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Fixed versus sun tracking solar panels: an economic analysis

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Abstract The performance of photovoltaic panels depends on many factors. One factor involves the light reception angles at the panels in which the intensity of the received solar radiation from the sun at the earth is affected significantly by the diurnal and seasonal movement of the earth. The maximum output of the panels is achieved when the panels are perpendicular to the sun's rays. This research is an empirical financial assessment of the benefit of using a dual-axis sun tracker versus a fixed-flat position, as well as a comparison of the performance of the two panels under such settings. The experiment was conducted using 190 W panels, a manual dual-axis sun tracker, and a data acquisition system, which collected and stored the experimental data. A significant improvement in output was noticed in the tracked panel. The overall average improvement for the entire data collection time interval was 82 %. The financial assessment was performed based on the energy market rate in Texas and the average price and operative expenses of the dual-axis sun trackers. The breakeven point for the dual-axis sun tracking system was found to be "never," 13, and 6 years for 1-, 4-, and 9-panel configurations, respectively, in each system.

Keywords Sustainable energy · Solar energy · Sun tracking · Economic analysis

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Introduction

The sun is a source of colossal energy. It is a giant nuclear reaction that transforms hydrogen into helium. This transformation generates energy (Hsieh 1986). The massive solar radiation that our planet receives is the source of all energy resources. The sun's light can also be used directly to generate electricity. Conversion of light into electricity through the use of photovoltaic cells, which are made of semiconductors, is called photovoltaic effect. The maximum output of the photovoltaic cell requires a perpendicular light on its surface. The earth's elliptical movement around the sun, as well as spinning itself, creates continuous change in sun ray reception angles. Influential factors include panel temperature, cleanness, power conversion and ambient temperature, wind speed, humidity, and pollution. Additionally, solar panel efficiency decreases over time due to aging and material degradation.

Sun tracking

To overcome seasonal and diurnal reception angles disparities in a designated photovoltaic panel, a sun tracking mechanism needs to be devised. The sun tracker controls photovoltaic panel positioning toward the sun's rays in order to achieve a perpendicular condition. By using sun trackers, the efficiency and output power of the photovoltaic panels will increase.

Many approaches and technologies have been used to create reliable and cost-effective sun trackers. The advancement in the efficiency of the photovoltaic panels, plus the development of enhanced manufacturing methods in the photovoltaic industry, reduced the energy payback time of the panels to 3–5 years (Rustemli and Dincer 2011). This energy payback time is reliant on multiple

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factors such as the irradiance level at the designated site. The cost of the photovoltaic panels is estimated to be $2.5 per watt peak and ambitiously forecasted to be $1 per watt peak by 2020 (Rustemli and Dincer 2011).

Solar energy has the potential to be one of the key alternative clean and renewable sources to supply the increasing demand. In 2009, the world's consumption of energy was 11,164.3 million tons of oil equivalent (mtoe). Comparing this figure with the amount of received solar radiation during the same year, we find that the input solar radiation is 11,300 times greater than the world's total primary energy consumption (Shepherd and Shepherd 2014). Solar energy is clean and friendly to the environment, and it will not be affected by fluctuations in the market, such as oil. The Solar Energy Industry Association (SEIA) report for 2014 shows a rapid growth in solar industry. Photovoltaic panels of 6201 MW have been installed plus 767 MW of concentrating solar power. This produces 20 gigawatts of total installed capacity, which is enough to power four million houses in the USA. The report also shows that the industry has 175,000 workers, more than Google, Apple, Facebook, and Twitter combined*. Solar energy is now estimated for one-third of the USA new generating capacity in 2014, surpassing both wind energy and coal for the second year in a row (Resch 2016; Solar Energy Industries Association 2016).

The global market of solar trackers is anticipated to grow to reach around 6.83 billion by 2022. Environmental awareness, governmental regulations and incentives plus many other factors lead to increase in photovoltaic size from 100.5 GW in 2012 to over 182.5 GW in 2014 ("Solar Tracker Market Size and Share | Industry Report, 2022" 2016).

Due to their low cost, single-axis trackers had a major share of the market in 2014. Residential and commercial areas had a high increase in purchases of these trackers. Dual-axis trackers are projected to be the fastest growing product as major companies prefer these types of trackers ("Solar Tracker Market Size and Share | Industry Report, 2022" 2016).

Sun trackers can be categorized based on their electricity consumption (aka drive type) and their actuator movements.

In the electricity consumption classification, the sun trackers can be divided into two main groups of passive and active sun trackers.

Passive sun trackers

A passive sun tracker is a non-precision mechanism for reorienting photovoltaic panels. It is often based on a low-boiling-point compressed gas fluid (e.g., Freon) that is driven from one side to another because of pressure created by the solar heat. The pressure causes the tracker to move. For example, Parmar et al. (2015) discussed a passive solar tracking system that inserts a low-boiling-point compressed gas fluid to metal canisters that are fixed on both sides of the photovoltaic panel mount, and these canisters are connected to each other by a metal pipe. A shadow is installed on both canisters, and the shadow covers the outer half portion of the canisters. When not shaded, the canisters are heated by the sun and the liquid inside the non-shaded side is forced to move to the shaded side. While this phenomenon is occurring, the solar panel that is placed between two metal canisters will follow the sun. This tracking system uses gravity as its moving force. Parmar et al. (2015) stated "*Zomework* increases the electrical output of photovoltaic modules by 23.33 % or more compared to modules on fixed mounts" (p. 144).

Clifford and Eastwood (2004) used a different passive sun tracking based on bimetallic strips. This passive sun tracker places two bimetallic strips made of aluminum and steel on a wooden frame symmetrically on either side of a central horizontal axis. Then, the bimetallic strips are introduced to shade, so the strip that is further from the sun absorbs solar radiation, while the other strip remains shaded. This was the same design as the compressed gas tracker; however, a different material was applied to the compressed gas tracker. According to this paper "this system also boasts the absence of complex fluid containment and accurate fitting of pistons" (p. 271). As a result of this tracker, solar panel efficiency can be increased by 23 %; however, the system in question requires manual reposition every morning. The paper suggests that a third bimetallic strip will fix this problem.

Active sun trackers

Based on actuator movements, sun trackers can be broadly classified into single- and dual-axis trackers. Sungur (2007) implemented an electromechanical control system of a photovoltaic panel tracking the sun on the axis it moves along according to its azimuth angle. In this experiment, the azimuth angle of the sun was measured by a PLC analog module, and the data collected were sent to the actuator motor, and then the actuator motor, which is on a single-axis system, moves the panel. According to measurements that were observed at 37.6 degrees latitude (Konya, Turkey), photovoltaic panels with a single-axis tracking system obtained 32.5 % more energy compared to fixed-position PV panels.

Comparison between single- and dual-axis tracking systems has not led to one absolute superiority for one versus other because it depends on a variety of environmental factors (e.g., sky clarity and location) and technical factors (e.g., photovoltaic/concentrated photovoltaic type and axis tilt/rotation mechanism). While dual-axis tracking systems are more accurate and produce more energy compared to single-axis tracking systems, these systems are more complex and consume more energy; thus, they are more expensive (Cooke 2011). Research by Afiqah et al. (2015) proposed a dual-axis solar tracking system in which the solar panel moves according to control from timer system for two encoder motors, a PIC microcontroller and driver L293D. This active solar tracker enabled a solar panel to collect 12.93 % higher sunlight compared to a fixed solar panel without a tracking system. Also, when using a tracking system, the output voltage was stable within a range of 18–20 V, while a solar panel without a tracking system was unstable. The average output voltage for a tracking system was 19.59 V as compared to 18.89 V for a non-tracking system. The tracking system was effective in avoiding the shading effect during sunrise and sunset. This study did not provide motor maintenance cost, although the use of the timer system reduced the need for real-time sun positioning sensors and their related operating and maintenance costs.

Aging and degradation

The lifespan of photovoltaic panels according to some manufacturers is 20 years (Honsberg and Bowden N. D.). The efficiency of the panels will decrease with time, and the quantification of power drop over time is known as the degradation rate. The median value of the degradation rate, in general, is 0.5 % per year (Jordan and Kurtz 2013). Many factors can contribute and cause this degradation: the environment (pollution is one major issue), discoloration of the encapsulation (EVA layer) or glass due to the ambient temperature, lamination defects, mechanical stress, and humidity cell contact breakdown (Kaplani 2012; Livingonsolarpower 2013, June 10). The different technologies used to manufacture photovoltaic panels can cause different types of degradation. Crystalline modules will suffer irreversible light-induced degradation due to defects activated by the initial light exposure (Livingonsolarpower 2013, June 10). Amorphous silicon cells may face a decrease in output power of 10–30 % in the first six months of light exposure; then, it will stabilize (Livingonsolarpower 2013, June 10).

This paper presents an empirical approach to measuring and comparing realistic power generation and associated benefits/costs by two similar solar panels where one is oriented by accurate manual sun tracking in 15-min time intervals and the other operated in a fixed horizontal position.

Method and Implementation

This research was conducted to include five hours in data collection time span over a sunny day in winter. The result was then extrapolated for the entire year based on historic sunny hours per year in Austin, TX. Additionally, using photovoltaic panel annual degradation rate, historical energy price index, investment cost and the energy consumption for the active sun tracking model, and interest rate, cost-effectiveness and breakeven point for the use of a fixed horizontal position solar panel against the sun tracking system were calculated for three scenarios of one-, four-, and nine-panel configurations.

Infrastructure

Suitable infrastructure to conduct this research was developed. The infrastructure included a mechanical system (Fig. 1) to hold and control the tilt and orientation of the photovoltaic panel, and an electrical system (i.e., wire-wound, adjustable tube resistors) and a Web-based data acquisition system (Fig. 2) . The data acquisition system used in this research consists of an eGauge, DC current transducer, power injector, RS485 to Ethernet converter, Sunny sensor box, ambient temperature sensor, photovoltaic panel temperature sensor, router, Ethernet cable, and wires.

Power generation

The system was comprised of two 190 Watt monocrystalline photovoltaic panels that contain 72 cells each with the following dimensions (125 × 125 mm) and a weight of 15 kg (Solar Systems USA Online Solar Panels 2016), rheostats, a manual dual-axis mechanical system, data acquisition system, and proper wiring. The power generated by these photovoltaic panels should be 90 % for ten years and 85 % for twenty-five years (Solar Systems USA Online Solar Panels 2016). In this research, the lifespan of the panels was assumed to be 25 years with a degradation rate of 0.5 % based on the relevant literature (Jordan and Kurtz 2013). A fixed-flat panel was mounted to the roof. The second panel was mounted to the manual dual-axis sun tracking system. Both panels were connected to the rheostats, as the loads to dissipate the generated electricity, and the data acquisition system. The experiment was conducted on February 16 starting at 10:50 a.m. and concluded at 4:00 p.m. The dual-axis tracker was controlled manually to attain the perpendicular condition. The perpendicular condition was sensed through the use of a shadow sensor, which consisted of a nail upright on cardboard. The shadow sensor was leveled to the panel. The manual sun tracker was adjusted every 15 min to retain perpendicular reception of the irradiance.

Power generation in sun tracking

The power consumption calculated in this research was based on a market-available dual-axis sun tracking system.

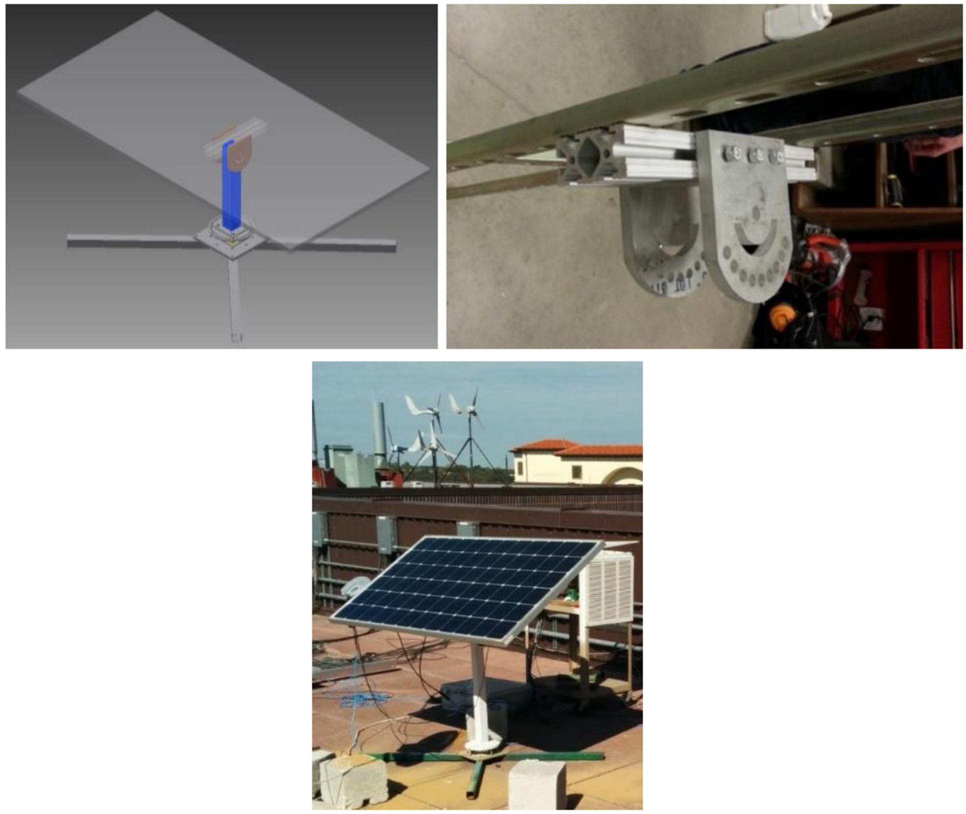

Fig. 1 Mechanical system design, manufacturing, and assembly

This system consisted of the following main components: 6″ actuator, 12″ actuator, a dual-axis solar tracker controller, and framing brackets. The nominal output of the system is 8–25 V (DC) with a max load current of 6 amps and no-load current of less than 1 amp. The solar tracker is equipped with a weather detector, which will alter the solar panels movements to yield the most efficient light energy capture, as the system will stop moving on a cloudy day and lie flat at night or on a rainy day. The system has a maximum load capacity of 1500 N (Eco-worthy Solar Tracking System N.D.). Based on this load capacity, up to 10 solar panels can be incorporated into the system, as each solar panel weighs 15 kgs (Solar Systems USA Online Solar Panels 2016). In this research, the life span of the sun tracking system was assumed to be more than 25 years, with a constant power consumption rate.

Configuration scenarios

Different sun tracking systems permit multiple panels to share a single tracking mechanism (Fig. 3). In this study, three feasible configurations were able to utilize 1, 4, and 9 panels installed on a single tracking systems. Additionally, realistic values for historic local sunny hours/year, solar panel annual degradation rate, historical energy price index, investment cost, energy consumptions in the sun tracking, and interest rate will make the results accurate for today's market.

Power data collection

The data acquisition system stored performance parameters for both panels used in the experiment. The unnatural spikes in the data were removed. The power output graphs of both panels were generated. The calculated area between the two curves represents the power saving achieved through the use of the dual-axis sun tracker.

As shown in the graph (Fig. 4), the power improvement by using dual-axis sun tracking versus fixed-flat solar panel ranges from 31 % in the midday to 294 % in the early and late times of the intervals. The overall average improvement for the entire interval was 82 %.

To accurately calculate the power generation difference between the two systems, areas between the power generation by the two systems between two reading times by the automated system were calculated as area for a trapezoid (Fig. 5).

$$A_{\mathrm{i}} = \frac{(W_1 + W_2)}{2} t_{\mathrm{i}} \tag{1}$$

$$\text{Average power saving} = \sum A_{\mathrm{i}} \Big/ T \tag{2}$$

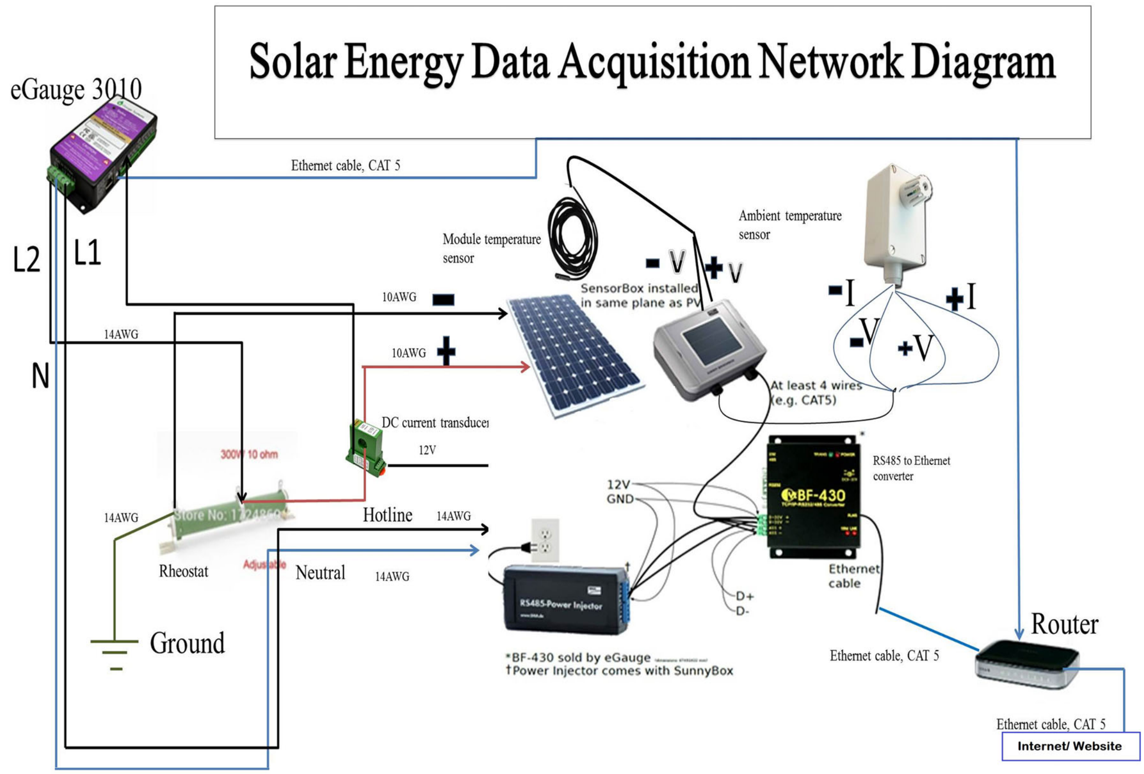

Fig. 2 Wiring diagram of the system used in the research

Fig. 3 Twelve solar panels share a single tracking system mechanism in a 6 × 2 configuration

Results

Power generation

Based on the power calculation shown in Eqs. 1 and 2, the average saving for one hour based on a five-hour-interval data collection was 0.0686 kWh (Table 1, Table 2). The extra power gained by a 1-, 4-, and 9-panel array using the dual-axis sun tracking system versus fixed horizontal format and considering 0.5 % degradation rate and historic local number of sunny hours per year (i.e., 2645 h in Austin Texas) [Average Annual Sunshine in American Cities n.d] was calculated (Eq. 3) for 25 years and is illustrated in Table 3.

$$\begin{aligned}&\text{Average power saving in year } i\\&\quad = \text{Number of sunny hours}\\&\qquad \times \text{ Average power gain per hour}\\&\qquad \times \left(1 - \text{ degradation rate}\right)^{i-1}\end{aligned} \tag{3}$$

Dual-axis sun tracking operating power consumption

Based on the specifications provided by the vendor, the max load current of the actuator is 3 amps, while the no-load current is less than 1 amp (approximated in this research to = 1 amp) (Eco-worthy Solar Tracking System N.D.). The no-load power consumption was calculated with the duty cycle reported to be 25 %. The speed of the actuator is given as 5.7 mm/s. The East/West Linear Actuator is 12 inches when fully extended and achieves a full 12-h day cycle of sun tracking. From the previous specification information, the max load time was calculated to be 0.03 h per 24 h.

Dual-axis sun tracking operating power consumption is calculated by adding *no-load consumption* and *with-load consumption*:

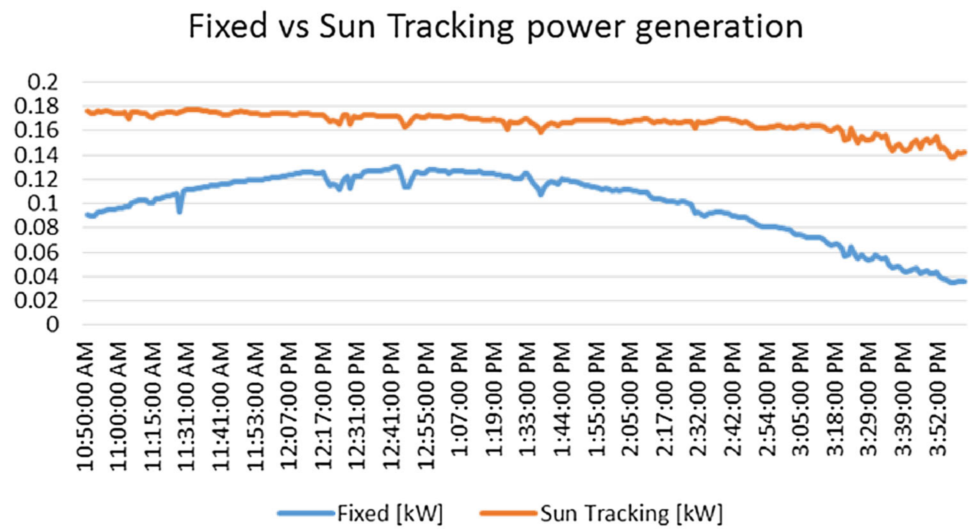

Fig. 4 Fixed versus sun tracking systems power generation

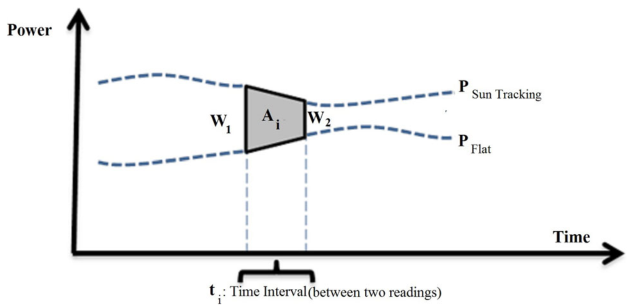

Fig. 5 Power difference calculation between two time readings

$$\text{Power Consumption} = VITD + MVITDE \quad (4)$$

where V is voltage (V.), I current (Amp.), T time, D duty cycle, M number of motors, and E motor efficiency.

Dual-axis sun tracking operating power consumption = 12 Volts × 1 Amp × 24 h × 365 days × 25 % duty cycle × 0.001 (Kilowatt conversion) + 2 motors × 12 Volts × 3 Amps × 0.03-h operating time × 24 h × 365 days × 25 % duty cycle × (1/80 %) motor efficiencies × 0.001 (Kilowatt conversion) = 26.34 kWh/year.

Table 1 Summary of two scenarios in the comparison study

Energy consumption (drive type)	Actuator movements	Configurations on a single system	Power generation/consumption	Variables considered	Variables not considered due to equal conditions for both scenarios
None	Fixed horizontal	1, 4, 9 panels	System output X (1, 4, or 9)	Historic sunny hours/year, panel annual degradation rate, historical energy price index, investment cost, energy consumptions in the sun tracking, and interest rate	Irradiance, wind speed, temperature, humidity, panel cleanness, panel model
Active Sun tracking	Dual axis	1, 4, 9 Panels	System output X (1, 4, or 9)—tracking consumption		

Table 2 Actuator specifications as reported by the vendor (Eco-worthy Solar Tracking System, N.D.)

	North/south actuator	East/west actuator
Voltage	12 V	12 V
Load capacity	1500 N	1500 N
Speed	5.7 mm/s	5.7 mm/s
Stroke length	6 inches	12 inch
Minimum installation distance	10.24 inches	16.54 inch
Duty cycle	25 %	25 %
Waterproof	IP65	IP65

Table 3 kWh extra power gained by using dual-axis sun tracking system against fixed horizontal system using 1, 4, and 9 panels over 25 years

Year	1-Panel system	4-Panel system	9-Panel system
1	181.4	725.8	1633.0
2	180.5	722.2	1624.9
3	179.6	718.5	1616.7
4	178.7	715.0	1608.7
5	177.8	711.4	1600.6
6	177.0	707.8	1592.6
7	176.1	704.3	1584.6
8	175.2	700.8	1576.7
9	174.3	697.3	1568.8
10	173.4	693.8	1561.0
11	172.6	690.3	1553.2
12	171.7	686.9	1545.4
13	170.9	683.4	1537.7
14	170.0	680.0	1530.0
15	169.2	676.6	1522.4
16	168.3	673.2	1514.7
17	167.5	669.9	1507.2
18	166.6	666.5	1499.6
19	165.8	663.2	1492.1
20	165.0	659.9	1484.1
21	164.1	656.6	1477.3
22	163.3	653.3	1469.9
23	162.5	650.0	1462.5
24	161.7	646.8	1455.2
25	160.9	643.5	1447.9

Benefits

To evaluate the monetary savings due to the use of the sun tracking mechanism, first the average power saving per hour was calculated (Table 3). Current local energy price rates and predicted inflation market price were applied in the calculation (i.e., the energy market rate is 11.3 cents per kWh in Texas with a historic average inflation rate of 1.81 % (Fig. 6) (The Price Of Electricity In Your State 2011).

$$\text{Benefits year } i = (P_i - C)R(1+F)^{i-1} \tag{5}$$

where P_i is average power saving in year i, C sun tracking power consumption, R energy rate in base year, and F average energy inflation rate.

System cost

Initial dual-axis sun tracking cost capable of moving up to 10 panels = \$1000.

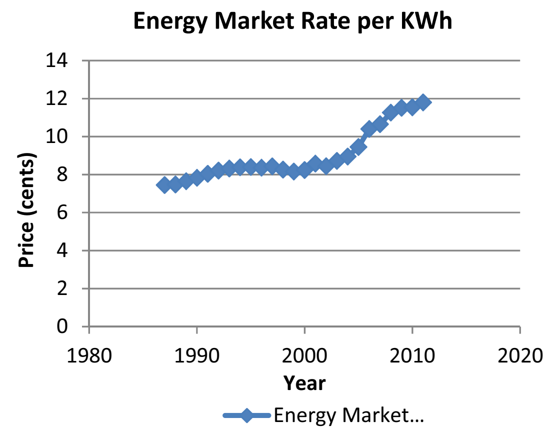

Fig. 6 Energy market rate in Texas over 25 years (The Price of Electricity in Your State 2011)

Financial assessments

Considering all power-saving benefits and investment cost, the present value for each year was calculated and shown in Tables 4, 5, and 6 and Figs. 7, 8, and 9.

Breakeven point for each scenario is calculated by Eq. 6:

$$\begin{aligned} NPV = & -\left[\$1000 * \text{integer}\left(\frac{25+n}{25}\right)\right] \\ & + \sum_{i=1}^{n} PV\Big[(\text{Average power saving in year } i \\ & - \text{Sun tracking power consumption}) \\ & * \text{Energy rate}*(1+\text{Energy inflation rate})^{i-1}\Big] \end{aligned} \tag{6}$$

where PV is present value, NPV is net present value, and n is the first year that NPV equation sign is turned from negative to positive.

Sensitivity analysis

Energy price is one of the most influential factors in this study, yet it is among the most volatile indexes in the world market scale. Any deviation in energy price may significantly change the financial feasibility of any project, including this study. To evaluate the impact of the energy price change in the breakeven points, the model is solved for two extreme scenarios, when the energy price inflates twice and deflates equal to the historical energy inflation rate. Table 7 illustrates sensitivity analysis of the breakeven points for three-panel configurations and three energy inflation/deflation scenarios.

As shown in Table 7, the increase in the energy price will positively impact the usage of the solar energy as it makes them to reach the breakeven point faster.

Table 4 Overall saving for dual-axis sun tracking versus fixed for a 1-panel configuration

Year	Benefit/cost	Present value	Sum of present values
0	−$1000.0	−$1000.0	−$1000.0
1	$17.5	$17.4	−$982.6
2	$17.7	$17.4	−$965.3
3	$18.0	$17.4	−$947.8
4	$18.2	$17.5	−$930.4
5	$18.4	$17.5	−$912.9
6	$18.6	$17.5	−$895.3
7	$18.8	$17.6	−$877.8
8	$19.1	$17.6	−$860.1
9	$19.3	$17.6	−$842.5
10	$19.5	$17.7	−$824.8
11	$19.8	$17.7	−$807.1
12	$20.0	$17.8	−$789.3
13	$20.3	$17.8	−$771.5
14	$20.5	$17.8	−$753.7
15	$20.7	$17.9	−$735.8
16	$21.0	$17.9	−$717.9
17	$21.2	$17.9	−$700.0
18	$21.5	$18.0	−$682.0
19	$21.8	$18.0	−$664.0
20	$22.0	$18.1	−$645.9
21	$22.3	$18.1	−$627.9
22	$22.6	$18.1	−$609.7
23	$22.8	$18.2	−$591.6
24	$23.1	$18.2	−$573.4
25	$23.4	$18.2-$1000	−$1555.1
26	27.45	21.2	−1533.95
27	–	–	–

Table 5 Overall saving for dual-axis sun tracking versus fixed for 4-panel configuration

Year	Benefit/cost	Present value	Sum of present values
0	−1000.0	−1000.0	−1000.0
1	79.0	78.3	−921.7
2	80.1	78.5	−843.3
3	81.1	78.7	−764.6
4	82.1	78.9	−685.7
5	83.2	79.1	−606.5
6	84.2	79.4	−527.2
7	85.3	79.6	−447.6
8	86.4	79.8	−367.8
9	87.5	80.0	−287.8
10	88.6	80.2	−207.6
11	89.8	80.5	−127.1
12	90.9	80.7	−46.4
13	92.1	80.9	34.5

Table 6 Overall saving for dual-axis sun tracking versus fixed for 9-panel configuration

Year	Benefit/cost	Present value	Sum of present values
0	−1000.0	−1000.0	−1000.0
1	181.6	179.8	−820.2
2	183.9	180.3	−640.0
3	186.3	180.8	−459.2
4	188.7	181.3	−277.8
5	191.1	181.8	−96.0
6	193.6	182.4	86.4

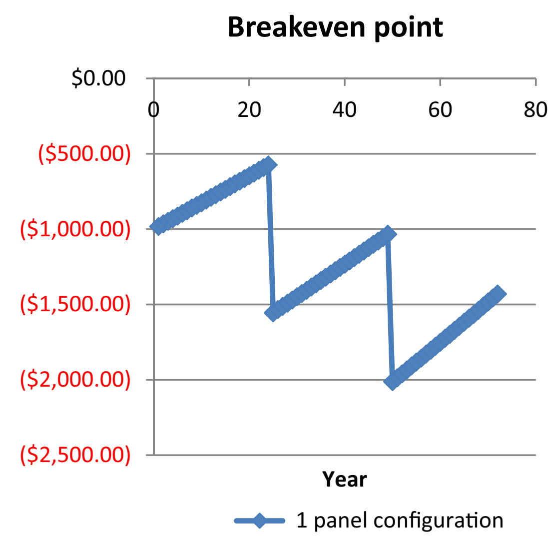

Fig. 7 Breakeven point for 1 panel (never)

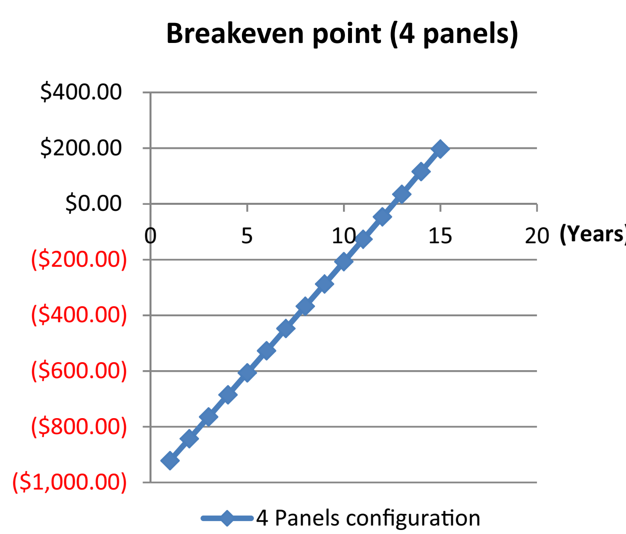

Fig. 8 Breakeven point for 4 panels (13 years)

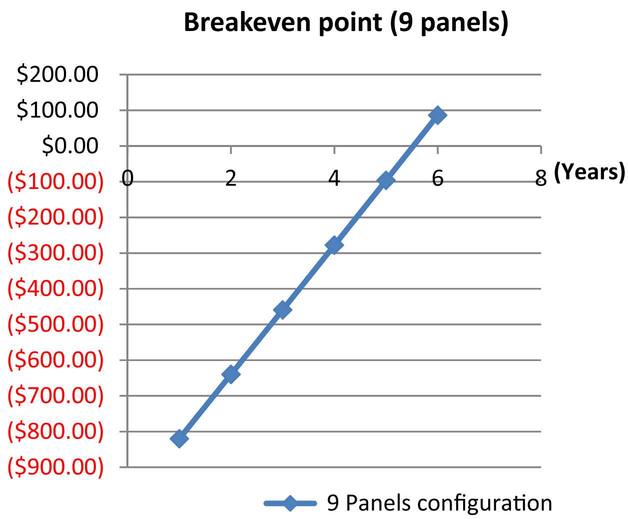

Fig. 9 Breakeven point for 9 panels (6 years)

Table 7 Sensitivity analysis of the breakeven points for three-panel configurations and three energy inflation/deflation scenarios

Panel configuration	Energy price inflation (3.62 %)	Base: Historical energy price inflation (1.81 %)	Energy price deflation (−1.81 %)
1-Panel configuration	69 years	Never	Never
4-Panel configuration	12 years	13 years	17 years
9-Panel configuration	6 years	6 years	7 years

Conclusion

This study conducted an experiment during the winter with a panel utilizing a dual-axis sun tracking mechanism. The generated power was saved and compared to the power generated by a flat panel. A significant improvement of an average of 82 % in panel performance was achieved by using the dual-axis sun tracking device. The power gained was calculated to include a degradation rate of .5 % per year for 25 years. A market-available dual-axis sun tracking system, with an initial cost of $1000, along with its specifications was used to calculate the power consumption and benefit. The breakeven point was found for three different scenarios. The first scenario with a system capacity for 1 panel had no breakeven point (NPV never turns positive). The second with a system capacity for 4 panels had a breakeven point of 13 years. The third system with a capacity of 9 panels had a breakeven point of 6 years. Finally, sensitivity analysis of the breakeven points for three-panel configurations and three energy inflation/deflation scenarios illustrated that higher energy prices make the sun tracking systems more economical.

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