

Impact of Solar Energy on the Future of Green Electricity in India

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Abstract—India's electricity sector is undergoing a major transformation driven by the need to reduce fossil fuel dependence and achieve sustainable growth. Solar energy has emerged as the most promising renewable resource due to its abundance, cost-effectiveness, and technological adaptability. The role of solar energy in shaping India's green electricity future by reviewing photovoltaic (PV), concentrated solar power (CSP), and hybrid technologies. It highlights the national trends such as capacity expansion, decentralized solutions, and policy initiatives including the Jawaharlal Nehru National Solar Mission, PM-KUSUM, and rooftop solar programs. Global perspectives on solar adoption, technological advancements, and investment frameworks are also discussed to place India's progress in context. The study further examines the benefits of solar power, including environmental protection, energy security, economic development, and public health improvement, while also addressing challenges like land use, grid integration, and solar waste management. Findings indicate that solar power is not merely an alternative energy source but a transformative force for India's sustainable future. With continued innovation, effective policy support, and responsible environmental management, solar energy will become the backbone of India's electricity system, contributing significantly to climate goals, rural electrification, and long-term economic growth.

Index Terms—Solar Energy, Photovoltaic Systems, Renewable Energy in India, Green Electricity, Energy Security, Sustainable Development.

I. INTRODUCTION

India is experiencing a rapid transformation in its energy sector, driven by the urgent need to reduce dependence on fossil fuels and to ensure sustainable growth. With increasing population, industrialization, and urbanization, the demand for electricity has risen sharply, creating both opportunities and challenges in balancing development with environmental

sustainability. Among the renewable energy sources, solar power has emerged as the most promising option, owing to India's geographical advantage of abundant sunshine throughout the year. Solar energy not only contributes to reducing carbon emissions but also plays a key role in achieving energy security, promoting rural development, and supporting India's commitments to global climate agreements. Thus, the impact of solar energy on shaping the future of green electricity in India is profound and multi-dimensional. Several research studies have highlighted different aspects of this transition. Naik and Bhakare (2023) [1] examined the legal perspectives, issues, and challenges in India's renewable energy sector, pointing out the gaps in policy implementation, power purchase agreements, and land acquisition that affect solar expansion. Suman and Ahamad (2018) [2] focused on India's solar energy potential and the role of the Jawaharlal Nehru National Solar Mission in driving large-scale deployment and reducing the cost of solar power. Chand (2025) [3] explored the economic impact of solar energy, emphasizing its contribution to job creation, investment, and sustainable growth.

In another contribution, Pachar, Singh, and Wahid (2021) [4] analyzed the implications of renewable energy for sustainable development in India, noting how solar power can generate employment, reduce pollution, and support green growth. Kaushik, Sharma, Mishra, and colleagues (2010) [5] provided an early but comprehensive view of India's renewable energy status and future potentials, stressing the importance of solar in reducing reliance on coal. Kumar and Majid (2019) [6] offered a detailed review of renewable energy for sustainable development, highlighting investment opportunities, job prospects, and the ambitious targets set by the Indian government. Finally, Pandey, Pandey, and Tumuluru

(2022) [7] reviewed solar energy production technologies in India, discussing the growth of photovoltaic systems, cost reductions, and the need for recycling solar waste.

Together, these studies form a strong foundation for analyzing how solar energy will impact the future of green electricity in India. This paper draws insights from these works to highlight the opportunities, challenges, and long-term implications of solar power for India's sustainable energy transition.

II. SOLAR ENERGY GENERATION CONCEPT

Solar energy is one of the most promising alternatives to conventional fossil fuels, as it directly harnesses sunlight to generate clean and sustainable electricity. The core idea revolves around harnessing solar radiation and transforming it into practical forms of energy. In India, with over 250–300 sunny days annually and an estimated potential of more than 5,000 trillion kWh per year, solar energy represents an abundant and underutilized source of green electricity. Two main technological pathways dominate this conversion: Photovoltaic (PV) systems and Concentrated Solar Power (CSP) systems, each with unique working principles, advantages, and limitations.

1. Photovoltaic (PV) Systems

Photovoltaic technology is the most widely deployed method of solar electricity generation. PV cells are made of semiconducting materials (commonly silicon) that absorb photons from sunlight, releasing electrons which create an electric current. PV systems can be classified into monocrystalline, polycrystalline, thin-film, and emerging perovskite cells.

- Monocrystalline PV cells are manufactured from a single continuous crystal structure, offering high efficiency (18–22%) and long lifespan. They are suitable for limited rooftop spaces due to their high-power output per unit area.
- Polycrystalline photovoltaic (PV) cells are produced using several silicon crystal fragments, making them more affordable to manufacture, though their efficiency is slightly lower at around 15–17%. Owing to their cost-effectiveness and simpler production process, they are commonly adopted in India.

- Thin-film solar cells use very thin layers of photovoltaic materials (such as cadmium telluride or amorphous silicon) deposited on glass or plastic. They are flexible, lightweight, and effective in diffuse sunlight, but they generally have lower efficiencies (10–12%) compared to crystalline cells.
- Perovskite solar cells, an emerging technology, offer very high efficiency potential (over 25%) and lower manufacturing costs. Yet, ensuring long-term stability and achieving large-scale commercial adoption continue to be major challenges.

PV systems can be deployed as on-grid systems, where generated electricity is fed directly into the national grid, or as off-grid systems that supply power to remote or rural areas using storage batteries. India has emphasized both rooftop solar installations for urban areas and large-scale solar parks in states like Rajasthan and Gujarat.

Inside a photovoltaic cell

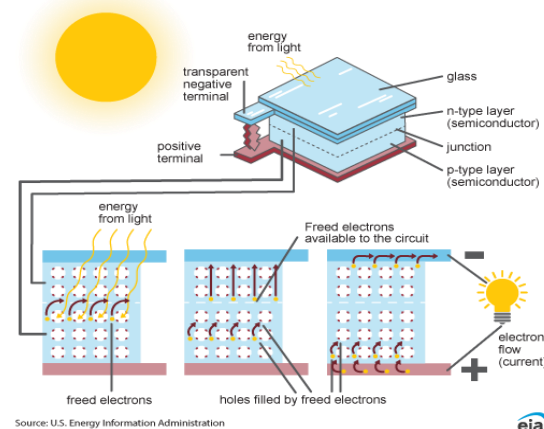


Fig 1: - photovoltaic System

2. Concentrated Solar Power (CSP) Systems

CSP systems generate electricity by using mirrors or lenses to concentrate sunlight onto a receiver, which heats a fluid to produce steam that drives a turbine. Unlike PV, which directly converts light into electricity, CSP relies on thermal energy conversion. Several CSP technologies are in use:

- Parabolic Trough Collectors (PTC): Curved mirrors concentrate sunlight onto a tube filled with heat transfer fluid (such as molten salt), reaching temperatures up to 600°C. The thermal energy obtained is utilized for electricity generation.

- **Solar Power Towers:** Large fields of mirrors (heliostats) direct sunlight onto a central tower receiver, creating extremely high temperatures for power generation. This method is efficient and suitable for utility-scale plants.
- **Dish Stirling Systems:** A parabolic dish concentrates sunlight onto a receiver coupled with a Stirling engine, which converts heat directly into mechanical energy and then electricity.
- **Linear Fresnel Reflectors** consist of multiple flat mirror strips arranged in rows that direct sunlight toward a central receiver, providing a cost-effective and simpler option compared to parabolic trough systems.

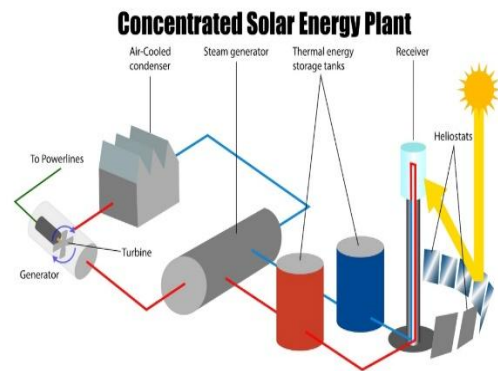


Fig 3: - Hybrid and Emerging

III. NATIONAL TRENDS

Although CSP plants are costlier compared to PV systems, they have the advantage of integrated thermal storage (using molten salts), allowing electricity generation even after sunset. This makes CSP valuable for meeting continuous energy demand.

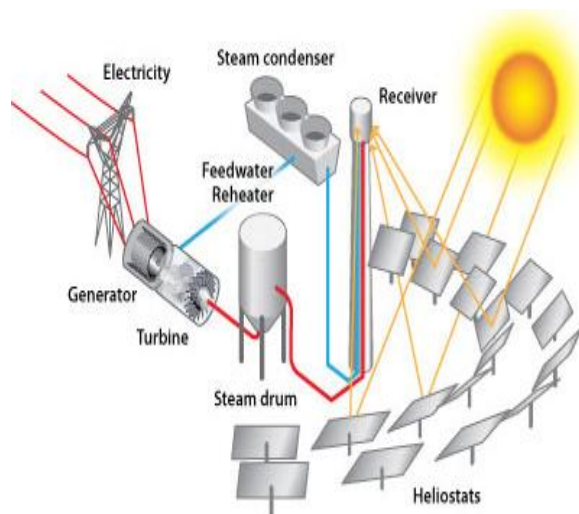


Fig 2: - Concentrated Solar Power

3. Hybrid and Emerging Concepts

Beyond traditional PV and CSP, hybrid solutions are being developed. PV-CSP hybrid systems combine the cost-effectiveness of PV with the storage benefits of CSP. In addition, solar thermal collectors are widely used in India for water heating, drying crops, and other industrial processes. Recent advances also include building-integrated photovoltaics (BIPV), floating solar plants, and agrivoltaics (using the same land for both agriculture and solar power generation).

India has emerged as one of the global leaders in solar energy deployment, driven by abundant solar resources, favorable policies, and international climate commitments. The country receives nearly 5,000 trillion kWh of solar radiation annually, with most regions experiencing 4–7 kWh per square meter per day, making solar a natural choice for powering its growing economy.

1. Massive Capacity Growth

India has rapidly positioned itself as one of the world's leading and fastest-expanding markets for solar energy. From a modest installed capacity of just 0.16 GW in 2010, the country has crossed the 100 GW milestone, with plans to achieve 500 GW of renewable capacity by 2030, out of which solar will contribute the largest share. The sharp decline in solar tariffs, expansion of large-scale solar parks in states like Rajasthan, Gujarat, and Madhya Pradesh, and proactive policy measures have accelerated this growth. This rapid expansion is not only vital for meeting domestic energy demand but also for achieving India's climate commitments of reaching Net Zero by 2070.

2. Government Initiatives

Policy support has been central to India's solar revolution. Flagship programs like the Jawaharlal Nehru National Solar Mission (JNNSM) laid the foundation, while newer schemes such as PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) are encouraging farmers to adopt solar-powered irrigation and sell surplus energy to the grid.

Similarly, the PM Surya Ghar Muft Bijli Yojana promotes residential rooftop solar adoption, aiming to provide free electricity to millions of households. These initiatives reflect the government's dual strategy of enhancing energy access and ensuring sustainable economic growth by empowering both urban and rural communities.

3. Decentralized Solar Solutions

In addition to utility-scale projects, India is witnessing a surge in decentralized solar adoption. Rooftop solar installations on residential, commercial, and institutional buildings are increasingly popular, supported by net metering policies and subsidies. Decentralized solar provides an opportunity to address energy access in rural areas through mini-grids, community solar farms, and solar pumps, reducing dependence on unreliable fossil-fuel-based electricity. This distributed model enhances resilience, reduces transmission losses, and fosters local participation in the energy transition.

4. Policy and Investment Framework

A strong policy and regulatory ecosystem have enabled India to attract substantial domestic and foreign investment in the solar sector. The Renewable Purchase Obligation (RPO) framework and Renewable Energy Certificates (REC) system ensure demand for clean power. International collaborations and foreign direct investment have further strengthened India's solar market, making it the fourth most attractive renewable energy market globally. However, issues such as land acquisition, power purchase agreement enforcement, and grid integration challenges still need effective resolution.

5. Technological Advancements

Technological improvements have played a pivotal role in reducing solar costs and increasing efficiency. The leveled cost of solar electricity in India has dropped significantly, making it cheaper than coal in many regions. Innovations such as bifacial PV modules, floating solar plants, perovskite solar cells, AI-based solar forecasting, and advanced storage systems are shaping India's future solar landscape. With these advancements, solar is expected to become the backbone of India's electricity system, driving both sustainability and affordability.

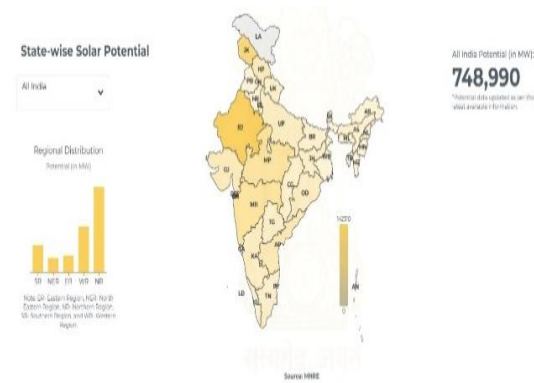


Fig 6: - National Trends

IV. GLOBAL TRENDS

Global solar energy trends show increasing global installations and rising awareness of its benefits, which strongly influence India's push for green electricity, driving its ambitious net-zero goals and massive solar expansion through policy support, foreign investment, and domestic manufacturing growth. India's own solar surge includes large parks and rooftop solutions, positioning it as a global leader and key player in the worldwide energy transition, with advancements in technology and evolving policy frameworks further accelerating its progress.

1. Accelerated Global Growth

Solar energy has become the fastest-growing renewable source worldwide. Global solar photovoltaic (PV) capacity expanded rapidly from just 15 GW in 2008 to more than 627 GW by 2019, with further record-breaking additions in 2022. This growth has been driven by falling technology costs, large-scale deployment in leading economies such as China, the United States, Japan, Germany, and India, and an increased global consensus on decarbonization. By 2030, solar is projected to account for the largest share of renewable energy additions globally, firmly positioning itself as the backbone of clean electricity supply.

2. Technological Advancements

Rapid innovation in solar technology has significantly improved efficiency and reduced costs. Advanced monocrystalline PV modules now achieve efficiencies exceeding 20%, while bifacial panels capture sunlight on both sides, boosting energy yield. Emerging technologies such as thin-film solar cells, **perovskite-**

based cells, floating solar plants, and AI-driven energy management systems are expanding the application potential of solar energy. These breakthroughs are not only lowering the levelized cost of electricity but also enhancing grid integration and reliability, making solar more competitive with conventional energy sources.

3. Sustainability Focus

Global energy transitions are increasingly aligned with climate commitments under the Paris Agreement and the UN Sustainable Development Goals. Many countries have recognized solar power as a key enabler for achieving low-carbon, sustainable, and cost-effective electricity systems. The integration of solar into urban infrastructure, transportation (e.g., solar charging for electric vehicles), and industrial processes underscores its growing importance. Moreover, international organizations such as the International Renewable Energy Agency (IRENA) emphasize that large-scale adoption of solar could reduce global carbon emissions substantially, thereby contributing to climate resilience and sustainable economic development.

4. Policy and Investment

The global solar surge is strongly supported by policy frameworks, subsidies, and foreign investments. Incentives such as feed-in tariffs, renewable portfolio standards, and tax credits have enabled countries like Germany, China, and the USA to scale solar adoption quickly. Investment trends reveal that solar energy consistently attracts the highest share of renewable energy financing worldwide, reflecting investor confidence in its profitability and long-term potential. Stable and transparent policies remain central to ensuring sustained growth and achieving climate neutrality in the coming decades.

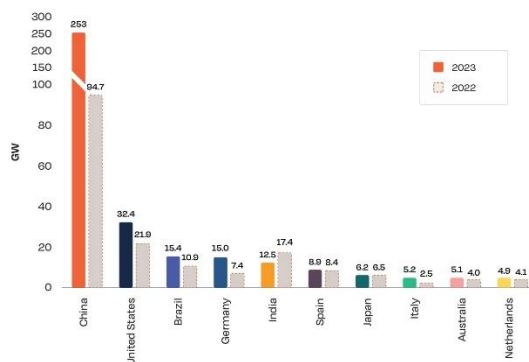


Fig 6: - Global Trend

V. UPCOMING SCOPE

The Solar energy is set to significantly transform India's green electricity landscape by rapidly increasing its renewable capacity, reducing fossil fuel dependence, and creating new economic opportunities. The country aims to reach over 360 GW of solar power by 2032, driving growth in grid-connected systems, manufacturing, and research to meet environmental and energy security goals.

1. Massive Capacity Growth

India is entering a transformative phase in its electricity sector, with solar power expected to dominate future capacity additions. Current installed solar capacity stood at 66.7 GW in 2023, but projections suggest a rapid increase to nearly 366 GW by 2032, making it the single largest contributor to India's renewable energy mix. This expansion is being driven by a combination of large-scale solar parks, decentralized rooftop solutions, and hybrid systems that integrate storage. By 2032, solar power will not only provide a significant share of India's total electricity but also act as the foundation for achieving the nation's green energy milestones.

2. Reduced Fossil Fuel Dependence

The accelerated adoption of solar energy is expected to gradually reduce India's reliance on fossil fuels such as coal, which currently accounts for the majority of the country's electricity generation. With coal becoming costlier due to supply constraints, import dependencies, and environmental penalties, solar energy offers a more sustainable and affordable alternative. Transitioning to solar-based systems will not only cut dependence on depleting non-renewable resources but also address pressing issues of air pollution, carbon emissions, and ecological degradation, positioning India on a path toward cleaner and more resilient energy production.

3. Economic Benefits

The solar energy industry has become a significant contributor to economic development. Expansion of solar infrastructure is expected to generate millions of direct and indirect jobs across installation, manufacturing, research, and maintenance activities. Furthermore, the rise of domestic manufacturing under initiatives like 'Make in India' and the production-linked incentive (PLI) schemes is strengthening India's

position in the global solar supply chain. Foreign investments, public-private partnerships, and green finance mechanisms are also stimulating economic activity, making solar energy a catalyst for sustainable economic development in the coming decade.

4. Enhanced Energy Security

By tapping into its vast solar potential—estimated at over 750 GW—India can significantly reduce its vulnerability to fuel price volatility and energy imports. Expanding domestic solar production ensures a more stable and reliable electricity supply, which is crucial for powering industries, agriculture, and households. In addition, the integration of grid-scale storage systems, microgrids, and smart grid technologies will further enhance resilience, enabling India to manage peak loads and supply electricity even during demand fluctuations. This self-reliance in energy not only strengthens national security but also establishes India as a global leader in renewable energy.

5. Environmental Advantages

The environmental benefits of solar energy adoption are profound. Large-scale deployment of solar power will significantly reduce greenhouse gas emissions (GHGs), a key contributor to climate change. By replacing coal-fired plants with clean electricity sources, solar energy will also improve air quality, reducing health hazards associated with particulate matter and carbon emissions. Furthermore, decentralized solar solutions in rural areas contribute to sustainable development by providing clean power without harming ecosystems. Overall, the transition to solar energy aligns with India's climate change mitigation strategies and international commitments under the Paris Agreement.

VI. BENEFITS OF SOLAR ENERGY IN INDIA

Solar energy is crucial for India's green electricity future, offering benefits like reduced pollution and greenhouse gas emissions, enhanced energy independence, significant job creation, and lower electricity bills. The increasing deployment of solar power supports national energy security, drives economic development, and aligns with sustainable development goals by providing a clean, inexhaustible energy source to meet rapidly growing energy demand in a developing country.

1. Environmental Protection

Solar power is one of the cleanest forms of renewable energy, producing no direct greenhouse gas emissions during operation. Unlike fossil fuels, it does not release harmful pollutants such as sulfur dioxide, nitrogen oxides, or particulate matter, which are major contributors to air pollution. Large-scale adoption of solar energy reduces the carbon footprint, slows global warming, and helps India meet its climate commitments under the Paris Agreement. Additionally, solar energy requires minimal water compared to coal or nuclear plants, contributing to water conservation and better protection of biodiversity and ecosystems.

2. Energy Security and Independence

India's dependence on coal and imported oil creates significant economic and geopolitical vulnerabilities. Solar energy, being abundant and domestically available, reduces reliance on fossil fuels and strengthens the country's energy independence. By diversifying the energy mix and expanding decentralized solar solutions such as rooftop panels and mini-grids, India can ensure a more stable, resilient, and self-reliant electricity supply. This independence becomes increasingly vital as India's population and industrial base grow, leading to surging energy demand.

3. Economic Development

The growth of the solar industry is creating new economic opportunities across the value chain. From manufacturing solar panels and inverters to installation, maintenance, and research, the sector has already generated hundreds of thousands of jobs and is expected to create millions more in the coming decades. Programs like PM-KUSUM and the Production-Linked Incentive (PLI) scheme are further boosting domestic manufacturing, reducing imports, and making India a competitive hub for solar technology. This expansion not only supports GDP growth but also strengthens rural and urban economies by providing clean power for households, agriculture, and businesses.

4. Cost Savings

One of the most direct benefits of solar energy is the significant cost reduction in electricity bills for households and businesses. Once installed, solar

systems provide nearly free electricity for decades, with minimal maintenance costs. The falling cost of photovoltaic (PV) technology has made solar power cheaper than coal in many parts of India, making it both an economically viable and environmentally friendly choice. Over time, these savings offset the initial investment, making solar energy a cost-effective solution for both rural and urban consumers.

5. Improved Public Health

By reducing dependence on coal and other polluting fuels, solar power contributes to cleaner air and healthier living conditions. Studies have shown that air pollution is one of India's leading causes of premature deaths and respiratory diseases. Transitioning to solar energy will lower emissions of harmful pollutants, thereby improving public health outcomes, reducing healthcare costs, and enhancing overall quality of life for millions of citizens.

VII. ENVIRONMENTAL EFFECT OF SOLAR IN INDIA

Solar energy has significant positive environmental impacts in India by reducing greenhouse gas emissions and improving air quality, but also introduces challenges like land use for large solar farms, potential decline of natural habitats for biodiversity and the involvement of harmful substances in the production and disposal of solar panels. For a research paper, focus on how these benefits and drawbacks will shape India's future green electricity goals, particularly regarding climate mitigation, rural electrification, and the responsible management of solar infrastructure throughout its lifecycle.

➤ Positive Environmental Impacts

1. Greenhouse Gas and Air Pollution Reduction

A major environmental benefit of solar energy is that it produces electricity without releasing harmful pollutants or emissions. Unlike coal-based plants, solar photovoltaic (PV) systems do not release greenhouse gases or air pollutants during operation. This is particularly important for India, which ranks among the top global carbon dioxide emitters. Widespread adoption of solar energy will therefore play a central role in meeting India's climate mitigation commitments under the Paris Agreement and its pledge to achieve net-zero emissions by 2070. By replacing

fossil fuels, solar energy contributes to cleaner air, lower health risks, and a more sustainable environment.

2. Reduced Dependence on Fossil Fuels

Solar deployment directly reduces reliance on non-renewable and carbon-intensive sources such as coal and petroleum. Given India's increasing energy demand, shifting towards renewable sources helps stabilize the energy supply while reducing the environmental costs associated with resource extraction and fuel imports. In the long run, this transition will support both environmental sustainability and energy independence, helping India to secure a low-carbon future.

3. Water Conservation

Conventional thermal power plants consume vast amounts of water for cooling, which is a growing concern in India's water-scarce regions. Many other energy technologies, solar PV systems need very little water to function. This shift helps conserve vital freshwater resources, ensuring their availability for agriculture and human consumption. Concentrated Solar Power (CSP) plants may have higher water requirements, but with proper technology and location selection, the overall water savings from solar adoption remain significant.

➤ Negative Environmental Impacts and Challenges

1. Land Use and Habitat Loss

Large-scale solar farms often require extensive tracts of land, sometimes located in ecologically sensitive regions. The conversion of agricultural or forested land for solar infrastructure can lead to habitat loss, displacement of wildlife, and reduced biodiversity. While innovative solutions such as floating solar panels and agrivoltaics (dual land use for farming and solar generation) are emerging, the challenge of balancing land needs with ecological preservation remains critical for sustainable solar expansion.

2. Hazardous Materials in Manufacturing and Disposal

Although solar panels are clean during operation, their production involves hazardous materials such as cadmium, lead, and other chemicals used in semiconductors. If not managed properly, these substances can contaminate soil and water during manufacturing or at the end of the panels' lifecycle.

Establishing robust recycling systems and sustainable waste management practices is therefore essential to minimize the long-term environmental footprint of solar technology.

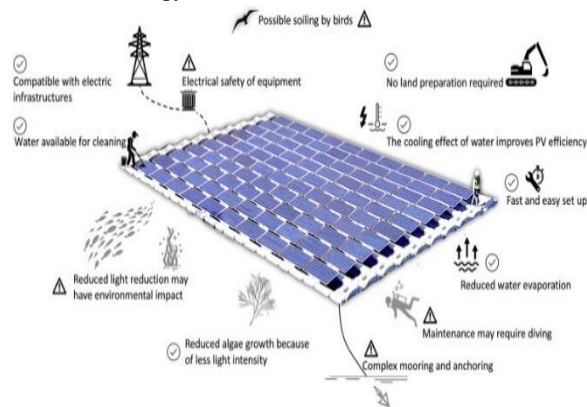


Fig 6: - Environmental Impact

VIII. ACKNOWLEDGMENT

It is with great pleasure that we present this research report on “Impact of Solar Energy on the Future of Green Electricity in India.” We sincerely thank our project guide, Prof. Rajashekhaer Koyyeda (Lecturer, Electrical Engineering Department), for his valuable guidance, timely suggestions, and constant support, without which this work would not have been possible. We are also grateful to all who directly or indirectly helped us in the successful completion of this report.

IX. CONCLUSION

From this study, it is learned that solar energy is the most promising solution for India’s green electricity future, offering clean power, economic growth, and energy security. The work highlights how PV, CSP, and hybrid technologies, supported by strong policies and innovations, can transform India’s energy sector. Future work should focus on addressing challenges like land use, recycling of solar panels, and efficient grid integration to ensure that solar energy becomes the backbone of India’s sustainable development.

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