Energy Gain between Automatic and Manual Solar Tracking Strategies in Large Scale Solar Photovoltaic System- 12 Cities Comparison

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***Abstract*—The electrical power generation from a solar photovoltaic (PV) system can be maximized by using automatic solar tracker via single-axis or dual-axis solar tracker system. However, such system is more expensive and complex than the fixed solar system. Manual tracker that changes the tilt angle of PV panel on periodical basis is another alternative that can be considered. This paper compares the energy output performance of a grid connected large scale solar (LSS) PV system with the following solar tracking strategies i) automatic single-axis ii) automatic dual-axis iii) manual monthly adjusted tilt angle and iv) manual seasonally adjusted tilt angle. 12 cities worldwide were chosen systematically for this study. The PV mathematical model was developed by using MATLAB software to simulate the energy output of 1 MW LSS PV system in terms of its annual average daily energy output (MWh/day). The results show that the energy output of a single-axis solar tracker PV system is close to the dual-axis tracker system for most cities, especially the one located at 40 degrees latitude and above. Thus, single-axis tracker system is preferred due to less expensive, lower cost operation & maintenance, less complex than the dual-axis tracker. Moreover, the results show that the energy output from manual tracker with monthly optimal tilt angle is greater than seasonally. With energy gain that can reach up to 8% depending on the location's latitude angle as well as the local climatic conditions of each city. Generally, manual trackers are much cheaper, easier, most reliable, and longer lifespan than automatic trackers. Thus, manual tracking with monthly optimum tilt angle can be considered as an alternative solution between the high energy gain, expensive automatic solar tracker system and the low energy gain (relatively), yet cheap fixed panel solar PV system.**

Keywords*—Dual-Axis, Single-Axis, Monthly Tracking, Seasonally Tracking, Fixed PV System, Large Scale Solar, and Optimum Tilt Angle.

I. INTRODUCTION

Automatic solar tracker system is able to track the sun rays throughout the day, hence maximizing the energy gain from the PV panel. Basically the tracker can be divided into single-axis and dual-axis system. In Single-Axis Tracker System, the PV modules are made rotating around one-axis. It comes in many types: Horizontal Single-Axis Solar Tracker (HSAT), Horizontal Tilted Single-Axis Solar Tracker (HTSAT), Vertical Single-Axis Solar Tracker (VSAT), and Vertical Tilted Single-Axis Solar Tracker (VTSAT). Compared to dual-axis, single-axis is more reliable, longer life span, lower cost operation& maintenance and less payback investment period. It's reported that the generated energy can be increased by around 24% - 35% compared to the fixed PV system. In Dual-Axis Tracking System, the PV modules are made rotating around two-axis simultaneously. They can rotate in both directions up and down to adjust the two angles during the day. The output generated energy can be increased in this tracker by around 26% - 40% compared to the fixed PV system. Also, this tracker is used in different applications, for example concentrated PV & heat conversion. However, this tracker is more expensive & complex than single-axis tracker. It has lower performance in overcast or cloudy weather.

The tracking techniques can be divided into passive and active tracker. Passive trackers use gas fluid pressed with low boiling point that rotates to one side or another to make the tracker movement in reaction to an imbalance. Active trackers use gear & motors to orient the tracker with controller, in respond to the solar direction.

This paper will compare the annual average daily energy gain of different solar tracking strategies i.e. automatic and manual solar tracker's for a 1 MW grid-connected large scale solar (LSS) PV plant. 12 cities around the world with different latitude angles between 0 degree and 55 degrees (with 5 degrees apart from one city to anther) were selected carefully for this study. The detailed PV mathematical models and its related PV equations were developed in Matlab software to simulate the energy gain from the LSS plant for each location for each PV tracking strategies.

This paper begins by explaining briefly the basic concept of the solar tracking methods and previous works. The next section will explain the methodology used for this study, which includes the 1 MW LSS plant model, the 12 cities/location, the PV model equations. The section after that will present the results of the LSS energy output from different tracking strategies. The results for the fixed PV panels (no tracking at all) is included for comparison. The last section concludes the findings of this paper.

II. SOLAR TRACKING SYSTEMS

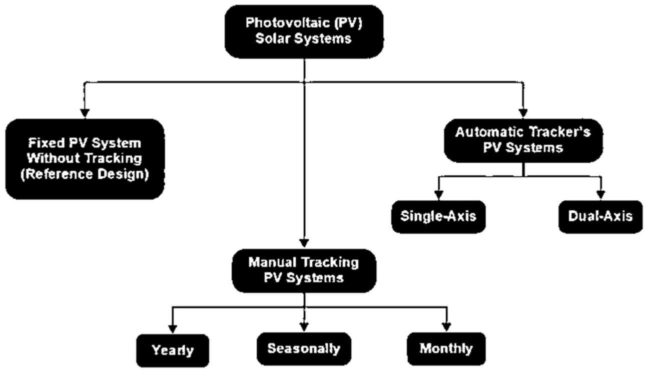


Fig. 1. Different solar PV tracking strategies

In general, solar energy output can be increased by using suitable tracking system. It helps to track the solar beams through the day so that the PV modules surface facing directly to it. As a result, the generated output energy can be increased by approximately up to 24% - 40% than the standard PV system. Solar trackers can be divided into two main strategies; i) manual ii) automatic. For manual tracking, the PV panels are adjusted manually on monthly or seasonally basis, based on the optimum tilt angle that maximizes the energy gain from the PV. For the automatic trackers, the PV panel is adjusted automatically based on the movement of the sun. There are two types of automatic trackers i) single-axis and ii) dual-axis. The classification of different tracking strategies is illustrated in Fig. 1.

Recent works of photovoltaic tracking systems are presented in reference [1-26]. Researchers in [1] reviews different PV tracking systems. They found that in general PV panel with tracking capability is more efficient compared to the fixed PV panel. Also, two-axis tracker is more efficient than one-axis tracker, because of the ability of the two-axis tracker to track more accurately the solar beams in two-axes.

Researcher in [5], classified different PV tracking systems based on their applications. Generally, there are two PV tracking systems according to their movement axes; single-axis tracker and dual-axis tracker. Based on the drive systems, there are five classifications of tracking technology; active, passive, semi-passive, manual, and chronological tracking. In addition, explained different of both components & tracking designs. It showed an increase interest in research about single-axis tracker more than dual-axis tracker. Simply, the active drive tracker is the most usage in PV applications after that it's for chronological tracker.

F. M. Hoffmann et. al. [6] developed a dual-axis solar tracker and evaluated its performance against the standard solar system. The experiment is conducted between June and November in south of Brazil. The results show that, the dual-axis tracker gave better efficiency and average energy gain per month, varying between 17% and 31%.

Researcher in [10] performs economic analysis to compare the tracking solar panels against the fixed panels. The analysis uses the rate of energy market in Texas, mean price, and cost operation for the dual-axis tracker system. The experiment uses a 190 watt solar module and the data for dual-axis solar tracker system is collected. The results show that, the output for the dual-axis tracker system improved significantly. The total mean improvement for the experiment was 82%. The financial evaluation was conducted based on the market rates of energy in Texas, the mean prices, and the operation expenses of the dual-axis tracker system.

The work in [19], compared the performance of dual-axis tracker with the fixed solar system that oriented to south direction with the optimum tilt angle. This study is included three different locations with different weathers throughout Europe; Athens-Greece, Stuttgart-Germany, and Aberdeen-United Kingdom. The yearly & monthly output energy for the dual-axis tracker is calculated for small scale electricity with rated power of 6.4 kW. The optimum angles yearly were determined for each selected location. Besides, the economic analysis & the diagrams have been presented based on the current data of economics and the local legislations, for evaluation any changes happen in the future of the feed in tariff (FiT) rates and the capital costs. The results show that, the performance depends on the local climatic conditions as well as the local legislation and the regional energy prices. Also, the two-axis tracker generates more outputs through the summer season at each location due to the longer of the sunshine hours.

III. Methodology

This section explains the LSS model used in this paper to compare the energy output performance of different solar tracking strategies (both automatic and manual) for 12 different locations worldwide. It also describes the method used in determining the energy output from the PV panels. The PV mathematical model is developed by using Matlab software to simulate the energy production. All related parameters were included in the model.

A. Large Scale Solar (LSS) Plant Model

For this study, the LSS plant model used for the simulation study is 1 MW. The total number of PV panels for this model is 2016 PV modules. It consists of 14 PV modules that are connected in series (string) and 144 PV strings that are connected in parallel (array). Each PV module has the following parameters: Maximum Power (P_{max}) = 500W, Maximum Power Voltage (V_{mp}) = 48.4V, Maximum Power Current (I_{mp}) = 10.33A, Open-circuit Voltage (V_{oc}) = 59.3V, Short-circuit Current (I_{sc}) = 10.54A, and Module Efficiency at (STC) = 19.51%. The total output energy from the LSS plant is: 2016 modules × 500 W/module = 1.008 MW.

B. LSS Plant Location

Twelve cities are chosen for the study. These cities are chosen carefully from different countries worldwide to cover a variety of local climatic conditions. Thus, this study covers the energy output performance under different weather conditions i.e. hot, warm, cool, tropical etc. Some of the selected cities are located on the Southern Hemisphere and some are located on the Northern Hemisphere. The 12 cities are strategically chosen from a latitude of 0° into 55° with an increment of 5°.

C. Mathematical Equations [27-33]

Solar declination angle (δ) is the angle between the earth orbit and the sun and it is mathematically represented by the following equation:

$$\delta = 23.45 \sin [(284 + d)/(365.25365)\ 360°] \qquad (1)$$

Where, d is the day order for one year beginning from January 1st (d = 1) until December 31st (d = 365). The daily direct solar radiation that falls on the titled surface, i.e. the direct solar energy that falls on the titled surface per day, $H_{D,T}$ is given by:

$$H_{D,T} = H_D R_b = 1.13\ R_b K_T H_B \qquad (2)$$

Where, H_D is the daily direct radiation that falls on the horizontal surface given by:

$$H_D = H_B - H_d = 1.13\ K_T\ H_B \quad (3)$$

Where H_B is the global solar radiation that measured on the horizontal surface.

The monthly average daily extraterrestrial solar insolation ($kWh/m^2/day$), H_{ext}, is given by:

$$H_{ext} = (24/\pi)\ G_{SC}\ [\cos\delta \cos\Phi \sin w_s + w_s \sin\delta \sin\Phi] \quad (4)$$

H_{ext} is the energy on the horizontal surface at the same latitude angle. Note that, all solar radiation in the extraterrestrial space is only direct radiation and thus no diffused radiation exists.

The global solar radiation (direct plus diffused) on the tilted surface, the monthly average daily radiation on the tilted surface, H_T is given by:

$$H_T = H_B\ [1.13\ K_T\ R_b + 0.5\ (1 + \cos\beta)\ (1 - 1.13\ K_T) + 0.5\ \rho\ (1 - \cos\beta)] \quad (5)$$

Where,

$$K_T = H_B/H_{ext} \quad .....(6)$$

The K_T improves as the sky becomes increasingly clearer.

$$R_b = (\cos\delta \cos(\Phi-\beta) \sin w_s' + w_s' \sin(\Phi-\beta) \sin\delta) / (\cos\delta \cos\Phi \sin w_s + w_s \sin\Phi \sin\delta) \equiv H_T/H_B \quad (7)$$

Where, K_T is the clearness index of the sky and R_b is the ratio between the direct solar radiations on the tilted surface to the direct solar radiations on the horizontal surface (H_T/H_B).

Note that, in case of the normal incident of the solar radiations i.e. the solar radiations will fall on the horizontal surface, thus, the tilt angle of the PV module/s (β = zero degree), thus, both of the tilted and the horizontal angles of incidence are equal ($\theta_T = \theta_h$), and thus, both of the tilted and the horizontal solar radiations are equal ($H_T = H_B$), based on all of those; ($R_b = 1$).

$$G_{ext} = G_{SC}\ [\cos\delta \cos\Phi \cos w + \sin\delta \sin\Phi] \quad (8)$$

Where, G_{ext} is the solar irradiance on horizontal extraterrestrial surface with constant value = 1.35 kW/m^2. Meanwhile, the maximum solar irradiance on earth's surface when the solar beams are normal to the surface is 1 kW/m^2 at the sea level. That means, about 25% of the extraterrestrial radiation is lost by absorption in the atmosphere, where, $G_{sc} / G_{ext} = 1 / 1.35 = 0.75$, which means, about 75% only from solar beams can reach the ground as well as the surface of PV module/s. The instantaneous global solar radiations on the tilted surface, i.e. instantaneous solar power (kW/m^2), G_T is given by:

$$G_T = (\pi/24)\ H_T\ (\cos w - \cos w_s'')/(\sin w_s' - w_s' \cos w_s'') \quad (9)$$

Equation (9) is used for manual tracking strategies. While, for single-axis and dual-axis tracker's PV systems, the G_T is multiplied with the following equation;

$$G_{Tracker\ single-axis} = G_T \times K_T \left(\frac{\cos\delta}{\cos\theta_T}\right) + (1 - K_T) \times G_T \quad (10)$$

Where, $G_{Tracker\ single-axis}$ is tracking the sun light from east (sunrise) to west (sunset) in case of single-axis tracker.

$$G_{Tracker\ dual-axis} = G_T \times K_T \left(\frac{1}{\cos\theta_T}\right) + (1 - K_T) \times G_T \quad (11)$$

Where, $G_{Tracker\ dual-axis}$ is tracking the sun light from east (sunrise) to west (sunset) in case of dual-axis tracker.

Then, the array current, I_A (amp), the array power, P_A (watt), and the array energy, E_A ($kWh/m^2/day$) of the PV system, are given by the following equations:

$$I_A = I_{SC}\ G_T - I_O\ (e^{(V/VT)} - 1) \quad (12)$$

$$P_A = V_B \times I_A \quad (13)$$

$$E_A = E_A + (P_A \times \Delta t) \quad (14)$$

Where, I_{SC} is short-circuit current, I_0 is the diode's saturation current and V_B is PV module voltage.

For PV with tracking capability, the equations (12)-(14) are replaced with the following equations:

$$I_{A\ track} = I_{SC} \times G_{Track} - I_O\ (e^{(V/VT)} - 1) \quad (15)$$

$$P_{A\ track} = V_B \times I_{A\ track} \quad (16)$$

$$E_{A\ track} = E_A + (P_{A\ track} \times \Delta t) \quad (17)$$

Where, G_{Track} is depending on tracking type (either $G_{Tracker\ single-axis}$ or $G_{Trackerdual-axis}$, $I_{A\ track}$, $P_{A\ track}$ and $E_{A\ track}$ are the array current, power and energy of the PV with respect to the tracking type.

D. Solar PV Tracking Strategies

1) Manual tracker

In manual tracking strategy, the PV modules/arrays will be adjusted at a fixed tilt angle throughout the lifetime of the solar system. This fixed tilt angle will be determined optimally, to extract the maximum output energy from the solar system during its lifetime. For this study, for each city, the optimum tilt angle is determined based on; i) monthly and ii) seasonally i.e. the tilt angle that would give the maximum energy output for a particular i) month ii) season.

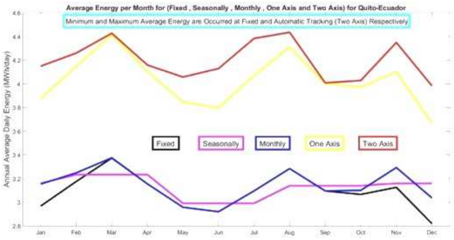
Also, the result of the fixed solar PV LSS is included in this study for comparison purpose.

2) Automatic tracker

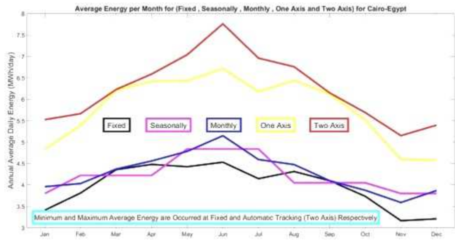
In this study, dual-axis automatic tracker PV system is based on the sunlight tracking from east (sunrise) to west (sunset) during the whole day (sunshine hours) for every day through the whole year. The optimum tilt angle of the PV arrays is set on day to day basis, based on the solar declination angle (that is function of the day). Thus, the optimum tilt angle will change once per day. While, for single-axis tracker, it is also based on the sunlight tracking from east (sunrise) to west (sunset) through the whole day (sunshine hours) and so on for every day during the whole year, but the optimum tilt angle of the PV arrays is fixed. In this study, the average optimum tilt angle of the PV array throughout the whole year will be determined for each city separately for 12 cities.

IV. RESULTS AND DISCUSSION

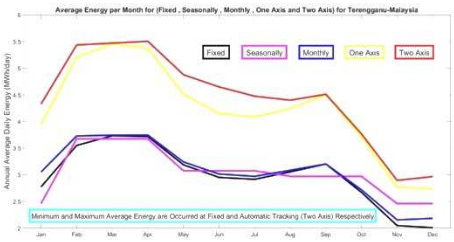
The annual average daily energy output for the 1 MW LSS for each month for different tracking strategies for 12 different cities is given in Fig. 2. It can be seen that the energy output from each tracking strategy varies for each month. To ease the comparisons, the annual average daily energy output (MWh/day) for different tracking strategies for 12 different cities is given in Table I.



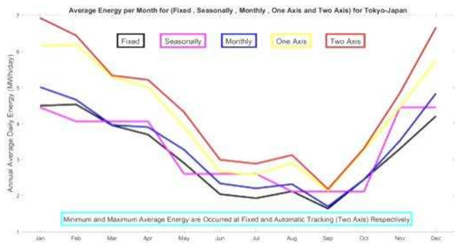
(i) Quito (latitude 0º)



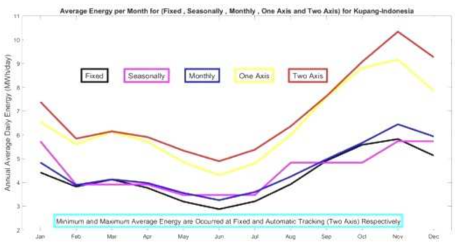
(vii) Cairo (latitude 30º)



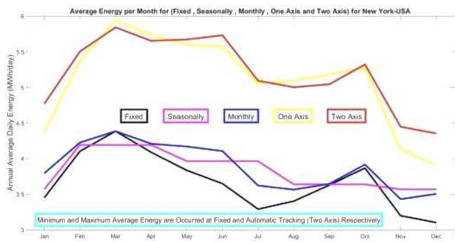
(ii) Terengganu (latitude 5º)



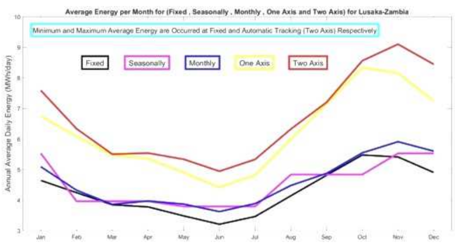
(viii) Tokyo (latitude 35º)



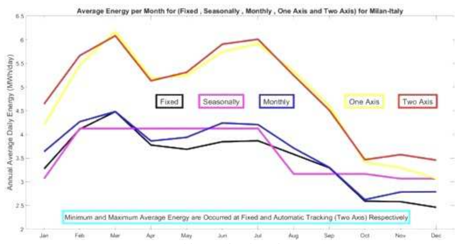
(iii) Kupang (latitude 10º)



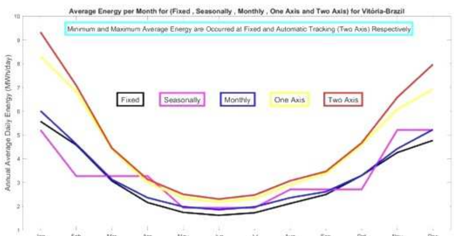
(ix) New York (latitude 40º)



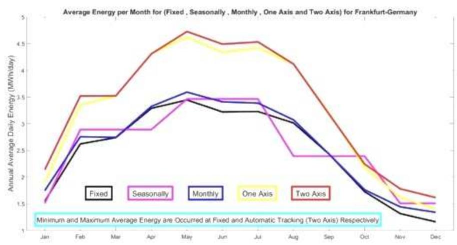
(iv) Lusaka (latitude 15º)



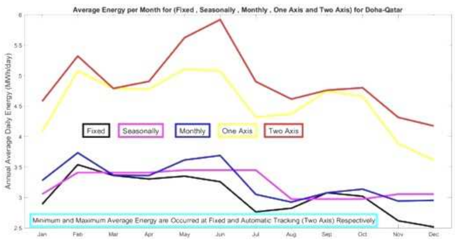
(x) Milan (latitude 45º)



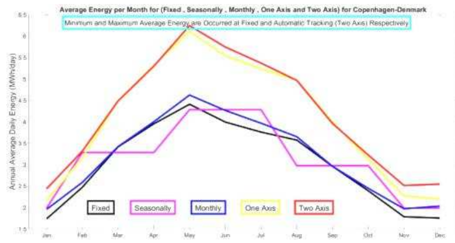
(v) Victoria (latitude 20º)



(xi) Frankfurt (latitude 50º)



(vi) Doha (latitude 25°)



(xii) Copenhagen (latitude 55°)

Fig. 2. Annual average daily energy output for each month for different tracking strategies for 12 different cities

TABLE I. AVERAGE DAILY ENERGY OUTPUT WITH ENERGY GAIN (AS COMPARED TO FIXED SYSTEM) FOR DIFFERENT TRACKING STRATEGIES FOR 12 CITIES

City	Latitude angle (°)	Average daily energy output (MWh/day)					Energy Gain (%)			
		Fixed	Manual Seasonally	Manual Monthly	Automatic One-Axis	Automatic Two-Axis	Gain (%) Seasonally	Gain (%) Monthly	Gain (%) One-Axis	Gain (%) Two-Axis
Quito	0	3.08	3.13	3.14	4.02	4.19	1.59	1.91	23.38	26.49
Terengganu	5	2.98	3.04	3.07	4.22	4.43	1.97	2.93	29.38	32.73
Kupang	10	4.23	4.48	4.54	6.45	6.96	5.58	6.82	34.41	39.22
Lusaka	15	4.28	4.52	4.58	6.22	6.68	5.30	6.55	31.18	35.92
Vitória	20	3.11	3.28	3.31	4.43	4.75	5.18	6.04	29.79	34.52
Doha	25	3.04	3.22	3.26	4.54	4.89	5.59	6.74	33.03	37.83
Cairo	30	3.97	4.22	4.28	5.78	6.24	5.92	7.24	31.31	36.37
Tokyo	35	3.10	3.30	3.34	4.19	4.52	6.06	7.18	26.01	31.41
New York	40	3.66	3.84	3.88	5.10	5.20	4.68	5.67	28.23	29.61
Milan	45	3.46	3.62	3.65	4.80	4.91	4.41	5.20	27.91	29.53
Frankfurt	50	2.47	2.56	2.58	3.25	3.34	3.51	4.26	24.00	26.04
Copenhagen	55	3.01	3.12	3.15	4.04	4.17	3.52	4.44	25.49	27.81

From the results, even with optimum tilt angle, the fixed PV panels produce the lowest energy output. However, it is a preferred since it is the cheapest, easiest, most reliable, and longest lifespan. To increase the energy output, manual PV tracking strategy can be used. In this paper, the manual seasonal tracker is based on the seasonal optimal tilt angle. The average value of this angle for each season will be determined and the PV panel will be tilted manually accordingly for each season. Thus, the maximum energy output for each season will be obtained.

It can be seen that from Table I, the energy gain from manual seasonal tracking can improve the energy gain more than 5% than the fixed PV panel. This advantage can be implemented by adjusting the tilt angle of PV array on seasonal basis, thus 4 times a year.

The energy output can be improved further if manual monthly tracking is implemented. In this paper, monthly tracking is done by adjusting the PV arrays' tilt angle on monthly basis, based on the average value of the optimum tilt angle for each month. By doing this, the maximum energy output for each month will be obtained. This is shown in Table I where the energy gain for PV panels can be improved up to 7% (for some cities) than the fixed one.

Using automatic trackers can improve the energy gain further. As can be seen from Fig. 2, the annual average daily energy output for each month for both dual and single axis trackers have significantly increased than the manual trackers. From Table I, it can be seen that the energy gain for dual-axis tracker can reach up to nearly 40% than the fixed PV system in some cities. However, for some cities (New York, Milan, Frankfurt, and Copenhagen) the output performance of the single-axis tracker is not far from the dual-axis tracker. Basically, the cities that are located between latitude 0 and 35 degrees have energy gain around 3-5% percent less than the dual-axis tracker. While, the cities that are located at latitude 40 degrees and above, the energy gain of the single-axis tracker is around 1-2% less than dual-axis tracker. Thus, for automatic trackers, the single-axis is a better choice since it is less expensive, less complex, and more reliable than the dual-axis tracker.

From the results, it is obvious that automatic trackers can give the highest energy output from LSS PV system. Nevertheless, it requires axis that can be automatically operated, which normally comes with excessive capital, high cost operation & maintenance, more complex, less reliable, and shorter lifespan than the fixed PV system. Manual tracker is a good option since it does not involve complex components and can be achieved by making the PV panels tilt-able. This can be done by modifying the structure of the fixed PV panel so that it can be tilted into several angles manually. By doing this, the tilt angle of the PV panels can be manually adjusted on monthly or seasonally basis to improve the output energy gain as proven in the presented results.

Therefore, its highly recommended to the PV solar industry sector (including the PV mounting factories) to produce flexible PV mounting products so that the PV panels can easily be tilted manually into several angles. Surely, it should come with suitable tilt angle step degrees which compatible with different locations worldwide instead of the fixed angle degree only. With this, the PV mounting product will be more attractive everywhere and at the same time profiting the LSS PV owner in terms of energy output improvements.

V. Conclusion

This paper has presented the output energy gain comparison between automatic trackers (single-axis & dual-axis) and manual tracking (seasonally & monthly) strategies and compared them to the fixed PV system with optimum tilt angle, simulated on 1 MW LSS PV system for 12 cities worldwide. Automatic dual-axis tracker produce the highest energy output but the performance of single-axis tracker in most cities is not much different (around 1-2 % less). Manual tracking strategies are good alternatives to the costly automatic trackers as it could also improve the energy gain up to 5-7%, thanks to the seasonal and monthly optimum tilt angle method that presented in this paper. Finally, these findings will be useful to the LSS PV designer to propose the best tracking strategy for a specific location.

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