



Solar Energy Harnessing The Power of The Sun For A Sustainable Future

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ABSTRACT

Solar energy represents one of the most promising and rapidly advancing fields in the global transition toward sustainable energy systems. This research paper provides a comprehensive examination of solar energy technologies, encompassing photovoltaic (PV) systems, concentrated solar power (CSP), and emerging innovations such as perovskite solar cells and bifacial modules. The paper analyzes the historical development of solar technologies, current global deployment trends, economic viability including leveled cost of energy (LCOE), environmental impact, grid integration challenges, and prospects. With global solar capacity surpassing 1.5 terawatts in 2025 and costs continuing to decline at unprecedented rates, solar energy has firmly established itself as the cornerstone of the clean energy transition. Key findings suggest that solar energy, combined with effective storage solutions and smart grid infrastructure, has the technical and economic potential to supply most of the global electricity demand by 2050. Policy frameworks, technological breakthroughs in storage, and international cooperation are identified as critical enablers for accelerating solar deployment at the scale required to meet climate targets.

Keywords: Solar Energy, Photovoltaics, Concentrated Solar Power, Renewable Energy, Energy Transition, Perovskite, Grid Integration, Sustainability, LCOE, Climate Change.

INTRODUCTION

The global energy landscape is undergoing a profound and irreversible transformation. As concerns over climate change, energy security, and fossil fuel depletion intensify, renewable energy sources — particularly solar — have moved from the margins of the energy conversation to its very center. Solar energy, derived from the radiant light and heat emitted by the Sun, is an abundant, inexhaustible, and geographically dispersed resource with the theoretical potential to satisfy the entirety of human civilization's energy demands many times over.

The Sun delivers approximately 173,000 terawatts (TW) of energy to the Earth's surface continuously. To put this in perspective, the total global energy consumption in 2023 was approximately 18 TW. In a single hour, the Earth receives more solar energy than the entire world consumes in a year. This staggering abundance, combined with dramatic reductions in technology costs, has catalyzed a solar revolution over the past two decades.

Solar photovoltaic (PV) capacity additions have shattered records year after year. In 2024 alone, over 400 gigawatts (GW) of new solar capacity was installed worldwide, bringing total global cumulative installations past the 1.5-terawatt milestone. Solar has become the cheapest source of electricity in human history in most parts of the world, with the leveled cost of energy (LCOE) from utility-scale PV falling by more than 90% since 2010.

This paper offers a comprehensive overview of solar energy — from its fundamental physics and technological diversity to its economic trajectory, environmental benefits and trade-offs, policy landscape, grid integration challenges, and long-term potential. The goal is to provide an authoritative, nuanced, and forward-looking assessment of solar energy's role in shaping a sustainable global energy future.

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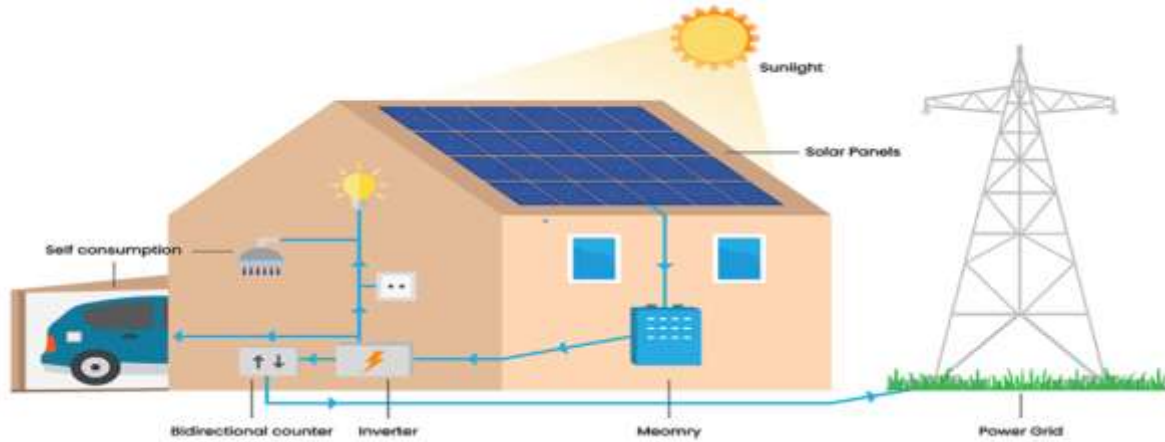


FIGURE 1.0: WORKING ARCHITECTURE OF SOLAR ENERGY

HISTORICAL DEVELOPMENT OF SOLAR ENERGY

Early Discoveries and Scientific Foundations

The story of solar energy begins in 1839, when French physicist Edmond Becquerel first observed the photovoltaic effect — the phenomenon by which light striking certain materials generates an electric current. While Becquerel's discovery was seminal, practical applications remained elusive for over a century. In 1876, William Grylls Adams and Richard Evans Day demonstrated that selenium produced electricity when exposed to light, further substantiating the photovoltaic principle. The pivotal breakthrough came in 1954 when scientists at Bell Laboratories — Daryl Chapin, Calvin Fuller, and Gerald Pearson developed the first practical silicon solar cell, achieving an efficiency of approximately 6%. Bell Labs' announcement of the solar battery was celebrated as a potential solution to the world's energy challenges, though widespread commercial deployment remained decades away due to prohibitive costs.

Space Age Adoption and Early Commercialization

The nascent space industry provided the first large-scale application for solar cells. In 1958, the Vanguard 1 satellite became the first spacecraft to use solar panels, demonstrating their reliability in powering space missions. Through the 1960s and 1970s, solar cells became standard equipment for satellites and space probes, driving incremental improvements in efficiency and reliability, albeit at costs far too high for terrestrial applications. The 1973 Arab oil embargo and resulting energy crisis jolted Western governments into action, spurring investment in alternative energy sources including solar. The United States established the Solar Energy Research Institute (now the National Renewable Energy Laboratory) in 1977. However, the subsequent collapse of oil prices in the mid-1980s led to significant reductions in solar R&D funding, slowing progress.

The Modern Solar Revolution (2000–Present)

The 2000s marked the beginning of a genuine solar revolution, driven by coordinated policy support, technological maturation, and manufacturing scale-up. Germany's Energiewende policy and its generous feed-in tariffs for solar energy created a large, stable market that enabled European manufacturers to scale production and reduce costs. Japan and Spain also implemented supportive policies that drove early growth. China's entry into solar manufacturing in the late 2000s fundamentally altered the industry's economics. Through massive investment in manufacturing capacity, supply chain integration, and domestic market development, China became the world's dominant producer of solar panels, driving module prices down by over 80% between 2008 and 2015. This dramatic cost reduction democratized solar energy, making it competitive with conventional power sources in an increasing number of markets. The period from 2015 to the present has seen solar energy transition from a niche technology requiring subsidies to the cheapest form of new electricity generation in most of the world. Record-breaking auction prices for solar power, such as the 1.04 cents per kilowatt-hour bid achieved in Abu Dhabi in 2020, signaled the arrival of solar as a truly mainstream energy technology.

Solar Energy Technologies

Photovoltaic (PV) Technology

Photovoltaic (PV) technology is a method of converting sunlight directly into electricity using semiconductor materials through the photovoltaic effect. It is one of the most widely adopted renewable energy technologies due to its clean

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operation, low maintenance requirements, and ability to generate electricity without producing greenhouse gas emissions during operation.

A photovoltaic system consists of solar cells, which are the fundamental building blocks of a solar panel. These solar cells are typically made from semiconductor materials such as crystalline silicon, thin-film materials, or emerging technologies like perovskites. When sunlight strikes the surface of a solar cell, photons transfer their energy to electrons within the semiconductor material. This process excites the electrons, creating an electric current that can be captured and used as electrical power. The basic structure of a solar cell includes a p-type semiconductor layer and an n-type semiconductor layer, forming a p-n junction. When sunlight is absorbed, electron-hole pairs are generated. The internal electric field at the p-n junction separates these charge carriers, causing electrons to move toward the n-type layer and holes toward the p-type layer, thereby generating direct current (DC) electricity. An inverter is then used to convert the DC electricity into alternating current (AC) suitable for residential, commercial, and industrial applications.

PV technologies are generally categorized into three generations:

First-Generation Solar Cells: These are primarily crystalline silicon solar cells, including monocrystalline and polycrystalline silicon technologies. They offer high efficiency and long operational lifetimes.

Second-Generation Solar Cells: These include thin-film technologies such as Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Amorphous Silicon (a-Si). They require less material and are generally less expensive to manufacture.

Third-Generation Solar Cells: Emerging technologies such as perovskite solar cells, organic photovoltaic cells, and quantum dot solar cells aim to achieve higher efficiencies and lower production costs while maintaining flexibility and lightweight characteristics. The efficiency of a PV system depends on several factors, including solar irradiance, temperature, panel orientation, shading, and the quality of system components. Recent advancements in PV technology have led to significant improvements in conversion efficiency, durability, and cost-effectiveness, making solar energy increasingly competitive with conventional energy sources.

Photovoltaic systems are widely used in grid-connected power plants, residential rooftop installations, commercial buildings, remote telecommunications, water pumping systems, and standalone off-grid applications. As global energy demand continues to rise and concerns about climate change increase, PV technology plays a crucial role in the transition toward sustainable and environmentally friendly energy systems.

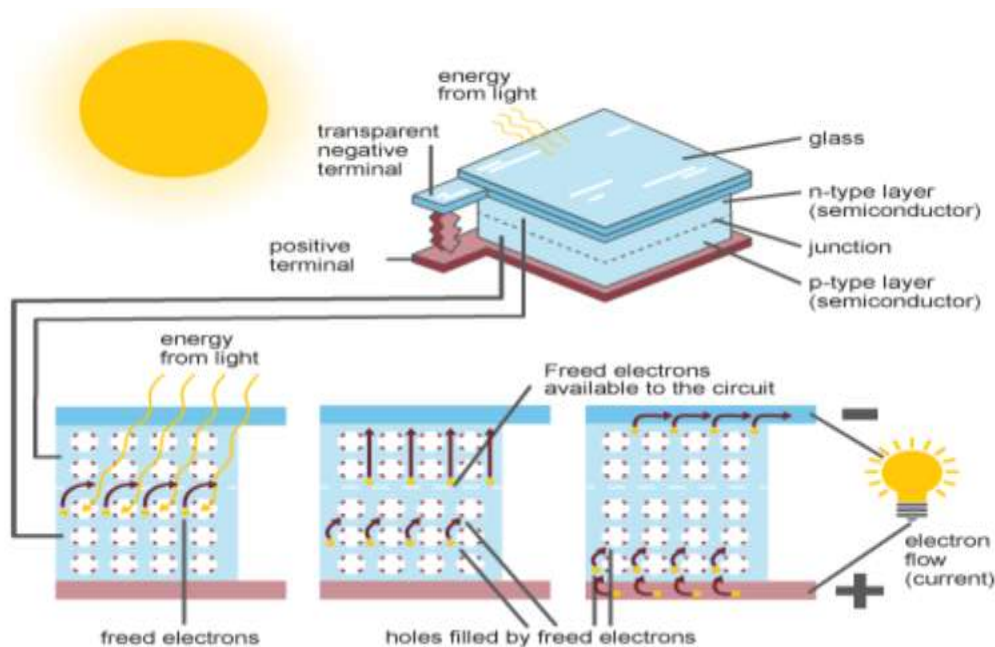


Figure 2.0: Inside work architecture of Photovoltaic



CRYSTALLINE SILICON SOLAR CELLS

Crystalline silicon (c-Si) solar cells dominate the global market, accounting for approximately 95% of total solar panel shipments. Two main variants exist: monocrystalline silicon, produced from a single crystal of pure silicon, and polycrystalline (or multi-crystalline) silicon, made from multiple silicon crystals. Monocrystalline cells offer higher efficiency (typically 20–24% for commercial panels) and a distinctive black appearance, while polycrystalline cells are slightly less efficient but historically offered a cost advantage that has largely eroded.

The fundamental operating principle of a silicon solar cell is the p-n junction. Photons from sunlight excite electrons in semiconductor material, creating electron-hole pairs. The built-in electric field at the p-n junction separates these charge carriers, driving a direct current (DC) that can be extracted through metal contacts. An inverter converts this DC to alternating current (AC) for grid compatibility.

Crystalline Silicon (c-Si) solar cells are the most widely used photovoltaic technology, accounting for the majority of the global solar photovoltaic market. Their popularity is attributed to high conversion efficiency, long operational life, proven reliability, and the abundance of silicon, which is the second most abundant element in the Earth's crust.

Crystalline silicon solar cells convert sunlight directly into electrical energy through the photovoltaic effect. The cells are fabricated from highly purified silicon wafers and are classified into two main types: **Monocrystalline Silicon Solar Cells** and **Polycrystalline Silicon Solar Cells**.

Monocrystalline Silicon Solar Cells

Monocrystalline silicon solar cells are manufactured from a single crystal structure of silicon. These cells are produced using the Czochralski process, where a silicon crystal is grown from molten silicon and sliced into thin wafers. Due to their uniform crystal structure, monocrystalline cells exhibit high electron mobility and reduced recombination losses, resulting in higher efficiencies, typically ranging from 20% to 27%.

Advantages of monocrystalline solar cells include:

- Higher energy conversion efficiency.
- Better performance under low-light conditions.
- Longer lifespan, often exceeding 25 years.
- Lower space requirements due to higher power density.

However, their manufacturing process is complex and expensive, leading to higher production costs.

Polycrystalline Silicon Solar Cells

Polycrystalline silicon solar cells are manufactured by casting molten silicon into molds and allowing it to solidify into multiple crystal grains. The resulting wafers contain grain boundaries that impede electron movement, leading to slightly lower efficiencies, typically between 15% and 22%.

Advantages of polycrystalline solar cells include:

- Lower manufacturing cost.
- Simpler production process.
- Reduced material wastage during fabrication.

Despite their lower efficiency compared to monocrystalline cells, polycrystalline modules remain widely used due to their cost-effectiveness.

Structure and Working Principle

A typical crystalline silicon solar cell consists of:

- Front metal contacts.
- Anti-reflective coating.
- N-type silicon layer.
- P-type silicon base.
- Rear metal contact.

When sunlight strikes the solar cell, photons with sufficient energy generate electron-hole pairs within the silicon semiconductor. The built-in electric field at the p-n junction separates these charge carriers, causing electrons to move toward the n-type region and holes toward the p-type region. This movement creates an electric current that can be extracted through external contacts and used to power electrical devices.

Performance Characteristics

The performance of crystalline silicon solar cells is evaluated using several parameters:

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- **Conversion Efficiency:** Ratio of electrical output power to incident solar power.
- **Open Circuit Voltage (Voc):** Maximum voltage produced when no current flows.
- **Short Circuit Current (Isc):** Maximum current generated when the cell terminals are shorted.
- **Fill Factor (FF):** Measure of the quality of the solar cell.
- **Power Conversion Efficiency (PCE):** Overall effectiveness of converting sunlight into electricity.
- **Advantages of Crystalline Silicon Solar Cells**
- High efficiency and energy yield.
- Mature and reliable technology.
- Long service life with minimal degradation.
- Environmentally friendly operation.
- Extensive industrial and commercial adoption.

Limitations

- Performance decreases with increasing temperature.
- Relatively high manufacturing energy requirements.
- Silicon wafer production can be costly.
- Efficiency losses due to shading and dust accumulation.

Applications

Crystalline silicon solar cells are widely used in:

- Residential rooftop photovoltaic systems.
- Commercial and industrial solar installations.
- Utility-scale solar power plants.
- Rural electrification projects.
- Space and remote power applications.

Due to their high efficiency, durability, and technological maturity, crystalline silicon solar cells continue to dominate the global photovoltaic market and play a significant role in the transition toward sustainable and renewable energy generation.

Thin-Film Technologies

Thin-film photovoltaic (PV) technologies represent the second generation of solar cells and are developed by depositing one or more thin layers of photovoltaic material onto a substrate such as glass, plastic, or metal. Unlike conventional crystalline silicon solar cells, thin-film solar cells require significantly less semiconductor material, resulting in lower manufacturing costs, reduced weight, and greater flexibility. Thin-film technologies have gained considerable attention due to their potential for large-scale production, lightweight design, and suitability for applications where traditional silicon panels may be impractical. Although their efficiency is generally lower than that of crystalline silicon solar cells, continuous advancements in materials and manufacturing processes have improved their performance and commercial viability.

Working Principle

Thin-film solar cells operate based on the photovoltaic effect. When sunlight strikes the semiconductor layer, photons transfer energy to electrons, creating electron-hole pairs. An internal electric field separates these charge carriers, generating an electric current that can be collected and utilized as electrical energy.

The thin semiconductor layers are typically only a few micrometers thick, making them much thinner than conventional silicon wafers, which are usually hundreds of micrometers thick.

Types of Thin-Film Solar Cells

Amorphous Silicon (a-Si) Solar Cells

Amorphous silicon solar cells use non-crystalline silicon deposited as a thin film on substrates such as glass, stainless steel, or plastic.

Advantages:

- Low manufacturing cost.
- Flexible and lightweight design.
- Good performance under low-light conditions.
- Suitable for portable and building-integrated applications.

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Limitations:

- Lower conversion efficiency (typically 6–12%).
- Performance degradation over time due to the Staebler-Wronski effect.

Cadmium Telluride (CdTe) Solar Cells

Cadmium Telluride technology is one of the most commercially successful thin-film photovoltaic technologies. CdTe has a near-optimal bandgap for solar energy conversion, enabling efficient absorption of sunlight.

Advantages:

- Relatively high efficiency among thin-film technologies.
- Low production cost.
- Excellent performance in high-temperature environments.
- Reduced energy payback period.

Limitations:

- Use of cadmium, a toxic heavy metal.
- Limited availability of tellurium.
- Environmental concerns regarding disposal and recycling.

Copper Indium Gallium Selenide (CIGS) Solar Cells

CIGS solar cells utilize a compound semiconductor consisting of copper, indium, gallium, and selenium. These cells exhibit excellent light absorption properties and can be fabricated on flexible substrates.

Advantages:

- High absorption coefficient.
- Flexible and lightweight modules.
- Higher efficiencies compared to many other thin-film technologies.
- Good performance under low-light conditions.

Limitations:

- Complex manufacturing process.
- High material costs due to indium and gallium.
- Challenges in large-scale production consistency.
- Performance Characteristics

The performance of thin-film solar cells is influenced by several factors:

Material composition.

- Film thickness.
- Deposition technique.
- Temperature conditions.
- Solar irradiance levels.

Typical efficiencies of commercial thin-film technologies range from 10% to 22%, depending on the material and manufacturing quality.

Advantages of Thin-Film Technologies

- Lower material consumption.
- Reduced manufacturing costs.
- Lightweight and flexible modules.
- Better performance under diffuse sunlight.
- Easier integration into building materials.
- Lower energy requirement during production.
- Limitations of Thin-Film Technologies
- Lower efficiency compared to crystalline silicon solar cells.
- Larger installation area required for the same power output.
- Potential environmental concerns associated with certain materials.

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- Shorter operational lifetime in some technologies.

Applications

Thin-film photovoltaic technologies are widely used in:

- Building-Integrated Photovoltaics (BIPV).
- Utility-scale solar power plants.
- Portable electronic devices.
- Solar-powered consumer products.
- Transportation and aerospace applications.
- Flexible and wearable energy systems.

Perovskite Solar Cells

Perovskite solar cells represent the most exciting emerging technology in the photovoltaics field. Named for their crystal structure (ABX₃), perovskite materials — typically hybrid organic-inorganic lead or tin halide compounds — have demonstrated extraordinary efficiency gains since their first application in solar cells in 2009, when they achieved just 3.8% efficiency. By 2025, certified perovskite single-junction cells have surpassed 26% efficiency, and tandem perovskite-silicon cells have broken through the 30% barrier.

The rapid efficiency improvement of perovskites stems from their exceptional optoelectronic properties: high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps. Their potential for low-cost solution-based manufacturing processes is particularly attractive. However, challenges remain in long-term stability (perovskites are sensitive to moisture, heat, and light-induced degradation), lead toxicity concerns, and scaling from laboratory cells to commercial modules without efficiency losses.

Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) technologies use mirrors or lenses to concentrate direct normal irradiance (DNI) from the sun onto a receiver, generating heat that drives a conventional power cycle (typically a steam turbine). Unlike PV, CSP inherently produces thermal energy, which can be stored efficiently and inexpensively using molten salt or other thermal storage media, enabling dispatchable solar power generation — a significant advantage for grid integration.

The four principal CSP configurations are: parabolic trough systems (the most mature technology), solar power towers (also called central receiver systems, with the highest concentration ratios and temperatures), linear Fresnel reflectors (lower cost but lower efficiency), and parabolic dish/Stirling engine systems (highest efficiency but limited commercial deployment). The Noor Ouarzazate complex in Morocco (580 MW) and the Ivanpah Solar Electric Generating System in California represent landmark CSP projects.

Solar Thermal Systems

Solar thermal systems capture sunlight as heat for direct use rather than electricity generation. Applications range from simple solar water heaters, which are enormously widespread in China and other markets, to solar space heating, solar cooling (via absorption chillers), industrial process heat, and solar desalination. Solar thermal collectors include flat-plate collectors, evacuated tube collectors, and concentrating collectors for higher-temperature applications.

Solar water heating is among the most cost-effective of all renewable energy technologies, with short payback periods in sunny climates. China alone has installed over 400 million square meters of solar thermal collectors, representing roughly two-thirds of the global total

Economics of Solar Energy

Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is the standard metric for comparing the cost of electricity generation across different technologies. It represents the average cost per unit of electricity generated over the lifetime of a power plant, accounting for capital costs, operating and maintenance costs, fuel costs (if any), and capacity factor. Solar PV's LCOE has experienced one of the most dramatic cost declines in energy history.

According to the International Renewable Energy Agency (IRENA), the global weighted-average LCOE of utility-scale solar PV fell from approximately \$0.38/kWh in 2010 to \$0.049/kWh in 2023 — a reduction of over 87% in thirteen years.

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In the sunniest regions of the world (the Middle East, Chile's Atacama Desert, and India's Rajasthan), utility-scale solar LCOE has fallen below \$0.02/kWh, making it the cheapest electricity in history by a significant margin.

Cost Drivers and the Learning Curve

Solar's cost reduction follows a classic experience curve (also known as Wright's Law or Swanson's Law for solar): for every doubling of cumulative installed capacity, the cost of solar modules has historically declined by approximately 20–24%. This learning rate, driven by manufacturing process improvements, economies of scale, supply chain optimization, and incremental technology improvements, has proven remarkably durable over several decades.

The main cost components of a solar PV system are modules (panels), inverters, mounting structures (racking), electrical balance of system (wiring, combiners, transformers), labor, land, and soft costs (permitting, interconnection, financing). Module costs have declined most dramatically, while balance-of-system and soft costs (often called the "soft cost" challenge) have become increasingly important contributors to total installed cost in mature markets.

Financial Mechanisms and Investment Landscape

Global investment in solar energy reached approximately \$380 billion in 2024, making it the largest single destination for new energy investment. The financing landscape has evolved considerably, with tax equity financing, power purchase agreements (PPAs), corporate procurement, green bonds, and infrastructure funds all playing important roles. The declining cost of capital for solar projects, enabled by strong track records of project performance and a growing investor base familiar with the technology, has contributed to cost reduction.

Emerging markets face higher financing costs due to currency risk, political risk, and less developed capital markets — highlighting the importance of international financial institutions (the World Bank, IFC, and regional development banks) and blended finance mechanisms in mobilizing private capital for solar deployment in developing countries.

Grid Integration and Energy Storage

Integration Challenges

As solar penetration in electricity grids rises, new technical challenges emerge related to the variability and intermittency of solar generation. Solar power output depends on weather conditions and follows a predictable daily and seasonal pattern but can change rapidly due to cloud cover. High solar penetration creates the well-known 'duck curve' phenomenon — named for its shape — in which net electricity demand (total demand minus solar and wind generation) dips sharply during midday hours and then rises steeply in the evening as solar output falls and demand increases.

Managing these fluctuations requires a combination of strategies: grid-scale energy storage (primarily batteries), demand-side flexibility (shifting flexible loads to align with solar generation), improved grid interconnection to balance generation across broader geographic areas, smart inverters that provide grid support services, and conventional or dispatchable renewable generation (hydro, geothermal, biomass, gas peakers) to fill gaps.

Battery Energy Storage Systems (BESS)

Lithium-ion battery energy storage systems (BESS) have emerged as the dominant near-term solution for pairing with solar generation. Battery costs have followed a trajectory remarkably similar to solar's, falling by over 90% since 2010. In 2024, four-hour duration lithium-ion battery storage added approximately 50 GW of new capacity globally, with the majority co-located with solar projects. Solar-plus-storage configurations are increasingly winning competitive auctions against gas peakers and providing firm capacity at competitive prices.

Beyond lithium-ion, a range of alternative storage technologies are under development for long-duration energy storage (LDES) — storage systems capable of storing energy for 8–24 hours or even weeks. These include flow batteries (vanadium, iron-air), compressed air energy storage, pumped hydro, green hydrogen (using solar electricity to produce hydrogen via electrolysis), and thermal storage. Long-duration storage is widely seen as critical for achieving very high penetrations of solar and wind power (80–100% of annual generation).

Smart Grids and Distributed Energy Resources

The integration of large numbers of distributed solar systems — rooftop panels on millions of homes and businesses — is transforming the distribution grid from a one-way power delivery system into a two-way interactive network. Managing this complexity requires advanced metering infrastructure (smart meters), distribution automation, demand response programs, virtual power plants (aggregations of distributed resources), and sophisticated grid management software.

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Prosumers consumers who both consume and produce electricity — are fundamentally changing the economics and operation of electricity markets. Net energy metering policies, which allow prosumers to sell excess solar generation back to the grid at retail rates, have been instrumental in driving residential solar adoption, though their long-term sustainability and appropriate design are subjects of ongoing policy debate

CONCLUSION

Solar energy has undergone a transformation of extraordinary speed and scale, evolving from an expensive space-age technology into the world's cheapest and fastest-growing source of electricity in just a few decades. The fundamental drivers of this transformation — inexorable cost reduction driven by learning curves, supportive policy frameworks, technology innovation, and growing awareness of the climate imperative — show no signs of abating.

The challenge ahead is not whether solar energy can be deployed at the scale required to meaningfully address climate change, but how to accelerate and deepen deployment in every region of the world, at every scale, and across every sector of the economy. This requires continued innovation in solar cell technology, storage solutions, grid infrastructure, and system integration; effective policy frameworks that provide long-term investment certainty and appropriate market signals; international cooperation to ensure that all countries, regardless of income level, can benefit from the solar revolution; and serious engagement with the environmental and social dimensions of the solar supply chain and deployment.

The solar century has begun. With the right enabling conditions, solar energy has the potential not only to decarbonize the global electricity sector but to provide the foundation for a broader clean energy economy — powering green hydrogen production, electrified transportation, sustainable industry, and expanded energy access for all. The sun shines on every nation; the task is to harvest its power wisely, equitably, and at sufficient scale to safeguard the planet's climate for future generations

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