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An Analytical Approach to Design a Cost Effective Dual Axis Solar Tracker Based on CSP and PV Technology

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Abstract—Now-a-days present world is facing crucial energy deficiency. Power is mostly generated using fossil fuels, which emit tons of carbon dioxide and other toxic materials. As the deposits of fossil fuel are dwindling and environment pollution has become a great threat to mankind, solar energy has become the most effective alternative to fossil fuels. Solar energy can be exploited averting environmental pollution and managing atmospheric emission. To make the best use of solar energy, we introduce a model in which both the direct and diffused solar radiation are utilized. This paper puts forward a design of an improved model of dual axis solar tracker combining with concentrated solar power (CSP) and photovoltaic (PV) technology. To increase the optimal energy generation, we propound a system which consists of dish stirling engine and PV panel. The PV panel is attached on the periphery of the parabolic dish. Apart from the mentioned design, this paper presents a structure and application of a microcontroller based azimuth-altitude dual axis solar tracker which tracks the system according to the direction of the solar radiation to increase the input to the stirling engine. An approximate cost evaluation shows that the model will be cheaper than typical solar panel based dual axis tracker.

Index Terms— Concentrated Solar Power (CSP), Dish stirling engine , Dual axis solar tracker, LDR, Microcontroller, Photovoltaic (PV) panel, Solar energy, Stepper motor.

1 Introduction

Solar energy is a revolutionary invention in the territory of power and energy. The sunlight is transformed into electricity directly by using PV cells. Concentrated solar power uses lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The discovery of the photoelectric mechanism and development of the solar cells (a semi conductive material that converts visible light into direct current) made it possible to extract useable electricity from the sun. Solar energy falls on the earth's surface at a rate of 120 peta-watts which evinces that the solar energy received from the sun per day is sufficient to meet up the whole world's energy demand for more than 20 years. The worldwide energy demand is expected increasing at 5% each year [1]. Since the supply of conventional energy is limited we have to bank on the solar energy to satisfy the steadily increasing demand for energy. The two most distinct solar energy technologies are photovoltaic and concentrated solar power technology. Solar photovoltaic made of semiconductor material directly converts solar energy into electricity by photovoltaic effect while concentrated solar power systems first convert the solar energy into thermal energy by capturing and concentrating the sun's energy and then further convert it into electrical energy through a thermal engine. A parabolic dish concentrator with stirling engine offers the highest thermal and optical efficiencies among all the concentrator options. A solar stirling engine has recorded highest conversion efficiency of 32% whereas a PV module has ideal conversion efficiency in the range of 20% [2][3]. Considering this statistics of energy conversion we propose a model using the both CSP and PV technology to maximize the energy conversion efficiency. To get the highest power output it is necessary to make it sure that the PV cell or the mirrors (which concentrates sun light into a beam) is aligned with the sun. The solar tracker helps us to get this alignment. If we use dual axis solar tracker in lieu of stationary panel, the efficiency can be increased by 57% [4].

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2 Solar Energy

Present world is mostly dependent on fossil fuel such as coil , oil, natural gas for electricity generation. But the deposit of these nonrenewable energy sources are limited and soon will run out. Moreover these non renewable energy sources cause green house effect which leads to global warming. Besides the price of theses non renewable energy sources are increasing at a high rate and the inflation is more than 70%[5]. Renewable energy sources such as solar, wind, hydroelectric, biomass, geothermal power generation have come out as potential alternatives to these traditional energy sources. Solar energy has

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turned up to be the most rapidly growing renewable sources of electricity. Wind turbine is also an effective way of power generation. But it requires more maintenance than solar power and makes huge noise causing noise pollution. Although hydroelectricity is effective but not suitable for building usage since it is generally supplied through the use of large dams. Biomass produces volatile organic compounds such as carbon monoxide and nitrogen oxides which endanger our planet and future generations. Thus solar energy is considered to be a mainstream source of electricity generation. The sun which is also known as ball of fire gives us solar energy as heat and light. Converting this heat and light into electricity we can meet the demand of electricity. We know that photovoltaic cells are used to convert solar power. In the recent few years the developed countries have paved a long way in the field of solar energy. In the year ended in 2012 eight countries in Europe, the United States, and Australia, three in Asia, had introduced more than 1 GW of solar energy to their grids. Germany has a record of 7.6 GW additional solar energy connected to their national grid over the previous two years, increasing its total energy to 32.4 GW [6]. Due to noncontaminated characteristics and versatile availability of solar power Germany installed thousands of solar panels and plans are made to use only renewable energy by 2050. The country has the record to be the top buyer of solar energy panels for several years and is also expected to continue their development in upcoming months [7]. So it is evident that the countries around the world are adopting solar power and its importance is increasing. Solar energy is economically feasible energy resource. For Bangladesh it has many significant potential. According to NASA Surface meteorology and Solar Energy RET Screen Data, Bangladesh has got a great future in the field of solar energy generation. Table1 unfolds the data obtained from this source shows the daily solar radiation of Dhaka city.

TABLE 1

NASA SURFACE METEOROLOGY AND SOLAR ENERGY FOR BANGLADESH

Month	Daily solar radiation-horizontal in kWh/m^2/day
January	4.36
February	4.92
March	5.59
April	5.76
May	5.30
June	4.53
July	4.23
August	4.29
September	4.02
October	4.32
November	4.28
December	4.21
Annual	4.65

3 DESIGNING OF AN IMPROVED SOLAR SYSTEM

Most of the electric devices work on alternating current (AC). Typical photovoltaic cells produce direct current (DC) which is then converted to AC to run the electric appliances. This gives rise to an energy loss of 4-12% [8]. On the contrary a parabolic stirling engine converting heat into mechanical energy first and then into electricity energy can generate DC power directly which leads to less conversion loss. In the proposed model, we use a stirling-dish system which consists of a parabolic dish shaped concentrator that reflects direct solar irradiation to a receiver at the focal point of the dish. A stirling engine is directly connected to the receiver which generates electric energy. A parabolic dish concentrates only the direct solar radiation that falls on the dish surface parallel to its optical axis. But the parabolic dish is not able to use diffuse solar rays. These diffused solar rays strike the solar parabolic dish from different directions and thus are not focused onto the stirling engine receiver. Again a parabolic dish works most efficiently in a hot shinning day, the output of the stirling engine deteriorates tremendously in a cloudy day. To compensate these problems we are in favor of using of photovoltaic panel on the periphery of the dish. As a PV panel a layer is able to collect both direct and diffuse irradiations, so this technology works even on cloudy days. Moreover the panel can reach about 10% of peak capacity even in a rainy day when the direct sunlight is almost zero [8]. Thus the system is more suitable for all seasons. The entire system works on dual axis solar tracking system. The dual axis tracking system enables the collector to follow the sun in order to concentrate the direct solar radiation onto the small receiver. Fig 1 shows the complete design of the system.

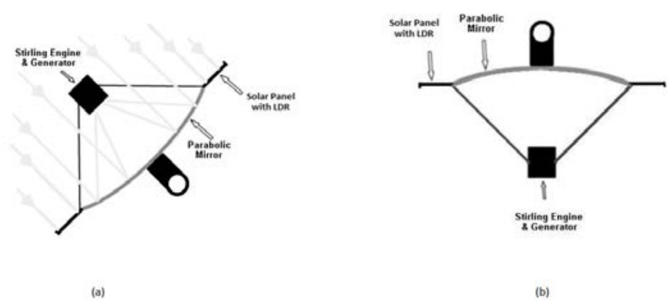


Fig 1: Design of the proposed solar model (a)Stirling engine during day(b) Stirling engine after sun set

4 REGULATTING THE SOLAR SYSTEM

4.1 Stirling Engine

A stirling engine is an external combustion engine that converts heat to mechanical work at different temperature level. It was originally conceived in 1816 as an industrial prime mover to rival the steam engine. Its practical use was largely confined to low-power domestic applications for over a century. Unlike PV solar panel stirling engine does not use photovoltaic effect. Instead it converts the sun rays into heat through a parabolic reflector. A thermo receiver connected with the stirling engine receive the concentrated rays from the reflector and produces heat at high temperature. This heat enables the stirling engine. Associated piston engine in the system transforms this heat into mechanical work. Mechanical energy will drive the generator and thus Electrical energy will be produced. Power generation capability of the stirling engine is related to the surface area of the parabolic dish. In our proposed model the radius of the parabolic dish is taken as 1.5m. The dish rotates automatically to align with the sunrays through tracking system. In a tropical day at a perpendicular position the maximum temperature inside the engine is 500^o.

4.2 Azimuth Altitude Dual Axis Solar Tracking Method

In our proposed model we use microcontroller based azimuth-altitude dual axis solar tracking system. The azimuth- altitude dual axis solar tracker pivots the dish in such a position where the dish will be perpendicular to the sun i.e the angle of incidence of sun beam will be 0^oC. The exact position of the sun is estimated by these two angles. The solar altitude angle is defined as the vertical angle positioned between the horizontal and the line connecting to the sun. At sunset or sunrise altitude angle is 0^oC and when the sun is at the zenith the altitude angle remains 90^o[9]. The azimuth angle represents the angle of the projected position of the sun in the horizontal plane. The azimuth and altitude angle can be calculated by the following equation.

$$\cos\varphi_A = (\sin\delta\times\cos\alpha - \cosh\times\cos\delta\times\sin\alpha)/\cos\theta_Z \qquad (1)$$

Where, φ_A is the solar azimuth angle, θ_Z is the solar altitude angle. Solar altitude angle = 90 - zenith angle of the sun. From this formula, it is clear that if θ_Z is changed then φ_A will be changed. Depending on this parameter, we can easily design our desired microcontroller based solar tracker to sense the maximum solar beam. The solar zenith angle β can estimated from spherical trigonometry-

$$\cos\beta = (\sin\alpha\times\sin\delta) + (\cos\alpha\times\cos\delta\times\cosh) \qquad (2)$$

Where, h is the hour angle in local solar time and α is the local latitude (for Bangladesh, it is 23.7^0). δ is the current sun declination and it is calculated from Coopers equation which is given below-

$$\delta = 23.45\times\sin\left[\frac{360}{365\times(284+N)}\right] \qquad (3)$$

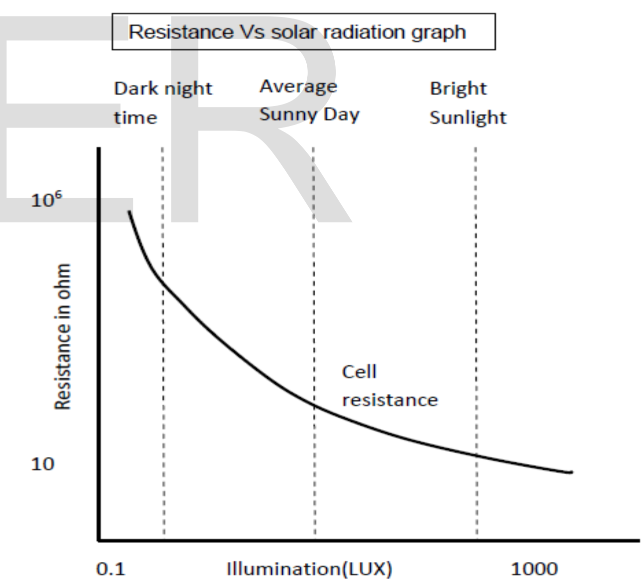
Here, N is the day of the year (1 to 365), if N is 1 then it is the 1st day of January.

Light dependent resistors (LDR) are used for sensing the positional change of the sun. This sensor continuously monitors the solar radiation and this data are transferred to the stepper motor via microcontroller. The stepper motor moves the dish where the intensity of light is maximum. At the initial condition two stepper motors start running. Since the sun changes its position after every four minutes the sensor detects the position of the sun. If the sun moves from east to west, the first steeper motor responsible for horizontal movement will start running. Only when the sun moves to north or south position, the second stepper motor will start running. The vertical and horizontal movement of the solar panel on azimuth and altitude angle is taken as a reference.

4.3 Sensing Mechanism

In the propounded system LDR is used as light sensing element. Photo-diode or photo-transistors could also be used for light sensing. Photo-diodes are temperature sensitive and costly than LDRs. On the other hand, a photo-transistor is slower in response time. Thus LDR is preferred as the connection of LDR is simple and it is also bidirectional. The LDRs are put into hollow tubes so that only perpendicular incident rays are sensed. Then these LDRs are connected to the controller circuit. When the sun moves from right to left, the incident light on the left LDR is more. Hence, the resistance of the left LDR decreases and vice versa. When the resistance of any particular LDR decreases; the controller circuit responses so that the panel is moved towards the position of that particular LDR. Therefore, dish is always kept at the position where the light intensity is maximum and making the dual axis solar tracker to be more efficient. Fig 2 demonstrates that with the increase of solar radiation the resistance of the LDR decreases.

Fig 2: Variation of efficiency of LDR with solar radiation



4.4 Stepper Motor

To rotate the dish along the axes the solar tracker needs two stepper motors. A stepper motor is a brushless DC motor that can be commanded to move and hold its position in particular angle. Basically, this motor divides a full rotation into equal steps; therefore, they are called stepper. A stepper motor has four coils with 90^o angles between them.

4.4.1 Working Method of Stepper Motor

In this tracker we use a bipolar stepper for tracking the altitude of the sun and a unipolar stepper motor in the azimuthal axis. Since a unipolar motor is center tapped, only half of the available coil windings are used for magnetizing the rotor. On the other hand, a bipolar stepper motor uses the whole wind-

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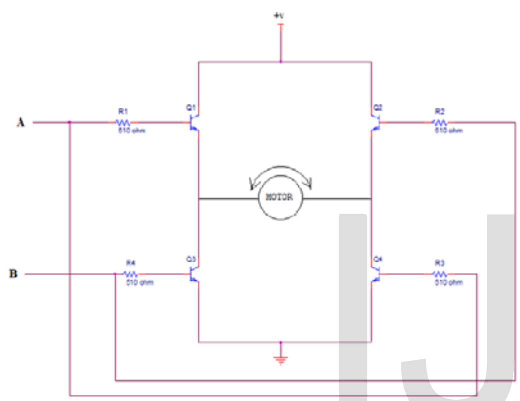
ing to magnetize the coil. Therefore, we can generate almost twice torque in a bipolar stepper motor that of a unipolar stepper motor. Hence, using a bipolar motor instead of a unipolar motor for tracking the altitude would let us mount larger solar dish.

4.4.2 Driving of Stepper Motor

The driving mode of a stepper motor refers to the sequence of energizing the coils. There are mainly two driving modes to drive the stepper motor.

- Full stepping
- Half stepping

In this solar tracker mechanism, half stepping driving mode has been used between these two driving mode. Besides, the bipolar motor being unidirectional, we need an H-bridge to make it bidirectional. For that purpose we use dual H-bridge motor driver IC L293. Fig 3 presents the circuit diagram of H-bridge motor driver IC L293.



A	B	Dir
0	0	Stop
0	1	CCW
1	0	CW
1	1	N/A

Fig 3: Circuit diagram of H-bridge motor driver

4.5 Control Circuit

An automatic controlling system is proposed to avoid manual interference. A timer based system is included in the control system that will automatically start the tracking mechanism soon after the sun rises. One stepper motor will be activated and the parabolic dish will rotate to a stand by position. Basically a rotation of 180º by the motor before the sensing mechanism will take place here. Later on the tracking system will start by LDR sensing method.

In our proposed model we used PIC18F452 for controlling the solar tracking system[10]. In control circuit, PORTB is used for input where four LDRs are connected. Two LDRs are for azimuth tracking and other two are for elevation tracking. PORTC and PORTD are used for output. RC0 to RC3 are connected to the motor controller IC-ULN2003A of Stepper motor1. Similarly RD0 to RD3 are connected to that of Stepper motor2. Motor1 is for azimuth rotation and motor2 is for altitude. A 5V battery will operate the Microcontroller. Another Battery will be required for ULN2003A as per the required power supply of stepper motor [11]. Motor2 will operate only during the seasonal change when the sun moves north or south direction. The whole circuit is simulated in proteus7 program by software MikroC PRO for PIC. The simulating diagram is given in Fig 4. For Programming purpose we consider the voltage drop across LDRs as V1,V2 from east to west in azimuth axis and V3,V4 from north to south in altitude axis. ADC converter is needed for getting the actual analog value of voltages at LDRs. The tracking system will start with the comparison of left most sensor voltage V1 and lowest voltage V0 found at LDR at intensity 1000W/m². In the next step voltage comparison will be done between two consecutive LDRs. At the end of the day all two LDR voltages will be compared with the highest Voltage Vm found at intensity 0W/ m². An equal voltage of Vm at all two LDRs will indicate end of day thus the tracking system will be automatically shut down after sunset consuming less power. The Stirling engine is proposed to connect with the dish in such a way that it goes to a safe position after sunset which is done by the backward 180º rotation by the motor that was supposed to use in the morning. The whole dish with the stirling engine will turn upside down and remain in this position till the next morning.

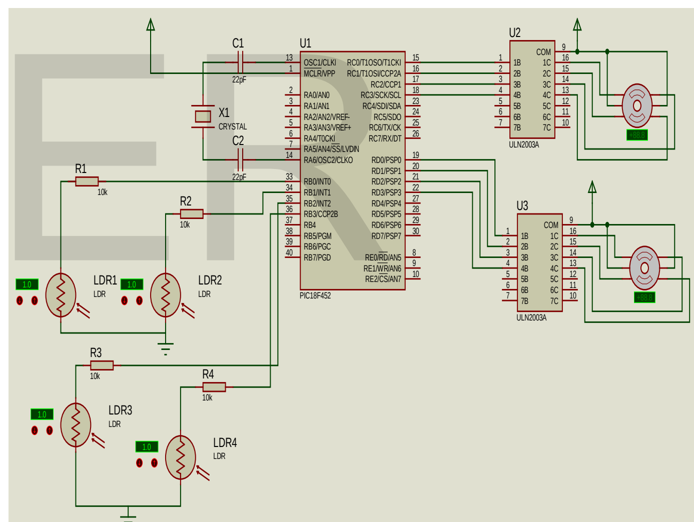


Fig 4.The detailed algorithm of control circuit

4.5.1 Algorithm of Microcontroller Circuit

Algorithm has been done for azimuth axis panel usingV1, V2 to move the solar tracker from East to West. Same Algorithm can be done for altitude axis panel using V3, V4 instead of V1, V2 and replacing East with North and West with south. There will be no rotation of sun along altitude during summer. So automatically motor2 will be turned off during summer. Detailed algorithm of the microcontroller of the solar tracker is given in Fig 5.

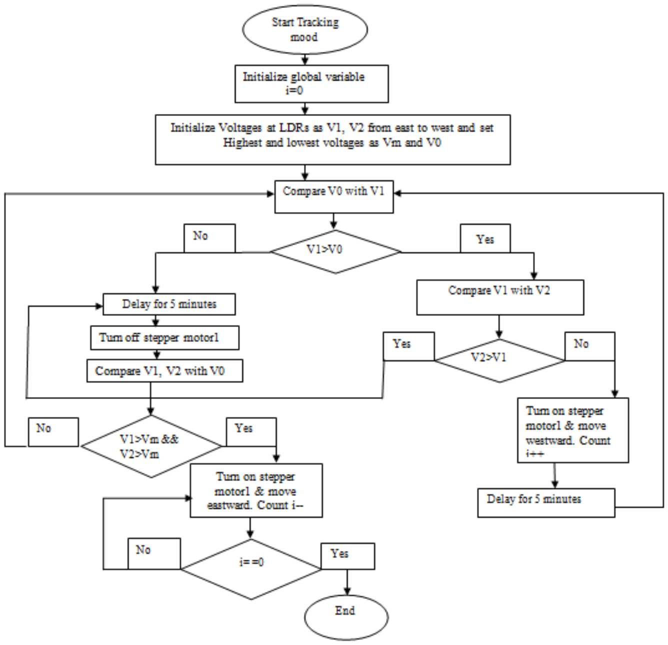


Fig 5: The detailed algorithm of control circuit

5 Cooling System

PV panels absorb up to 80% of the solar radiation of which, only 5-20% of the incident energy is converted into electricity and the remaining energy is converted into heat [12]. The efficiency of a PV module decreases with the increase of temperature. Fig 6 evinces that the increase in temperature results in lower solar cell efficiency.

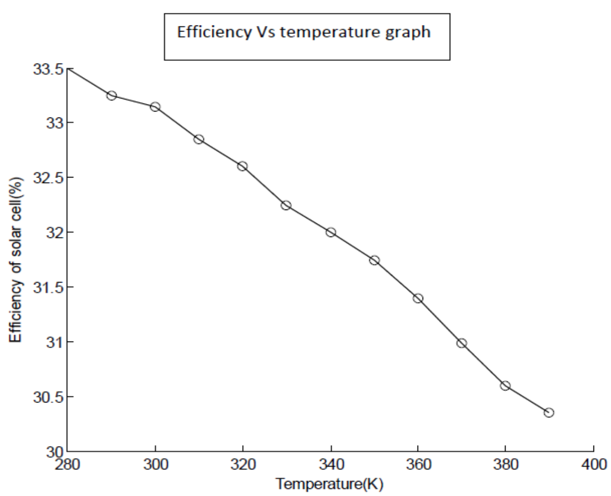


Fig 6: Efficiency of Solar panel at different temperature

The temperature of the module can raise upto 40-50ºC in a hot summer day. Again the temperature of the adjacent mirror of the parabolic dish also increases with the increase in solar radiation causing structural damage to the PV module. The output power of the PV module may drop by 0.45% with per degree celsius temperature rise [13]. To keep the PV panel electrically efficient a cooling system is required to remove this excess heat. Cooling of the PV module may be achieved by circulating a colder fluid, water or air, at its rear or front or both surfaces. Regarding the high installation cost we prefer the natural air cooling system. In air cooling system, a duct is thermally attached to the rear surface of the panel. Thin fins are suspended at the back wall of the air duct as heat transfer augmentations in an air cooled system. In our proposed model the depth of air duct is kept 10cm with 5cm long fin and the thickness of the fin is 2cm. Fins and air duct are constructed with aluminum due to its high thermal conductivity(205 $Wm^{-1}K^{-1}$). In air cooling system PV module captures the incident solar radiation and then transmits a part of it to the airflow in the duct and the back wall in the form of heat. This heat is conducted along the fin and spontaneously the fin dissipates heat by convection to the flowing air and increases the rate of heat convection in the channel. The net result is the lowering of PV module temperature. Thus the air circulation by natural flow in the air channel reduces the temperature of the panel by at least 5ºC and contributes to improve electrical output power [14].

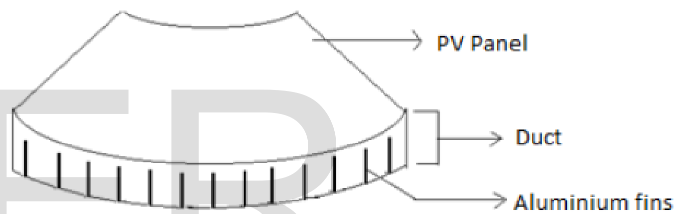


Fig 7: Part of the PV panel in the proposed model indicating the cooling system

6 Performance Analysis of the System

6.1 Power Generation

6.1.1PV Panel

The model consists of a parabolic dish of 2m opening diameter including the PV panel around the periphery. The only diameter of the parabolic dish concentrator is taken about 1.5m. The total surface area of the system including dish and panel-

$$A_t = \pi r^2 = \pi \times 1^2 = 3.1416\, m^2 \tag{4}$$

The Surface collecting area of the parabolic dish (without PV Panel):

$$A_d = \pi \frac{d^2}{4} = \pi \times \frac{1.5^2}{4} = 1.77\, m^2 \tag{5}$$

The surface area of the PV panel :

$$A_p = A_t - A_d = 1.37\, m^2 \tag{6}$$

Let us assume that the maximum radiation intensity is I=1000W/m² falling perpendicularly to the solar panel. But we will not get the maximum radiation throughout the day. We are taking our theoretical calculations for 12hours among which for 8 hours the radiation is taken 1000W/m² and for 4 hours the radiation is 400W/m². As the total system is based on dual axis tracking mechanism the panel is always perpendicular to the solar radiation. So inclination angle will be 0^o. For maximum solar radiation the power generated from the panel is

$$P_1 = I \times Sdt = 1000 \times 1.37 \times (8 \times 60 \times 60)$$
$$= 39.456 \times 10^6 = 10.96 kWh/day \quad (7)$$

For solar radiation $400W/m^2$ the output power from the panel is:

$$P_2 = 400 \times 1.37 \times (4 \times 60 \times 60) = 7.8912 \times 10^6$$
$$= 2.192 kWh/day \quad (8)$$

Total output from PV panel:

$$P_3 = P_1 + P_2$$
$$= 10.96 + 2.192 \, kWh/day \quad (9)$$
$$= 13.152 \, kWh/day$$

6.1.2. Dish-Stirling Engine

The solar parabolic dish, concentrating solar radiation into stirling engine raises the the temperature of the fluid significantly which leads to higher solar power conversion efficiency. The highest conversion efficiency of the concentrating solar power technologies has been recorded to be 32%[2]. In our numerical analysis we are taking into account the power conversion efficiency 32%

The output power of the stirling engine-

$$P_4 = 13.152 + 13.152 \times 32\%$$
$$= 17.36 \, kWh/day \quad (10)$$

Table 2 shows the total output power generated from our proposed system:

TABLE 2

GENERATED POWER FROM THE PROPOSED SYSTEM

Technology	Power generated in kWh/day
CSP(sirling engine)	17.36
Photovoltaic (PV Panel)	13.15
Total	30.5

6.2 Proposed Utility of the Model

Table 3 unfolds our conception about an ideal solar house model.

TABLE 3

TOTAL LOAD POWER OF A FAMILY OF FOUR MEMBERS

Electric Loads	Wattage	Qty	Yearly Avg.Duty Cycle (hr)	Load Power (kWh)
LED Lights	16	3	08	0.384
LED(low power)	08	2	06	0.096
Ceiling Fan	75	03	10	2.25
Fridge	475	01	24	11.4
colour TV	150	01	05	0.75
Computer	200	01	03	0.6
Toaster oven	400	01	0.25	0.1
Total Load Power(kWh/day)				15.58
Total Load Power(kWh/year)				5686.7

From the above Table 3 we can perceive that the total energy required for a family per day is 15.58kWh . And from Table 2 we can discern that the solar energy which our proposed system can generate daily is 30.5kWh. Thus the system can meet the daily energy demand of approximately 2 families.

7 COST COMPARISON BETWEEN TYPICAL DUAL AXIS SOLAR TRACKER AND THE PROPOSED MODEL

7.1 Cost of PV Panel based Dual Axis Solar Tracker

To meet the daily power demand of a family with the installation of PV based dual axis solar tracker we require around 2 m^2 dual axis solar tracker generating 15.58kWh energy per day. A market price analysis of a PV based dual axis solar tracker reveals that the installation cost of a dual axis solar tracker is approximately $1-3 per watt. Thus a typical dual axis solar tracker installed for satisfying the power demand of a family will cost approximately $23000 taking into account $1.5/watt

10.2 Cost of the Proposed Model

Our proposed system consists of a dish-stirling engine, solar panel, cooling and tracking system. Table 4 shows the approximate cost of the model.

TABLE 4

APPROXIMATE COST OF THE PRPOSED SYSTEM

Parameters	unit	Cost $/unit	Total cost($)
PV Panel	16.44kW	0.76	13
Dish-stirling (with tracking system)			25,000
Cooling sytem (aluminum fin and duct) and other accessories			200
Total cost			25,213

From the above calculation we can perceive that 2 families can consume the power at a cost of $25,213. Thus each family has to contribute $12,757 for the installation of the proposed model. The cost evaluation evinces that at the same installation cost a 2m2 solar panel based dual axis solar tracker can meet the power requirement of one family whereas our proposed system can serve almost 2 families. Thus the energy efficient system proves to be cost effective.

The Fig 8 deals with the cost comparison of the three solar technologies. The graph shows the total amount of cost spent by per family to meet their daily energy demand. A solar panel based dual axis solar tracker has the highest installation cost. An isolated stirling engine can generate electric energy at a lower rate, but it is not able to generate sufficient amount of energy. The graph manifests that by using our pv-dish stirling system we can optimize the energy generation at a lower rate.

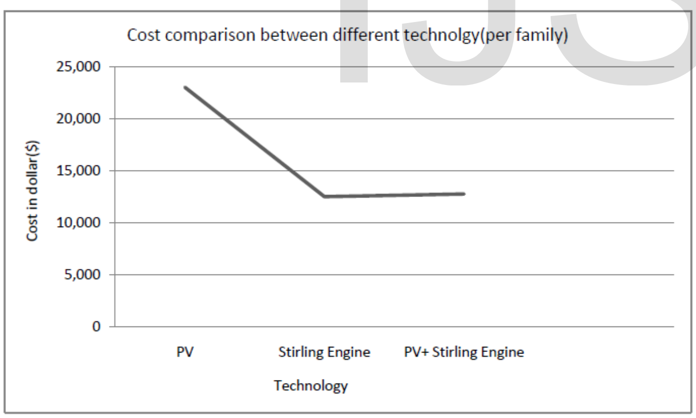


Fig 8: Cost comparison between three technologies

11 Conclusion

The above analysis manifests that the proposed model can generate 43% more power than isolated CSP and 57% more than PV system. With the aggregation of two technologies we can maximize the power output. Moreover the cost analysis demonstrates that the system can be installed with a lower cost significantly in comparison with solar panel based dual axis solar tracker. The proposed model will cost approximately 38% less price than typical dual axis solar tracker. Thus the conception of establishing low cost combined pv-dish-stirling engine make sense. The proper installation of this microcontroller based dual axis tracking system can be a great boon to meet the increasing demand of energy. As the system is cost effective it will lead to economic escalation of a country.

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