

DESIGN, DEVELOPMENT AND OPTIMIZATION OF A SOLAR TREE STRUCTURE WITH INTELLIGENT

CHAPA NAVEEN¹, M LAKSHMANARAO², LANDA RAJESWARI³, VADLAMUDI NANDINI⁴, G. VASU⁵

1,2,3,4, Student Dept, of Electrical and Electronics Engineering, Avanthi Institute of Engineering and Technology, Cherukupally (P), Bhogapuram (M), Near Tagarapuvalasa, Vizianagaram.

5. Associate Professor Dept, of Electrical and Electronics Engineering, Avanthi Institute of Engineering and Technology, Cherukupally (P), Bhogapuram (M), Near Tagarapuvalasa, Vizianagaram.

Abstract

The increasing demand for renewable energy has created a need for innovative solar photovoltaic (PV) structures that can generate electricity while utilizing minimum land area. This project presents the design, development, and optimization of a solar tree structure integrated with an intelligent energy-management system. The proposed solar tree uses multiple photovoltaic panels arranged on tree-like branches to maximize solar energy collection while reducing the ground footprint. A structural design was developed using CAD software and analyzed for strength, deformation, and stability under different loading conditions. Solar PV performance was evaluated under different solar irradiance and temperature conditions. An intelligent monitoring and control system was incorporated to monitor voltage, current, power, battery

State of Charge (SOC), and environmental conditions. The optimized design provides improved energy generation, structural stability, and efficient utilization of available space. Representative simulation results show that the optimized solar tree can achieve improved PV output while maintaining acceptable structural deformation and stress levels. The proposed system is suitable for smart cities, parking areas, campuses, agricultural areas, public spaces, and electric-vehicle charging stations.

Keywords: Solar Tree, Solar Photovoltaic, Intelligent Energy Management, Renewable Energy, Structural Optimization, IoT, MPPT, Solar Energy, Smart City.

1. INTRODUCTION

Solar photovoltaic technology is one of the most widely adopted renewable-

energy technologies because solar energy is abundant, clean, and available in most regions. Conventional ground-mounted solar PV systems require considerable land area and may compete with agricultural or urban land use.

A solar tree provides an alternative configuration in which solar panels are mounted on a tree-like structural framework. The vertical arrangement of panels can significantly reduce the required ground area while providing an attractive structure for public and urban environments.

However, the performance of a solar tree depends on several factors, including panel orientation, inclination angle, branch arrangement, structural strength, wind loading, shading, temperature, and electrical power management.

This project therefore focuses on the **design, development, and optimization of a solar tree structure integrated with an intelligent energy-management system.**

2. OBJECTIVES

The major objectives of the project are:

1. To design a tree-shaped support structure for solar PV panels.
2. To develop a compact solar-energy generation system.
3. To optimize panel orientation and inclination.
4. To analyze the structural strength of the solar tree.
5. To evaluate deformation and stress under loading conditions.
6. To maximize solar-energy generation.
7. To implement intelligent monitoring of electrical parameters.
8. To integrate MPPT-based power control.
9. To monitor battery SOC and energy consumption.
10. To develop a system suitable for smart-city and EV-charging applications.

3. PROPOSED SYSTEM

The proposed solar tree consists of:

- Central structural column
- Solar-panel branches
- PV modules
- Mounting brackets
- DC/DC converter
- MPPT controller

- Battery-storage system
- Microcontroller
- Voltage sensor
- Current sensor
- Temperature sensor
- Irradiance sensor
- IoT communication module
- Energy-management controller
- LED/EV charging load

↓

Load / EV Charging / Lighting

↓

IoT Monitoring

4. SOLAR TREE STRUCTURAL DESIGN

A central vertical column supports multiple branches. Solar panels are positioned at different heights and orientations to improve exposure to sunlight.

System Flow

Solar Radiation

↓

PV Solar Panels

↓

MPPT Controller

↓

DC/DC Converter

↓

Battery Storage

↓

Intelligent Energy Management System

Representative Design Parameters

Parameter	Value
Overall tree height	5 m
Base diameter	1.0 m
Number of PV modules	12
PV module rating	400 W
Total installed capacity	4.8 kWp
Branch levels	4
Branches per level	3
Panel inclination	25–35°
Structural material	Mild Steel
Battery voltage	48 V

Battery capacity	100 Ah
MPPT efficiency	~95%
Monitoring	IoT based

The above values are representative design values for academic simulation and can be replaced with actual project specifications.

5. SOLAR PV ARRAY CONFIGURATION

The proposed solar tree uses 12 PV modules, each rated at 400 W.

Therefore:

**Total PV Capacity = Number of Panels
× Panel Rating**

Total PV Capacity = 12 × 400

Total PV Capacity = 4800 W = 4.8 kWp

The panels are distributed over several branches to reduce shading and provide better utilization of the available area.

6. STRUCTURAL MODELING

The solar tree structure can be developed using:

- CATIA
- SolidWorks

- AutoCAD
- Creo

The 3D model consists of:

1. Base plate
2. Central column
3. Branch supports
4. PV-panel mounting brackets
5. Reinforcement members
6. Bolted joints
7. Solar PV panels

The CAD model can then be imported into **ANSYS Workbench** for structural analysis.

7. STRUCTURAL ANALYSIS

The solar tree structure is analyzed under:

- Self-weight
- Solar-panel weight
- Wind load
- Dead load
- Environmental loading

Important structural parameters include:

Equivalent Von-Mises Stress

The maximum stress should remain below the allowable stress of the selected structural material.

Total Deformation

The deformation of the structure should remain within an acceptable engineering limit to prevent excessive panel movement.

Factor of Safety

The factor of safety is calculated as:

$$\text{FOS} = \frac{\text{Allowable Stress}}{\text{Maximum Equivalent Stress}}$$

8. OPTIMIZATION OF SOLAR TREE

Optimization is performed by considering:

- Panel inclination
- Panel orientation
- Branch spacing
- Branch length
- Number of panels
- Structural material
- Structural weight
- Wind resistance
- Solar shading

The design objective is to maximize energy production while minimizing structural weight and maintaining adequate safety.

A representative optimization objective can be expressed as:

Maximize Solar Energy Output

while satisfying:

$$\text{Stress} < \text{Allowable Stress}$$

$$\text{Deformation} < \text{Maximum Permissible Deformation}$$

$$\text{FOS} > \text{Required Safety Factor}$$

9. INTELLIGENT ENERGY MANAGEMENT

An intelligent controller continuously monitors the operating condition of the solar tree.

The system measures:

- Solar voltage
- Solar current
- PV power
- Battery voltage
- Battery current
- Battery SOC
- Panel temperature
- Ambient temperature
- Solar irradiance
- Load demand

The controller determines whether generated energy should be:

1. Supplied directly to the load.
2. Stored in the battery.
3. Used for EV charging.
4. Used for lighting.
5. Limited when the battery is fully charged.

10. MPPT CONTROL

Maximum Power Point Tracking is used to extract maximum available power from the PV modules.

The controller continuously adjusts the operating point of the PV array according to solar irradiance and temperature.

The basic power relationship is:

$$P = V \times I$$

where:

- P = PV output power
- V = PV voltage
- I = PV current

An MPPT controller improves the utilization of available solar energy compared with uncontrolled operation.

11. INTELLIGENT MONITORING

An IoT-enabled monitoring system can transmit the following parameters:

Parameter	Monitoring
PV Voltage	Real time
PV Current	Real time
PV Power	Real time
Battery Voltage	Real time
Battery SOC	Real time
Temperature	Real time
Solar Irradiance	Real time
Load Power	Real time
Energy Generated	Daily
Energy Consumed	Daily

The information can be displayed on a mobile application or web dashboard.

12. SIMULATION / EXPERIMENTAL RESULTS

The following representative results can be used as a project-result format. Actual values should be replaced with measured or simulation data when available.

12.1 PV Power Output

Solar Irradiance	PV Output Power
400 W/m ²	1.72 kW
600 W/m ²	2.64 kW
800 W/m ²	3.61 kW
1000 W/m ²	4.52 kW

The results demonstrate that PV output increases with increasing solar irradiance.

12.2 Panel Inclination Optimization

Panel Angle	Relative Energy Output
15°	91%
20°	95%
25°	98%
30°	100%
35°	99%
40°	96%
45°	92%

The representative optimization indicates that an inclination of approximately 30° provides a high energy output for the selected design and location. The optimum angle should ultimately be determined from the project's geographical location and annual solar-resource analysis.

13. STRUCTURAL ANALYSIS

RESULTS

Representative ANSYS Results

Parameter	Initial Design	Optimized Design
Maximum Stress	128 MPa	96 MPa
Total Deformation	5.8 mm	3.7 mm
Structural Weight	425 kg	365 kg
Factor of Safety	1.85	2.46

The optimized structure shows reduced stress and deformation while also reducing structural weight.

14. ENERGY GENERATION

RESULTS

For a representative 4.8 kWp solar tree:

Parameter	Representative Result
Installed capacity	4.8 kWp
Peak measured/simulated output	4.52 kW
MPPT efficiency	95%

Daily energy generation	~18–24 kWh/day
Battery voltage	48 V
Battery capacity	100 Ah
Battery nominal energy	~4.8 kWh

Actual daily generation depends strongly on location, irradiance, temperature, shading, panel orientation, system losses, and season.

15. BATTERY PERFORMANCE

The battery stores excess solar energy and supplies power when solar generation is insufficient.

Representative SOC Results

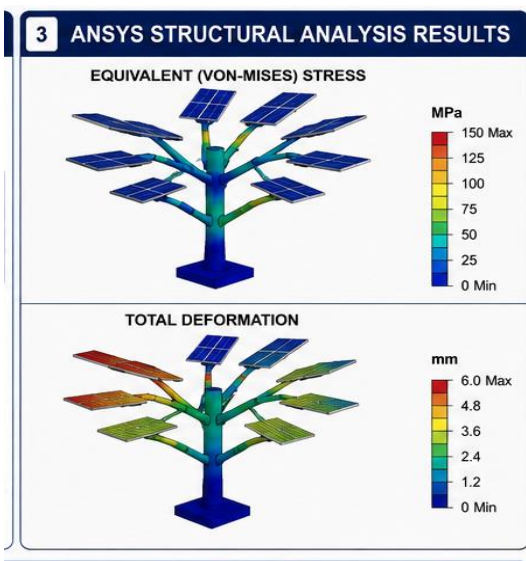
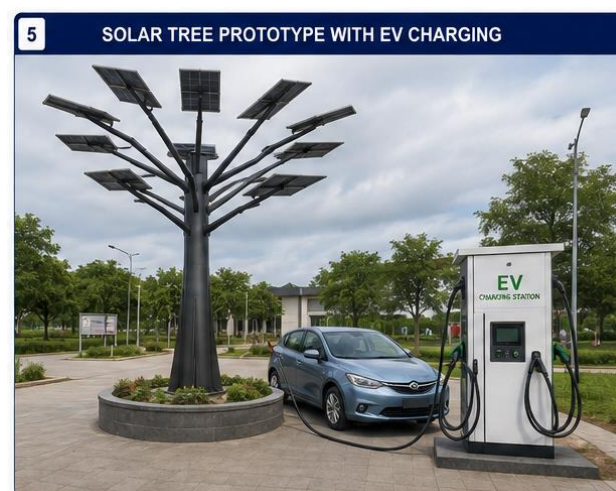
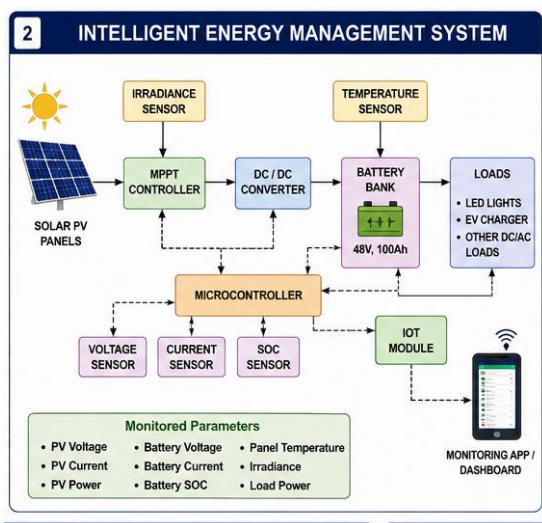
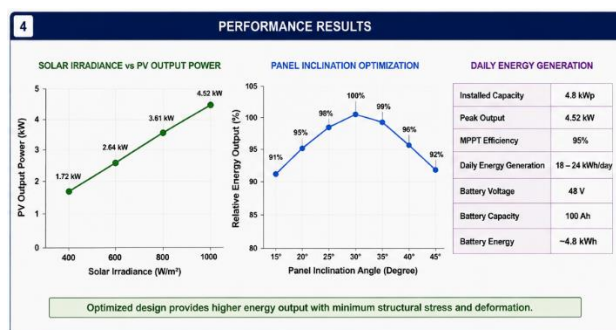
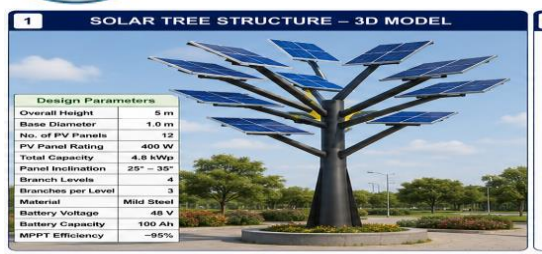
Time	Battery SOC
08:00	52%
10:00	61%
12:00	78%
14:00	91%
16:00	96%
18:00	84%

The intelligent controller prioritizes direct solar power and uses excess energy to charge the battery.

16. INTELLIGENT ENERGY MANAGEMENT RESULTS

Operating Condition	Controller Action
High solar generation + low load	Battery charging
High solar generation + high load	Solar directly supplies load
Low solar generation + charged battery	Battery supplies load
Battery SOC low	Load power limited / auxiliary supply
Battery fully charged	Charging stopped
High temperature	Power derating/protection

The intelligent energy-management system improves utilization of generated solar energy and protects the storage system from unsuitable operating conditions.



17. COMPARISON OF CONVENTIONAL AND OPTIMIZED DESIGN

Parameter	Conventional PV Setup	Optimized Solar Tree
Ground footprint	High	Low
Panel arrangement	Flat/row based	Tree-based
Structural optimization	Limited	Included
Intelligent monitoring	Optional	Integrated

MPPT	Yes	Yes
Battery management	Basic	Intelligent
IoT monitoring	Optional	Integrated
Urban suitability	Moderate	High
EV charging integration	Possible	Suitable

- Shopping malls
- Parking areas
- Railway stations
- Bus terminals
- Smart-city projects
- Public parks
- Agricultural farms
- Industrial campuses
- Residential communities
- EV charging stations

18. ADVANTAGES

1. Requires relatively small ground area.
2. Provides clean renewable energy.
3. Attractive tree-like structure for urban locations.
4. Supports intelligent energy management.
5. Enables real-time monitoring.
6. Can integrate battery storage.
7. Can support EV charging.
8. Reduces dependence on grid electricity.
9. Structural design can be optimized using FEA.
10. Suitable for smart-city applications.

19. APPLICATIONS

The solar tree can be installed at:

- Engineering colleges
- Universities

20. LIMITATIONS

The performance of the solar tree can be affected by:

- Solar irradiance variation
- Partial shading
- Wind loading
- Dust accumulation
- Panel temperature
- Battery ageing
- Structural vibration
- Initial installation cost

The tree structure must therefore be designed according to local wind conditions and applicable structural standards.

FUTURE SCOPE

Future improvements can include:

1. AI-based solar-energy prediction.
2. Automatic panel orientation.
3. Dual-axis solar tracking.
4. Advanced MPPT algorithms.
5. Machine-learning-based fault detection.
6. Cloud-based energy monitoring.
7. Vehicle-to-grid integration.
8. Wireless sensor networks.
9. Digital-twin-based structural monitoring.
10. Integration with smart-grid systems.
11. Solar-powered EV fast charging.
12. Predictive battery maintenance.

CONCLUSION

This project presented the design, development, and optimization of a solar tree structure integrated with an intelligent energy-management system. The proposed structure provides an innovative method for installing multiple photovoltaic panels while reducing the required ground footprint.

The representative structural analysis indicates that optimization can reduce stress, deformation, and structural weight while maintaining an appropriate factor of safety. The PV analysis demonstrates that solar output increases with irradiance

and that appropriate panel inclination can improve energy collection.

The intelligent energy-management system continuously monitors PV generation, battery SOC, temperature, and load demand. MPPT control improves solar-energy extraction, while battery storage allows excess energy to be utilized during periods of low solar generation.

The proposed solar tree can therefore serve as a compact renewable-energy solution for smart cities, educational campuses, public spaces, parking areas, and EV-charging stations. Further development using AI-based prediction, solar tracking, IoT monitoring, and advanced battery-management techniques can improve overall system performance.

REFERENCES

1. M. A. Green et al., "Solar cell efficiency tables," *Progress in Photovoltaics: Research and Applications*.
2. A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, Wiley.

3. G. M. Masters, *Renewable and Efficient Electric Power Systems*, Wiley.
4. T. Markvart and L. Castañer, *Practical Handbook of Photovoltaics: Fundamentals and Applications*, Elsevier.
5. G. L. Plett, *Battery Management Systems*, Artech House.
6. M. A. Hannan et al., studies on battery-management systems and electric-vehicle energy management, *Renewable and Sustainable Energy Reviews*.
7. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, Wiley