Design and Development of Spherical Lens based Solar Energy Generator using Multi-Junction Solar Cell

[1]Jai Subash Devmane, [2]Prof.Niyati Raut, [3]Prof.Aniket Deshmukh
[1]B.E. Mechanical Engineering, Viva Institute of Technology, Virar, India
[2]Head of Department, Mechanical Engineering Department, Viva Institute of Technology, Virar, India
[3]Assistant Professor, Mechanical Engineering Department, Viva Institute of Technology, Virar, India

Abstract: This paper discusses the use of a Spherical Ball Lens to converge light at a single point and to use Multi-Junction Solar cells mounted on an Automatic Cradle and Slider to capture solar energy throughout the presence of the Sun in the sky. The Cradle and Slider are mounted on low inertia DC motor drives. These DC servomotors are controlled by the Arduino Microcontroller which uses an array of Photodetectors to track the movement of the Sun. The paper also discusses how multijunction cells could replace conventional Photovoltaic (PV) cells in solar energy generation systems due to higher energy conversion efficiency.

***Index Terms* – Solar Energy, Solar Tracker, Arduino, Multi-Junction Cell, Spherical Lens**

I. INTRODUCTION

The Sun is the largest source of sustainable and renewable source of energy and is referred to as Solar energy. The Earth receives 174,000 terawatts (TW) of incoming solar radiation (insolation) at the upper atmosphere. Approximately 30% is reflected to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. Most people around the world live in areas with insolation levels of 150 to 300 W/m^2 or 3.5 to 7.0 kWh/m^2 per day. The total solar energy absorbed by Earth's atmosphere, oceans, and land masses is approximately 3,850,000 exajoules (EJ) per year.

Solar Power is the conversion of sunlight into electricity, either directly using photovoltaics (PV), or indirectly using concentrated solar power (CSP). CSP systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. PV converts light into electric current using the photoelectric effect. Solar power is anticipated to become the world's largest source of electricity by 2050, with solar photovoltaics and concentrated solar power contributing 16 and 11 percent to the overall global consumption, respectively. Solar Energy is the most sustainable and renewable source of energy available in ample amount throughout the surface of the earth. It is the solution to the world's problem of Energy crisis and depletion of Non-renewable sources.

The paper looks to solve the below problems of current Solar Energy Generation Systems:

A. Movement of the Sun through the day that makes static Solar Panels inefficient

As the Earth rotates around the sun on an annual cycle, it is tilted at an angle on its vertical axis. As a result, this impacts how the sun's rays strike various locations on Earth. The Earth is its most extreme tilt at the winter and summer solstices. The sun appears to rise in the east, and it sets in the west. In actuality, the Earth is rotating on its axis and around the Sun. This affects how low or high the sun appears relative to the horizon. In the winter, the sun is relatively low in the sky with its lowest arc through the sky on the winter solstice or December 2lst. In the summer, the sun travels a high path through the sky and is at its highest angle on the summer solstice or June 21st.

This renders the conventional static solar energy systems in-efficient due to their inability to track the movement of the sun and change the panel's alignment accordingly.

B. Low efficiency of traditional single junction solar cells

In Physics, the Shockley Queisser Efficiency Limit or SQ Limit refers to the maximum theoretical efficiency of a solar cell using a single p-n junction to collect power from the cell. William Shockley and Hans-Joachim Queisser first calculated it at Shockley Semiconductor in 1961. The limit is fundamental to solar energy production and is considered to be one of the most important contributions in the field. The limit places maximum solar conversion efficiency around 33.7% assuming a single p-n junction with a band gap of 1.34 eV (using an AM 1.5 solar spectrum). That is, of all the power contained in sunlight falling on an ideal solar cell (about 1000 W/m), only 33.7% ever can be turned into electricity (337 W/m^2). The most popular solar cell material - Silicon has a less favorable band gap of 1.1 eV, resulting in maximum efficiency of about 32%.

Modern commercial monocrystalline solar cells produce about 24% conversion efficiency, the losses primarily due to practical concerns like the reflection off the front surface and light blockage from the thin wires on its surface. The Shockley-Queisser limit only applies to cells with a single p-n junction; cells with multiple layers can outperform this limit. In the extreme, with an infinite number of layers, the corresponding limit is 86.8% using concentrated sunlight.

C. Wastage of real estate when traditional solar cells are used with dual axis tracking

Traditional Solar cells are larger owing to lesser efficiency and more substantial output requirement. These solar panels are usually mounted on a Ball and Socket joint using a driver motor to track the movement of the sun which requires a large area around the system to be vacant to avoid any kind of interference with the movement of the system or to avoid the shadow of any other component from falling on the system. In the current global scenario where there is an extreme shortage of real estate because of population explosion, this becomes unfeasible especially in urban areas that are significant consumers of power.

Use of a high-efficiency multi-junction solar cell helps in reducing the static area requirement of the system. A spherical ball lens is used as a concentrator to increase the efficiency further. Also, it facilitates the use of a tracker that revolves around the concentrator because of the spherical geometry of the ball.

II. RESEARCH METHODOLOGY

The report presented is empirical, based on both primary and secondary sources of data. The framework of the analysis has been constructed from the data collected through recorded data and meetings with various suppliers and manufacturers of the industry.

2.1 System Components and Selection

2.1.1 Multi- Junction Solar Cell

Multi-Junction (MJ) solar cells are solar cells with multiple p–n junctions made of different semiconductor materials. Each material's p-n junction will produce an electric current in response to different wavelengths of light. The use of multiple semiconducting materials allows the absorbance of a broader range of wavelengths, improving the cell's sunlight to electrical energy conversion efficiency. Cells made from multiple materials have multiple band gaps. So, it will respond to multiple light wavelengths, and some of the energy that would otherwise be lost to relaxation as described above can be captured and converted.
The only problem that Multi-Junction Solar Cells face is a need for concentrated solar power. This project looks at solving this problem with the use of a Dual-axis tracking system and a spherical ball lens that converges diffused sunlight on a smaller area.

After a thorough market survey for a solar cell with higher efficiency, we discovered Multijunction solar cell on the internet. We searched for a multijunction cell in the domestic market through national level suppliers such as Waaree Group, IndoSolar, and others. After a meeting with Waaree Group's Engineering department General Manager, it was realized that multijunction cells are not available in the Indian market. Moreover, we were blessed with additional information that there are no Solar cell manufacturers in India at all. All the solar cells are imported from Taiwan, China, and Canada and only converted into modules in factories of India. Also, prominent technologies in India are CdTe and Silicon Wafer. After researching some more, we found multijunction wafers from Spectro Labs, USA through a supplier in Nashik who imports these from the USA.

After procuring the solar cell, an investigation was carried out to identify terminals of the cell. A digital multimeter was used for the purpose. The terminals of the multimeter were made to contact various surfaces of the cell, and finally, terminals were identified on the side of the cells which are known as busbar.

2.1.2 Spherical Ball Lens

Ball lenses are great optical components for improving signal coupling between fibers, emitters, and detectors. They are also used in endoscopy, barcode scanning, ball pre-forms for aspheric lenses, and sensor applications. Ball lenses are manufactured from a single substrate and can focus or collimate light, depending upon the geometry of the input source. Half-ball lenses are also conventional and can be interchanged with full ball lenses if the physical constraints of an application require a more compact design.

After selection of a multijunction cell, research was carried out to identify appropriate material for the Spherical Ball Lens. The materials considered for the study were Acrylic, Crown Glass, Flint Glass, and Polycarbonate. There are five critical parameters needed to understand and use ball lenses:

1. Diameter of Input Source (d),
2. Diameter of Ball Lens (D),
3. Effective Focal Length of Ball Lens (EFL)
4. Back Focal Length of Ball Lens (BFL)
5. Index of Refraction of Ball Lens (n)

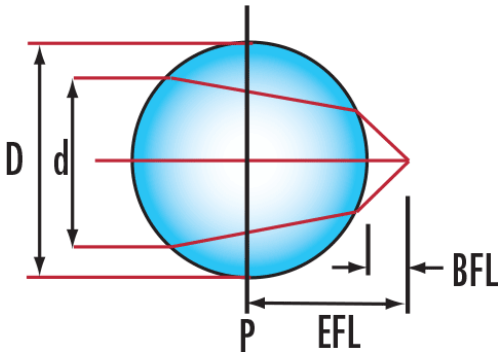

Figure 2.1 Different Parameters of a Spherical Lens

EFL is very simple to calculate since there are only two variables involved: Diameter of Ball Lens (D) and Index of Refraction (n). EFL is measured from the center of the ball lens, indicated by R in the Figure. BFL is easily calculated once EFL and D are known.

$$EFL = \frac{nD}{4(n-1)}$$ .....Equation (1)

$$BFL = EFL - \frac{D}{2}$$ .....Equation (2)

A comparative study of cost, refractive index, effective focal length, optical aberration, machinability, and market availability was carried out to determine the most suitable material. The following tables were plotted to determine suitable parameters for the system.

Table 2.1 BFL (Back Focal Length) for various lenses

BFL for various lenses				
	Acrylic	Crown Glass	Polycarbonate	Flint Glass (Impure)
D(mm) \ n	1.49	1.52	1.6	1.82
100	26.020408	23.077	16.67	5.488
120	31.22449	27.692	20	6.585
140	36.428	32.308	23.33	7.683
160	41.633	36.923	26.67	8.78
180	46.837	41.538	30	9.878
200	52.041	46.154	33.33	10.976

For optimum energy generation, we require the MJ Solar Cell to be within a distance range of 20mm – 30mm from the spherical lens to converge it at a single point on the cell. Acrylic fulfills this criterion, its cost is lower compared to other materials and is also more readily available across different markets. Crown Glass although within the prescribed range is not selected due to higher costing and non-availability factors. Other materials do not satisfy the required criteria as they focus the sun rays at a very short distance. Hence, Acrylic was chosen as the lens material keeping in mind the design, market availability, machinability and cost factors.

2.1.3 Circuit Description

2.1.3.1 ATMega 328 PU

An Arduino board consists of an Atmel 8-bit AVR microcontroller with complementary components that facilitate programming and incorporation into other circuits. An essential aspect of the Arduino is its standard connectors, which lets users connect the CPU board to a variety of interchangeable add-on modules known as shields. Some shields communicate with the Arduino board directly over various pins, but many shields are individually addressable via an I²Cserial bus—so many shields can be stacked and used in parallel. Most boards include a 5-volt linear regulator and a 16 MHz crystal oscillator (or ceramic resonator in some variants) and dispense with the onboard voltage regulator due to specific form-factor restrictions. An Arduino's microcontroller is pre-programmed with a bootloader that simplifies uploading of programs to the on-chip flash memory, compared with other devices that typically need an external programmer. This makes using an Arduino more straightforward by allowing the use of an ordinary computer as the programmer.

The ATMega 328 PU is a single chip micro-controller created by Atmel and belongs to the megaAVR series. The Atmel 8-bit AVR RISC-based microcontroller combines 32 KB ISP, flash memory with read-while-write capabilities, 1 KB EPROM, 2 KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes and internal and external interrupts. It also has a serial programmable USART, a byte-oriented 2-wire serial interface, SPI serial port, 6-channel 10-bit A/D converter (8 channels in TQFP and QFN/MLF packages), programmable watchdog timer with internal oscillator, and five software selectable power saving modes. The device operates between 1.8 - 5.5 Volts. The device achieves throughputs approaching 1 MIPS per Mhz.

2.1.3.2 Light Dependent Resistor (LDR)

A light-dependent resistor is a light-controlled variable resistor. The resistance of an LDR decreases with increasing incident light intensity, in other words, it exhibits photoconductivity. An LDR can be applied in light-sensitive detector circuits, and light and dark-activated switching circuits. The LDR is made of a high resistance semiconductor. In the dark, an LDR can have a resistance as high as several mega ohms (MΩ), while in the light, an LDR can have a resistance as low as a few hundred ohms. If incident light on an LDR exceeds specific frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electrons (and their hole partners) conduct electricity, thereby lowering resistance. The resistance range and sensitivity of an LDR can substantially differ among different devices. Moreover, unique LDRs may react substantially different to photons within certain wavelength bands.

A photoelectric device can be either intrinsic or extrinsic. An intrinsic semiconductor has its charge carriers and is not an efficient semiconductor, for example, silicon. In intrinsic devices, the only available electrons are in the valence band, and hence the photon must have enough energy to excite the electron across the entire bandgap. Extrinsic devices have impurities, also called dopants, and added electrons whose ground state energy is closer to the conduction band, since the electrons do not have as far to jump, lower energy photons (that is, longer wavelengths and lower frequencies) are sufficient to trigger the device. If a sample of silicon has some of its atoms repel by phosphorus atoms (Impurities), there will be extra electrons available for conduction.

2.1.3.3 Servomotor

A servomotor is a rotary actuator that allows for precise control of angular position, velocity, and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. It also requires a relatively sophisticated controller, often a dedicated module explicitly designed for use with servomotors. A servomotor is a closed-loop servomechanism that uses position feedback to control its motion and final position. The input to its control is some signal, either analog or digital representing the position commanded for the output shaft. The motor is paired with some encoder to provide position and speed feedback. In the simplest case, only the position is measured. The measured position of the output is compared to the command position, the external input to the controller. If the output position differs from that required, an error signal is generated which then causes the motor to rotate in either direction, as needed to bring the output shaft to the appropriate position. As the positions approach, the error signal reduces to zero and the motor stops.

The simplest servomotors use position-only sensing via a potentiometer and bang-bang control of their motor; the motor always rotates at full speed (or is stopped). This type of servomotor is not widely used in industrial motion control, but it forms the basis of the cheap and straightforward servos used for radio-controlled models. More sophisticated servomotors use optical rotary encoders to measure the speed of the output shaft and a variable-speed drive to control the motor speed. Both of these enhancements, usually in combination with a PID control algorithm, allow the servomotor to be brought to its commanded position more quickly and more precisely, with less overshooting.

2.1.4 Working of Circuit

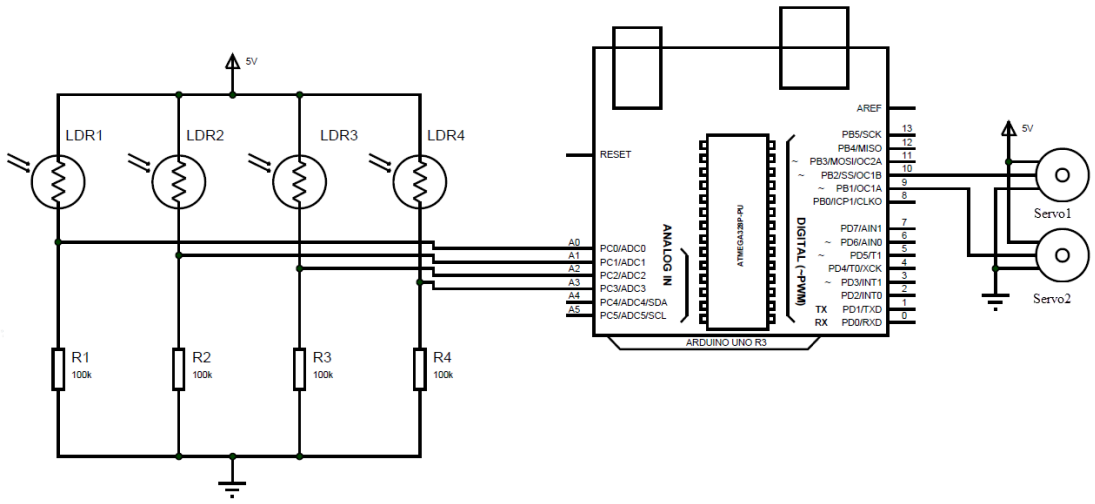

Figure 2.2 – Circuit Diagram of Tracking Mechanism

All the LDRs are connected to the Analog input from A0 to A3. The two servomotors are connected to digital output pin 9 and 10. Pins 9 & 10 are Pulse Width Modulation pins (PWM) which are required for operation of servomotors.

The microcontroller ATMega 328PU is a microcontroller with pre-loaded bootloader with Arduino. Programming was carried out using Arduino IDE with C language coding. The two servomotors are calibrated as Horizontal Servo and Vertical Servo. The default for Horizontal Servo is 180° and for Vertical 45°. When sunlight falls on LDR, the LDR with maximum intensity sends an input to the microcontroller. The microcontroller interprets this input and manipulates the servomotor to position the multijunction Solar Cell towards the position of the Sun for maximum Solar input.

III. RESULTS AND DISCUSSION

3.1 Observations

The apparatus was tested on a rooftop in broad daylight. The observations recorded during the several test rounds are recorded below in the form of a table.

Table 3.1 – Observations

Observation No.	Temperature (°C)	Distance between Cell and Lens (mm)	Voltage Recorded (V)
1.	30	24	4.5
2.	30	26	5
3.	30	30	4.7
4.	32	24	4.4
5.	32	26	4.8
6.	32	30	4.1
7.	34	24	3.7
8.	34	26	4.2
9.	34	30	3.9
10.	30	24	2.5
11.	30	26	2.5
12.	30	30	2.5

Since a cooling arrangement was not made for the cell, it was also noted that the efficiency of the system was decreasing due to repeated exposure to sunlight. The maximum voltage of 5 Volts obtained at 30°C at Focal Length was not obtained again. Instead, the maximum voltage obtained from the cell fell to 2.5 Volts and remained constant thereafter.

3.2 Results

The maximum voltage of 5 Volts obtained for a 10mm X 10mm sized solar cell is substantial compared to a traditional solar cell. A traditional cell of comparable size would produce a maximum of 1.2 – 1.5 Volts, which makes an MJ Solar Cell 3 – 4 times more efficient. It can be noted that for every degree rise in the operating temperatures after 30°C, the solar cell loses its capacity to produce high potential difference and hence a cooling system is mandatory to sustain the cooling cell for longer terms of usage at higher operating temperatures.

The motion of the Sun from 12 PM in the noon to 5 PM in the evening traced an arc of length 56mm at the focal length. Also, the arc moved towards the north with passing weeks. It can be concluded that the path followed by the Sun from sunrise to sunset is not the same every day but moves towards the northern pole. The acrylic ball lens used acted as an excellent lens to converge the sunlight to a point focus. The ball lens did not lose its form due to overheating, and the performance of the lens remained constant.

The tracker mechanism fabricated using ATMega 328PU functioned as expected. Only the integration of the LDR into the system to position both the LDR and the solar cell at the same position has to be researched. Sunlight is converged into a point focus, and there is not a lot of dispersed light around it. The LDR requires dispersed light around the focal point to activate and send signals to the microprocessor. Hence the integration can be a challenge that needs to be addressed.

IV. CONCLUSION

4.1 Optimum Voltage from Cell

From Table 3.1, it can be seen that the optimum voltage produced from the multijunction cell is 5 Volts. The current produced was 2.8mA. The multimeter did record a voltage from the cell even without the use of lens but the maximum voltage obtained

was 1.8 - 2.2 Volts which is less than half the capacity of the cell. Hence, the use of concentrated sunlight is mandatory for multijunction Solar Cells.

4.2 Proof of Concept

The project aimed to prove that solar cells used in space technology can very well be utilized for domestic applications, that a multijunction Cell is far more efficient than a traditional solar cell and that a spherical transparent ball can be utilized as a lens. Moreover, during the entire research, we have successfully demonstrated the same. Hence this project goes out as a proof of concept for the viability of clean energy. The system may look expensive at first, but with further research and development of the system, we believe, can be made feasible and cost-effective.

4.3 Scope for Future Work

The original property of the multi-junction cell is already so eminent a reason that one should not require any justification for its usage in energy production. However, sound engineering design can further enhance its functionality and aesthetic to make it an everyday household product. Some of the future developments in the system may include utilization of heat energy from the sun along with the light energy, a cooling mechanism to increase the sustainability of the product and a more extensive system with an array of cells instead of a single cell.

We know that the sun does emit not only light but also a tremendous amount of heat energy. A provision can be made to utilize this heat energy and further boost the capacity of the system. One of the ways to do so is by using a thermocouple or a sterling engine. The thermocouple is a device that converts a temperature difference into electric current directly. A sterling engine, on the other hand, is a type of engine that converts a temperature difference into reciprocating motion. This reciprocating motion using mechanical links can be used to crank an electric generator. Utilization of the heat energy will add to the total energy being converted by the solar cell and increase its energy output.

Since multi-junction solar cells are known to lose their capacity due to heating causing thermal runoff, the introduction of a cooling mechanism to keep the cell at optimum temperature can help the functionality of the cell. This can be done by something as simple as the use of water filled lenses which trap the heat of the sun and only let light pass through it. Another way to do this can be the use of a heat sink below the solar cell.

Use of multiple solar cells in the form of arrays will also undoubtedly be more feasible and cost-effective. Development of systems with more feasibility and adaptability to meet the requirements of different energy needs is the aim of the engineering process which is quite achievable. Systems in various sizes can be developed so that it can exist right from a desk to charge mobile phones to rooftops to power an entire complex of buildings.

4.4 Recommendations

While the above research is promising, there are currently limitations for widespread adoption. Heat is a major byproduct of converging solar rays on the multijunction cell. The heat causes thermal runoff in the multi-junction cell and limits the maximum output voltage. Hence, future research has to be done to limit the thermal runoff. Also, utilizing this excessive heat in a productive capacity is the way ahead for the transparent energy.

REFERENCES

[1] M. Riedl, Optical Design Fundamentals for Infrared Systems, Second Edition, SPIE Press, Bellingham, WA (2001), ISBN: 9780819440518, Volume: TT48, pg. 90-92

[2] Enss, Christian (2005), Cryogenic Particle Detection, Springer, Topics in Applied Physics 99, ISBN 3-540-20113-0

[3] Green, Martin A. (2003), Third Generation Photovoltaics: Advanced Solar Energy Conversion, Springer, pg. 65

[4] Haugan, H.J., Elhamri, S.; Szmulowicz, F.; Ullrich, B.; Brown, G.J.; Mitchel, W.C. (2008), Study of residual background carriers in midinfrared InAs/GaSb superlattices for uncooled detector operation, Applied Physics 92 (7): 071102. Bibcode: 2008ApPhL.92g1102H, DOI: 10.1063/1.2884264

[5] High Efficiency, Multi-Junction Solar Cells for large-scale solar electricity generation, Sarah Kurtz, APS March Meeting, 2006

[6] New World record for solar cell efficiency at 46%, French-German co-operation confirms competitive advantage of European photovoltaic industry, Fraunhofer-Institut fur Solare Energie Systeme ISE, Press Release 26/14, December 1. 2014, Bernin, France and Freiburg, Germany