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Performance of flat-plate collectors with two-positional active tracking

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Abstract. Northern European regions such as Estonia at a 60° latitude receive yearly about 980 kWh·m^{-2} of solar radiation. These low insolation levels motivate inclusion into solar collectors a tracking mechanism to increase the yield. Classical active tracking is complicated and energy intensive, negating tracking benefits for PV modules and thermal flat-plate collectors. In this paper, the performance of PV modules with daily two-positional tracking is studied. The positions are symmetrical about the north-south axis, corresponding to the positions of the sun in the morning and in the afternoon. The tracking drive is simple and requires a minimum energy input during the brief daily triggering of the movement. Results indicate that the seasonal energy yield is increased by 10–20% over the yield from a fixed south-facing collector, tilted at an optimal angle. The results are based on long-term solar data, measured at the Tartu–Tõravere Meteorological Station in Estonia, and have been confirmed with experiments in summer 2004 at Tallinn University of Technology.

Key words: solar collectors, PV modules, daily triggering, energy gain.

1. INTRODUCTION

The solar resource in Northern Europe is relatively scarce [1], with Estonia receiving yearly appoximately 980 kWh·m^{-2} of solar radiation at a latitude of 60° N. In addition, the solar resource varies considerably throughout the year, being negligible during short winter days, with 80% of the yearly total resource concentrated between April and September. Within this summer period, useful intervals of incident angles, when the sun is high enough for collectors, further limit the resource. Furthermore, North-Atlantic cyclones frequently move across Scandinavia, the Baltic States and Northwestern Russia, blanketing the area with cloudy skies and variable solar radiation. Of the total irradiation, the share of beam (s) and diffuse (D) components are practically equal.

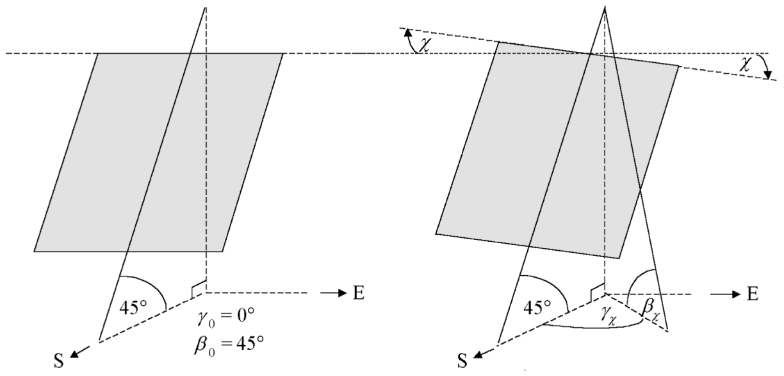
Methods to increase the solar energy yield for PV and thermal flat-plate collectors (FPC) have to be studied. Tracking technology is widely known [2,3], but classical two-axis active tracking [4] is not economical with its complicated drive system and high energy requirement. For FPC more suitable are single-axis tracking devices [5,6], but these are also complicated and energy intensive. At low latitudes, the horizontal S-N axis may be realized [7,8] and a solar-powered hydraulic drive used [9] although this technology is oriented mainly to beam radiation and is useless for nordic climate. A compromise is to track the FPC to discrete positions during the day. The drive mechanism for discrete tracking is simple, being widely used to control gates and doors and is less energy intensive while performing in the pulse regime. Triggering the collector movement both daily and seasonally is possible. In this paper, tracking to two discrete daily positions is studied.

2. DISCRETE TRACKING POSITIONS

Fixed flat-plate collectors perform best when facing south with the zero azimuth $\gamma_0 = 0$ in the northern hemisphere and oriented at the optimal tilt angle. The tilt angle of $\beta_0 = 45°$ is used for a latitude of 60° N as shown in Fig. 1a, to obtain the highest average irradiance I_T on the surface. This position is used as the basis for comparison. For daily triggering to discrete positions, the collector is rotated about its tilted axis twice per day to the deflection angles $\pm\chi$ as shown in Fig. 1b. The two positions may be characterized by the new tilt angle β_χ and two new collector azimuth angles $\pm\gamma_\chi$. The average irradiance I_χ on the collector surface in the new position is increased during the morning while facing east, as shown in Fig. 1b, as well as in the afternoon while facing west. Both orientations will suffer lower irradiance around solar noon due to an increased incident angle when the sun is from south.

For the two symmetrical orientations of the collector, the functional dependence of β_χ and γ_χ on χ is shown in Fig. 2. Initial tilt angles β_0 of the N–S axis of 15°, 45° and 60° are considered. A single new tilt angle is shown as the deflection angle, which in the morning and afternoon hours is symmetrical about the N–S axis. This symmetrical deflection angle is useful if average daily radiation conditions for the region are symmetrical about solar noon. However, if the average data shows an asymmetrical irradiation pattern about solar noon, the two positions can be adjusted to better match the expected pattern. The results of this study can be applied also to vertical and horizontal collectors. In the case of a vertical collector (e.g., facade PV collector), the tilt angle would remain 90° by tracking and the deflection angle would be equal to the collector azimuth angle

$$\beta_0 = \beta_\chi = 90°, \quad \pm\gamma_\chi = \pm\chi. \tag{1}$$



(a) (b)

Fig. 1. Flat-plate collectors facing south (a) and deflected about its initial N–S tilted axis to face southeast (b).

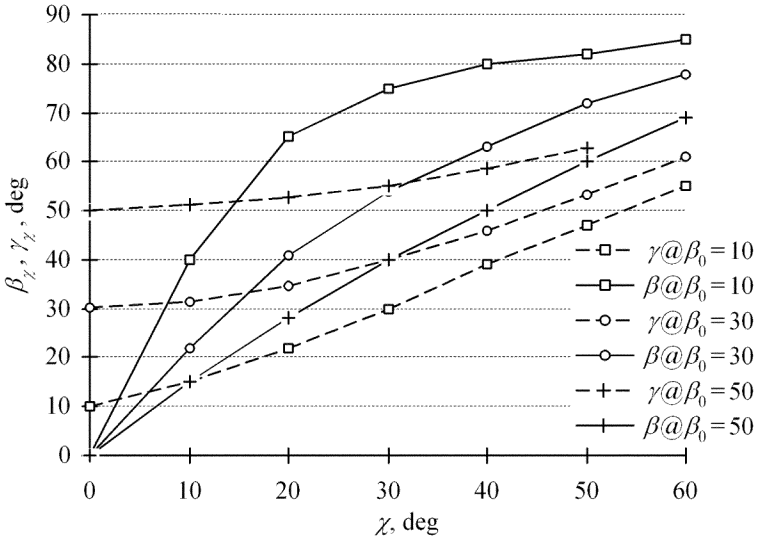


Fig. 2. Azimuth γ_χ (dashed lines) and tilt angle β_χ (solid lines) of the deflected collector as a function of the angle of deflection χ and initial tilt angle β_0.

In the case of a horizontally positioned FPC, the tilt angle would equal the deflection angle by tracking

$$\beta_0 = 0, \quad \beta_\chi = \chi, \quad \pm\gamma_\chi = \pm 90°. \tag{2}$$

The horizontally positioned FPC with N–S axis [7,8] is actual for equatorial regions; at high latitudes the attack angle (of the beam radiation) is high and collector or PV-module performance is poor. The horizontal E–W axis should be used if additionally the seasonal tracking is used. Daily triggered vertical collectors (e.g. facade PV modules) have significant benefits for high latitudes and were studied in [10].

3. THEORETICAL AND EXPERIMENTAL INVESTIGATIONS

The increased daily gain G of the flat plate collector in the tracking position relative to the basic south-facing orientation is given as

$$G = I_{T_\chi} \Big/ I_T . \tag{3}$$

It is the ratio of the theoretically calculated or experimentally observed total irradiation on the collector with two-positional tracking I_{T_χ} to the theoretical total irradiation I_T on a south-facing collector, based on average solar radiation data for the region.

The gain is studied as a function of the initial tilt angle β_0, angle of deflection χ and irradiation conditions, including horizontal beam and diffuse components. Theoretical calculations are based on the long-term average values of the hourly irradiance in the summer season, measured at the Tartu–Tõravere Meteorological Station (T–TMS, 58°15′ N and 26°28′ E, 70 m above sea level) during 1955–2000 [11]. In the simulation of the average irradiation, an isotropic model for the diffuse component has been used [12]. In this model the effect of ground reflection is ignored, although a revised model can include an albedo of approximately 13% for the surrounding area, consisting of pine forest, stretching to the horizon.

The experimental measurements were made on the roof of the Tallinn University of Technology (TTU) during the summer of 2004 from April to September, using three calibrated pyranometers (Savinov–Yanishevsky M-115M) as shown in Fig. 3. The central sensor has a tilt angle of 45° and was oriented

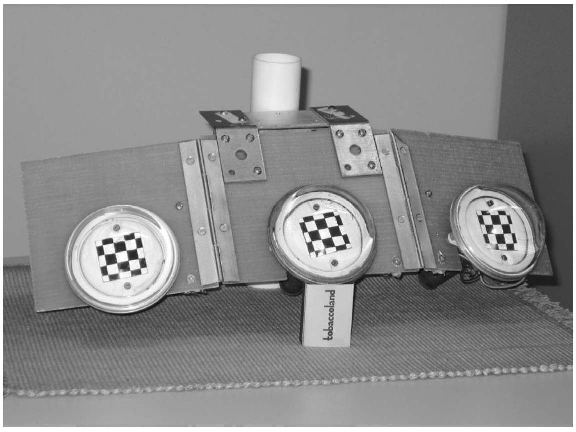


Fig. 3. Pyranometers used to measure solar radiation.

south, with side sensors deflected at ±30°. Data from the eastern sensor was used to determine total irradiation before solar noon while data from the western sensor was used after solar noon. The sampling interval was 10 min from 06:00 until 18:00 solar time [13].

4. RESULTS

Overall results indicate an average increase of 10–20% in the yield obtained with a FPC with two-positional active tracking over a FPC with a fixed optimal south-facing orientation. The average daily gain is shown to vary with the collector tilt and deflection angles, and is assessed over hourly, monthly and seasonal periods.

4.1. Seasonal average daily gain

The dependence of the seasonal gain on the initial tilt and deflection angles is shown in Fig. 4, based on calculations from historical data of T-TMS. Zero deflection corresponds to a south-facing surface at the initial tilt angle, which is the baseline case, and there is no increase in yield. For tilt angles $\beta_0 = 45°$ and $60°$, the gain reaches the maximum at an optimum deflection angle of $\chi_{\text{opt}} \approx 50°$, indicating that the selected deflection will optimize the performance of the FPC. For a smaller tilt angle $\beta_0 = 30°$, the optimum is not reached within the upper limit of the 60° deflection angle. For larger initial tilt angles ($\beta_0 = 90°$, vertical FPC) deflection is expected to be very effective by increasing the gain, and will be considered in a further study. However, it must be recognized that for any large deflection, shadowing will be an important factor, especially in large collector arrays. Of key importance is that for each deflection

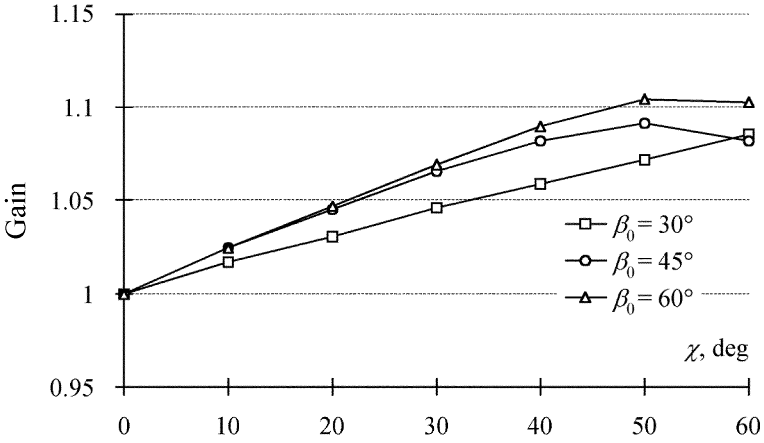


Fig. 4. Dependence of the theoretical seasonal gain on the initial tilt (β_0) and deflection (χ) angles.

angle, the FPC with tracking outperforms the fixed south-facing FPC over the duration of the summer season.

4.2. Monthly average daily gain

Evaluation of the daily average gain for various summer months is shown in Table 1, which also indicates an increase in yield for each month when two-positional tracking is utilized. For each initial tilt angle β_0, the daily energy yield increases for each set of symmetrical deflections chosen. The last two columns are experimentally measured values from 2004, taken at TTU, while the remaining data are computed from standard long term averages, taken at T-TMS. Figure 5 shows that the 2004 data deviate from the standard, due to relatively sunny spring and cloudy midsummer. Only data for September 2004 match the standard values of average daily yield.

Table 1. Theoretical and experimental daily energy gain, kWh·m^{-2}·day^{-1}

Month	β_0 = 0°	β_0 = 30°		β_0 = 45°			β_0 = 60°			Exp. β_0 = 45°	
		χ, deg									
		0	30	0	30	50	0	30	50	0	30
Apr	3.41	3.95	4.14	3.95	4.22	4.33	3.74	4.00	4.14	5.38	7.19
May	4.48	4.96	5.19	4.84	5.16	5.29	4.46	4.78	4.94	5.49	6.85
Jun	4.96	5.40	5.63	5.20	5.54	5.66	4.74	5.06	5.23	4.48	5.62
Jul	4.64	5.08	5.30	4.92	5.22	5.33	4.50	4.80	4.95	3.65	4.57
Aug	3.78	4.28	4.48	4.23	4.51	4.62	3.96	4.23	4.37	4.27	5.37
Sep	2.46	2.94	3.10	3.02	3.24	3.33	2.93	3.14	3.25	2.52	3.15

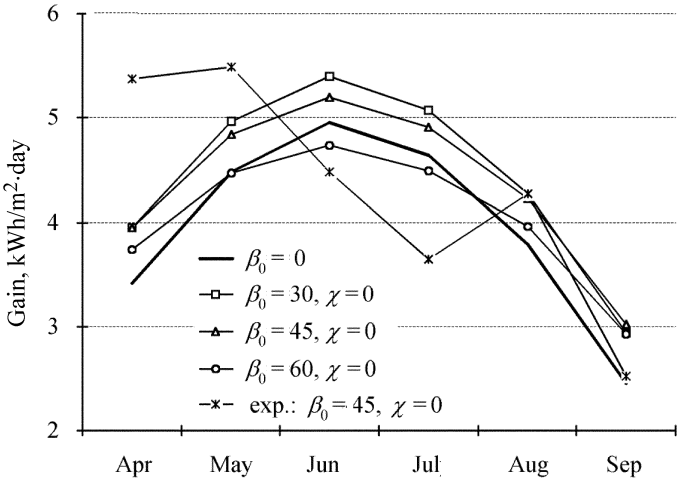


Fig. 5. Monthly average daily energy gain for various initial tilt angles β_0 and comparison to experimental results for β_0 = 45°.

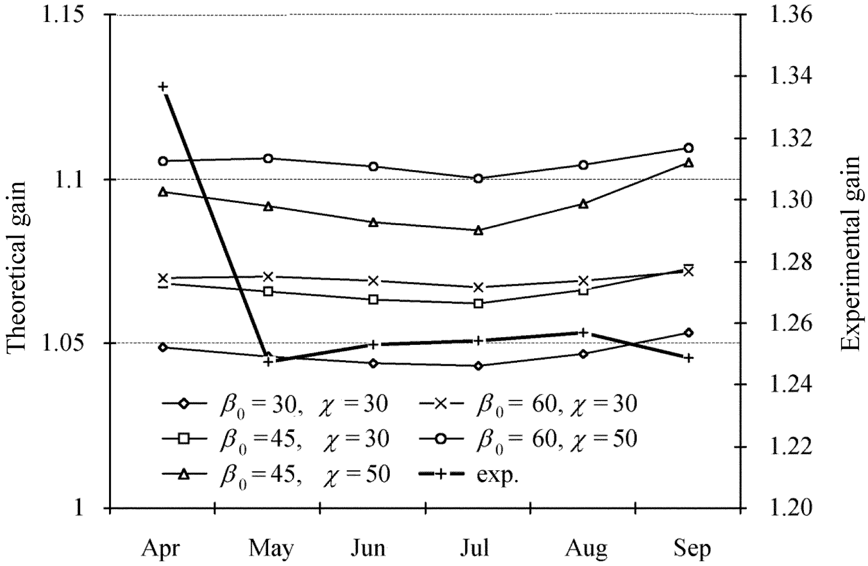


Fig. 6. Long-term monthly average daily energy gain for various initial tilt and deflection angles and experimental results for $\beta_0 = 45°$.

Figure 6 indicates on the basis of the long-term data that the gain does not vary through the summer season, with a slight minimum occurring during the midsummer months. With the optimal deflection angle $\chi_{\mathrm{opt}} \approx 50°$, the data supports high possible values of gain. Higher initial tilt angles are necessary for the $60°$ latitude, and they also yield higher gain. The gain measured in 2004 is also plotted in Fig. 6. It shows consistently higher values throughout the summer season. This could be due to the reflected radiation not being considered in the theoretical calculations or due to the isotropic model used.

4.3. Hourly average gain

The hourly effect on the gain is shown in Fig. 7. It is determined by the collector orientation during the day. The collector gain is shown to have its maximum in the morning and evening hours, when the FPC is deflected most directly towards the rising and setting sun, respectively. The small loss in yield during the noon hour is not significant in comparison to the increase in yield during the rest of the day. The experimental results support the trends shown by the long-term data.

To offset the reduction in gain during the solar noon period, three discrete positions of tracking may be employed. However, the increase in gain of less than 0.3% during the noon period does not merit the additional complication and operational cost. Therefore only two daily positions of the collector to track the sun are recommended as a simple and effective improvement over non-tracking collectors.

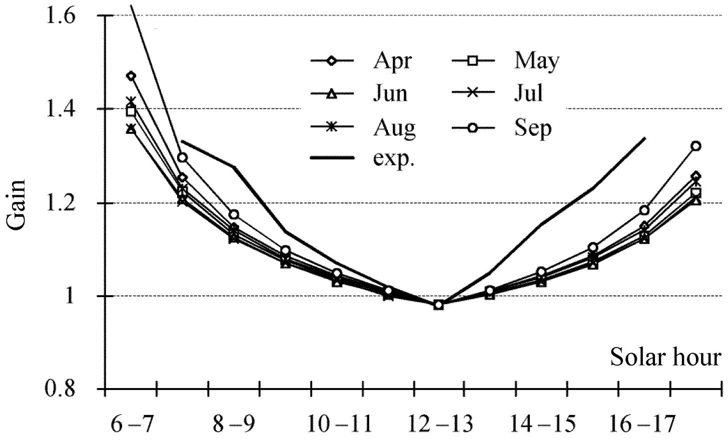


Fig. 7. Average hourly gain as a function of solar hour for β_0 = 45° and χ = 30°.

4.4. Effect of the irradiation quality on gain

The effects of collector orientation and period of collection have been assessed, although the gain can also be shown to be a function of the value of irradiation. This dependence is shown in Fig. 8, giving the gain as a function of global irradiance for the case of the initial tilt angle 45° and a deflection of 30°. Lower values of gain are based on data, recorded in May in the years 1999–2002 at T–TMS. The number of data points covers 4 years. The data at the Tallinn University of Technology was recorded in May 2004. The number of points is

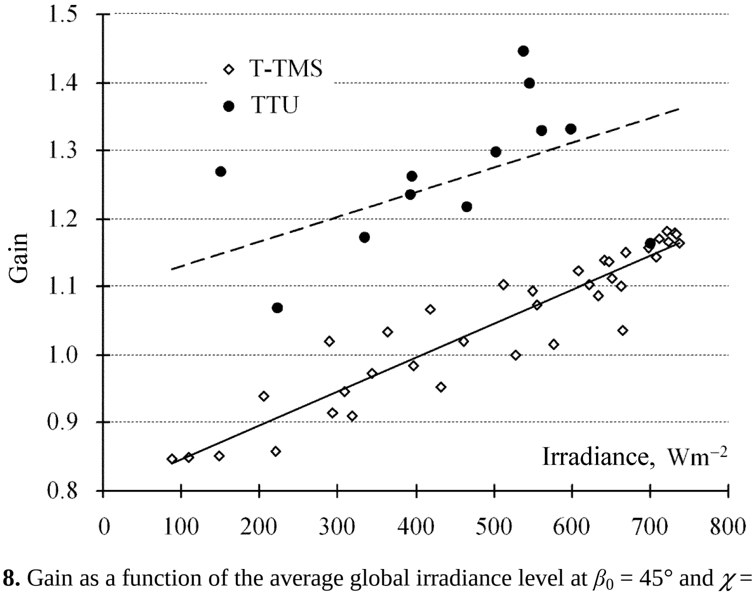


Fig. 8. Gain as a function of the average global irradiance level at β_0 = 45° and χ = 30°.

limited, but the trend is similar. For both data sets, the gain increases at higher global irradiation values. This trend is valid both for the beam and diffuse components. This result is promising and merits a further study in regions with higher insolation values as the increase in gain from two-positional tracking may become even more significant.

4.5. Non-isotropic diffuse radiation model

To estimate the effect of the directional dependence of the diffuse radiation we made a virtual experiment, assuming that at the constant value of the global irradiance on the horizontal plane a part of the diffuse radiation is transferred from the isotropic to the circumsolar form as follows:

$$s' + D = s^{\#} + D^{\#}. \tag{4}$$

It means the isotropic diffuse irradiance D was reduced to the value $D^{\#} = D(1-e)$; coefficient $e \in \{0, 0.25, 0.5, 0.75\}$ in Fig. 9 is a formal parameter. According to Eq. (4), the beam irradiance on the horizontal plane s' increased to the value $s^{\#} = s' + D(1-e)$.

Figure 9 shows that increased ratio s/D does increase the gain. Therefore azimuth sensitivity of the part of diffuse irradiance (and possibly of the reflected irradiance) is quite probable reason for the difference in simulated and experimentally measured results. Also we proved that in more sunny areas (with the higher beam irradiance level) flat-plate collectors with two-positional active tracking perform better.

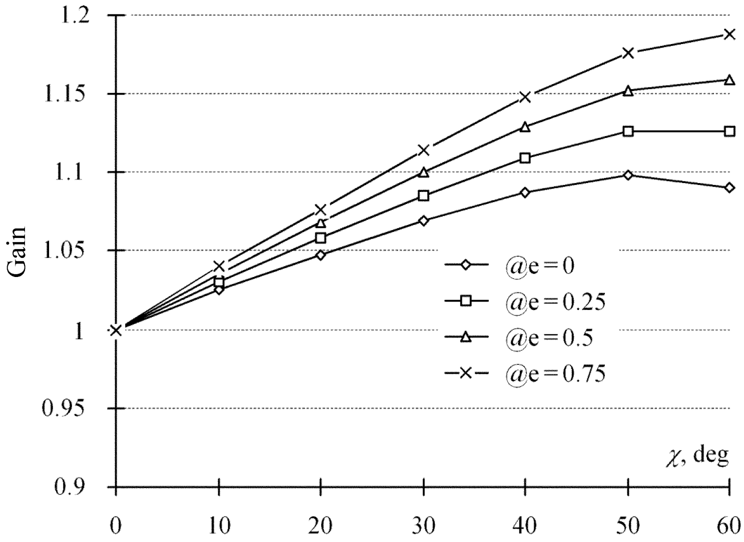


Fig. 9. Dependence of the gain on the deflection angle χ and coefficient e for the diffuse component of irradiation.

5. CONCLUSIONS

Two-positional tracking can be recommended as an economical method for increasing the solar energy yield. The study has to be continued as in the collector farm neighbouring modules evoke optical barriers and gain may not achieve values, assessed for a stand-alone collector.

1. Two-positional active tracking in the Baltic area increases the yield from a FPC by 10–20% over that from a fixed south-facing FPC.
2. For high latitudes of 60° N, an initial tilt angle of about 45° and deflection of about 50° provides the highest gain.
3. The gain is practically constant during the summer season.
4. The highest gain is obtained in the morning and evening hours, which matches the electrical load well for PV modules.
5. The gain increases with the increase of the beam–diffuse irradiance ratio.
6. Three-positional tracking is not expected to improve the daily gain enough to merit the additional complication and cost.

These conclusions are valid for a stand-alone solar collector. Performance of a two-positional solar collector in a collector farm has to be studied especially.

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Lameda heliokollektori funktsioneerimine kahepositsioonilises jälgivas režiimis

Teolan Tomson ja Gunnar Tamm

Põhja-Euroopa päikeseenergia madal ressurss (Eestis 980 $\mathrm{kWh \cdot m^{-2}}$ aastas) motiveerib päikest jälgivate süsteemide kasutamist. Klassikaline aktiivne pidev jälgimismehhanism on keerukas, kallis ja suure omatarbega ega õigusta ennast fotoelektriliste ja soojuslike lamedate heliokollektorite rakendamisel. Artiklis on uuritud lameda heliokollektori toimimist kahes fikseeritud asendis, mis saavutatakse kollektori pööramisega ümber kaldtelje ida suunas hommiku- ja lääne suunas õhtupoolikuti. Lihtsustatud kahepositsiooniline pööramismehhanism töötab energiasäästlikus impulssrežiimis ja on laialt rakendatud näiteks väravate ja uste teenindamisel. Teoreetiline analüüs baseerub Tartu–Tõravere Meteoroloogiajaama pikaajalistel keskmistel andmetel ja 2004. aasta suvel Tallinna Tehnikaülikoolis sooritatud mõõtmistel. Kahepositsiooniline heliokollektor lubab tõsta sesooni energiasaagist keskmiselt 10–20%.