Er.Gurpreet kaur, 2026, 14:1
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Techno-Economic Analysis of Solar Photovoltaic Systems for A Sustainable Future

Er.Gurpreet kaur[1], Er.Kawalpreet singh[2], Er.Kirandeep kaur[3]
[1]Er.Gurpreet kaur, Assistant Professor, Electrical Engineering, Ludhiana Group of Colleges, Chaukimann,
[2]Er.Kawalpreet singh, Assistant Professor, Electronics and communication Engineering, Ludhiana Group of Colleges, Chaukimann,
[3]Er.Kirandeep kaur, Assistant Professor, Electrical Engineering, Ludhiana Group of Colleges, Chaukimann,

Abstract- The accelerating shift toward sustainable energy frameworks has significantly increased the adoption of renewable technologies, among which solar photovoltaic (PV) systems have become a major pathway for achieving decarbonization objectives. This paper presents a comprehensive techno-economic analysis of solar PV systems, focusing on their working principles, technologies, performance characteristics, and economic viability. Various PV configurations such as grid-connected, stand-alone, rooftop, ground-mounted, and floating solar PV systems are discussed. The study also highlights recent advancements including bifacial modules, micro inverters, tracking systems, and floating solar PV. An overview of the Indian power sector and renewable energy scenario is presented to assess the role of solar PV in achieving sustainable development goals. The results indicate that despite high initial costs, solar PV systems offer long-term economic and environmental benefits, making them a viable solution for a sustainable energy future.

Keywords: Solar photovoltaic (PV), techno-economic analysis, renewable energy, sustainable development, floating solar PV, grid-connected systems.

I. INTRODUCTION

Energy transition represents a complex and interconnected process influenced by advancements in technology, evolving policy instruments, market dynamics, and broader socio-cultural transformations. Meeting net-zero emission targets by mid-century and restricting global temperature rise to 1.5 °C requires the establishment of an energy system that is environmentally sustainable, reliable, and economically competitive. Photovoltaic technology has gained prominence due to its clean nature, modularity, and declining costs.

Solar energy conversion through PV systems directly transforms solar radiation into electrical energy without intermediate mechanical processes. This characteristic makes solar PV systems environmentally benign and suitable for both centralized and distributed generation. The present study examines the techno-economic aspects of solar PV systems and evaluates their contribution to sustainable development.

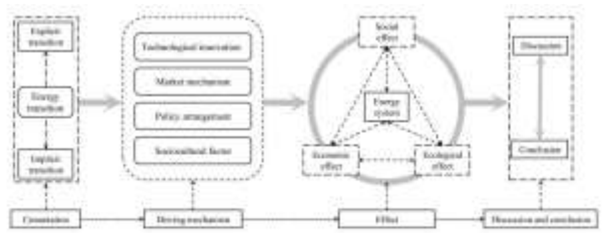


Fig 1. Energy transition analytical framework

II. NEED FOR ENERGY TRANSITION

Rising global energy demand, the gradual exhaustion of fossil fuel resources, and growing environmental concerns including climate change and air quality degradation have accelerated the transition toward renewable energy alternatives. Solar PV systems address these challenges by providing clean, abundant, and scalable energy. The transition also involves implicit changes in energy governance, energy security, and social equity, which are critical for a just and inclusive energy future.

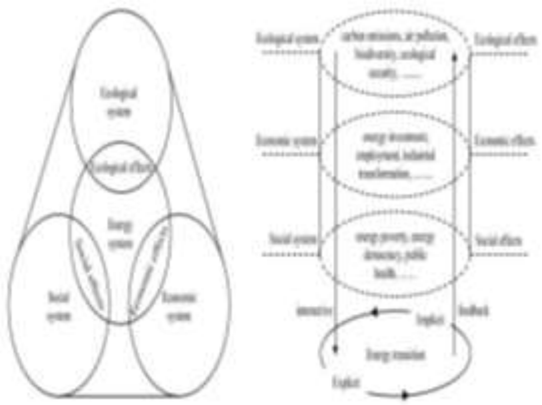


Fig2. Research framework of energy transition effects

III. PRINCIPLES OF SOLAR PV SYSTEMS

Solar photovoltaic cells function on the principle of the photovoltaic effect, in which incoming solar radiation excites charge carriers within a semiconductor, leading to the generation of electrical current, resulting in an electric current. The electrical behavior of a PV cell is commonly represented using equivalent circuit models.

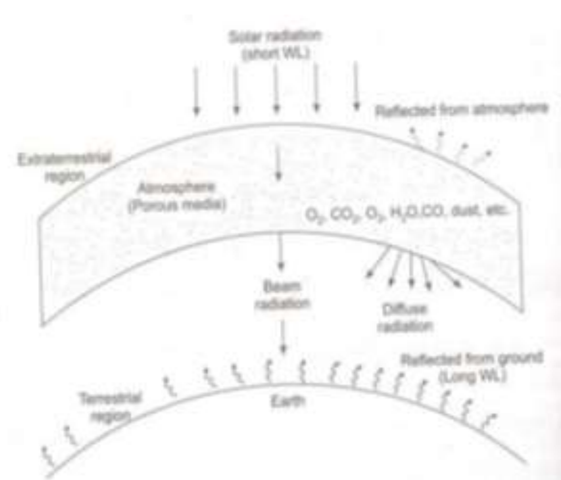


Fig3: propagation of solar radiations through the atmosphere

A. Equivalent Circuit Models

An ideal PV cell model consists of a current source and a diode. However, practical models include series resistance (Rs) representing internal losses and shunt resistance (Rsh) representing leakage currents. These parameters significantly affect the performance, efficiency, and fill factor of PV modules.

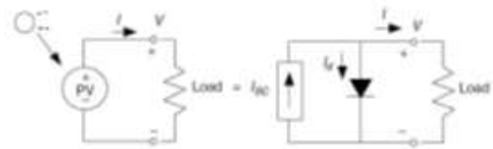
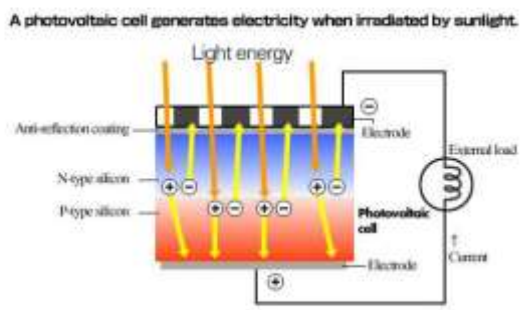


Fig 4: simple equivalent circuit for PV cell consists of a current source driven by sunlight in parallel with a real diode.



Complex Equivalent Circuit for a PV cell

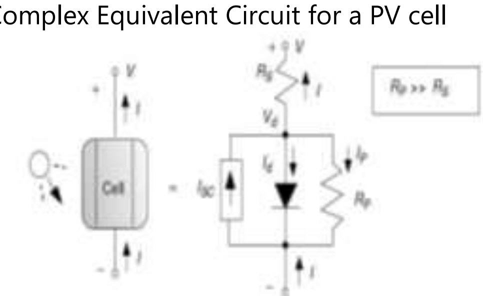


Fig4: more complex equivalent circuit for a PV cell including both parallel and series resistance

B. I–V and P–V Characteristics

The current–voltage (I–V) and power–voltage (P–V) characteristics of a PV module define its operating behavior under varying irradiance and temperature conditions. The fill factor (FF), defined as the ratio of maximum power to the product of open-circuit voltage and short-circuit current, is a key performance indicator.

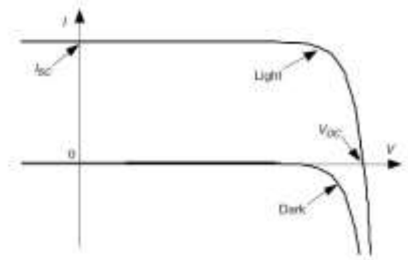


Fig5: Photovoltaic current-voltage relationship for dark (no sunlight) and light. The dark curve is just the diode curve turned upside -down. The light curve is the dark curve plus Isc.

$$I_d = I_0(e^{qV_d/kT} - 1)$$

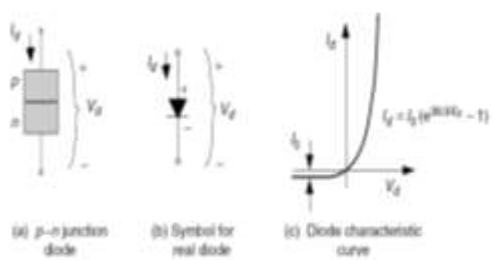


Fig 6: a) p-n junction) symbol c) characteristics

A p–n junction diode is a basic semiconductor device formed by joining p-type and n-type semiconductor materials. It allows electric current to flow in one direction only, which is why it is widely used as a rectifier.

Formation

- p-type semiconductor: Doped with trivalent impurities (e.g., Boron) → majority carriers are holes.
- n-type semiconductor: Doped with pentavalent impurities (e.g., Phosphorus) → majority carriers are electrons.
- When joined, a depletion region forms at the junction due to recombination of electrons and holes.
- An internal electric field and barrier potential are created.

IV. SOLAR PV TECHNOLOGIES

Solar PV technologies are broadly classified into crystalline silicon and thin-film technologies.

A. Crystalline Silicon Modules

Monocrystalline and polycrystalline silicon modules dominate the market due to their high efficiency and reliability. Typical fill factors range from 70–75%.

B. Advanced PV Technologies

Recent advancements include passivated emitter and rear contact (PERC) cells, bifacial modules, and multi-junction cells. Bifacial modules generate power from both sides using reflected radiation, enhancing energy yield.

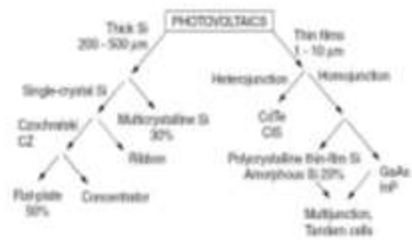
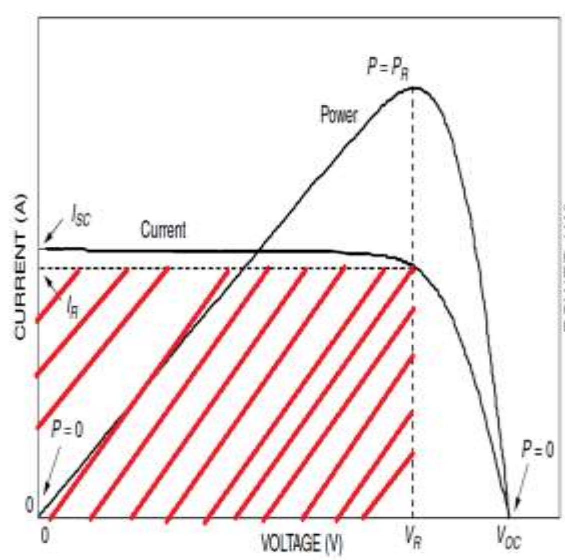


Fig7: photovoltaic technologies

I –V and P-V Characteristics of a Solar Module

Fill Factor = ImppVmpp/ ISCVOC (Fill Factor is Always between 0 to 1)



Fill factor around 70-75% for crystalline silicon solar modules are typical while for multijunction amorphous -Si modules,its closer to 50-60%.

Impact of PV Module mismatch:

Features of Micro inverter:

- Increased generation over string systems
- Safest solution with DC eliminated on roof
- Shading & soiling tolerant
- Most reliable (<48V DC processed)

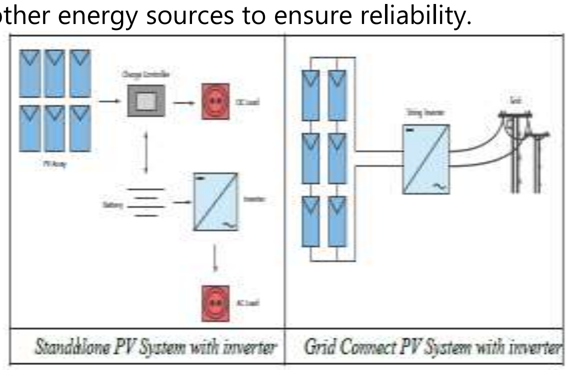
V. SYSTEM CONFIGURATIONS AND POWER ELECTRONICS

A. Grid-Connected Systems

Grid-connected PV systems deliver power directly to the utility grid through inverters synchronized in voltage and frequency. These systems require the presence of the grid for operation.

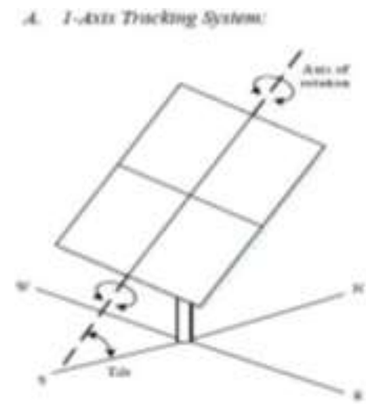
B. Stand-Alone and Hybrid Systems

Stand-alone systems operate independently using battery storage and charge controllers, while hybrid systems integrate solar PV with diesel generators or other energy sources to ensure reliability.

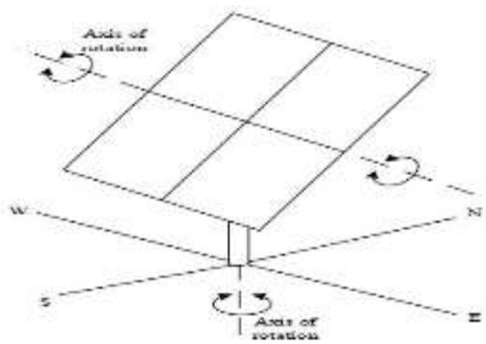


C. Micro inverters and Tracking Systems

The use of micro inverters enhances overall energy yield by minimizing mismatch losses while simultaneously improving system-level safety. Mismatch losses and enhancing safety. [2]Solar tracking systems increase energy generation by maintaining optimal panel orientation throughout the day.

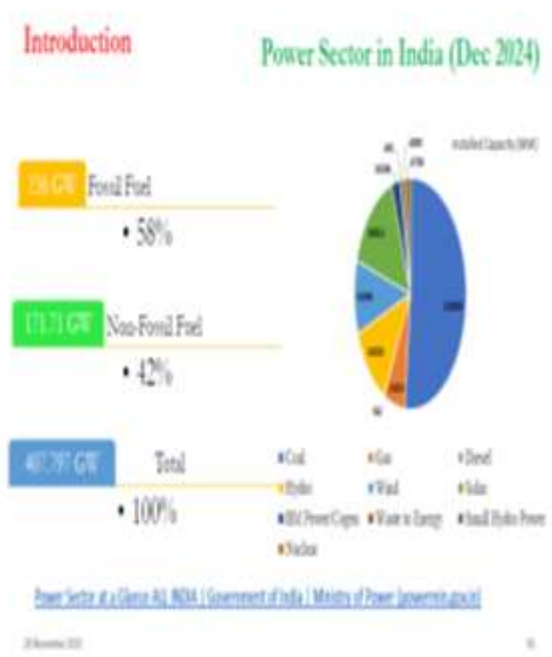


B.

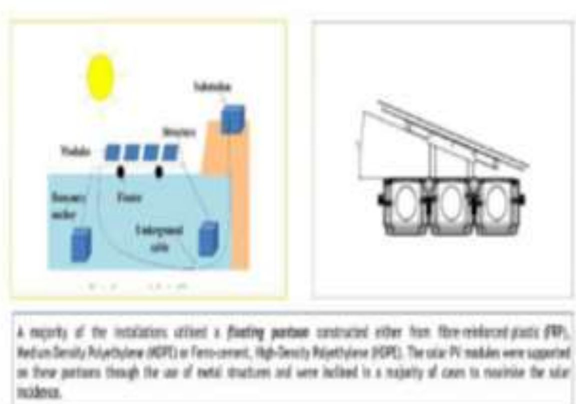


VI. TECHNO-ECONOMIC ANALYSIS

The economic feasibility of solar PV systems depends on capital cost, land requirement, performance degradation, and operational lifespan. On average, installing 1 kW power of solar PV capacity requires nearly 10 m² of unobstructed installation space. A 1 MWp plant costs approximately INR 5–6 crores and has a degradation rate of 0.5–0.8% per year, maintaining 80–90% output even after 25 years.[4]



Floating solar PV installations provide multiple benefits, including minimized land occupation, improved efficiency resulting from natural cooling, and reduced evaporation losses and shared infrastructure. Although capital costs are slightly higher, long-term benefits justify their deployment.



Technical Performance Analysis

The variation in performance indicators between fixed solar photovoltaic (FSPV) and ground-mounted solar photovoltaic (GSPV) systems is primarily influenced by the operating temperature of the PV cells and the associated thermal and environmental losses.

A. Solar Irradiation on a Tilted PV Plane

The daily extraterrestrial solar irradiation incident on a horizontal surface is expressed as:

$H_0 = (24/\pi) \times L \times [\cos\delta \times \cos\varphi \times \sin\omega_{sr} + \sin\delta \times \sin\varphi \times \omega_{sr}]$

The solar irradiation incident on a tilted PV surface is given by:

$H_{at} = \{[(1 - \gamma_t) \times (1 + \cos\beta)/2] + [\rho \times (1 - \cos\beta)/2]\} \times K_t \times H_0$ [3]

where:

δ = solar declination angle (degrees)
L = solar insulation (kW/m^2)
β = tilt angle of the PV module (radians)
φ = latitude angle (radians)
γ_t = overall tilt factor
ω_{sr} = sunrise hour angle (radians)
ρ = ground reflection coefficient
K_t = clearness index
H_0 = daily solar irradiation incident on a horizontal PV surface ($kWh/m^2/day$)

B. Module Temperature

The operating temperature of the PV module is calculated using:

$T_{mo}d = [(\tau\,\alpha) \times G / U] + T_{am}b$ (2.6)

The overall heat loss coefficient is defined as:

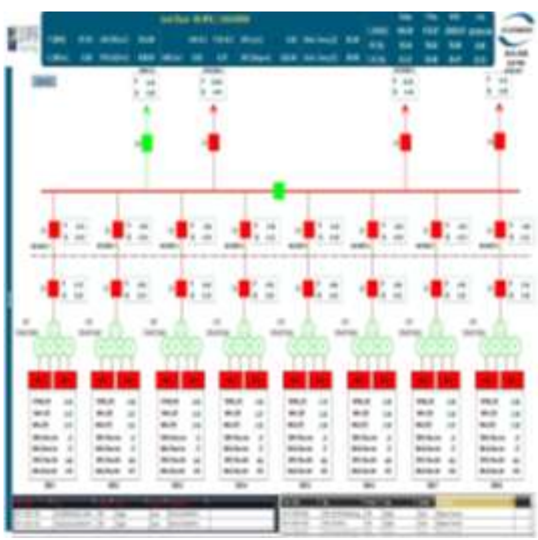
$U = U_c + (U_v \times V)$ (2.7)

where:

$T_{am}b$ = ambient temperature (°C)
G = solar irradiance (W/m^2)
$\tau\,\alpha$ = transmittance–absorptance product
U = total heat loss coefficient ($W/m^2 \cdot K$)
U_c = constant heat loss coefficient
U_v = wind-dependent heat loss coefficient ($W/m^2 \cdot K$ per m/s)
V = wind speed (m/s)

Recent Technologies at solar power plant (Recent Operations)

1. Digital & Advanced Monitoring
2. System called SCADA SYSTEM



ICR-SLD

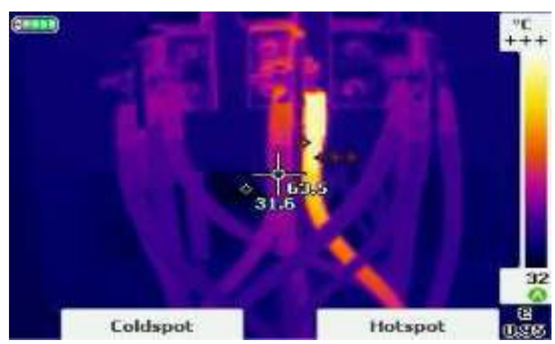
REACTIVE POWER CONTROLLER SHEET

ROBOTICS BASED PANEL CLEANING

Fully autonomous dry-cleaning robots reduce water usage by 80–90%.

- Daily or scheduled cleaning improves production and reduces soiling losses.
- Useful in desert and dusty regions.

3.Thermal imaging cameraUsed for hotspot detection in: Solar modules, Inverter panels Cables & connectors Transformers & switchgear Helps identify loose connectionsoverheating components and early-stage failures. Used during preventive maintenance and monthly inspections.



VII. INDIAN RENEWABLE ENERGY SCENARIO

As of December 2024, India has a total installed power capacity of approximately 407.8 GW, with renewable energy contributing about 42%. Solar energy plays a pivotal role in meeting national targets for sustainable development and energy security [5]. Strong governmental policies and targeted initiatives have significantly boosted the deployment of solar PV systems across diverse applications such as rooftop, ground-mounted, canal-top, and floating projects.

VIII. CONCLUSIONS

This paper presented a comprehensive techno-economic analysis of solar PV systems, highlighting their role in sustainable energy transition. Solar PV technology offers significant environmental and economic advantages despite challenges such as high initial costs and storage requirements. Advancements in PV technologies, power electronics, and innovative installations like floating solar PV enhance system performance and feasibility. Solar PV technology is expected to play a pivotal role in advancing sustainable development objectives while supporting an equitable and inclusive energy transition.

REFERENCES

1. Y. Yang, S. Xia, P. Huang, and J. Qian, "Energy transition: Connotations, mechanisms and effects," Energy Strategy Reviews, vol. 52, 2024.
2. G. M. Masters, Renewable and Efficient Electric Power Systems, Wiley-Interscience, 2004.
3. K. Shivarama Krishna and K. Sathish Kumar, "A review on hybrid renewable energy systems," Renewable and Sustainable Energy Reviews, vol. 52, pp. 907–916, 2015.
4. Ministry of Power, Government of India, "Power Sector at a Glance," 2024.
5. Ministry of New and Renewable Energy (MNRE), Government of India, Official Reports.