# Design and Fabrication of Solar Tree

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***Abstract***

*Sunlight is the cleanest and most abundant energy resource in our world. Solar energy is also a "free" source of energy. The most popular method to harness solar energy is by using photovoltaic conversion technology, which converts solar energy into electricity.*
*The biggest problem with harnessing solar energy is the large amount of ground space required for the setting up of PV panels. To overcome this problem, the solar tree power generation method is proposed. This report focuses on the design and fabrication of a solar tree model for the generation of energy while considering various factors such as solar panel tilt angle, location, materials to be used, and the cost. The dimensions of branches, trunk, panels and other components are considered as used from standard components available in the market.*

*The designs' structural stability is validated by simulations using structural analysis software that use Finite Element Analysis (FEA). Panel placement and energy generation is based on solar simulations. Energy generation and panel tracking is implemented using IoT and open-source Arduino-based software.*

*The final designed model for a 0.6kW tree requires 0.196 $m^2$ of ground space. The fabricated prototype for 120 W tree requires 0.196 $m^2$ of ground space. The final cost was INR 57,100.*
*The designs are feasible for usage in any geographical locations, within limits.*

***Keywords:*** *Sunlight, Photovoltaic Cells, Solar Tree*

## 1. INTRODUCTION:

### 1.1 Background

Conventional sources of energy are bound to be extinguished in the near future. Moreover, they are the primary source of pollution. Hence, the shift towards non-conventional sources of energy has transpired. Non- conventional sources are produced continuously in nature and are considered inexhaustible. Hence, they can also be called renewable sources of energy. The various sources are wind energy, tidal energy, solar energy, geothermal energy, etc. Solar energy is the best, considering safety and feasibility, among all the other sources.

### 1.2 Solar Tree

Solar Trees are a blend of natural art and technology, where the panels are arranged as leaves on the branches of the tree. The proposed solar tree model aims to harness solar energy and maximize energy output by using the most efficient model with the layout of all leaves and panels positioned appropriately. The solar tree generates more electricity per unit area than ground-based PV cells and requires only 1% land as compared to the conventional flat arrangement, but conventional solar trees are expensive and unfeasible for renewable power generation compared to ground-based units. Therefore, the designed solar tree must balance energy generation while considering various factors such as cost, feasibility, energy generation, shading losses, ground space required etc, while also taking into account the movement of Sun throughout the year.

### 1.3 Working of Solar

**PV cells:**

PV cell is an electric component which uses the photovoltaic principle to convert sunlight into electrical energy. For this energy conversion, a material, usually silicon, which absorbs sun rays and increases the photon to enhanced energy state is used.

Solar cell (crystalline silicon) consists of N type semiconductor (Emitter), P-type semiconductor (Base), to form P-N junction. The surface is coated with anti-reflection coating to prevent loss of energy due to reflection.

### 1.4 Basic components of a solar tree:

1. Photo voltaic modules
2. Cables for connecting modules
3. Inverter
4. Batteries
5. Steel structure
6. Charging points/ LED’s

### 1.5 Advantages:

1. Less land requirement
2. Eco friendly
3. Helps to avoid greenhouse gases and pollution
4. Inexhaustible
5. Lower electricity cost
6. Low maintenance

## 2. LITERATURE SURVEY

### 2.1 Chapter Summary

Review of journal and conference papers, and utilising unique ideas presented by each, while focusing on the methodology of each paper to combine and improve the collective ideas.

### 2.2 Literature Survey

Dey and Pesala[1] proposed a location-specific design for maximized energy output from a tree, while using minimal structural materials. The dimensions of branches and trunk were optimised after conducting stress analysis to find structural stability. They then identify various methods of orienting and position of panels to maximise energy generation. The shading losses and effects are identified, and then modifications are made to reduce these losses. By increasing branch length and reducing the distance between layers, shading losses are reduced, but this also causes more strain on the trunk.

Hydera *et al* [2] designed a Solar PV Tree using a three-dimensional structure which replicates natural trees. The main idea of this solar tree is to reduce ground space required in urban areas and to generate electricity using clean methods. By using PVGIS simulation software, a 5kW solar PV tree and a 5kW land-based setup were compared, and it was found that the solar PV tree was more efficient due to less shading loss, and could also be further improved by adding more panels as the tree required less area. The energy yield of various existing trees was compared based on various factors such as cost, location, energy generation, stability, material availability, complexity etc, to find the most cost-effective tree design. The spiral structure was found to be most effective at energy generation, but would also require the most maintenance and material requirements.

Hyder *et al* [3] considered six different semidome shape solar PV structured, with each design having an increasing number of layers and panels. The performance of the trees at three locations, namely Kuala Lumpur, Bhopal, and Barcelona were compared and analysed through simulation. The tilt angle for the solar PV tree structure is varied from 0-46°, as the Sun's elevation angle varies by 46 degrees around a location during a year. It was found that by increasing the number of layers would increase land footprint due to the radius of semi-dome structure would increase and would also increase the number of panels. More energy could be generated, but the drawback was the large amount of shading losses on the bottom panels. It was also confirmed that the efficiency of the setup in various locations would vary due to the local weather conditions and sun angles.

Ahmed *et al* [4] designed and fabricated a 120W Solar Tree Structure Power Generation pilot plant for efficient LED street lighting. The entire structure was designed based off a 12-panel system. The total cost for the tree after fabrication was approximately Rs. 50,000. The battery power required was calculated for days without sufficient lighting. A charge controller was also integrated to stabilize power input and output and control LED lighting when required.

Madhavan and Subash [5] designed a sun tracking system using an Arduino control mechanism connected to two LDRs and Atmega-based microcontroller. By using a sun tracking device, it ensures that the panels are always faced towards the sun throughout the day. They also implemented a cleaning device using a high-speed motor to blow dust off the panels. If there is dust on the panels, energy generation is hampered.

Baci *et al* [6] proposed a new model (solar tree) compared to the traditional ground-based one-panel system. The performance of photovoltaic systems is strongly affected by climatological parameters (solar radiation and temperature) and by the type of solar cell. The optimum angle of inclination is found to be 35°deg in Algeria, where the study was conducted. In the same ground space, the power generated by a solar tree is greater than the ground-based panel by almost 20%.

### 2.3 Literature Survey Summary

Various existing models were compared, and trees with less shading loss were considered most efficient. The trees also must be structurally stable and should be resistant to the elements and long-time use. Von Mises Structural Analysis was carried out to ensure structural stability.

Solar simulations were carried to find optimum angles for solar panels to minimise shading lose and maximise energy generation.

By using ideas from all papers, a solid structure was designed while considering all the pros and cons.

The focus was on the material used, structural stability, and shading loses.

### 2.4 Gaps in literature

Using only steel is expensive. By using alternate materials like PVC and aluminium, cost is reduced, and the weight of tree is also lesser.

- One design is not suitable for all environments, the same design is considered for all locations, and the efficiency is varied.
- Inverter losses due to misalignment of panels, which leads to different I-V and P-V curve. This results in severe losses in solar-to-DC conversion efficiency.
- The literature does not account for locations with irregular sunlight.
- Overheating of panels decreases efficiency, so they require a cooling system**.** This reduces power output.
- Multiple papers do not consider shading losses when orienting panels. The larger the shading loss, lesser the energy which can be generated.

## 3. DESIGN PROCEDURE:

### 3.1 Objectives:

The objectives of Solar Tree are:

- To use solar trees as an alternative to ground-based solar cells to reduce ground space in urban areas
- To enhance the efficiency of solar PV systems using a three-dimensional structure replicating a natural tree.
- To reduce energy used and electricity costs.
- To display various outputs such as voltage, energy generation etc.
- To provide shade as well as generate power by using aesthetic design.
- To raise awareness about renewable and sustainable energy.

### 3.2 Methodology Adopted:

- Step-1: Literature survey
- Step-2: Choosing Optimal design and designing the model
- Step-3: Performing calculations, Analysis, and simulations on the designed model
- Step 4: Create miniature prototype (1:6 scale) to observe shading losses and check panel tilt mechanism
- Step 5: Fabrication of working prototype (1:2 scale)
- Step 6: Integrate live-tracking of energy generation and battery status

**Design**

The prototype was designed after taking into all previous problems. This time the material used is cold rolled cold annealed steel. The metal is rolled in temperatures below its recrystallization temperature. CRCA material are harder and have a smooth finish. This design was considered for a 6-panel system. The height of the trunk is 4.27m, to allow for sufficient ground clearance. The trunk is mounted on a base plate which is then bolted into a concrete stand.

The panels are arranged in a 2 layers system. The bottom layer is at a height of 3m and the upper layer is at 4m, with 1m gap between the two layers. Using 2 layers reduces the stress on the trunk from all 6 branches at the same point radially. The branches in the upper and lower layer are angled at $60^0$ to each other, with the branches in the same layer angled to each other at $120^0$.

The branches are all I-beams140cm in length to allow for sufficient space between panels in equal intervals around the hexagonal base, and are supported by a T-Beam of length 70cm.

Fig 1. Isometric View

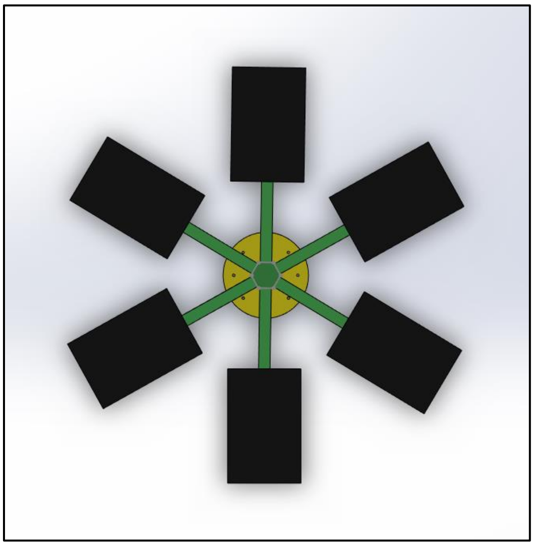


Fig 2. Top View

All the panels were oriented with their shorted sides place perpendicularly to the branches. The solar panels used are of the company Luminous, with dimensions 103.5cmX67cm and a thickness of 3.4 cm. Each solar panel has 72 cells of Silicon polycrystalline.

**Table 1. Part Dimensions for Final Tree**

| Part | Dimensions (in cm) | | |
|---|---|---|---|
| | L | W | H |
| Solar Panel | 103.5 | 67 | 3.4 |
| T-Beam | 70 | 6 | 6 |
| I Beam | 140 | 6 | 9 |
| Trunk | L - 424 cm | Thickness- 1cm | |
| Base Plate | Diameter -50cm | Thickness- 3cm | |

*The dimensions (**Table 1**) for all parts of tree are standardised, and can be found available in the market.*

**Structural stability**

This design was found to be the most structurally stable. It was observed the minimum FOS (**Fig 3**) was 1.83 at the point where the T-beams were supporting the main I-beam. The maximum FOS was found to be 15 at the base and apex of trunk. The maximum stress (**Fig 4**) observed was at the supporting point, with 153.21 MPa.

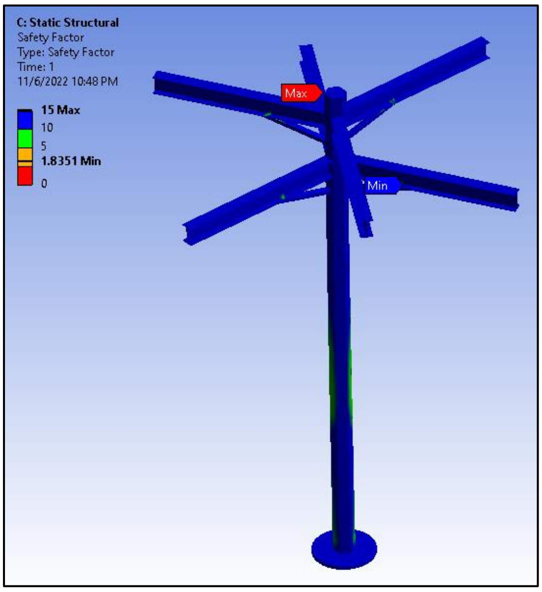



Fig 3. FOS

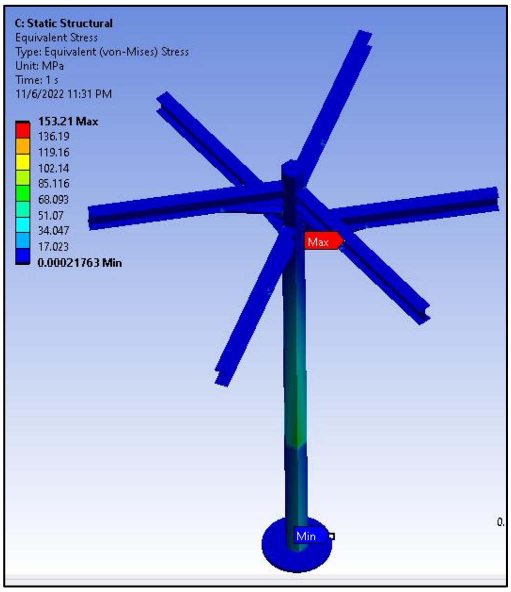



Fig 4. Stress Plot

**Shading Losses**

Shading losses were calculated using PVSOL software, which is a simulation tool for sunlight on PV cells. Sunlight was simulated for an average year in Bangalore.

After analysis, it was observed that on average 13-18% (**Fig 5)** shading losses occurred in a year on this design. The South panel had the least at 13.2%, followed by the NW panel with 13.5% and the NE panel with 17.6%. The shading loss is considerable and the performance ratio dropped to 67%. Only the lower panels suffer from shading loss, the upper panels have negligible shading loss.

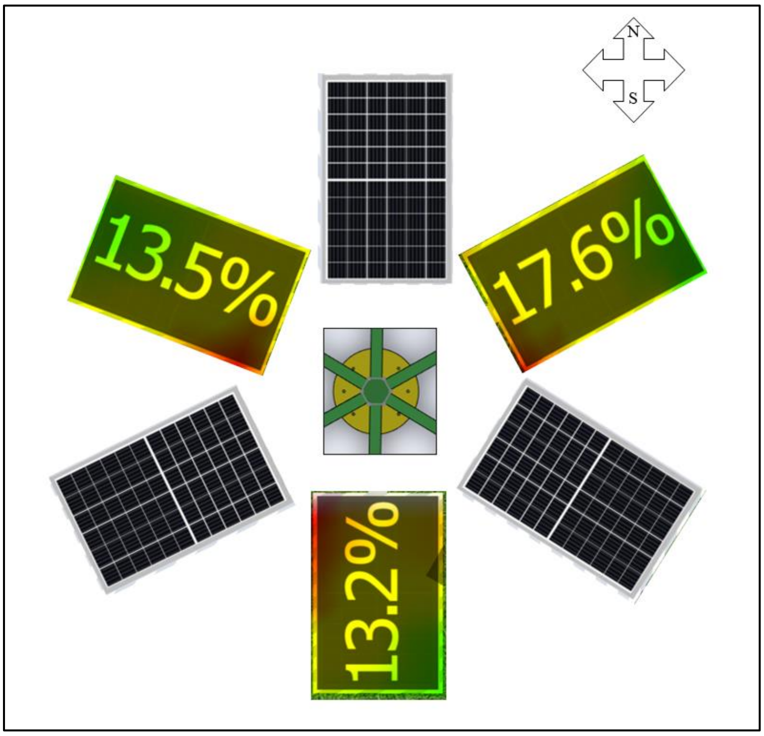



Fig 5. Shading Loss

### Improved Design

The final design (**Fig 6, 7 & 8**) is an improved model of the earlier design. By concluding the structure, itself was stable enough, all the structural specifications were kept same.

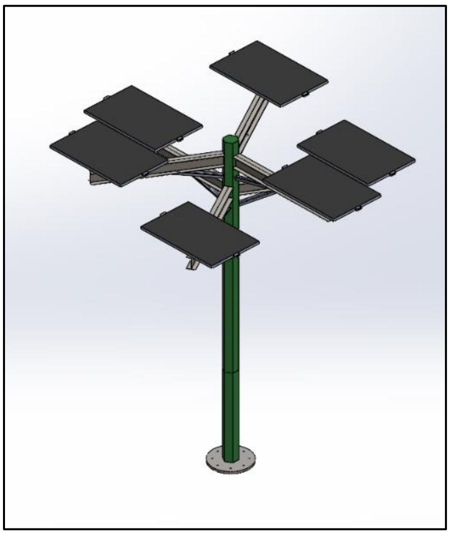


Fig 6. Isometric View

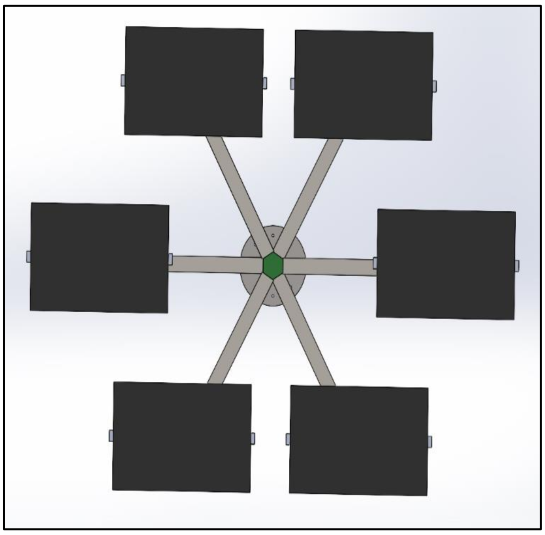


Fig 7. Top View

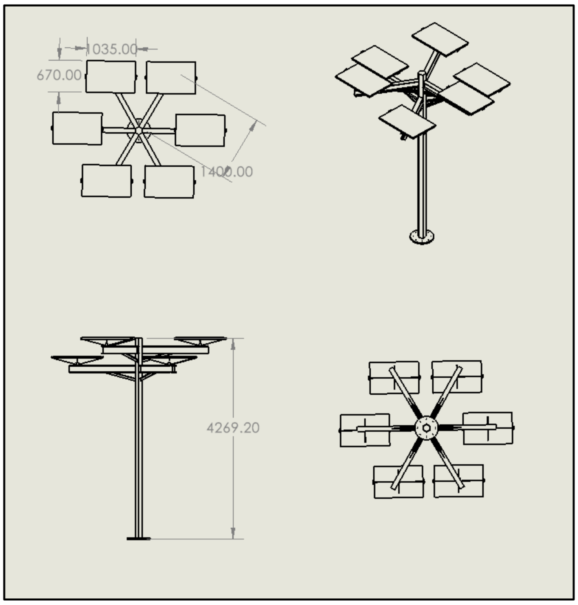



Fig 8. 2-D Drawing View

### Panel Orientation

One change was made from the previous model. All the panels are placed tilted oriented towards South. By doing this, shading loss (**Fig 9**) was reduced by 70%. The northmost panel had the least shading loss at 0.4%, followed by the SW at 3.4% loss, and 4.3% loss. The performance ratio increased to 80%.

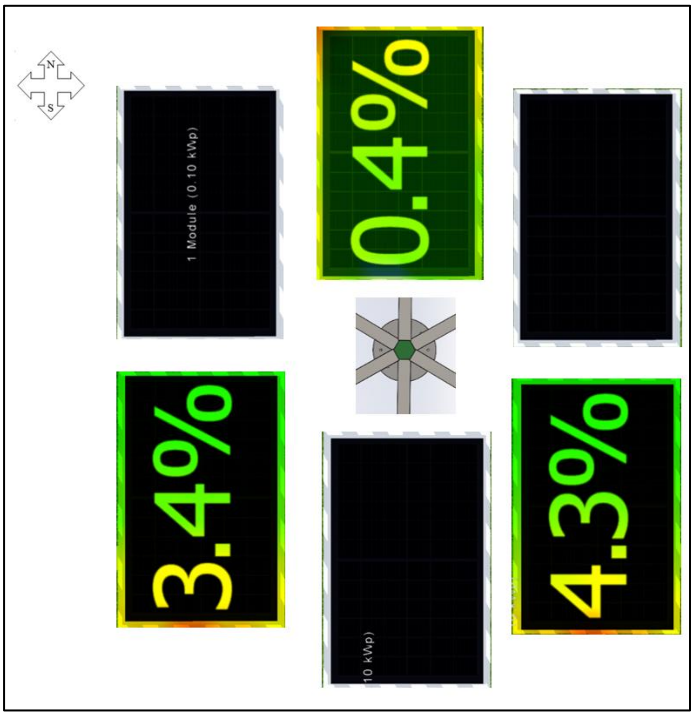



**Fig 9. Shading Loss**

**Shading Effects**

Shading loss is the result of electrical losses in interconnected PV modules due to the shadow of another adjacent module. The obstruction blocks direct sunlight from falling on the solar cell and hence, curbs electrical output.

The aim of this design is to minimise the effect of shading loss on adjacent panels. The panels are arranged around the main trunk in 2 layers, at equal intervals of $120^0$ in each layer, and $60^0$ with respect to each other when seen from directly above. By equally spacing out the panels, this ensures that at any point the maximum shading is 3-5%.

To further reduce the effects of shading loss, each panel is connected in parallel electrical circuits to ensure they generate electricity individually and the shading effects of one panel will not be carried on to the other.

The 6 panels are connected in parallel, so that each will have its own current. The current is added and is passes through the charge controller to stabilise output. When wired in parallel, the system is able to have 6 panel system, instead of the conventional single panel, without exceeding the operating voltage limits of the inverter(since voltage does not add up in parallel). By wiring solar panels in parallel, this ensures that inverter limitations are met. Even if one panel is under shadow, which is when maximum current is not obtained, it does not affect overall system. Therefore, the system achieves its maximum power point(MPP).

**Wind Simulation**

By using SOLIDWORKS flow simulation, wind simulations (**Fig 10**) were carried out at speeds of 175km/hour to check stability of structure at extreme wind conditions.

Considering the inlet and outlet walls around an imaginary box of sides 10m around the tree as the boundary conditions and considering the base as fixed support, analysis was carried out.

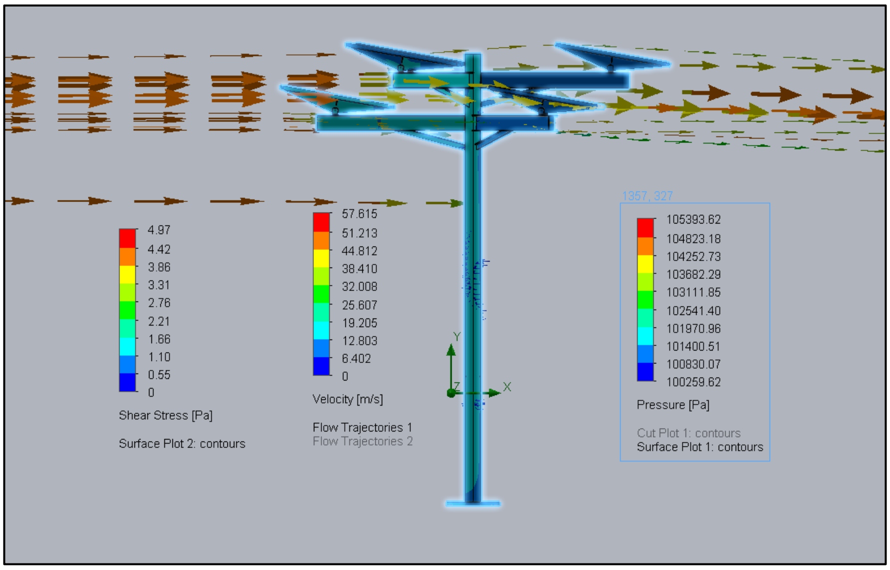



**Fig 10. Wind Simulation**

On simulating wind in all directions, it was concluded that the most wind resistance was when wind direction flows from north to south. This is due to the tilting of panels towards south, so the underside of the panels is angled against the direction of wind.

At speeds of up to 175kmph, the maximum stress and the maximum pressure observed was 4.97 Pa and 105.4 KPa respectively at the panel mounts. As the bending strength of CRCA steel is upwards of 340MPa, this results in negligible bending.

**Energy Generation**

An average year in Bangalore enables the solar tree setup to generate 9895kWh.

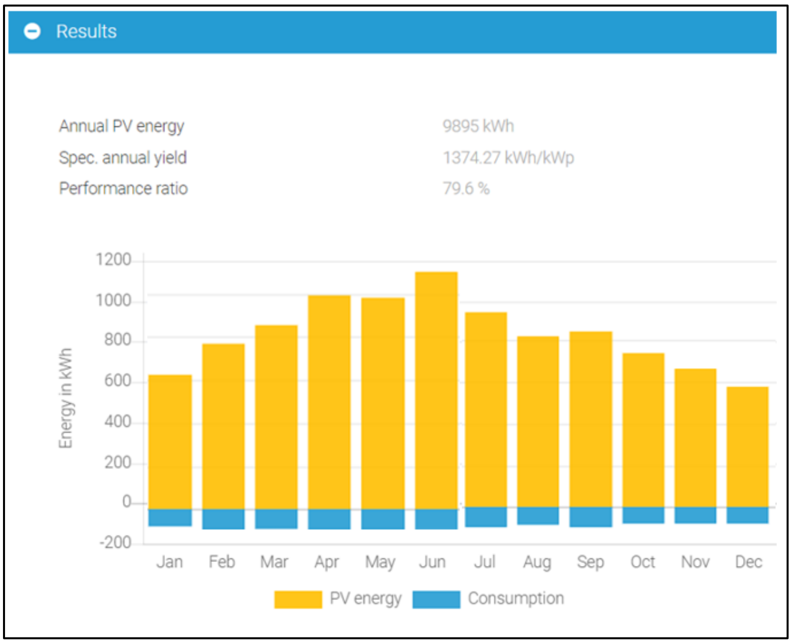



**Fig 11. Energy Generation**

It was found that 1022kWh was consumed annually, out of which 862kWh was generated through PV cells.
It was also found that more than 5000kg/year of $CO_2$ emissions were avoided due to clean energy generation by using PV cells instead of conventional methods.

For the initial design, a 6-panel setup was selected. By calculating average usage of various devices throughout a day, the electrical requirement was found to be around 2.8kW-h/day, and through load calculation, it was verified that 6 panel system each of 100W would be sufficient.

### 3.4 Fabrication of Working Protype

A working prototype was designed and fabricated. Using sheets of CRCA standard dimensions of 4mm, 6mm and 8mm, all parts were laser cut using CNC machines. All electrical components are also up to market standards. The solar panels used are Luminous 20W (45X35 cm). A 12V Lead Acid battery is used to store electricity.

**Table 2. Part Dimensions of Solar Tree**

| Part | Dimensions (in cm) | | |
|---|---|---|---|
| | L | W | Thickness |
| Solar Panel | 45 | 35 | 1.5 |
| I Beam | 63 | 8 | 0.4 |
| T Beam | 48 | 2.5 | 0.4 |
| Trunk | L - 190 | | Thickness- 0.6 |
| Base Plate | Diameter -50 | | Thickness- 0.8 |
| Total Cost (Including cutting and fabrication) | | | 30000 |

**Table 3. Components for Prototype**

| S. No | Component | Quantity | Cost |
|---|---|---|---|
| 1 | Solar panels(20W) | 6 | 8100 |
| 2 | Solar Charge Controller | 1 | 1900 |
| 3 | Inverter | 1 | 6000 |
| 4 | Electrical components (IoT) | 1 | 5000 |
| 5 | Battery | 1 | 4000 |
| 6 | Motors | 3 | 2100 |
| Total | | | 27100 |

*All components are available in the market up to industrial standards.*

### 3.5 Rotating Panel Mechanism

Conventional solar panels are stationary, and do not rotate. This hinders energy generation during certain periods. Throughout the year, the angle of sunrays falling in an area changes. To counter this, a rotating bracket mechanism was designed.
The panels are mounted on the rotating mount using screws. An Arduino system is used for rotating the panels. Currently, the panels rotate seasonally (every 3 months). This minimises the energy required for tilting mechanism, while also ensuring the panels are faced towards the sun for most of the season.
The panels tilt $36^0$ in winter, $13^0$in spring, $0^0$ in summer, and $13^0$ in monsoon. By

incorporating a tilt mechanism, shading loss is also further reduced.
By tilting panels every 3 months, it minimises energy losses while maximising energy generation seasonally.

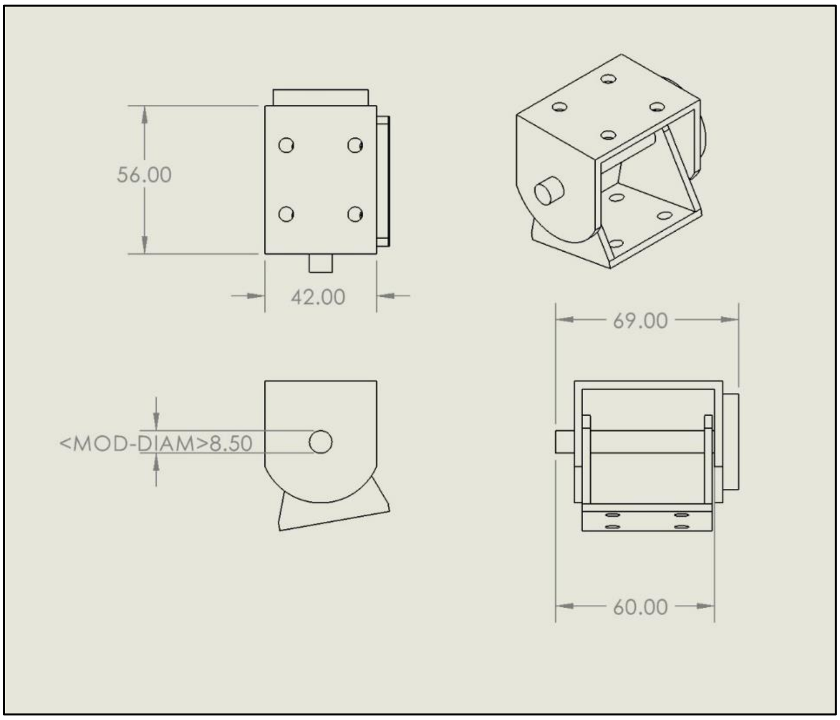



**Fig 12. Tilt Mechanism**

# 4. RESULTS & DISCUSSION

## 4.1 Chapter Summary

This chapter discusses the results obtained by performing analysis and simulations on software, and highlights the final product. The results obtained are based on the structure's FOS, stress and strength. The software used to obtain these results are, SOLIDWorks, Ansys Fluent and PVsol. It highlights extra features implemented such as solar panel tilting, data tracking, street lighting and seating.

## 4.2 Structural Stability

Using Ansys and SOLIDWorks, solid structure was obtained with a minimum FOS of 1.8 and maximum FOS of 15. The maximum stress observed is 153MPa. The tensile strength of CRCA steel is 1.47GPa. Therefore, the structure is very stable.
The tree structure was able to withstand extreme wind conditions of up to 175kmph easily with almost negligible bending.

## 4.3 Shading Losses Reduction

Using PVSOL, solar analysis was conducted and shading losses were found. By angling all panels in the same direction, shading losses were reduced by almost 70%. This increased performance ratio from 67% to 80% with an overall of almost 1600kWh more generated per year.

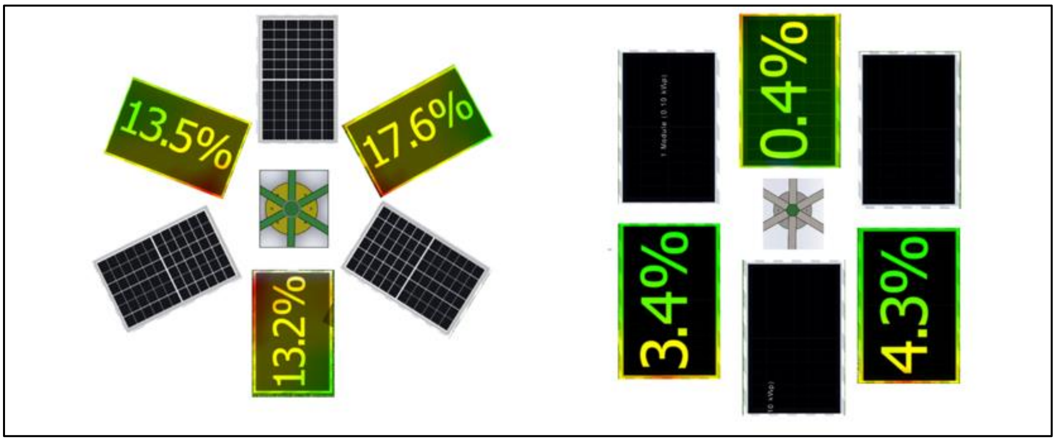


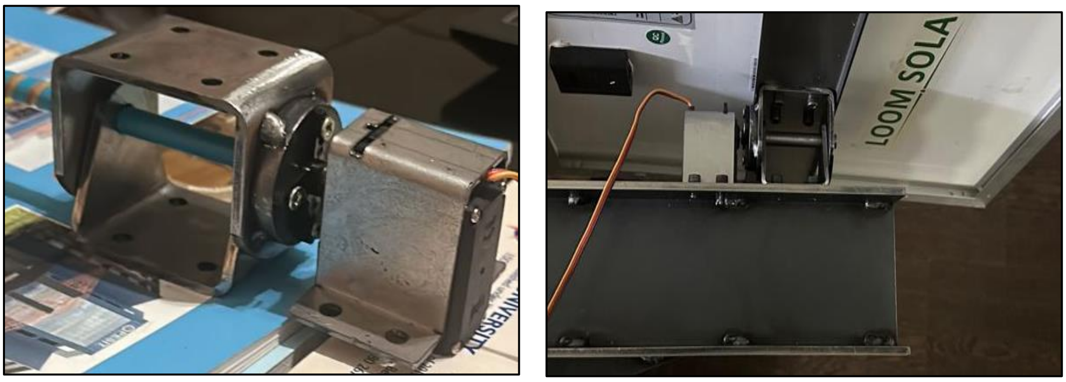

**Fig 13. Shading Loss Comparison**

### 4.4 Final expenses

The electrical equipment costs around Rs. 27,100 and the fabrication of metal parts costs around Rs. 30,000. This amounted to a total of Rs. 57,100. (**Ref. Table 2 & 3**)
Estimated cost for final design amounts to Rs 95,000.

### 4.5 Rotating Panel Mechanism

A rotating panel mechanism is used. To achieve this mechanism, a servo motor of 8kg holding torque is used.




**(a) Isometric View** **(b) Under Panel View**

**Fig 14. Tilt Mechanism**

For larger panels in the final model, the panels would require a motor of 15kg torque, and would require more energy.
The panels tilt $36^0$ in winter, $13^0$in spring, $0^0$ in summer, and $13^0$ in monsoon. By incorporating a tilt mechanism, shading loss is also further reduced.

The tilt mechanism is automated, and panels are tilted seasonally. Currently it is not feasible to tilt the panels at shorter intervals, but on using larger panels with more energy output, it would be possible to incorporate sun-tracking mechanism.
By incorporating sun tracking, panels automatically follow the sun throughout the day so that maximum energy is always generated.

**4.6 Data collection using IoT**

IoT is integrated along with the tree to collect live data of the solar panels at any point of time. The data includes information of the tilt angle for the solar panels, voltage and current running through the panels and the energy stored in battery. This information is stored and analysis can be made on it to come up with solutions that can help improve the efficiency of power generation.

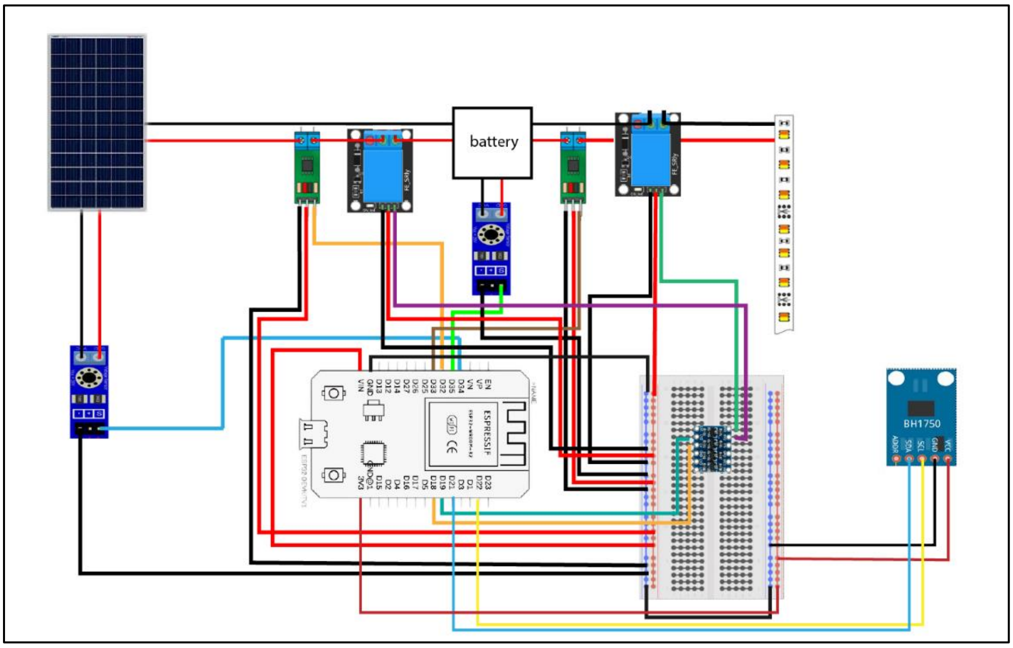



**Fig 15. Circuit diagram for data collection using IoT**

The webpage (**Fig 16**) tracks the battery status, power generated from each panel, the voltage, current, and the amount of light intensity. The user is able to identify if any panel is unoptimized.

The user is also able to check if there is sufficient voltage in the circuit. This is the charging time for the battery. When there is suboptimal lighting, the circuit generates less than 4V and a signal is sent and the battery discharges. This results in the LED lights lighting up due to low lighting.

Data is collected every 15 seconds, and the user is able to connect their device to the Wi-fi repeater in the solar tree and can open the webpage remotely later.

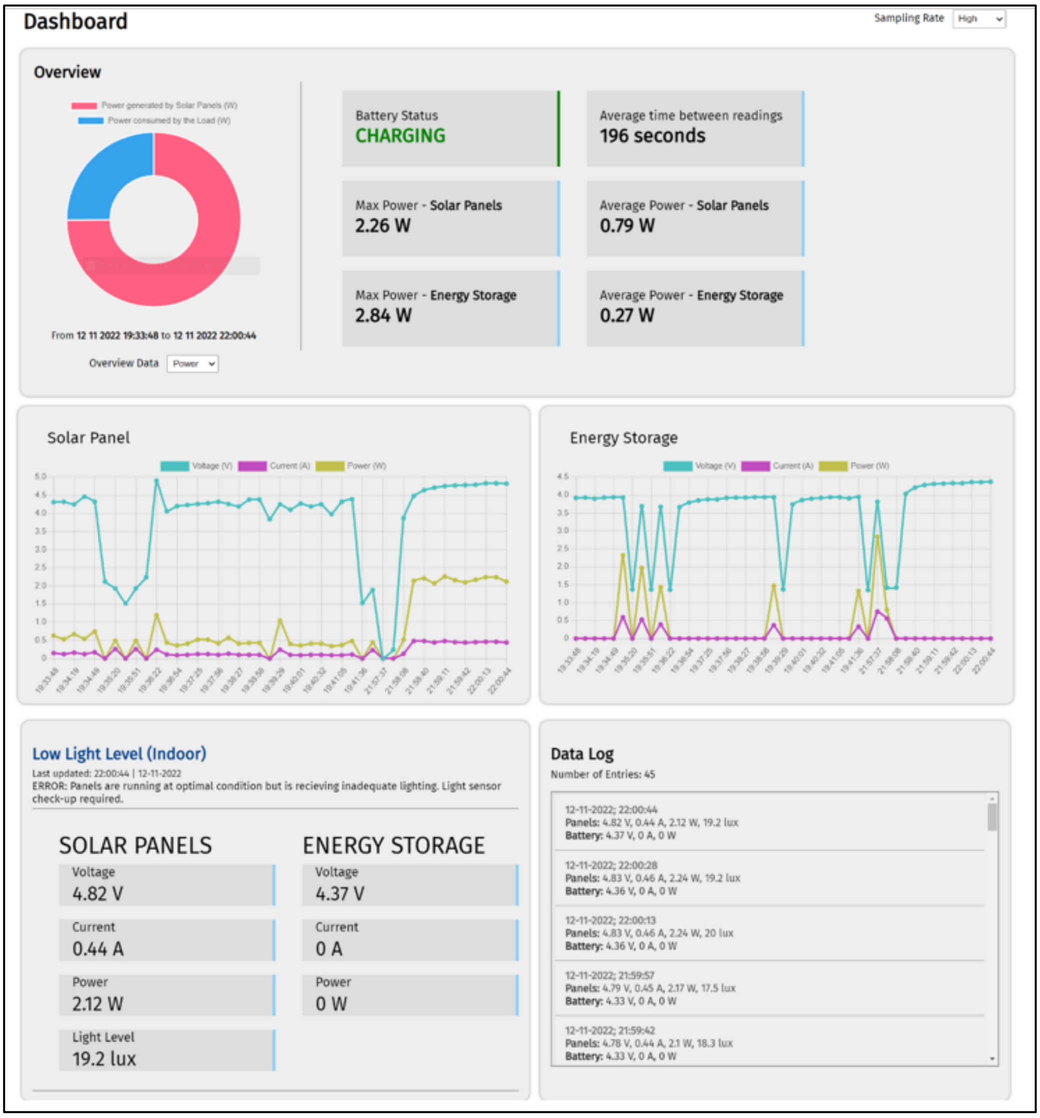



**Fig 16. Web Page for Data Monitoring**

### 4.7 Street Lighting

Using the same battery charging system and a Luxmeter, the system charges when there is sufficient lighting. When the luxmeter detects low amount of light, the battery stops charging. It then acts as the source and powers LEDs which light up.

The battery charges during the day in strong sunlight, and at night, the battery discharges, and powers the LED strips stuck onto the tree, providing light. This can be used for street lighting, or as an alternative to lampposts in parks.

### 4.8 Safety

To ensure safety, various precautions have been taken:

- Industrial standard wires with rubber insulation have been used. On the exterior of the tree, insulation pipe has been used to cover wiring from elements.

- Battery, inverter, charge controller and other electrical components are covered by the wooden seating at the base of trunk
- MCB is used to protect from short circuiting.

**4.9 Seating**

A hollow wooden box for seating has been added. The cube has dimensions of 76.2cm(2.5ft) and can be opened and locked with a clamp mechanism. The box covers all the electronic components, i.e., the battery, inverter, charge controller.
There is a clearance fit hole for trunk, and acts as a seating area under tree.
Plug points are provided for charging electronics.

**4.10 Fabricated Prototype**

The final prototype which generated 0.12kWh was fabricated.
The final prototype is 190cm tall and covers a ground space of 0.577 $m^2$ (including the base seat) and 0.196$m^2$ without seating.


(a) (b)

**Fig 17. Fabricated Prototype**

## 5. Conclusion, Scope for Future & Improvements To be Made:

**5.1 Conclusion**

- A working scale down prototype was fabricated, which can produce a peak power of upto120W-h.
- Solid structure was obtained with a minimum FOS of 1.8 and maximum FOS of 15, with high stability even in wind speeds of up to 175kmph.
- A tilt mechanism for solar panels was implemented
- Minimal shading loss of 3-5% was obtained by optimising design
- Live data-logging through IoT was achieved and displayed on a webpage

### 5.2 Future Scope

At the ‘Energy for Sustainable Growth’ webinar in March 2022, Prime Minister Narendra Modi said that installing a solar tree in every home saves around 15-20% on energy bills and energy usage. He also urged architects and builders to include concepts of solar tree while designing and constructing.

The National Solar programme by the government promotes ecologically sustainable growth to address India’s rising ever rising population and energy needs.

### 5.3 Improvements to be made:

Currently, the prototype tree generates only 0.12kW. The seasonal panel-tilting mechanism could be improved by implementing sun tracking, but this would require more energy generation throughout the day. Therefore, while sun-tracking is not feasible on the prototype, it would be feasible on the final tree model.

By improving the design to make the tree more versatile so that it can be used in multiple environments depending on the requirements.

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**Shyle Shaju**
**Sohan R Katare**
**Sujan Chowdary**


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