

## Experimental Evaluation of Electrical Gain and Thermal Load in Dual-Axis Tracked PV Systems: Comparison with PCM-Based Passive Thermal Management

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**Abstract-** Dual-axis solar tracking raises the irradiance collected by a photovoltaic (PV) module, but the additional solar input also raises its operating temperature. This study quantifies that electrical–thermal trade-off outdoors in Kırıkkale, Türkiye, on 12 W modules logged at 5 min intervals, and compares it with a passive phase change material (PCM) strategy. In Phase 1 an uncooled fixed module was compared with an uncooled dual-axis tracking module. Tracking increased the in-plane irradiation from 6.74 to 8.35 kWh m<sup>-2</sup> (+23.9%) and the delivered energy from 42.98 to 61.14 Wh (+42.3%; mean power 3.54 versus 5.03 W). The tracking module ran on average 6.2 °C hotter (13.5 °C hotter in the morning), although peak rear-surface temperatures were similar (62.2 versus 60.5 °C). After a cloud passage the module temperature needed about 25 min to recover, peaking 20 min after the irradiance maximum. A matched-condition check at equal irradiance and temperature revealed that the tracking channel delivered about 23% more power irrespective of orientation, so the irradiation gain is the conservative measure of the tracking benefit. In Phase 2 the tracking module was compared with a fixed module fitted with paraffin PCM (melting range 48–66 °C) in 18 aluminium containers. The PCM module was not cooler: it peaked at 62.9 °C against 61.0 °C and was warmer in 62% of the records. Because orientation and thermal treatment changed together, Phase 2 is a system-level comparison rather than an isolated test of PCM cooling, and a same-orientation control test is required.

**Index Terms-** Dual-axis solar tracking, passive cooling, phase change material, photovoltaic, thermal load.

## INTRODUCTION

Photovoltaics (PV) accounted for about 70% of the electricity-generating capacity newly installed worldwide in 2024 [1], and the global installed solar PV capacity rose from 1,407 to 1,859 GW during that year [2]. The field performance of a PV module depends on two coupled quantities: the irradiance that reaches the module plane and the temperature at which the cells operate [3]. A module that receives more irradiance produces more electricity, but most of the absorbed solar energy is converted to heat, and for crystalline-silicon modules the resulting temperature rise is commonly associated with power losses of about 0.4–0.65% per °C above reference conditions [4–6]. The benefit of improved solar capture should therefore be assessed together with the thermal response of the module.

Solar tracking addresses the optical side of this problem by continuously adjusting module orientation. Review articles classify trackers by the number of axes, the drive type and the control strategy [7–9] and report higher energy yield than for fixed mounting [9–12]. For the contiguous USA, Drury et al. [13] estimated that two-axis tracking increases PV generation by 30–45% relative to south-facing fixed systems with a 25° tilt. The same mechanism, however, increases the thermal load. Tracking panels reach higher temperatures than

fixed panels because they receive more radiation [14]; in their European analysis, Huld et al. [15] found that temperature-related degradation is stronger for two-axis tracking systems, whereas shallow-angle reflection losses penalise fixed systems more. Sharaf Eldin et al. [16] went further and reported that the energy gain from tracking was about 39% in a cold climate (Berlin) but below 8% in a hot climate (Aswan) because of panel overheating. This electrical–thermal trade-off is the central subject of the present work.

Phase change materials (PCMs) offer a passive way to manage this heat. During melting, a PCM absorbs a substantial amount of thermal energy without the pumps or fans required by active cooling, and PCM layers attached to the rear of PV modules have been studied since the early work on building-integrated PV [17–19]. Reviews report that the peak module temperature can be lowered by up to about 20 °C and the electrical conversion efficiency raised by up to about 5%, while also concluding that PV/PCM systems remain largely at the research stage and are not yet economical [20–22]. The outcome depends strongly on the melting temperature, thermal conductivity, container geometry and inclination, which has motivated internal fins [18], segmented containers [23], nano-enhanced PCMs [24], shape-stabilised composites [25] and hybrid PCM/thermoelectric arrangements [26].

Tracking and PCM cooling have mostly been investigated separately. The closest precedent is the work of Adibpour et al., who attached a PCM layer to a two-axis tracked panel and compared it with an identical tracked panel without PCM [27], and later modelled the same configuration numerically [14]; their fixed-panel reference was measured on a separate day. Rustemli et al. [28] reviewed sun tracking and cooling side by side. What is seldom reported is a same-day, side-by-side measurement of both the electrical gain and the thermal penalty of dual-axis tracking on small modules at sub-hourly resolution, particularly under an intermittently cloudy sky. This study addresses that gap with two outdoor tests on 12 W modules:

1. identical fixed and dual-axis tracking modules without PCM were logged side by side, so that the additional irradiation, the delivered electrical energy and the accompanying rear-surface temperature could be compared directly;
2. the thermal load of tracking was quantified through the time-resolved temperature difference between the two modules and through the transient response after a cloud passage;
3. a matched-condition check was used to separate the optical gain of tracking from a module-independent offset between the two measurement channels;
4. the uncooled tracking module was compared with a fixed module fitted with paraffin PCM. Because orientation and thermal treatment differ simultaneously in this second test, its results are treated as a system-level comparison rather than as proof of a PCM cooling effect.

## RELATED WORK

### A. Tracking gain and its thermal side

The gain from tracking depends on location, solar geometry, diffuse fraction and tracker architecture [13, 15]. Table 1 collects representative values. Three experimental studies concern Türkiye. Şenpınar and Cebeci [29] reported for Elazığ that the daily output power of a two-axis tracking module was 13–15% higher than that of a fixed module. Eke and Senturk [30] measured 30.79% more electricity over one year from a double-axis tracking 7.9 kWp system at Muğla than from an identical system fixed at a 28° tilt, with monthly gains between 17% in January and 42% in June. Sungur [31] obtained 42.6% more energy from a PLC-controlled two-axis tracker at Konya (37.6° latitude). Longer campaigns give larger figures: a one-year test of five module technologies on fixed and dual-axis platforms found 28% more received solar energy and 29.6% more electrical energy with tracking [32], and a two-year comparison of two 1 kWp systems found gains of 35.6% and 44.7% in successive years with the actuator consumption included [33]. Prototype-scale studies reported 24.6% [34] and 37.2% [35]. For Türkiye, a PVsyst model of a 500 kW plant in Bitlis, benchmarked against the measured production of the existing fixed plant, estimated 25% more collector-plane energy with single-axis and 42% more with dual-axis tracking [36].

Sky conditions matter. Using 18 days of hourly data for five tracking and two fixed configurations, Koussa et al. [37] found the largest gains for two-axis tracking on completely clear days,

whereas under a completely overcast sky all configurations produced almost the same energy. Parasitic consumption matters as well, especially for small systems: Mousazadeh et al. [10] concluded that tracking is not recommended for small panels because of losses in the drive system and put the tracker consumption at 2–3% of the increased energy, Sharaf Eldin et al. [16] used 5–10% of the generated energy, and Lazaroiu et al. [38] included the tracker consumption in a comparison of two low-power systems, each feeding a maximum power point tracking converter and a battery: their single-axis tracker raised the daily energy by 12–20% depending on the weather, mainly in the morning and evening.

The thermal side of tracking has received less attention. Besides the system-level findings of Huld et al. [15] and Sharaf Eldin et al. [16], Eke and Senturk [30] recorded an average module temperature of 50 °C on the tracker against 44 °C on the fixed array on a clear August day, with the same maximum of 58.5 °C on both. Pretorius and Nielsen [39] derived heat-dissipation factors experimentally for fixed-tilt and single-axis tracked open-rack modules and found enhanced heat dissipation for the tracked modules in no- and low-wind conditions, and Almalki [40] used simulated data for fixed, single-axis and dual-axis configurations to show that plane-of-array irradiance dominates power output while module temperature governs the normalised performance.

### B. PCM cooling of PV modules

Huang et al. [18] showed experimentally that a PCM with internal fins can reduce the temperature rise of a PV/PCM system by more than 30 °C relative to a flat aluminium plate during phase change, and Hasan et al. [19] obtained with five PCMs a maximum temperature reduction of 18 °C for 30 min and of 10 °C for 5 h at 1000 W m<sup>-2</sup>. Outdoor studies have since reported a wide range of outcomes. Li et al. [41] measured a PV temperature difference of up to 23 °C and 5.18% more electricity for a PV/PCM module; Stropnik and Stritih [42] measured a maximum surface-temperature difference of 35.6 °C and simulated a 7.3% increase in annual electricity production; Maghrabie et al. [43] obtained 15.8% more power with a 3 cm layer of RT-42 at a 30° tilt; and Arifin et al. [44] lowered the operating temperature from 60.7 to 52.5 °C at 1100 W m<sup>-2</sup> with beeswax. More modest effects were found by Waqas et al. [45], whose PCM-filled aluminium tubes lowered the average module temperature by 2.4–2.8 °C and the peak temperature by 6–9 °C.

Three design factors explain much of this spread. The first is the melting temperature. In a global model, Smith et al. [46] found that the optimal melting temperature rises with ambient temperature; Ma et al. [6] obtained the best performance when the melting temperature was about 5 °C above ambient; and Waqas and Ji [47] recommended a melting point 10–12 °C above the average minimum ambient temperature of the hottest month. Mazzeo et al. [48] tested three PCMs with melting temperatures of 18, 29 and 48 °C on full-size modules: the energy output changed by –0.65%, +3.14% and +6.84%, respectively, and the authors noted that a PCM layer that stays in a single phase increases the overall thermal resistance and has an insulating effect. The second factor is quantity: once the PCM is fully melted, its rate of heat extraction falls and the

**Table 1.** Reported gains of dual-axis tracking over fixed mounting. Values are quoted from the cited sources; “energy” refers to electrical energy unless stated otherwise.

| Source                                    | Site                 | Method and basis                                                                       | Dual-axis gain                                                                               |
|-------------------------------------------|----------------------|----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| Drury et al. [13]                         | Contiguous USA       | Modelling, annual; fixed 25° tilt as reference                                         | 30–45%                                                                                       |
| Sharaf Eldin et al. [16]                  | Berlin; Aswan        | Experimentally validated model                                                         | ≈39% (cold); <8% (hot)                                                                       |
| Şenpınar and Cebeci [29]                  | Elazığ, Türkiye      | Experiment, daily output power                                                         | 13–15%                                                                                       |
| Eke and Senturk [30]                      | Muğla, Türkiye       | Experiment, one year, two identical 7.9 kWp systems; fixed 28° tilt as reference       | 30.79% (17% in January to 42% in June)                                                       |
| Sungur [31]                               | Konya, Türkiye       | Experiment                                                                             | 42.6%                                                                                        |
| Moldovan et al. [32]                      | Braşov, Romania      | Experiment, one year, five module types                                                | 29.6% (28% in received solar energy)                                                         |
| Frydrychowicz-Jastrzębska and Bugała [33] | Poznań, Poland       | Experiment, two years, 1 kWp systems, actuator consumption included                    | 35.6% and 44.7%                                                                              |
| Shang and Shen [34]                       | Shanghai, China      | Experiment, prototype; fixed 30° tilt as reference                                     | 24.6%                                                                                        |
| Hraich et al. [35]                        | —                    | Experiment, prototype, tracker consumption included                                    | 37.2%                                                                                        |
| Aktaş and Kocaman [36]                    | Bitlis, Türkiye      | PVsyst simulation, annual, 500 kW plant                                                | ≈42% (collector-plane energy)                                                                |
| Adibpour et al. [27]                      | Melbourne, Australia | Experiment, power during stable irradiance; tracked versus fixed panel                 | 15.7% (without PCM); 18.6% (with PCM)                                                        |
| <b>This study</b>                         | Kırıkkale, Türkiye   | Experiment, one partly cloudy day (12 June), 12 W modules; fixed 30° tilt as reference | 23.9% (in-plane irradiation); 42.3% (delivered energy, including a channel offset; see text) |

PV temperature rises rapidly [49], and a review estimated that about 2.6 kg of PCM per square metre of module is needed for each degree of peak-temperature reduction [22]. The third is geometry. Nižetić et al. [23] replaced one full container by several small ones and raised the performance improvement from about 2.5% to 10.7% while using 47% less PCM and 36% less aluminium, and Waqas et al. [45] observed that discrete PCM tubes enhanced rather than suppressed natural convection from the module rear.

### C. Inclination, tracking and PCM

Inclination affects PCM melting through natural convection. Khanna et al. [50] computed that the PV temperature of a PV/PCM system falls from 43.4 to 34.5 °C as the tilt increases from 0° to 90°, and Abdulmunem et al. [51] and Maghrabie et al. [43] found experimentally that the performance of PV/PCM modules improves with tilt. On a two-axis tracker the inclination changes continuously. Adibpour et al. [27] measured an average temperature reduction of 9.1 °C (maximum 16.3 °C) and an average efficiency 4.6% higher for a tracked panel with PCM than for a tracked panel without. In the same study the tracked panel without PCM was on average 9.4 °C warmer than the fixed panel, and the PCM layer had an insulating, negative effect once it was fully melted. Their numerical study showed that conduction dominates in the solid PCM and natural convection in the molten PCM [14]. These results indicate that a PCM assembly designed for a fixed tilt cannot be assumed to behave identically on a tracker, and that outdoor comparisons must distinguish direct observations from mechanism-level claims.

## MATERIALS AND METHODS

### A. Experimental setup

The outdoor experiments were carried out at a test site in Kırıkkale, Türkiye (39.84° N, 33.51° E; altitude approximately 750 m). Identical PV modules measuring 355 × 255 × 20 mm were used in all configurations; their rated values are listed in Table 2.

The reference module was fixed facing due south at a tilt of 30° from the horizontal. Its electrical circuit comprised the PV module, the measurement instrumentation, a maximum power point tracking (MPPT) charge controller, a 3.7 V lithium-ion battery and a resistive lamp load (Fig. 1d). The tracking module used the same module type and circuit and followed the sun in azimuth and elevation (Fig. 1c). Four light-dependent resistors (LDRs) arranged in a cross pattern supplied the error signal to an Arduino-based controller, which drove two DC motors through a motor driver. Active trackers of this kind are the most widely used drive category, accounting for about 76% of the applications surveyed by Hafez et al. [7].

For the passive thermal-management configuration, fully refined paraffin with a reported melting range of 48–66 °C was placed in 18 separate aluminium containers attached to the rear of the fixed module (Fig. 1a,b). Each container was fabricated from 2 mm aluminium sheet with nominal dimensions of 45 × 45 × 5 mm. The segmented layout was chosen to distribute the PCM over the rear surface while keeping a direct conductive path through the aluminium; the layout is comparable to the small-container concept of Nižetić et al. [23]. The containers cover about 364 cm<sup>2</sup>, i.e. 40% of the 905 cm<sup>2</sup> rear surface, and their gross external volume of about 182 cm<sup>3</sup> is an upper bound on the PCM volume.

### B. Solar geometry

Solar geometry was used to support the tracking algorithm and to define the fixed-module orientation. The relations below

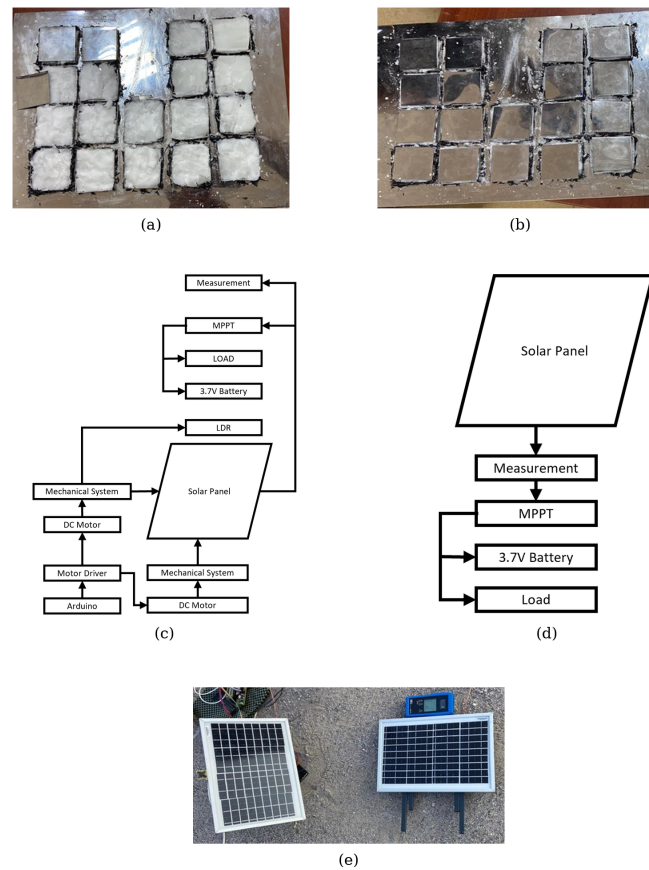


**Figure 1.** Experimental apparatus: (a) PCM filling process, (b) segmented PCM enclosure on the module rear, (c) block diagram of the dual-axis tracking system, (d) block diagram of the fixed system, and (e) outdoor deployment.

**Table 2.** Test module and PCM assembly.

| Parameter                 | Value                     |
|---------------------------|---------------------------|
| Rated maximum power (STC) | 12 W                      |
| Open-circuit voltage      | 24.6 V                    |
| Short-circuit current     | 0.64 A                    |
| Maximum-power voltage     | 20.84 V                   |
| Maximum-power current     | 0.61 A                    |
| Module dimensions         | 355 × 255 × 20 mm         |
| Module area               | 0.0905 m <sup>2</sup>     |
| Fixed-module orientation  | due south, 30° tilt       |
| PCM                       | Fully refined paraffin    |
| Reported melting range    | 48–66 °C                  |
| Containers                | 18, aluminium, 2 mm sheet |
| Nominal container size    | 45 × 45 × 5 mm            |
| Rear-surface coverage     | ≈40%                      |

follow Duffie et al. [52]; the angles are illustrated in Fig. 2. The declination  $\delta$ , the angular position of the sun with respect to the equatorial plane, was calculated with the approximation of Cooper [53]:

$$\delta = 23.45^\circ \sin \left[ \frac{360^\circ (284 + n)}{365} \right], \quad (1)$$

where  $n$  is the day of the year ( $1 \leq n \leq 365$ ). The hour angle  $h$ , the angular displacement of the sun east or west of the local meridian, is

$$h = 15^\circ (t_s - 12), \quad (2)$$

where  $t_s$  is the local solar time in hours. The zenith angle  $z$  between the sun's rays and the local vertical follows from

$$\cos z = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos h, \quad (3)$$

where  $\varphi$  is the latitude of the site, and the solar azimuth  $\alpha$ , measured in the horizontal plane from due south, from

$$\cos \alpha = \frac{\cos \delta \sin \varphi \cos h - \sin \delta \cos \varphi}{\sin z}, \quad (4)$$

with  $\alpha$  taking the sign of  $h$ . For the two test days ( $n = 163$  and  $n = 171$ ), Eq. (1) gives  $\delta = 23.2^\circ$  and  $23.4^\circ$ , so the zenith angle at solar noon was about  $16.5^\circ$  and the angle of incidence on the fixed module, tilted at  $30^\circ$ , was about  $13.5^\circ$ . All times in this paper are local clock times (UTC+3); with the longitude and equation-of-time corrections [52], solar noon at the site fell at about 12:46.

### C. Data acquisition and test procedure

Measurements were collected in two outdoor phases at 5 min intervals. Phase 1 (12 June 2025, 06:05–18:10, 146 records) compared the uncooled fixed and uncooled dual-axis tracking

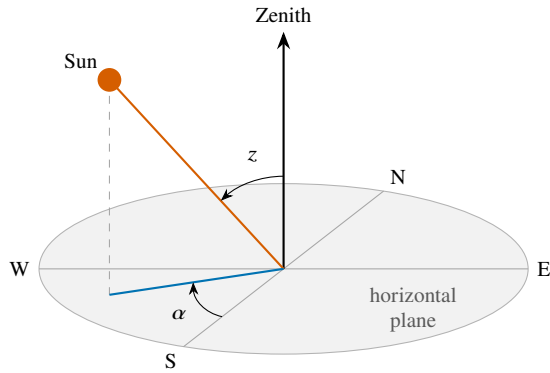


**Figure 2.** Solar position in the horizon coordinate system: zenith angle  $z$  and solar azimuth  $\alpha$  measured from due south. The hour angle  $h$  and the declination  $\delta$  enter through Eqs. (3) and (4).

modules; since neither carried PCM, this phase addresses the effect of tracking. Phase 2 (20 June 2025, 11:30–18:00, 79 records) compared the uncooled tracking module with the fixed module fitted with paraffin PCM. Phase 2 does not isolate PCM cooling, because orientation and thermal treatment differ between the two configurations.

For each module the output voltage  $V$ , the output current  $I$ , the in-plane solar irradiance  $G$  and the rear-surface temperature  $T_{PV}$  were recorded, together with the tilt angle of the tracking module. Ambient temperature and wind speed were not recorded.

#### D. Data reduction

Electrical power was calculated as  $P = VI$ . The delivered energy  $E$  and the in-plane irradiation  $H$  were obtained by trapezoidal integration of the 5 min records,

$$E = \sum_{i=1}^{N-1} \frac{1}{2} (P_i + P_{i+1}) \Delta t, \quad H = \sum_{i=1}^{N-1} \frac{1}{2} (G_i + G_{i+1}) \Delta t, \quad (5)$$

with  $\Delta t = 1/12$  h, and the relative gain of tracking as  $(X_{tr} - X_{fx})/X_{fx}$  for  $X = E$  or  $H$ , where the subscripts tr and fx denote the tracking and fixed modules. The thermal load of tracking was expressed as the paired difference  $\Delta T = T_{PV}^{tr} - T_{PV}^{fx}$  at each record. The relation between rear-surface temperature and irradiance was summarised by ordinary least-squares regression; under steady conditions the module temperature rises approximately linearly with in-plane irradiance, with a slope set by the wind-dependent heat-loss coefficient [39, 54].

To test whether the two measurement channels were equivalent, records were selected in which both in-plane irradiances exceeded  $900 \text{ W m}^{-2}$ , differed by no more than 3% and, in Phase 1, the two rear-surface temperatures differed by no more than  $3^\circ\text{C}$ . Such records occur within about an hour of solar noon, when the angle of incidence on the fixed module is between about  $13^\circ$  and  $19^\circ$  (cosine of at least 0.94) and the two planes are almost parallel. Under these matched conditions the two modules face nearly the same optical and thermal state, so the ratio of their powers measures a channel offset that is independent of orientation.

**Table 3.** Phase 1 indicators (12 June 2025, 06:05–18:10).

| Indicator                                    | Fixed | Tracking | Difference            |
|----------------------------------------------|-------|----------|-----------------------|
| In-plane irradiation ( $\text{kWh m}^{-2}$ ) | 6.74  | 8.35     | +23.9%                |
| Delivered energy (Wh)                        | 42.98 | 61.14    | +42.3%                |
| Mean power (W)                               | 3.54  | 5.03     | +42.3%                |
| Peak power (W)                               | 6.63  | 7.84     | +18.2%                |
| Peak irradiance ( $\text{W m}^{-2}$ )        | 1027  | 1060     | +3.2%                 |
| Mean $T_{PV}$ ( $^\circ\text{C}$ )           | 41.3  | 47.5     | +6.2 $^\circ\text{C}$ |
| Peak $T_{PV}$ ( $^\circ\text{C}$ )           | 60.5  | 62.2     | +1.7 $^\circ\text{C}$ |

Peak values are the respective daily maxima, which did not all occur at the same time; their differences are descriptive and are not same-time comparisons.

## RESULTS

### A. Irradiance capture and electrical output of tracking

Fig. 3 shows the Phase 1 records and Table 3 the derived indicators. The sky was clear until about 13:30 and intermittently cloudy afterwards. The tracking module received  $8.35 \text{ kWh m}^{-2}$  of in-plane irradiation against  $6.74 \text{ kWh m}^{-2}$  for the fixed module, a gain of 23.9%. It delivered 61.14 Wh against 42.98 Wh, a gain of 42.3%; the corresponding mean powers were 5.03 and 3.54 W. Peak power was 7.84 W for the tracking module (13:00–13:05) and 6.63 W for the fixed module (14:40).

The gain was concentrated in the early morning and late afternoon (Table 4). Between 06:05 and 09:30 the tracking module received 89% more irradiance and delivered 132.5% more power (5.02 versus 2.16 W); this is a relative increase in power, not in conversion efficiency. In the three hours around solar noon the irradiance on the two planes differed by less than 10%. This pattern is the expected consequence of the incidence-angle (cosine) loss of a fixed surface, which is largest when the sun is far from the surface normal [52]; Lazaroïu et al. [38] likewise found that the additional production of a small tracked system arises mainly in the morning and evening.

### B. Thermal load of tracking

The additional irradiance was accompanied by a higher operating temperature. Averaged over the day the tracking module was  $6.2^\circ\text{C}$  warmer than the fixed module (47.5 versus  $41.3^\circ\text{C}$ ), and it was the warmer of the two in 119 of the 146 records (Fig. 3d). The difference was largest in the morning,  $13.5^\circ\text{C}$  on average, when the fixed module was still weakly irradiated; it fell to  $5.2^\circ\text{C}$  in the late morning and vanished around solar noon, when the two planes received nearly the same irradiance (Table 4). The daily maxima differed little:  $62.2^\circ\text{C}$  for the tracking module and  $60.5^\circ\text{C}$  for the fixed module, both at 14:30. The thermal load of tracking is therefore better described by the mean and the time-resolved temperature difference than by the peak values.

Fig. 4 relates rear-surface temperature to in-plane irradiance. The regression lines are  $T_{PV} = 35.6 + 0.0181 G$  ( $R^2 = 0.41$ ) for the tracking module and  $T_{PV} = 27.1 + 0.0262 G$  ( $R^2 = 0.53$ ) for the fixed module, with  $T_{PV}$  in  $^\circ\text{C}$  and  $G$  in  $\text{W m}^{-2}$  (records with  $G > 0$ ). The moderate coefficients of determination reflect the unmeasured ambient temperature and the cloud transients of the afternoon.

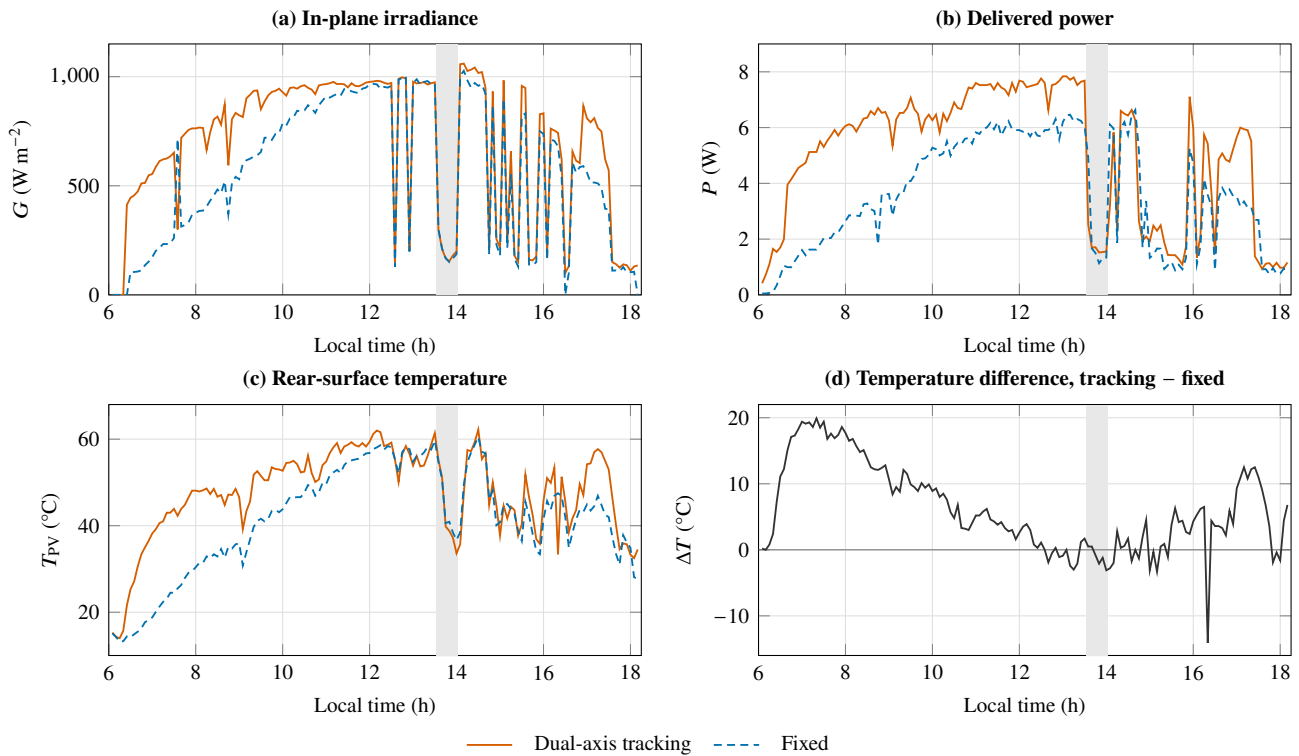


**Figure 3.** Phase 1 (12 June 2025), uncooled fixed and uncooled dual-axis tracking modules, 5 min records. The shaded band marks the cloud passage of 13:35–14:00 used for the transient analysis.

**Table 4.** Phase 1 means by time window (tr: tracking; fx: fixed).  $\Delta T$  is the mean of the paired differences.

| Window      | <i>N</i> | Irradiance ( $\text{W m}^{-2}$ ) |     |        | Power (W) |      |         | $T_{PV}$ ( $^{\circ}\text{C}$ ) |      |            |
|-------------|----------|----------------------------------|-----|--------|-----------|------|---------|---------------------------------|------|------------|
|             |          | tr                               | fx  | gain   | tr        | fx   | gain    | tr                              | fx   | $\Delta T$ |
| 06:05–09:30 | 42       | 627                              | 332 | +88.6% | 5.02      | 2.16 | +132.5% | 40.1                            | 26.6 | +13.5      |
| 09:35–12:30 | 36       | 954                              | 875 | +9.1%  | 7.07      | 5.55 | +27.2%  | 56.0                            | 50.8 | +5.2       |
| 12:35–15:30 | 36       | 675                              | 648 | +4.2%  | 4.61      | 4.17 | +10.6%  | 49.7                            | 50.0 | −0.4       |
| 15:35–18:10 | 32       | 479                              | 379 | +26.2% | 3.23      | 2.36 | +36.6%  | 45.2                            | 40.2 | +5.0       |
| Whole day   | 146      | 687                              | 554 | +24.0% | 5.03      | 3.54 | +42.3%  | 47.5                            | 41.3 | +6.2       |

Those transients show the thermal inertia of the module. Between 13:35 and 14:00 a cloud reduced the irradiance on the tracking module to  $150\text{--}300 \text{ W m}^{-2}$  and its rear-surface temperature fell from  $61.4$  to  $33.6^{\circ}\text{C}$ . When the cloud cleared, the irradiance returned to  $1057 \text{ W m}^{-2}$  at 14:05 and reached the daily maximum of  $1060 \text{ W m}^{-2}$  at 14:10, about 9% above the level of roughly  $970 \text{ W m}^{-2}$  recorded before the cloud. The temperature followed with a delay:  $35.7^{\circ}\text{C}$  at 14:05,  $47.5^{\circ}\text{C}$  at 14:10,  $57.5^{\circ}\text{C}$  at 14:15 and  $62.2^{\circ}\text{C}$  at 14:30. The temperature maximum thus lagged the irradiance maximum by 20 min, and about 90% of the recovery was completed within 10 min of the irradiance step, which corresponds to an effective first-order time constant of roughly 4–8 min at the 5 min resolution of the record.

### C. Matched-condition check of the two channels

The delivered-energy gain (42.3%) is considerably larger than the irradiation gain (23.9%). Around solar noon the two modules received nearly the same irradiance and were at nearly the same temperature, yet their powers differed (Fig. 3a,b).

Seventeen Phase 1 records satisfied the matched-condition criteria, sixteen of them between 11:50 and 13:30 and one at 14:40; the angle of incidence on the fixed module was below  $20^{\circ}$  in all but the last. In these records the mean irradiance was 973 and  $967 \text{ W m}^{-2}$ , the mean rear-surface temperature  $57.0$  and  $56.9^{\circ}\text{C}$ , and the mean voltage 19.74 and 19.64 V for the tracking and fixed modules, respectively, but the tracking channel delivered  $1.23 \pm 0.09$  times the power of the fixed channel (mean  $\pm$  standard deviation), with the same ratio in current. The check was repeated on Phase 2 with the irradiance criterion alone: in 17 records between 11:50 and 13:30 the ratio was  $1.24 \pm 0.06$ .

A difference of about 23% at equal irradiance, temperature and voltage cannot be attributed to orientation. It indicates an offset between the two channels that was present on both test days. The consequences for the interpretation are discussed below; here it is noted that the irradiation gain is unaffected by this offset.

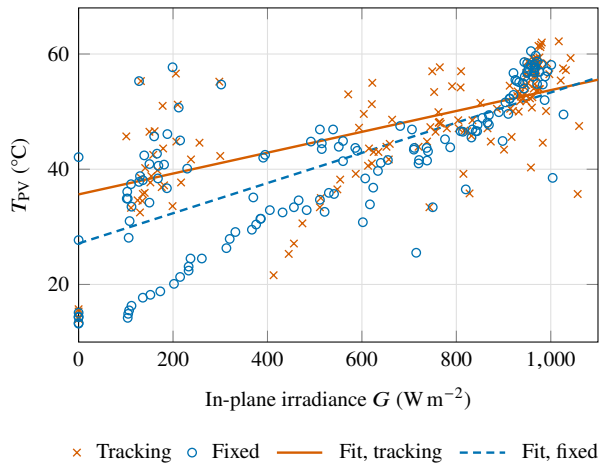


**Figure 4.** Rear-surface temperature against in-plane irradiance in Phase 1, with least-squares lines.

#### D. Tracking versus fixed PV/PCM

Fig. 5 and Table 5 summarise Phase 2. The tracking module received  $5.66 \text{ kWh m}^{-2}$  and delivered  $44.98 \text{ Wh}$  between 11:30 and 18:00; the fixed PV/PCM module received  $4.89 \text{ kWh m}^{-2}$  and delivered  $32.83 \text{ Wh}$ . Peak power was  $8.48 \text{ W}$  for the tracking module and  $6.90 \text{ W}$  for the fixed PV/PCM module.

The PCM-fitted module was not cooler than the uncooled tracking module. Its rear-surface temperature peaked at  $62.9^\circ\text{C}$  (13:25) under a peak irradiance of  $986 \text{ W m}^{-2}$ , whereas the tracking module peaked at  $61.0^\circ\text{C}$  (12:30) under  $1018 \text{ W m}^{-2}$ . Its mean temperature was  $52.6^\circ\text{C}$  against  $51.3^\circ\text{C}$ , and it was the warmer module in 49 of the 79 records. Between 11:30 and 14:30 it was on average  $5.1^\circ\text{C}$  warmer while receiving slightly less irradiance ( $953$  versus  $989 \text{ W m}^{-2}$ ); only after 16:00, when its irradiance had fallen to about two thirds of that on the tracker, was it cooler ( $44.0$  versus  $49.8^\circ\text{C}$ ).

The operating voltage of the fixed PV/PCM module stayed within  $18.5\text{--}20.3 \text{ V}$  ( $19.61 \pm 0.32 \text{ V}$ ) while its irradiance exceeded  $800 \text{ W m}^{-2}$ . The uncooled tracking module showed an equally narrow band in the same records ( $18.8\text{--}20.6 \text{ V}$ ,  $20.08 \pm 0.37 \text{ V}$ ). The narrow voltage band is therefore a property of both circuits and cannot be attributed to the PCM. The rear-surface temperature of the PV/PCM module changed less from one record to the next than that of the tracking module (mean absolute step  $1.5$  versus  $2.6^\circ\text{C}$ ), but the uncooled fixed module of Phase 1 was also steadier than the tracker ( $2.0$  versus  $2.9^\circ\text{C}$ ), so this difference cannot be assigned to the PCM either.

## DISCUSSION

#### A. Electrical gain of tracking

The irradiation gain of  $23.9\%$  on a partly cloudy June day lies within the range of Table 1. It is above the  $12\text{--}20\%$  that Lazaroiu et al. [38] measured on a comparable low-power single-axis system and below the  $42\%$  that Eke and Senturk [30] measured for June at Muğla, where the monthly gain was highest in summer. A value below that clear-month figure is expected for a day with a cloudy afternoon, because

**Table 5.** Phase 2 indicators (20 June 2025, 11:30–18:00).

| Indicator                                    | Fixed PV/PCM | Tracking |
|----------------------------------------------|--------------|----------|
| In-plane irradiation ( $\text{kWh m}^{-2}$ ) | 4.89         | 5.66     |
| Delivered energy (Wh)                        | 32.83        | 44.98    |
| Mean power (W)                               | 5.03         | 6.89     |
| Peak power (W)                               | 6.90         | 8.48     |
| Peak irradiance ( $\text{W m}^{-2}$ )        | 986          | 1018     |
| Mean $T_{\text{PV}}$ ( $^\circ\text{C}$ )    | 52.6         | 51.3     |
| Peak $T_{\text{PV}}$ ( $^\circ\text{C}$ )    | 62.9         | 61.0     |
| Mean voltage (V)                             | 19.41        | 20.05    |
| Peak voltage (V)                             | 20.3         | 20.9     |

tracking gains are largest under clear skies and vanish under overcast skies [37,38].

The delivered-energy gain of  $42.3\%$  coincides with the June value of Eke and Senturk [30], but it cannot be taken as the gain of tracking alone, because the matched-condition check showed that the tracking channel delivered about  $23\%$  more power than the fixed channel at the same irradiance, temperature and voltage. Three explanations are consistent with the data and cannot be separated with the present records: a difference between the two nominally identical modules, a difference between the operating points imposed by the two charge controller, battery and load circuits, and a difference in the calibration or placement of the irradiance sensor on the two planes. The second is supported by the operating voltage. Both modules worked at about  $19.7 \text{ V}$  in the matched records, close to the rated maximum-power voltage at  $25^\circ\text{C}$  ( $20.84 \text{ V}$ ) although the modules were at about  $57^\circ\text{C}$ . Since the voltage of crystalline-silicon cells falls as they heat [52], the modules were probably operating on the high-voltage side of their maximum power point, where the current is sensitive to small differences between modules. The recorded power is thus the power delivered at the operating point set by each circuit, and is not necessarily the maximum power of the module.

If the noon ratio is taken as a constant multiplicative offset, the delivered-energy gain attributable to tracking becomes  $1.423/1.23 - 1 \approx 16\%$ . This first-order figure is lower than the irradiation gain, which is the direction expected for a tracking module that runs hotter, but the offset need not be constant over the range of irradiance, and the difference between  $16\%$  and  $23.9\%$  should not be read as a measured thermal penalty. Reflection losses act in the opposite direction: they increase with incidence angle and therefore penalise the fixed module [15,55], an effect that an in-plane irradiance measurement does not capture. On balance, the irradiation gain of  $23.9\%$  is the most defensible estimate of the tracking benefit in this test, and the  $42.3\%$  figure is an upper bound that includes the channel offset.

None of these figures includes the consumption of the tracker. For a  $12 \text{ W}$  module this consumption can be a significant fraction of the gain [10,16,38], and it was not measured here; the reported values are gross gains.

#### B. Thermal load and transient response

The mean temperature rise of  $6.2^\circ\text{C}$  supports the view that tracking trades optical gain against thermal load [14–16]. It

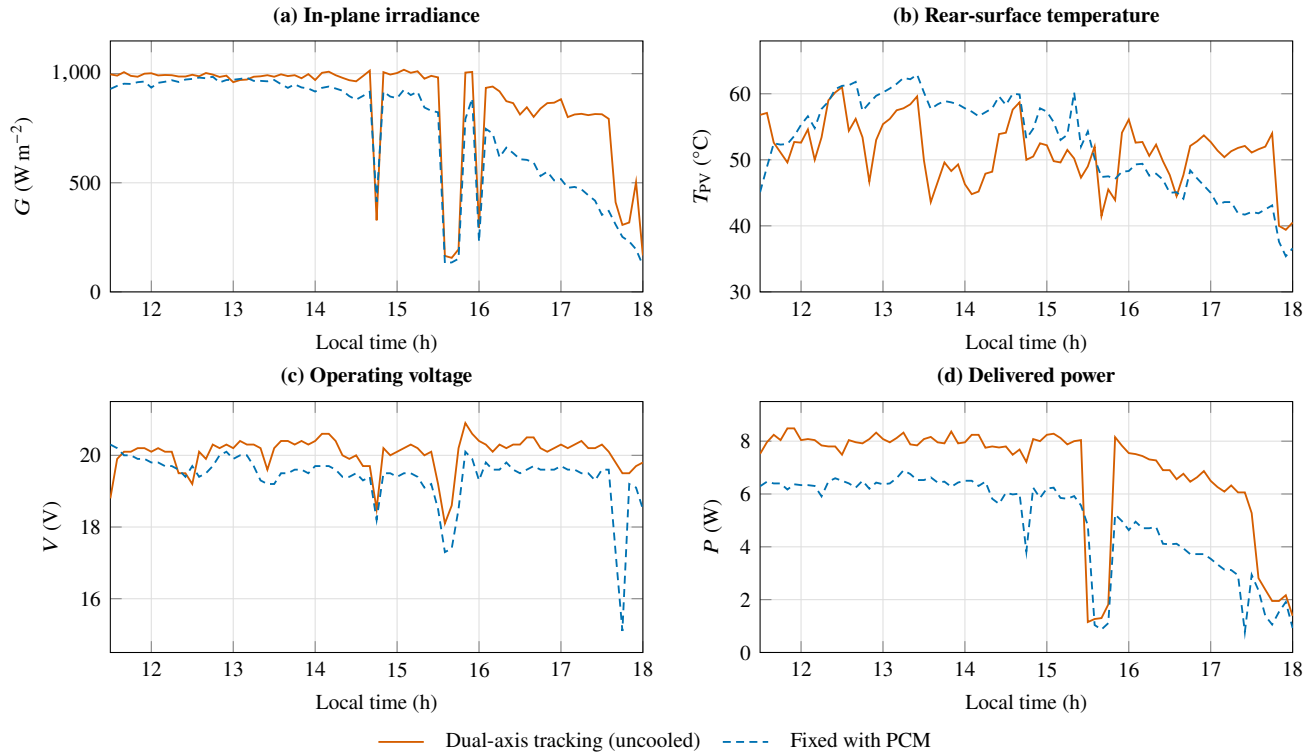


**Figure 5.** Phase 2 (20 June 2025), uncooled dual-axis tracking module and fixed module with paraffin PCM, 5 min records.

agrees with the 6 °C difference in average module temperature that Eke and Senturk [30] recorded on a clear August day at Muğla, where the maximum temperature was likewise the same for the tracked and fixed modules, and it is of the same order as the 9.4 °C that Adibpour et al. [27] measured between a tracked and a fixed panel without PCM. With the temperature coefficients quoted in the Introduction, a rise of this size would correspond to a loss of roughly 2.5–4% at maximum-power operation, which is small compared with the irradiation gain under the mild conditions of this test. Two features of the data qualify this estimate. First, most of the temperature difference arose in the morning, when both modules were still well below their midday temperatures; around solar noon, when thermal losses matter most, the two modules were equally hot. Second, the penalty grows with ambient temperature, and Sharaf Eldin et al. [16] showed that it can consume most of the tracking gain in hot climates. The present dataset does not allow the thermal loss to be measured independently; that would require temperature-coefficient normalisation, current–voltage curve tracing or a controlled efficiency analysis.

The response after the cloud passage agrees with published thermal models. Module temperature does not follow irradiance instantaneously because of the heat capacity of the laminate. Jones and Underwood [56] observed a time constant of about 7 min after a rapid drop in irradiance and noted that under rapidly moving cloud the peaks and troughs of module temperature lag those of irradiance, and Armstrong and Hurley [57] cite earlier estimates between 5 and 10.5 min. Kaplanis and Kaplani [58] obtained time constants of about 4.5–5.5 min for crystalline-silicon modules, falling to 2–2.5 min at wind speeds above 1–2 m s<sup>-1</sup>, and Prilliman et al. [59] adopted a 20 min averaging window on the basis of the temperature

stabilisation time after a large step in irradiance. The effective time constant of 4–8 min and the 20–25 min needed to reach the maximum in the present record are consistent with these values. The episode also illustrates the combination described by Järvelä and Valkealahti [60]: the module cools during the shaded period and the irradiance is then enhanced by nearby clouds [61], so that for some minutes a cool module is exposed to above-clear-sky irradiance. The irradiance maximum of the day (1060 W m<sup>-2</sup>) occurred in exactly this situation, which is why the daily peak values in Table 3 say little about the steady thermal load.

### C. Interpretation of the PCM configuration

Phase 2 gave no evidence that the PCM assembly lowered the operating temperature of the fixed module: the PV/PCM module was warmer than the uncooled tracking module for most of the high-irradiance period although it received less irradiance. Because the two modules had different orientations, and because ambient temperature and wind were not recorded, this cannot be read as proof that the PCM raised the temperature. The literature nevertheless suggests why the configuration tested here is unlikely to produce a strong cooling effect.

The first reason is the melting range. The optimal melting temperature increases with ambient temperature [46]; it has been placed about 5 °C above ambient [6] or 10–12 °C above the average minimum ambient temperature of the hottest month [47]. A paraffin that melts between 48 and 66 °C begins to store latent heat only when the module has already reached its typical midday temperature, and the measured rear-surface temperature never exceeded 62.9 °C, so the upper part of the melting range was not reached. Below the melting

range the PCM contributes only sensible heat capacity, and a PCM layer that remains in one phase adds thermal resistance at the module rear and has an insulating effect [27, 48].

The second reason is quantity. With the density of about  $0.88 \text{ g cm}^{-3}$  and the latent heat of about  $200 \text{ kJ kg}^{-1}$  reported for paraffin [41, 45], the gross container volume of  $182 \text{ cm}^3$  corresponds to at most  $0.16 \text{ kg}$  of PCM and about  $32 \text{ kJ}$  ( $9 \text{ Wh}$ ) of latent storage. The rule of thumb of  $2.6 \text{ kg m}^{-2}$  per degree of peak-temperature reduction [22] gives  $0.24 \text{ kg}$  per degree for a module of  $0.0905 \text{ m}^2$ . The installed quantity is therefore below what would be needed to lower the peak temperature by  $1^\circ\text{C}$ , and once a PCM is fully melted the module temperature rises rapidly again [49]. The actual PCM mass was not weighed, and the estimate should be replaced by a measured value in future work.

The third reason is geometry. Segmented containers can outperform a single full container [23], and discrete elements may preserve convective cooling of the uncovered rear surface [45]; but the containers used here cover about 40% of the rear surface, their internal depth is at most a few millimetres, and paraffin has a low thermal conductivity, which limits the heat that reaches the PCM [18, 24]. Inclination also matters, since natural convection in the molten PCM strengthens with tilt [43, 50, 51]. None of these mechanisms was measured in the present experiment, and they are offered as design considerations rather than as identified causes.

#### D. Practical implications

Tracking and PCM address different limitations. Tracking acts on the optical side by increasing the incident irradiance; it requires motors, control electronics and moving joints, consumes some of the energy it gains, and raises the average module temperature. A PCM assembly acts on the thermal side without consuming electrical power, but it adds mass and its benefit depends on a melting temperature matched to the climate and on a sufficient quantity of material. For a small module in the conditions tested, tracking produced a clear gain in collected irradiation, whereas the PCM assembly as built did not produce a measurable thermal benefit. Combining the two, as in the work of Adibpour et al. [27], is attractive precisely because tracking raises the thermal load, but the PCM must then be selected for the higher and continuously re-oriented heat input of a tracked module [14].

#### E. Limitations and recommended follow-up

The conclusions are subject to the following limitations.

1. Each phase covers a single day, and Phase 2 covers only the period after 11:30.
2. The two measurement channels differed by about 23% at matched conditions. Before further tests the two modules should be characterised side by side at the same orientation, preferably by current–voltage curve tracing.
3. Phase 2 changed orientation and thermal treatment together. A same-orientation control is needed: two fixed modules, one with and one without PCM, and the same pair on two trackers.
4. Ambient temperature, wind speed, PCM temperature and PCM mass were not measured, and the tracker consumption was not recorded.
5. The power is the delivered power at the operating point set by the charge controller and load. Maximum-power measurements are needed for efficiency and temperature-coefficient analysis.
6. During fast cloud transients the readings within one 5 min record may not have been strictly simultaneous, which adds scatter to the afternoon data of Phase 1.
7. Measurement uncertainties of the instruments were not propagated and should be reported in future work.

## CONCLUSION

This study examined the electrical gain and thermal load of dual-axis PV tracking on 12 W modules and compared the tracking module with a fixed module using paraffin-based passive thermal management.

In the direct fixed-versus-tracking test, tracking increased the in-plane irradiation by 23.9% ( $8.35$  versus  $6.74 \text{ kWh m}^{-2}$ ) and the delivered energy by 42.3% ( $61.14$  versus  $42.98 \text{ Wh}$ ). The gain was concentrated in the morning, when the tracking module received 89% more irradiance. A matched-condition check showed that the tracking channel delivered about 23% more power than the fixed channel at equal irradiance and temperature, so the irradiation gain is the conservative measure of the tracking benefit and the delivered-energy gain is an upper bound.

Tracking raised the mean rear-surface temperature by  $6.2^\circ\text{C}$  over the day and by  $13.5^\circ\text{C}$  in the morning, while the peak temperatures of the two modules were similar ( $62.2$  and  $60.5^\circ\text{C}$ ). After a cloud passage the module temperature reached its maximum 20 min after the irradiance maximum, in agreement with published thermal time constants of PV modules.

The fixed PV/PCM module was not cooler than the uncooled tracking module: it reached  $62.9^\circ\text{C}$  against  $61.0^\circ\text{C}$  and was the warmer module in 62% of the records. Because orientation and PCM use changed together, this test does not isolate a PCM effect; a melting range of  $48\text{--}66^\circ\text{C}$  and a PCM quantity of at most about  $0.16 \text{ kg}$  are, however, unfavourable for this module according to published design guidance.

A follow-up experiment should use matched PCM and non-PCM controls at the same orientation, characterise the modules side by side beforehand, record ambient temperature, wind speed, PCM temperature and tracker consumption, and use a PCM whose melting temperature is matched to the site.

## APPENDIX

### Abbreviations and symbols

| Symbol     | Definition                                                      |
|------------|-----------------------------------------------------------------|
| PV         | Photovoltaic                                                    |
| PCM        | Phase change material                                           |
| STC        | Standard test conditions                                        |
| MPPT       | Maximum power point tracking                                    |
| LDR        | Light-dependent resistor                                        |
| $G$        | In-plane solar irradiance ( $\text{W m}^{-2}$ )                 |
| $H$        | In-plane irradiation ( $\text{kWh m}^{-2}$ )                    |
| $T_{PV}$   | PV rear-surface temperature ( $^{\circ}\text{C}$ )              |
| $\Delta T$ | Temperature difference, tracking – fixed ( $^{\circ}\text{C}$ ) |
| $V, I$     | Output voltage (V) and current (A)                              |
| $P$        | Electrical power (W)                                            |
| $E$        | Delivered electrical energy (Wh)                                |
| $\delta$   | Solar declination ( $^{\circ}$ )                                |
| $h$        | Hour angle ( $^{\circ}$ )                                       |
| $z$        | Zenith angle ( $^{\circ}$ )                                     |
| $\alpha$   | Solar azimuth from due south ( $^{\circ}$ )                     |
| $\varphi$  | Latitude ( $^{\circ}$ )                                         |
| $n$        | Day of the year                                                 |
| $t_s$      | Local solar time (h)                                            |

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## Declaration of ethical standards

The materials and methods used in this study do not require ethics committee approval or legal-specific permission.

## Author contributions

T. Ş.: conceptualisation, methodology, experimentation, formal analysis, investigation, visualisation, writing – original draft. Ö. R.: supervision, validation, literature review, writing – review and editing.

## Conflict of interest

The authors declare no conflict of interest.

## REFERENCES

1. N. M. Haegel and S. R. Kurtz, "Global progress toward renewable electricity: Tracking the role of solar (Version 5)," *IEEE Journal of Photovoltaics*, vol. 15, no. 6, pp. 740–751, 2025, doi: 10.1109/JPHOTOV.2025.3604876.
2. International Renewable Energy Agency, *Renewable Capacity Statistics 2025*. Abu Dhabi: IRENA, 2025, ISBN 978-92-9260-652-7.
3. E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," *Solar Energy*, vol. 83, no. 5, pp. 614–624, 2009, doi: 10.1016/j.solener.2008.10.008.
4. A. Ahmad, H. Navarro, S. Ghosh, Y. Ding, and J. N. Roy, "Evaluation of new PCM/PV configurations for electrical energy efficiency improvement through thermal management of PV systems," *Energies*, vol. 14, no. 14, p. 4130, 2021, doi: 10.3390/en14144130.
5. M. A. Sheik, M. K. Aravindan, N. Beemkumar, P. K. Chaurasiya, R. Jilte, S. Shaik, and A. Afzal, "Investigation on the thermal management of solar photo voltaic cells cooled by phase change material," *Journal of Energy Storage*, vol. 52, p. 104914, 2022, doi: 10.1016/j.est.2022.104914.
6. T. Ma, J. Zhao, and Z. Li, "Mathematical modelling and sensitivity analysis of solar photovoltaic panel integrated with phase change material," *Applied Energy*, vol. 228, pp. 1147–1158, 2018, doi: 10.1016/j.apenergy.2018.06.145.
7. A. Z. Hafez, A. M. Yousef, and N. M. Harag, "Solar tracking systems: Technologies and trackers drive types – A review," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 754–782, 2018, doi: 10.1016/j.rser.2018.03.094.
8. S. Seme, B. Štumberger, M. Hadžiselimović, and K. Sredenšek, "Solar photovoltaic tracking systems for electricity generation: A review," *Energies*, vol. 13, no. 16, p. 4224, 2020, doi: 10.3390/en13164224.
9. R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, "A review and comparative analysis of solar tracking systems," *Energies*, vol. 18, no. 10, p. 2553, 2025, doi: 10.3390/en18102553.
10. H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, "A review of principle and sun-tracking methods for maximizing solar systems output," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1800–1818, 2009, doi: 10.1016/j.rser.2009.01.022.
11. A. Awasthi, A. K. Shukla, S. R. Murali Manohar, C. Dondariya, K. N. Shukla, D. Porwal, and G. Richhariya, "Review on sun tracking technology in solar PV system," *Energy Reports*, vol. 6, pp. 392–405, 2020, doi: 10.1016/j.egyr.2020.02.004.
12. K. Kumba, P. Upender, P. Buduma, M. Sarkar, S. P. Simon, and V. Gundu, "Solar tracking systems: Advancements, challenges, and future directions: A review," *Energy Reports*, vol. 12, pp. 3566–3583, 2024, doi: 10.1016/j.egyr.2024.09.038.
13. E. Drury, A. Lopez, P. Denholm, and R. Margolis, "Relative performance of tracking versus fixed tilt photovoltaic systems in the USA," *Progress in Photovoltaics: Research and Applications*, vol. 22, no. 12, pp. 1302–1315, 2014, doi: 10.1002/pip.2373.
14. S. Adibpour, A. Raisi, A. Sajadi, and G. Rosengarten, "A numerical examination on the use of phase change materials to improve the sun-tracking photovoltaic panels' performance," *Journal of Energy Storage*, vol. 70, p. 108075, 2023, doi: 10.1016/j.est.2023.108075.
15. T. Huld, M. Šúri, and E. D. Dunlop, "Comparison of potential solar electricity output from fixed-inclined and two-axis tracking photovoltaic modules in Europe," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 1, pp. 47–59, 2008, doi: 10.1002/pip.773.
16. S. A. Sharaf Eldin, M. S. Abd-Elhady, and H. A. Kandil, "Feasibility of solar tracking systems for PV panels in hot and cold regions," *Renewable Energy*, vol. 85, pp. 228–233, 2016, doi: 10.1016/j.renene.2015.06.051.
17. M. J. Huang, P. C. Eames, and B. Norton, "Thermal regulation of building-integrated photovoltaics using phase change materials," *International Journal of Heat and Mass Transfer*, vol. 47, no. 12–13, pp. 2715–2733, 2004, doi: 10.1016/j.ijheatmasstransfer.2003.11.015.

18. M. J. Huang, P. C. Eames, and B. Norton, "Phase change materials for limiting temperature rise in building integrated photovoltaics," *Solar Energy*, vol. 80, no. 9, pp. 1121–1130, 2006, doi: 10.1016/j.solener.2005.10.006.
19. A. Hasan, S. J. McCormack, M. J. Huang, and B. Norton, "Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics," *Solar Energy*, vol. 84, no. 9, pp. 1601–1612, 2010, doi: 10.1016/j.solener.2010.06.010.
20. T. Ma, H. Yang, Y. Zhang, L. Lu, and X. Wang, "Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 1273–1284, 2015, doi: 10.1016/j.rser.2014.12.003.
21. S. S. Chandel and T. Agarwal, "Review of cooling techniques using phase change materials for enhancing efficiency of photovoltaic power systems," *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 1342–1351, 2017, doi: 10.1016/j.rser.2017.02.001.
22. A. Waqas, J. Ji, L. Xu, M. Ali, Zeashan, and J. Alvi, "Thermal and electrical management of photovoltaic panels using phase change materials – A review," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 254–271, 2018, doi: 10.1016/j.rser.2018.04.091.
23. S. Nižetić, M. Jurčević, D. Čoko, and M. Arıcı, "A novel and effective passive cooling strategy for photovoltaic panel," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111164, 2021, doi: 10.1016/j.rser.2021.111164.
24. S. Sharma, L. Micheli, W. Chang, A. A. Tahir, K. S. Reddy, and T. K. Mallick, "Nano-enhanced phase change material for thermal management of BICPV," *Applied Energy*, vol. 208, pp. 719–733, 2017, doi: 10.1016/j.apenergy.2017.09.076.
25. A. Al Miaari, K. O. Mohaisen, A. Al-Ahmed, and H. M. Ali, "Experimental investigation on thermal management and performance enhancement of photovoltaic panel cooled by a sustainable shape stabilized phase change material," *Case Studies in Thermal Engineering*, vol. 67, p. 105763, 2025, doi: 10.1016/j.csite.2025.105763.
26. A. Khan, N. Shahzad, A. Waqas, M. Mahmood, M. Ali, and S. Umar, "Unlocking the potential of passive cooling: A comprehensive experimental study of PV/PCM/TEC hybrid system for enhanced photovoltaic performance," *Journal of Energy Storage*, vol. 80, p. 110277, 2024, doi: 10.1016/j.est.2023.110277.
27. S. Adibpour, A. Raisi, B. Ghasemi, A. R. Sajadi, and G. Rosen Garten, "Experimental investigation of the performance of a sun tracking photovoltaic panel with phase change material," *Renewable Energy*, vol. 165, pp. 321–333, 2021, doi: 10.1016/j.renene.2020.11.022.
28. S. Rustemli, F. Dincer, E. Unal, M. Karaaslan, and C. Sabah, "The analysis on sun tracking and cooling systems for photovoltaic panels," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 598–603, 2013, doi: 10.1016/j.rser.2013.02.014.
29. A. Şenpınar and M. Cebeci, "Evaluation of power output for fixed and two-axis tracking PV arrays," *Applied Energy*, vol. 92, pp. 677–685, 2012, doi: 10.1016/j.apenergy.2011.07.043.
30. R. Eke and A. Senturk, "Performance comparison of a double-axis sun tracking versus fixed PV system," *Solar Energy*, vol. 86, no. 9, pp. 2665–2672, 2012, doi: 10.1016/j.solener.2012.06.006.
31. C. Sungur, "Multi-axes sun-tracking system with PLC control for photovoltaic panels in Turkey," *Renewable Energy*, vol. 34, no. 4, pp. 1119–1125, 2009, doi: 10.1016/j.renene.2008.06.020.
32. M. Moldovan, B. G. Burduhos, and I. Visa, "Efficiency assessment of five types of photovoltaic modules installed on a fixed and on a dual-axis solar-tracked platform," *Energies*, vol. 16, no. 3, p. 1229, 2023, doi: 10.3390/en16031229.
33. G. Frydrychowicz-Jastrzębska and A. Bugała, "Solar tracking system with new hybrid control in energy production optimization from photovoltaic conversion for Polish climatic conditions," *Energies*, vol. 14, no. 10, p. 2938, 2021, doi: 10.3390/en14102938.
34. H. Shang and W. Shen, "Design and implementation of a dual-axis solar tracking system," *Energies*, vol. 16, no. 17, p. 6330, 2023, doi: 10.3390/en16176330.
35. A. Hraich, A. Haddi, A. El Fadar, and O. A. Begdouri, "Experimental evaluation of energy efficiency of four sun-tracking photovoltaic configurations," *Energies*, vol. 18, no. 22, p. 5943, 2025, doi: 10.3390/en18225943.
36. A. Aktaş and B. Kocaman, "Sabit ve güneş takipli fotovoltaiik sistemlerin karşılaştırmalı analizi [Performance analysis of constant and solar tracking photovoltaic systems]," *Mühendislik Bilimleri ve Araştırmaları Dergisi*, vol. 6, no. 2, pp. 208–221, 2024, in Turkish, doi: 10.46387/bjesr.1515936.
37. M. Koussa, A. Cheknane, S. Hadji, M. Haddadi, and S. Nouredine, "Measured and modelled improvement in solar energy yield from flat plate photovoltaic systems utilizing different tracking systems and under a range of environmental conditions," *Applied Energy*, vol. 88, no. 5, pp. 1756–1771, 2011, doi: 10.1016/j.apenergy.2010.12.002.
38. G. C. Lazaroiu, M. Longo, M. Roscia, and M. Pagano, "Comparative analysis of fixed and sun tracking low power PV systems considering energy consumption," *Energy Conversion and Management*, vol. 92, pp. 143–148, 2015, doi: 10.1016/j.enconman.2014.12.046.
39. J. Pretorius and S. Nielsen, "Understanding heat dissipation factors for fixed-tilt and single-axis tracked open-rack photovoltaic modules: Experimental insights," *Progress in Photovoltaics: Research and Applications*, vol. 33, no. 2, pp. 326–343, 2025, doi: 10.1002/pip.3852.
40. N. Almalki, "Decoupling irradiance gain and thermal efficiency loss in photovoltaic tracking systems using explainable machine learning," *Energies*, vol. 19, no. 12, p. 2766, 2026, doi: 10.3390/en19122766.
41. Z. Li, T. Ma, J. Zhao, A. Song, and Y. Cheng, "Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material," *Energy*, vol. 178, pp. 471–486, 2019, doi: 10.1016/j.energy.2019.04.166.
42. R. Stropnik and U. Stritih, "Increasing the efficiency of PV panel with the use of PCM," *Renewable Energy*, vol. 97, pp. 671–679, 2016, doi: 10.1016/j.renene.2016.06.011.
43. H. M. Maghrabie, A. S. A. Mohamed, A. M. Fahmy, and A. A. Abdel Samee, "Performance enhancement of PV panels using phase change material (PCM): An experimental implementation," *Case Studies in Thermal Engineering*, vol. 42, p. 102741, 2023, doi: 10.1016/j.csite.2023.102741.
44. Z. Arifin, S. D. Prasetyo, B. A. Tribhuwana, D. D. D. P. Tjahjana, R. A. Rachmanto, and B. Kristiawan, "Photovoltaic performance improvement with phase change material cooling treatment," *International Journal of Heat and Technology*, vol. 40, no. 4, pp. 953–960, 2022, doi: 10.18280/ijht.400412.
45. A. Waqas, J. Ji, A. Bahadar, L. Xu, Zeshan, and M. Modjinou, "Thermal management of conventional photovoltaic module

- using phase change materials – An experimental investigation,” *Energy Exploration & Exploitation*, vol. 37, no. 5, pp. 1516–1540, 2019, doi: 10.1177/0144598718795697.
46. C. J. Smith, P. M. Forster, and R. Crook, “Global analysis of photovoltaic energy output enhanced by phase change material cooling,” *Applied Energy*, vol. 126, pp. 21–28, 2014, doi: 10.1016/j.apenergy.2014.03.083.
  47. A. Waqas and J. Ji, “Effectiveness of phase change material for cooling of photovoltaic panel for hot climate,” *Journal of Solar Energy Engineering*, vol. 140, no. 4, p. 041006, 2018, doi: 10.1115/1.4039550.
  48. D. Mazzeo, E. Ogliaari, A. Lucchini, A. Dolara, I. M. Carraretto, G. Manzolini, L. P. M. Colombo, and S. Leva, “Integration of photovoltaic modules with phase change materials: Experimental testing, model validation and optimization,” *Energy*, vol. 319, p. 134959, 2025, doi: 10.1016/j.energy.2025.134959.
  49. S. Khanna, K. S. Reddy, and T. K. Mallick, “Optimization of solar photovoltaic system integrated with phase change material,” *Solar Energy*, vol. 163, pp. 591–599, 2018, doi: 10.1016/j.solener.2018.01.002.
  50. S. Khanna, K. S. Reddy, and T. K. Mallick, “Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions,” *Energy*, vol. 133, pp. 887–899, 2017, doi: 10.1016/j.energy.2017.05.150.
  51. A. R. Abdulmunem, P. M. Samin, H. Abdul Rahman, and H. A. Hussien, “Effects of different tilt angles on the thermo-electrical performance of a PV/PCM system,” *Journal of Engineering Science and Technology*, vol. 15, no. 3, pp. 1731–1746, 2020.
  52. J. A. Duffie, W. A. Beckman, and N. Blair, *Solar Engineering of Thermal Processes, Photovoltaics and Wind*, 5th ed. Hoboken, NJ: Wiley, 2020, doi: 10.1002/9781119540328.
  53. P. I. Cooper, “The absorption of radiation in solar stills,” *Solar Energy*, vol. 12, no. 3, pp. 333–346, 1969, doi: 10.1016/0038-092X(69)90047-4.
  54. D. Faiman, “Assessing the outdoor operating temperature of photovoltaic modules,” *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 4, pp. 307–315, 2008, doi: 10.1002/pip.813.
  55. N. Martín and J. M. Ruiz, “Annual angular reflection losses in PV modules,” *Progress in Photovoltaics: Research and Applications*, vol. 13, no. 1, pp. 75–84, 2005, doi: 10.1002/pip.585.
  56. A. D. Jones and C. P. Underwood, “A thermal model for photovoltaic systems,” *Solar Energy*, vol. 70, no. 4, pp. 349–359, 2001, doi: 10.1016/S0038-092X(00)00149-3.
  57. S. Armstrong and W. G. Hurley, “A thermal model for photovoltaic panels under varying atmospheric conditions,” *Applied Thermal Engineering*, vol. 30, no. 11–12, pp. 1488–1495, 2010, doi: 10.1016/j.applthermaleng.2010.03.012.
  58. S. Kaplanis and E. Kaplani, “A new dynamic model to predict transient and steady state PV temperatures taking into account the environmental conditions,” *Energies*, vol. 12, no. 1, p. 2, 2019, doi: 10.3390/en12010002.
  59. M. Prilliman, J. S. Stein, D. Riley, and G. Tamizhmani, “Transient weighted moving-average model of photovoltaic module back-surface temperature,” *IEEE Journal of Photovoltaics*, vol. 10, no. 4, pp. 1053–1060, 2020, doi: 10.1109/JPHOTOV.2020.2992351.
  60. M. Järvelä and S. Valkealahti, “Operation of a PV power plant during overpower events caused by the cloud enhancement phenomenon,” *Energies*, vol. 13, no. 9, p. 2185, 2020, doi: 10.3390/en13092185.
  61. M. Järvelä, K. Lappalainen, and S. Valkealahti, “Characteristics of the cloud enhancement phenomenon and PV power plants,” *Solar Energy*, vol. 196, pp. 137–145, 2020, doi: 10.1016/j.solener.2019.11.090.

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