} , and without PCM, η_{ex} , is determined by the equations

$$\eta_{ex} = \frac{Ex_e}{Ex_{solar}} \times 100$$

$$\eta_{ex}^{pcm} = \frac{Ex_e^{pcm} + Ex_v}{Ex_{solar}} \times 100$$

where:

Ex_e : Exergy associated to E_e , (Wh/m²)

Ex_e^{pcm} : Exergy associated to E_e^{pcm} (Wh/m²).

Ex_v : Exergy associated to a E_v (Wh/m²).

Is calculated through

$$Ex_v = \sum_{m=1}^{m=12} Ex_{v, dm} \cdot n_m$$

$$Ex_{v, dm} = \sum_{h=1}^{h=24} Ex_{v, hm}$$

where:

$Ex_{v, hm}$: Exergy associated with maximum monthly hourly average thermal energy available for building (Wh/m²), is calculated as follows:

$$Ex_{v, hm} = E_{v, hm} \cdot \left(1 - \frac{T_{a, hm}}{T_{p, hm}} \right)$$

$E_{v, hm}$: Exergy associated with maximum monthly daily average thermal energy available for building (Wh/m²)

n_m : Number of days of the month 'm'

Ex_{sun} : Exergy of the annual average global tilted radiation over the tilted surface of the PV module (Wh/m²). Is calculated through the equations:

$$Ex_{sun} = \sum_{m=1}^{m=12} Ex_{sun, dm} \cdot n_m$$

$$Ex_{sun, dm} = \sum_{h=1}^{h=24} Ex_{sun, hm}$$

where:

$Ex_{sun, hm}$: Exergy of the monthly hourly average global tilted radiation over the tilted surface of the PV module (Wh/m²) calculated from the equation

$$Ex_{sun, hm} = G_{hm} \cdot \left(1 + \frac{1}{3} \left(\frac{T_{a, hm}}{T_{sol}} \right)^4 - \frac{4}{3} \frac{T_{a, hm}}{T_{sol}} \right)$$

$Ex_{sun, dm}$: Exergy of the monthly daily average global tilted radiation over the tilted surface of the PV module (Wh/m²)

n_m : Number of days of the month 'm'

T_{sol} : Temperature of the sun as heat reservoir (5777K).

Similarly, it follows the exergetic performance percentage increase due to PCM $\Delta \eta_{ex}$ from the equation

$$\Delta \eta_{ex} = \eta_{ex}^{pcm} - \eta_{ex}$$

5 RESULTS

In table I shows a summary of the obtained values for the variables described above at the selected cities.

It is observed that the PCM requirements are significant, ranging between 31 and 193 kg/m², with thicknesses between 3.9 and 24.2 cm/m². It is also remarkable that with slight increases of the collection surface it can be generated the same increments of electricity produced without the use of PCM.

Table I: Standing waves ratio

City	E_e (Wh/m ²)	ΔE_e (Wh/m ²)	%	E_v (Wh/m ²)	M_{pcm} (kg/m ²)	e_{pcm} (cm/m ²)	ΔS_p (%)
SEVILLE	227795,47	24317,9	10,68	1664732,55	192,9	24,12	10,68
HELSINKI	141036,36	2823,51	2	93330,54	36,5	4,56	2
LONDON	127357,77	2607,98	2,05	67238,65	31,5	3,94	2,05
CAIRO	247971,82	35701,9	14,4	2230685,21	176,8	22,1	14,4
NAIROBI	223820,37	17503,51	7,82	1134303,39	89,1	11,14	7,82
SIDNEY	210643,24	16014,26	7,6	982000,73	87,9	10,98	7,6

Table 1.- Annual results obtained in different climates

E_e - Electricity generated by the PV System
 ΔE_e - Increase in generated electric energy due to PCM.
 E_v - Maximum thermal energy available for building
 M_{pcm} - PCM mass required
 e_{pcm} - PCM thickness required
 ΔS_p - Increased photovoltaic surface required to produce the same power as with PCM

In Figure 1 it is represented the evolution of the maximum available monthly daily average thermal energy for the building due to PCM for the 6 analyzed cities:

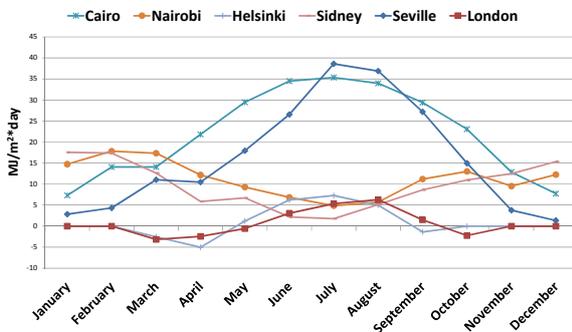


Figure 1. - Evolution of the maximum available monthly daily average thermal energy for the building due to PCM for the 6 analyzed cities.

It is observed how, in the summer months, the monthly daily average thermal energy available varies between 3 MJ/m²·day y 38 MJ/m²·day. In hot climates like Seville and Cairo, the available energy is high, although it is noted that the demand for heat in the summer at the temperature of 298 K is practically nil and therefore this energy utility is negligible this energy utility.

In colder climates like London or Helsinki thermal energy available in summer is very low. By contrast, in winter heat energy available varies between 0 MJ/m²·day and 18 MJ/m²·day being Nairobi and Sidney where there is the most availability.

Figure 2 depicts the evolution of the monthly average daily production Increase of electric energy by the PV system due to PCM for the 6 cities

analyzed:

Figure 2 depicts the evolution of the monthly daily average increase of electric energy production by the PV system due to PCM for the 6 analyzed cities:

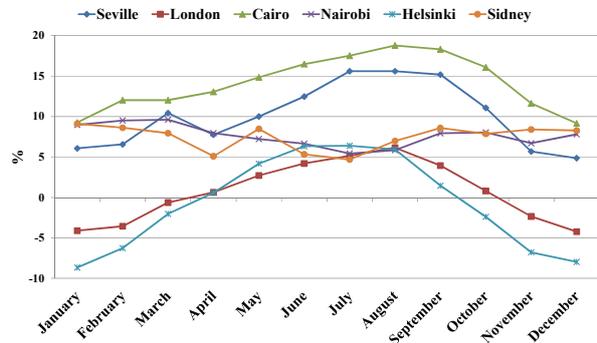


Figure 2. - Evolution of the monthly daily average increase of electric energy production by the Pv the 6 analyzed cities.

It is observed that the largest increases in monthly daily average power due to the inclusion of the PCM, of course, occur in warm climates such as Seville and Cairo, with monthly mean maximum increases up to 15.5% and 18% respectively. It can be seen that in cold climates as Helsinki and London negative increases are given almost throughout the year, which means that the inclusion of PCM in photovoltaic modules to limit the temperature to 298 K is harmful from the point of view of electricity production from PV modules.

In the Figure 3 it is represented the values of the energy performance of the module by its use in construction, with and without PCM, for the 6 analyzed cities:

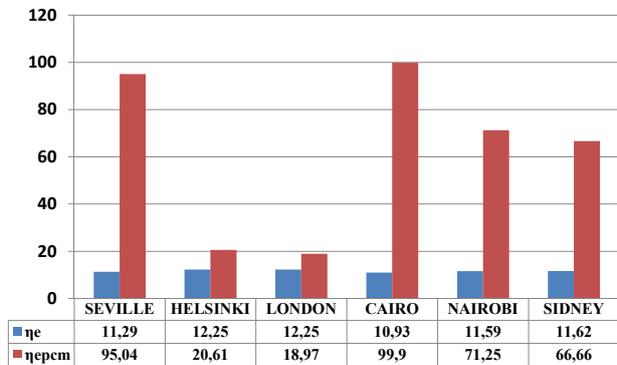


Figure 3. - Evolution of the monthly daily average increase of electric energy production by the PV for the 6 analyzed cities.

In an annual level and from a theoretical point of view, it is cities with warmer climates, such as Cairo, Seville and Nairobi, where there are the greatest increases in energy efficiency, with values up to 99.9%, 95.04% and 71.25% respectively.

In the Figure 4 it is represented the exergy efficiency values of the module through its use in construction, with and without PCM, for the 6 analyzed cities:

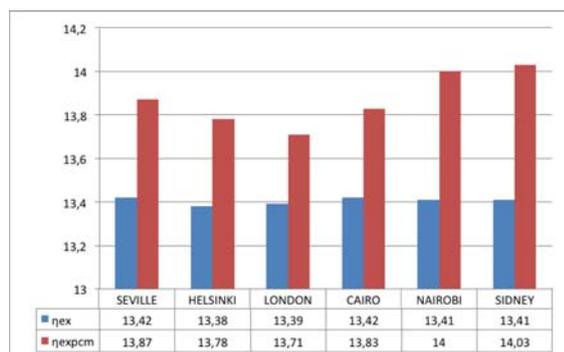


Figure 4. - Evolution of the monthly daily average increase of electric energy production by the PV for the 6 analyzed cities.

The results show that the maximum use of PCM depends heavily on the climate, therefore in hot climates as Seville, Cairo and Nairobi, the improvements in energy efficiency are very important (multiplied from six to nine times), while in cold climates as London and Helsinki, the improvements are not that significant. (Multiply by 1.5-2). The exergetic efficiency improvements range from about 5% for all climates, due to the low operating temperature of the PCM.

According to the results, if there is no proper utilization of all annual and thermal energy released by the PV module PCM use does not allow for significant energy benefits not only with the photovoltaic module but also with combined use with the building, due to the required mass.

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