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THE PHYSICS AND APPLICATIONS OF SOLAR ENERGY: UNDERSTANDING SOLAR FUSION, RADIATION, TECHNOLOGIES AND MODERN UTILISATION

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ABSTRACT

The sun is the primary engine driving nearly all natural and technological energy systems on Earth. This article presents a comprehensive exploration of the scientific mechanisms by which the sun generates and delivers energy, beginning with nuclear fusion processes that convert hydrogen into helium via the proton–proton cycle. These reactions release immense quantities of thermal and electromagnetic radiation that sustain life and form the basis for renewable energy systems. The paper examines the structure and temperature profile of the sun, the historical evolution of theories about its energy source, and modern understanding of mass–energy conversion and binding energy. It further explains solar radiation behaviour, including atmospheric scattering, diffuse and direct components, and spatial–temporal variation in solar irradiance.

The study then transitions to contemporary solar technologies, detailing photovoltaic mechanisms, silicon doping, solar cell generations, concentrated photovoltaics, and solar thermal systems such as flat-plate collectors, evacuated tubes, parabolic troughs, and thermal energy storage techniques. Global renewable energy trends based on IEA projections are reviewed, highlighting solar PV as the fastest-growing energy technology and a major contributor to future electricity supply. Additionally, diverse applications of solar energy—including ventilation, water and space heating, pumping, lighting, cooking, and battery charging—are discussed alongside the environmental, economic, and operational challenges that limit its large-scale deployment. Despite issues of intermittency, land demand, manufacturing pollution, high initial costs, and low efficiency, solar energy remains one of the most promising long-term renewable resources. The article concludes that ongoing innovation in materials science, storage technologies, and system integration is essential for achieving cost-effective, efficient, and sustainable solar utilisation in the decades ahead.

1. INTRODUCTION

The sun serves as the fundamental energy source for Earth, driving climate systems, sustaining ecological processes, and enabling virtually all life forms through photosynthesis. As a massive nuclear fusion reactor composed primarily of hydrogen and helium, the sun continuously converts matter into energy through the proton–proton (pp) fusion cycle under extreme temperatures and pressures (Severino, 2017). This fusion process transforms approximately 508 million tonnes of hydrogen into 504 million tonnes of helium each second, releasing nearly four million tonnes of converted mass as radiant energy (Green et al., 2004). The abundance, reliability, and longevity of solar radiation—expected to continue for billions of years—position solar energy as a vital focus for renewable energy research and technological development (West, 1993).

Understanding the scientific mechanisms behind solar energy production is foundational for harnessing this resource efficiently. Early scientific explanations of solar energy relied on chemical combustion analogies, which proved inadequate after geological evidence showed Earth's age exceeded 100 million years, far surpassing the lifespan chemical reactions could sustain (Bland, 2004). Subsequent hypotheses, such as gravitational contraction proposed by Helmholtz, extended estimates to millions of years but remained insufficient to explain the sun's multi-billion-year lifecycle (Cahan, 2004). It was not until the early 20th century—following the discovery of nuclear reactions, atomic structure, and Einstein's mass–energy equivalence—that scientists correctly attributed the sun's energy source to nuclear fusion.

Modern solar technologies, including photovoltaic (PV) systems and solar thermal collectors, are rooted in these scientific principles. Solar PV cells convert sunlight into electricity using semiconductor materials such as silicon, while solar thermal systems capture solar heat for domestic, commercial, or industrial use (Tiwari, 2005). Advances in materials science have produced multiple generations of solar technologies, ranging from monocrystalline silicon panels to thin-film and concentrated photovoltaic (CPV) systems (Misak & Prokop, 2016). Meanwhile, global energy trends indicate unprecedented expansion in renewable energy capacity, particularly solar PV, which now represents the fastest-growing electricity source worldwide (International Energy Agency [IEA], 2024).

Despite its potential, solar energy faces challenges including intermittency, land requirements, manufacturing impacts, and high upfront system costs. Nonetheless, ongoing research on energy storage, solar fuels, semiconductor innovation, and system integration aims to increase efficiency and reduce environmental and economic barriers. This article examines the scientific foundations of solar energy, the mechanisms of solar radiation, the evolution of solar technologies, and the expanding global role of solar power in modern energy systems.

2. LITERATURE REVIEW

The scientific understanding of solar energy begins with the nature of the sun as a fusion-based energy source. Nuclear fusion occurs when hydrogen nuclei combine to form helium under extreme temperature and pressure conditions in the solar core (Severino, 2017). The dominant energy pathway in sun-like stars is the proton–proton (pp) chain, which releases energy in the form of gamma radiation, neutrinos, and kinetic energy of reaction byproducts (Green et al., 2004). Einstein's mass–energy relation ($E = mc^2$) explains how the small mass difference between reactants and products is converted into enormous amounts of energy (Cahan, 2004). This discovery resolved earlier misconceptions attributing the sun's heat to chemical or gravitational mechanisms (Bland, 2004).

Solar radiation reaching Earth consists of direct and diffuse components influenced by atmospheric scattering, absorption, and reflection (Goga, 2010). The Earth's axial tilt, orbital geometry, and atmospheric composition cause spatial and temporal variations in solar irradiance (Newton, 2015). Measurements of radiation in watts per square meter (W/m^2) or kWh/m^2 are essential for solar energy system design, especially in the placement of photovoltaic and thermal collectors (U.S. Department of Energy, 2021). The distribution of solar radiation determines site suitability, system output, and technology selection.

Photovoltaic technology converts sunlight directly into electricity using semiconductor materials such as silicon, cadmium telluride, or copper indium gallium diselenide (CIGS). The foundational mechanism relies on the photoelectric effect, where absorbed photons excite electrons, creating an electric current (Tiwari, 2005). Silicon remains the dominant PV material due to its stability, abundance, and favourable electronic properties. Monocrystalline silicon panels achieve efficiencies above 20%, while polycrystalline panels typically reach around 15% efficiency (GreenMatch, 2015). Thin-film technologies, including amorphous silicon (a-Si) and CdTe, offer advantages in flexibility and lower production cost, though often at lower efficiencies.

Emerging PV innovations include concentrated photovoltaics (CPV), which use lenses or mirrors to focus sunlight onto high-efficiency multi-junction cells capable of exceeding 40% efficiency (Misak & Prokop, 2016). Biohybrid solar cells represent another research frontier, mimicking photosynthesis pathways to potentially achieve much higher conversion efficiencies (Tiwari, 2005).

Solar thermal systems capture solar heat for domestic, industrial, or power-generation purposes. Flat-plate collectors and evacuated tubes are widely used for water heating, while parabolic troughs, heliostats, and Fresnel lenses enable high-temperature applications such as electricity generation (O'Keefe & Pike, 2004). Energy storage technologies—including sensible heat storage, latent heat using phase change materials (PCM), and high-temperature molten salt systems—enhance system reliability by enabling thermal retention and dispatchability (Tiwari, 2005).

Chemical storage methods, such as thermochemical reactions using $Ca(OH)_2$, offer long-duration storage potential but require further research to reduce operating temperatures and improve reversibility. According to the IEA (2024), solar PV is responsible for roughly 80% of projected renewable energy expansion through 2030, with global capacity expected to more than double. Falling costs, supportive policies, and improved manufacturing have made PV one of the most cost-effective electricity sources worldwide. China leads global deployment, while India, the EU, Middle East, and North Africa show rapid adoption trends. Challenges remain, including supply chain concentration, grid integration, financing barriers, and limitations in energy storage.

Despite its benefits, solar energy adoption faces several obstacles. Environmental concerns include land use impacts, toxic materials in PV manufacturing, and end-of-life waste disposal (Murphy-Mariscal et al., 2018). Economic challenges involve high upfront system costs, lengthy payback periods, and the continued expense of battery storage (Walden Labs, 2021). Intermittency and dependence on weather conditions further require robust storage and grid integration strategies. Nonetheless, continued technological innovations promise to improve performance, reduce costs, and enhance sustainability.

3. The energy of the sun. Comprehending the mechanisms of solar function

3.1 Thermal energy and Light

The sun (Figure1) is a colossal fusion reactor. Fusion refers to the process of combining hydrogen atoms to form helium. This transpires on the sun due to its extreme heat. The sun is exceedingly hot due to the substantial heat released by fusion processes. Fusion is referred to be a chain reaction for this reason. The energy source is derived from fusion events that convert hydrogen into helium, predominantly via the proton-proton (pp) cycle (Severino G., 2017).

The sun's nuclear fusion process transforms 508 million tonnes of hydrogen into 504 million tonnes of helium each second. The residual 4 million tonnes of matter are transformed into energy, resulting in an exceedingly high core temperature of the sun. Albert Einstein discovered that a little quantity of matter can be transformed into a substantial amount of energy. One ounce of matter transformed to energy by fusion might provide sufficient energy for a whole year for your home and vehicle, in addition to serving the needs of five thousand other households and vehicles.

Solar radiation is superior to alternative energy sources due to its abundance and longevity, expected to persist for millions of years (West M., 1993).
What is the origin of the sun's energy? This subject is vital, given solar light and heat underpin nearly all life on Earth. Sunlight sustains plant life through photosynthesis, whereas animals depend on consuming plants for survival. Nearly all microscopic life forms (bacteria, protozoa, etc.) sustain themselves by harnessing solar energy.

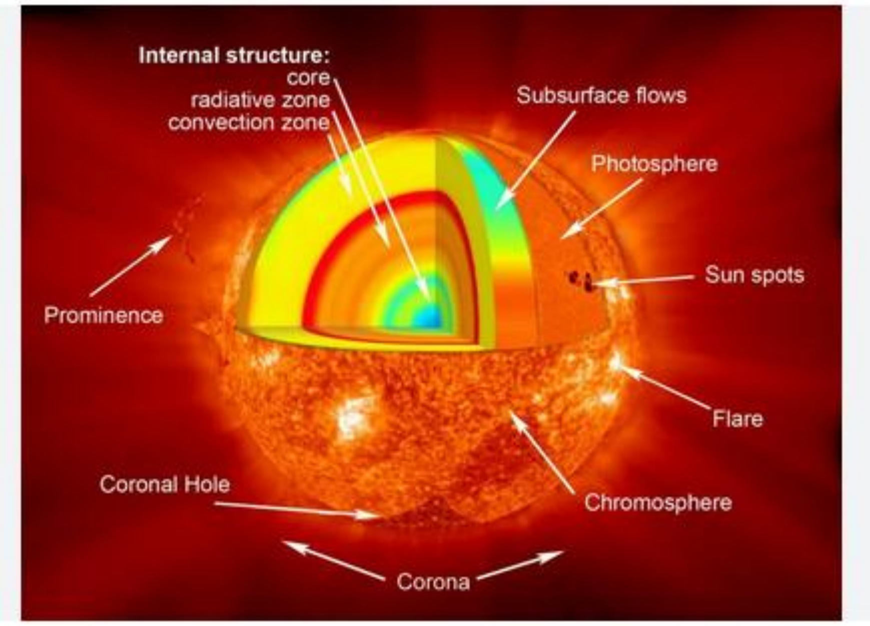


Figure. 1 Composition of the Sun
Source: *https://science.nasa.gov/blogs/the-sun-spot/2023/09/26/layers-of-the-sun/*

3.2 Surface Temperature

The sun is a spherical body with a diameter of 1,400,000 km, composed primarily of heated gases, predominantly hydrogen and helium, with a surface temperature of approximately 6,000 degrees Celsius (around 11,000 degrees Fahrenheit). Any surface at that temperature will emit heat and light. The burners of an electric stove or toaster oven do not reach 6,000 °C; yet, when activated, they become "red hot," emitting both heat and red light. If we could elevate the temperature to 6,000 °C. They would attain a "white hot" state and radiate light akin to that of the sun. A fire is a zone of gases with a temperature sufficiently elevated to produce heat and light (Goga, 2010). The inquiry shifts from the origins of heat and light to the source of energy that maintains the sun's surface temperature at 6,000 degrees.

For a scientist in the 18th or 19th century, before to the advent of electrical gadgets, the most probable method of comprehending the sun's energy would be to draw a parallel to fire. A combustion occurs when a material reacts chemically with oxygen in the air. Despite the lack of knowledge regarding the sun's chemical composition, one could reasonably infer that a chemical reaction occurs, generating heat and maintaining the sun's temperature. The issue is determining the duration until the combustible chemicals are entirely consumed and the fire extinguishes, analogous to how logs in a fireplace reduce to ash within a few hours.

3.3 The lifespan of the sun

Arriving at a preliminary answer to that issue is straightforward, as we possess knowledge of the sun's mass. The mass is determined through the law of universal gravity and the established orbits of the planets. Assuming the mass consists entirely of carbon, one can estimate the sun's lifespan to be approximately 50,000 years. Any chemical combustion will result in a lifespan within the approximate range (Bland P., 2004).

Nineteenth-century geologists posited that the Earth's age exceeded 100 million years. The calculations were estimative, grounded in plausible assumptions regarding the deposition of salt into the ocean and the accumulation of marine sediment onto the present continents. Assuming that all oceanic salt originated from river deposition, and given the current deposition rate, we can calculate the duration required to achieve the present salt concentrations in the oceans. Furthermore, since the Earth orbits the Sun, it is difficult to conceive of the Earth being older than the Sun. Consequently, the concept of the sun as a chemical fire was untenable.

3.4 Gravitational Energy

In approximately 1850, physicist Hermann von Helmholtz posited that the sun's energy source may be attributed to gravitation, specifically the universal gravitational force exerted by each component of the sun on every other component (Cahan D., 2004). Gravity may generate energy, as illustrated by the act of dropping an object, such as a baseball, and allowing it to descend to the earth. Kinetic energy is generated when the ball descends. Considering the sun as a vast sphere of gases, each atom within the gas experiences a net gravitational pull towards the centre of the sphere, resulting in a collective inclination of all atoms to "descend" towards the core. During this process, they hit with other atoms, resulting in intense yet random motion. The fast, erratic movement of atoms in a gas indicates elevated temperatures. Based on the established energy production rate of the sun, Helmholtz was able to approximate the duration for which the sun, considering its mass, could sustain this energy generation. His findings indicated a duration of approximately 20 million years, far above the estimate derived from chemical combustion, and aligning more closely with contemporary assessments of the Earth's age.

Billions of years; nonetheless, millions of years are insufficient. The most accurate estimate for the age of the solar system, including the sun and the planets, is 4.6 billion years. Radioactive dating indicates that certain rocks solidified approximately 4 billion years ago, and that primitive bacteria emerged nearly 3.5 billion years ago. Thus, gravitation cannot account for the source of the sun's energy.

3.5 Nuclear Reactions

The convergence of significant developments occurred in the early twentieth century with the identification of the atomic nucleus (1911), the investigation of nuclear reactions (1920s), and Einstein's theory of relativity (1905). In a standard nuclear reaction, many subatomic particles converge, interact, and yield various (potentially distinct) particles. A series of reactions occur in the sun, culminating in the following combination of particles.

3.6 Hydrogen combustion

The overall nuclear fusion reaction in the Sun, where four hydrogen nuclei fuse into one helium nucleus, is:

$$4{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu + \text{energy}$$

This process is more accurately a series of reactions, known as the proton-proton chain, where hydrogen protons combine under extreme heat and pressure to form helium, releasing energy in the form of positrons (e^{+}), neutrinos (ν), and photons (γ) The left side of this reaction displays four protons and four electrons, essentially representing four hydrogen atoms. Hydrogen serves as the fundamental beginning point, as the majority of matter in the sun and other stars consists of hydrogen gas. Hydrogen, being the most fundamental element, logically suggests that a significant portion of the cosmos in its primordial state would consist of hydrogen. The terminus is helium, recognised as the second most prevalent element in the sun. The process is commonly termed "hydrogen burning" to helium, with hydrogen frequently designated as "fuel"; nevertheless, it is essential to recognise that this reaction does not constitute burning in the conventional sense of a chemical reaction involving a fuel, such as coal or wood, and oxygen. This constitutes a nuclear reaction (Green et al., 2004).

3.6 Mass Transformed into Energy

Energy is produced during this reaction due to the total mass of the particles on the right side being smaller than that on the left side. The deficiency of electrons on the right is not the sole factor. The primary distinction is that the mass of the helium nucleus (42He) is significantly lower than the cumulative mass of the four protons on the left. This exemplifies binding energy: The isotope 42He comprises two protons and two neutrons, although its mass is inferior to the cumulative mass of the individual protons and neutrons. Given that the mass on the left side exceeds that on the right, energy is generated throughout the reaction, equivalent to the mass difference multiplied by c^{2}. This energy exists in two forms: the kinetic energy of particles in the sun and gamma radiation.

3.7 The Proton-Proton Cycle

Equation (1) represents the cumulative result of a sequence of more fundamental reactions. The procedure outlined in Equation (1) is referred to as the proton-proton cycle, as it commences with the contact of two protons. The process of combining tiny nuclei to form larger ones is termed fusion, and the sequence occurring in the sun resembles (though is not identical to) the fusion reactions being investigated as a potential source of electrical energy on Earth (Severino G., 2017).

3.8 The binding energy of the alpha particle

What is the reason behind nature (the sun and the stars) exerting such effort to create 42He's? Among the several tiny nuclei participating in the proton-proton cycle, 42He is the most tightly bonded. The binding energy of 42He is significantly substantial, indicating that its formation by nature results in the release of a considerable quantity of energy. Energy is released at each stage of the cycle, with the majority occurring in the last step, where 42He is produced.

3.9 Gravitational Collapse

The prevailing concept for the sun's beginning posits that a cloud of hydrogen gas initiates collapse due to its own gravitational forces, leading to an increase in temperature. While this cannot serve as the mechanism for the sun's energy generation over billions of years, it may function as a triggering or ignition mechanism (O'Keefe and Pike, 2004).

3.10 A heated plasma

Consequently, the cloud compresses, and at elevated temperatures, the gas transforms into a plasma. The hydrogen atoms dissociate into protons and electrons, which then exhibit random motion. The temperature reaches its peak near the centre of the cloud, where protons exhibit such high energy that the reaction in Equation (1) commences, initiating the proton-proton cycle.

3.11 Equilibrium

These activities persist at the core of the cloud, elevating the temperature to approximately 10,000,000 degrees. At this temperature, the sun attains equilibrium, when the outward pressure from the "combusting" gases counterbalances the gravitational force exerting an inward draw on the matter. The energy generated in the core consistently radiates outward, maintaining the sun's overall temperature. The outside areas are significantly cooler than the centre; nonetheless, they possess sufficient heat to emit energy into space, manifested as the heat and light that illuminate the Earth (Green and Jones, 2004).

3.12 The lifespan of the sun

The sun can maintain this equilibrium for around 10 billion years. Considering the sun's age is approximately 4.6 billion years, it may be inferred that we have roughly 5 billion years remaining. Ultimately, the majority of the hydrogen in the core will be depleted, leading the sun into a terminal phase. The proton-proton cycle fuels not just the sun but also the majority of medium to small mass stars. Stars exceeding the size of the sun generate energy through a more intricate series of processes; yet, the overall outcome remains consistent with Equation (1), wherein hydrogen is converted into helium (Tyson, 2017).

3.13 Solar Radiation

Commonly referred to as solar resource, it denotes the electromagnetic radiation emitted by the sun. Solar radiation can be harnessed and converted into valuable energy forms, including heat and electricity, through various technologies. The technical feasibility and economic viability of these systems at a particular site are contingent upon the solar resource availability. Every area on Earth receives sunlight for a portion of the year. The quantity of solar radiation that reaches a specific location on the Earth's surface fluctuates according on:

a. Geographical place
b. Temporal designation
c. Period
d. Regional topography

4. REGIONAL METEOROLOGICAL CONDITIONS

The Earth's spherical shape causes sunlight to touch the surface at varying angles, from 0° (horizon level) to 90° (straight overhead). When the sun's beams are perpendicular, the Earth's surface receives maximum energy. The greater the angle of the sun's rays, the longer their passage through the atmosphere, resulting in more scattering and diffusion. The Earth's spherical shape results in the polar regions never experiencing direct sunlight, and due to the axial tilt, these locations receive no sunlight at all for a portion of the year. The Earth orbits the sun in an elliptical path, being nearer to the sun at certain times of the year. When the sun is closer to the Earth, the Earth's surface receives additional solar energy. The Earth is closer to the sun during summer in the southern hemisphere and winter in the northern hemisphere. Nonetheless, the existence of extensive oceans mitigates the anticipated hotter summers and colder winters in the southern hemisphere due to this disparity.

The 23.5° inclination of the Earth's rotational axis is a crucial determinant of the solar irradiance received at specific locations on the planet. Axial tilt causes extended daylight in the northern hemisphere from the vernal equinox to the autumnal equinox, whereas the southern hemisphere experiences prolonged daylight for the subsequent six months. The equinoxes, occurring annually on or around March 23 and September 22, have days and nights that are precisely 12 hours in duration.

The sun is the source of all energy on Earth. Plants utilise sunlight to synthesise nourishment. Decomposed vegetation from hundreds of millions of years ago generated the coal, oil, and natural gas utilised today. Solar energy is mostly harnessed through the utilisation of solar cells. Solar energy can indeed be utilised to illuminate or heat a room through strategically positioned windows and skylights. Solar energy can also be utilised to dry our garments in sunlight. Solar cells are utilised to harness solar energy for powering electrical gadgets. https://www.energy.gov/eere/solar/articles/solar-radiation-basics

4.1 Fundamental Principles of Solar Energy

Solar energy is generated by the light and heat emitted by the sun, manifesting as electromagnetic radiation. Contemporary technology enables us to harness this radiation and convert it into practical forms of solar energy, like heating and power. Solar energy is the continuous energy produced by the sun's nuclear fusion reactions. The average solar radiation intensity at Earth's orbit is 1367 kW/m^2. The Earth's equatorial circumference is 40,000 km, allowing for the calculation of energy received by the Earth, which is around 173,000 TW. At sea level, the standard peak intensity is 1 kW/m^2, while a place on the Earth's surface receives an annual average radiation intensity of 0.20 kW/m^2, equating to approximately 102,000 TW of energy over 24 hours. Humans depend on solar energy for survival, alongside all other renewable energy sources, excluding geothermal resources. Although the total solar energy available is ten thousand times greater than human energy consumption, its low density and variability due to location and season present significant challenges for the development and utilisation of solar energy (Tiwari G, 2005).

The need for this sector of renewable energy sources is increasingly rising due to global economic development and population growth. The latest IEA research indicates that, driven by solar energy, renewables are projected to satisfy about half of worldwide electricity consumption by the decade's conclusion.

According to a new IEA report released today, supportive policies and favourable economic conditions are anticipated to drive a significant increase in the world's renewable power capacity throughout the remainder of this decade, with global additions projected to approximate the current power capacity of China, the European Union, India, and the United States combined.

The Renewables 2024 report, the IEA's premier yearly publication on the industry, indicates that the global addition of renewable energy capacity would exceed 5,500 gigawatts (GW) from 2024 to 2030, nearly tripling the increase observed from 2017 to 2023.

The analysis indicates that China is projected to represent over 60% of the total renewable capacity installed globally from now until 2030, contingent upon prevailing market trends and current governmental policy frameworks. By the end of this decade, China is projected to account for about fifty percent of the global renewable power capacity, an increase from one-third in 2010. China is increasing its renewable energy capacity the most, while India is expanding at the highest rate among major economies.

Solar photovoltaic technology is projected to constitute a substantial 80% of the expansion in worldwide renewable capacity from now until 2030, driven by the establishment of new large-scale solar power facilities and a rise in rooftop solar installations by businesses and residences. Despite persistent hurdles, the wind sector is positioned for a resurgence, with the growth rate expected to double from 2024 to 2030 compared to the interval from 2017 to 2023. Currently, wind and solar photovoltaic technologies represent the most economical choices for augmenting electricity generation in nearly all nations.

Consequently, about 70 nations, which together represent 80% of worldwide renewable power generation, are set to achieve or exceed their existing renewable targets for 2030. The expansion does not entirely align with the objective established by almost 200 governments at the COP28 climate change summit in December 2023 to triple the world's renewable capacity within this decade; the analysis predicts that global capacity will attain 2.7 times its 2022 level by 2030. However, IEA analysis suggests that achieving the triple aim is completely feasible if governments capitalise on immediate possibilities for action. This entails delineating ambitious strategies in the forthcoming iteration of Nationally Determined Contributions under the Paris Agreement, scheduled for next year, and enhancing international collaboration to reduce elevated financing costs in emerging and developing economies, which are hindering the expansion of renewable energy in high-potential areas like Africa and Southeast Asia.

Renewable energy sources are advancing more rapidly than national governments can establish targets for them. According to IEA Executive Director Fatih Birol, this trend is primarily motivated not only by the desire to reduce emissions or enhance energy security, but increasingly because renewable energy sources now represent the most cost-effective solution for establishing new power plants in nearly all nations globally. This analysis indicates that the expansion of renewable energy, particularly solar power, will revolutionise electricity networks worldwide within this decade. By 2030, the global renewable power capacity is projected to increase by about 5,500 gigawatts, approximately equivalent to the current power capacity of China, the European Union, India, and the United States combined. By 2030, we anticipate that renewable energy sources will fulfil fifty percent of worldwide electricity consumption.

By the conclusion of this decade, the proportion of wind and solar photovoltaic energy in worldwide electricity generation is projected to quadruple to 30%, as per the forecast. The analysis underscores the necessity for governments to intensify their efforts to securely incorporate these variable renewable sources into power infrastructure. Recently, the incidence of curtailment—where renewable electricity generation is not utilized—has significantly risen, currently approximating 10% in various nations. Countries should prioritise enhancing power system flexibility to address this issue. A concerted effort to resolve policy ambiguities and expedite permitting procedures, alongside the construction and modernisation of 25 million kilometres of electricity grids and achieving 1,500 GW of storage capacity by 2030, as emphasised in prior IEA analyses, would facilitate a greater proportion of electricity generation from renewable sources.

The proportion of renewables in final energy consumption is projected to rise to about 20% by 2030, up from 13% in 2023, mostly driven by the substantial expansion of renewable power. Concurrently, renewable fuels, addressed in a dedicated chapter of the report, are underperforming, highlighting the necessity for targeted policy assistance to decarbonise sectors that are challenging to electrify. The analysis indicates that achieving international climate objectives necessitates not only the expedited deployment of renewable energy but also a substantial acceleration in the uptake of sustainable biofuels, biogases, hydrogen, and e-fuels. Due to their higher costs compared to fossil fuels, their proportion in global energy is projected to stay under 6% by 2030.

The research additionally examines the condition of manufacturing in renewable technologies. Global solar production capacity is anticipated to exceed 1,100 GW by the conclusion of 2024, more than doubling the projected demand. The supply surplus, primarily in China, has contributed to a reduction in module costs, which have decreased by almost fifty percent since early 2023; nevertheless, this situation has also resulted in substantial financial losses for some manufacturers.

In light of the increasing worldwide emphasis on industrial competitiveness, solar PV production capacity in both India and the United States is projected to triple by 2030, contributing to global diversification. Producing solar panels in the United States is three times more costly than in China and twice as expensive as in India. The research advises authorities to balance the higher costs and benefits of local production, prioritising job growth and energy security.

4.2 Renewable Energy Trends 2025: Capacity to Double by 2030

Notwithstanding the favourable trends, the IEA cautions that the COP28 goal of tripling clean energy capacity is unattainable. To regain momentum, nations should mitigate regulatory ambiguities, shorten permitting durations, enhance grid investments, broaden flexibility to support the integration of intermittent renewables, and alleviate finance risks. In early October 2025, the IEA published its “Renewables 2025” report, an annual sectoral analysis that outlines the current trends, projections, challenges, and opportunities in renewable energy, informed by recent legislation and market developments. The analysis indicated that, despite challenges, renewable energy, particularly solar PV, continues to expand globally—a crucial trend for maintaining the Paris Agreement objectives. Significantly, the persistent reduction in technology and energy prices, together with the advantages of energy security, will markedly expedite the deployment of renewable energy capacity in several nations, with Asia poised to emerge as the most dynamic market. The IEA's Renewables 2025 report indicates that global renewable energy trends forecast an addition of 4,600 GW in new capacity by 2030.

The primary conclusion of the IEA's analysis is that worldwide renewable power capacity is projected to double by 2030, increasing by 4,600 GW. The organisation observes that this is about tantamount to incorporating the power generation capacity of China, the EU, and Japan collectively into the global energy mix. The agency anticipates that renewables will emerge as the predominant global energy source, accounting for over 45% of power generation by 2030, with an increase of 60% — from 9,900 TWh in 2024 to 16,200 TWh in 2030.

4.3 Solar Energy

The IEA reports that solar PV, projected to more than quadruple in the next five years, constitutes about 80% of the global rise, succeeded by wind, hydropower, biofuels, and geothermal energy. The government observes that reduced costs, expedited permitting, and widespread social acceptability will facilitate growth. The increase in retail electricity rates due to the energy crisis has spurred the adoption of solar photovoltaic systems, prompting individuals and companies to install these systems to lower their electricity expenses.

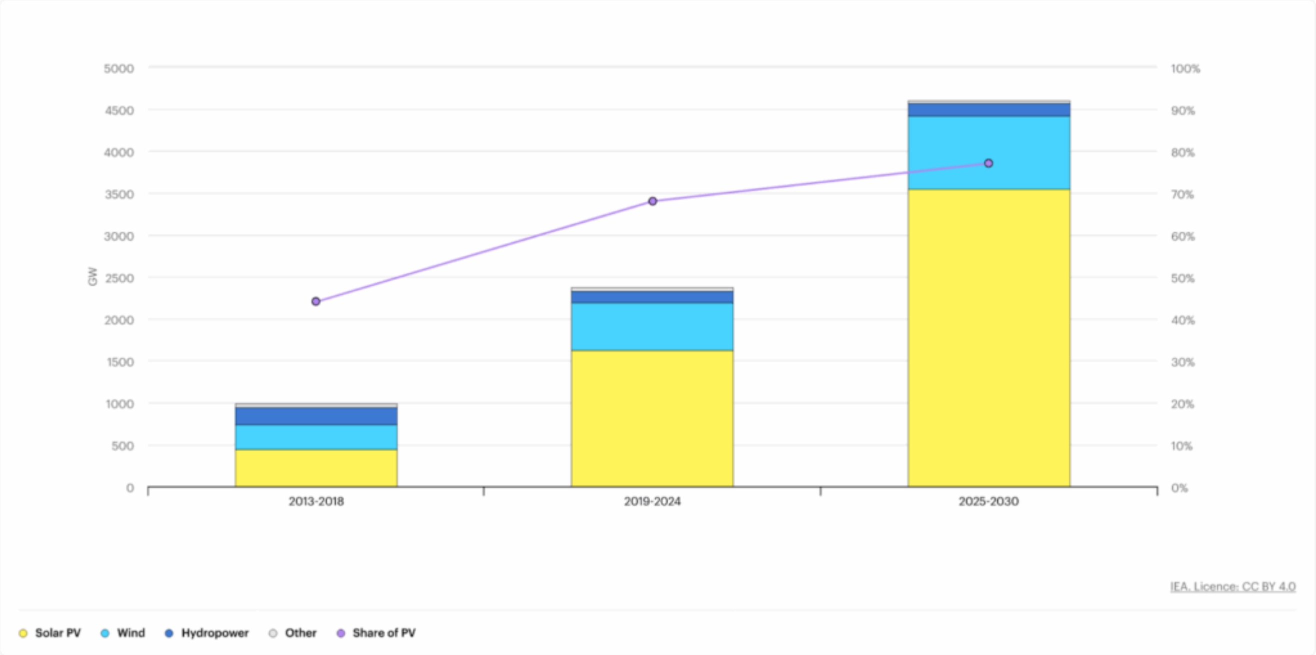


Figure 2. Renewable Electricity Capacity Growth by Technology Segment, and Solar PV Share, Main Case, 2013-2030. Source:(IEA)

4.4 Wind Energy

The organisation indicates that worldwide wind power capacity is projected to roughly double to exceed 2,000 GW by 2030, primarily propelled by China and the EU. Relative to the prior era (2019-2024), the IEA's projection anticipates a 45% increase in cumulative onshore wind capacity additions from 2025 to 2030, totalling 732 GW. Offshore wind capacity expansion is projected to exceed 140 GW, more than twice the growth of the preceding five-year period. The yearly offshore wind market grows from 9.2 GW in 2024 to over 37 GW by 2030, with China representing nearly 50% of this growth.

4.5 Hydroelectric power

The IEA forecasts that hydropower will constitute 3% of new renewable energy installations by 2030.

4.6 Geothermal Energy

By 2030, annual geothermal capacity additions will achieve a record high, tripling the amount observed in 2024, propelled by advancements in the United States, Indonesia, Japan, Turkey, Kenya, and the Philippines.

The IEA acknowledges that, although the findings are promising, its prediction for the period from 2025 to 2030 is 5% lower than its study from 2024, indicating alterations in policy, regulation, and market conditions. The agency now anticipates a reduction of 248 GW in renewable capacity to be operational during the next five years. Solar and wind energy can fulfil energy requirements. Nonetheless, as per Ember's "Global Electricity Mid-Year Insights 2025" study, the contributions from solar and wind energy are already sufficient to satisfy the increasing worldwide electricity demand. Analysts report that solar and wind energy fulfilled all electricity demand growth in the first half of this year, resulting in a minor decline in fossil fuel generation relative to the same period in 2024. Significantly, Ember observes that renewable energy sources have surpassed coal for the first time in history, with unprecedented solar development and consistent wind expansion gradually transforming the global energy landscape. Solar and wind energy are expanding rapidly to satisfy the increasing global demand for electricity, stated

Małgorzata Wiatros-Motyka, senior electricity analyst at Ember. This signifies the onset of a transition in which clean energy is aligning with the growth in demand.

5. FOCUS ON IEA'S REGIONAL INSIGHTS AND TRENDS IN THE RENEWABLE ENERGY MARKET

The IEA's analysis indicates that in over 80% of nations globally, renewable electricity capacity is projected to expand more rapidly from 2025 to 2030 than over the preceding five years. The organisation indicates that alterations in policy within the US and China account for the 5% reduction in the prediction for worldwide renewable power capacity increase compared to last year's study. The United States, under President Trump, is the primary outlier, with its projection adjusted downward by over 50%. Notwithstanding the transition from fixed tariffs to auctions and its effect on project economics, China still represents about 60% of worldwide renewable capacity expansion and is poised to achieve its recently declared 2035 wind and solar objective five years in advance.

The IEA's 2025 renewable market outlook is more favourable for India, Europe, and most emerging and developing markets compared to the prior edition. In India, the rise of renewable energy is propelled by increased auction volumes, enhanced support for rooftop solar initiatives, and expedited hydropower permitting processes. The IEA observes that the country is poised to achieve its 2030 objective and emerge as the second-largest growth market for renewables, with capacity projected to expand by 2.5 times within the next five years.

The IEA has adjusted its growth prediction for the EU somewhat upward, propelled by unexpectedly large installations of utility-scale solar PV capacity and robust corporate power purchase agreement (PPA) activity in significant countries. The expansion is adequate to counterbalance a diminished forecast for offshore wind, the experts observe. The Middle East and North Africa (MENA) area continues to excel, with its prediction increased by 25%. This represents the most substantial regional enhancement, propelled by the swift expansion of solar photovoltaic technology in Saudi Arabia. ASEAN ranks second behind the MENA area, exhibiting a 15% higher projection. In Southeast Asia, the deployment of solar photovoltaic and wind energy is rapidly advancing, characterised by more ambitious objectives and new auctions.

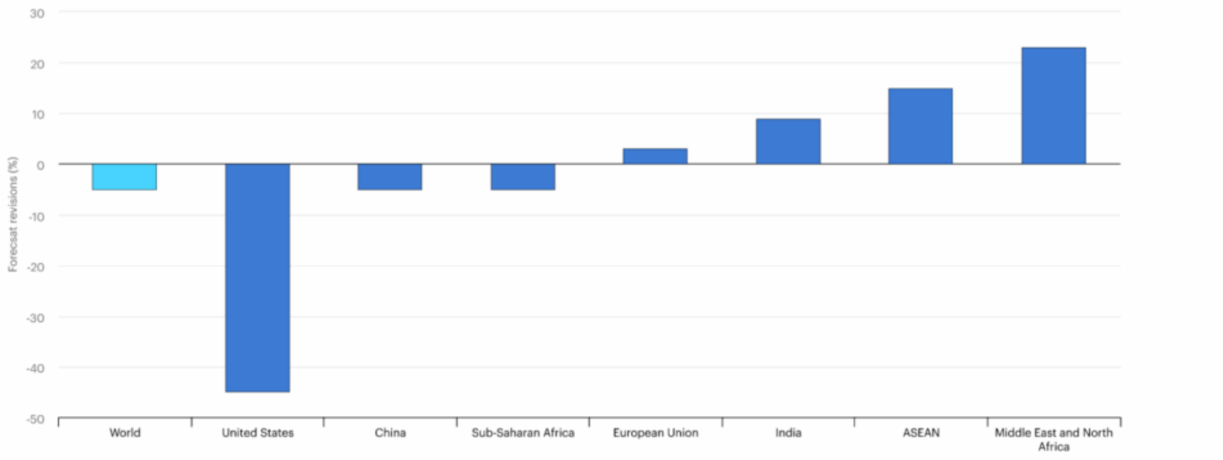


Figure 3. Renewable Capacity Expansion Changes from Renewables 2024 to Renewables 2025 in Selected Countries or Regions, 2025-2030. Source: IEA

The IEA's analysis indicates that the adoption of distributed solar PV systems with storage is increasing in nations with unreliable electrical grids, such as Pakistan, where the implementation of commercial and large-scale off-grid solar PV systems is significantly enhancing electricity availability. Annual onshore wind capacity additions throughout the forecast period are anticipated to increase across Africa, the Middle East, ASEAN nations, Latin America, and Eurasia, as well as in Europe and India.

This advancement is already occurring in China and India. Ember observes that both nations experienced a decline in fossil fuel generation during the first half of 2025, as the expansion of sustainable energy surpassed demand. China continued to dominate clean energy expansion, contributing more solar and wind capacity than the entirety of the global total, resulting in a 2% reduction in fossil fuel generation (58.7 TWh) during the first half of 2025.

During the same era in India, the expansion of clean energy sources exceeded the growth in demand by more than threefold. Nonetheless, demand remained remarkably low at 1.3% (12 TWh), in contrast to the corresponding period last year at 9% (75 TWh). India's unprecedented increase of solar and wind energy, along with diminished demand, resulted in a reduction of fossil fuel use, with coal decreasing by 3.1% (22 TWh) and gas by 34% (7.1 TWh). Transition to Renewable Energy and Associated Challenges

The IEA's research delineates several hurdles currently jeopardising the expansion of the renewable energy market, including overcapacity, depressed prices, trade impediments, and regulatory changes. These factors have hindered new investments in solar PV supply chains within China, whereas manufacturing capacity beyond China is currently increasing. The IEA cautions that obstacles, including grid integration, supply chain vulnerabilities, and financing, will escalate over the next five years.

The analysis forecasts that solar photovoltaic supply chains and rare earth elements for wind turbines will remain significantly concentrated in one country, underscoring supply chain security vulnerabilities. By 2030, supply chain concentration for critical production segments will persist over 90%, mirroring current levels, with China maintaining its dominance in the mining and processing of rare earth elements. Notwithstanding diversification initiatives, mining and refining are projected to remain significantly concentrated until 2030.

The agency observes that wind power would have supply chain difficulties, escalating costs, and permitting delays, with certain locations potentially unable to effectively tackle these constraints to facilitate expansion. The offshore wind sector is anticipated to encounter numerous hurdles in the forthcoming five years, with its projected growth adjusted downward by more than 25%. The IEA reports that numerous developers have already diminished their 2030 deployment objectives. The agency observes that diminished expectations are attributable to the policy shift in the United States and to project cancellations and delays in Europe, Japan, and India, resulting from elevated costs and supply chain difficulties.

The IEA observes that the rising proportions of wind and solar photovoltaic energy are exacerbating integration issues. By 2030, variable renewables are projected to account for approximately 30% of the global electricity supply, roughly double the current level. The agency indicates that this necessitates a swift enhancement of power system flexibility and grid investment across a growing number of nations.

The IEA cautions that wind and solar producers face challenges, as many are already experiencing financial difficulties and reporting substantial losses despite a rise in global installations. The agency indicates that the economic viability of equipment makers is a concern, referencing China, where solar PV prices have plummeted by more than 60% since 2023 due to an oversupply of modules and fierce rivalry for market share. This has reduced the margins of the top manufacturers to negative 10%, with total losses approaching USD 5 billion since the start of 2024. The agency reports that wind manufacturers outside of China have faced difficulties, with total losses amounting to USD 1.2 billion in 2024.

The IEA observes that the demand for clean energy from developers and purchasers continues to be robust over the forecasted period. Experts have determined that renewable developers have either augmented or sustained their capacity deployment objectives for 2030 since the previous year, with both developers and purchasers reaping advantages from reduced solar PV costs. Closing the Divide Between Aspiration and Execution is Essential for Tripling Clean Energy Capacity

The IEA projects that worldwide renewable power capacity will attain 2.6 times its 2022 level by 2030, although it will still be insufficient to meet the COP28 doubling commitment. Nevertheless, the agency observes that the objective remains attainable provided nations enact improved policies to address disparities in both aspiration and execution.

The IEA proposes an expedited scenario in which global renewable capacity might attain 2.8 times its 2022 level by 2030.

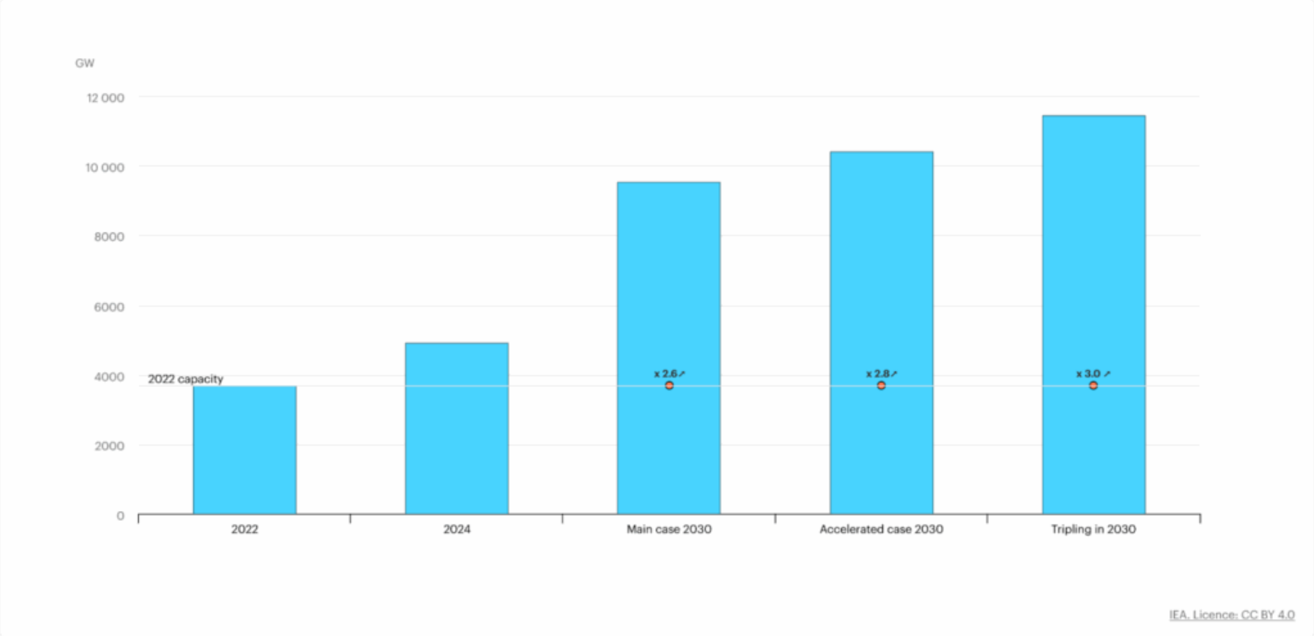


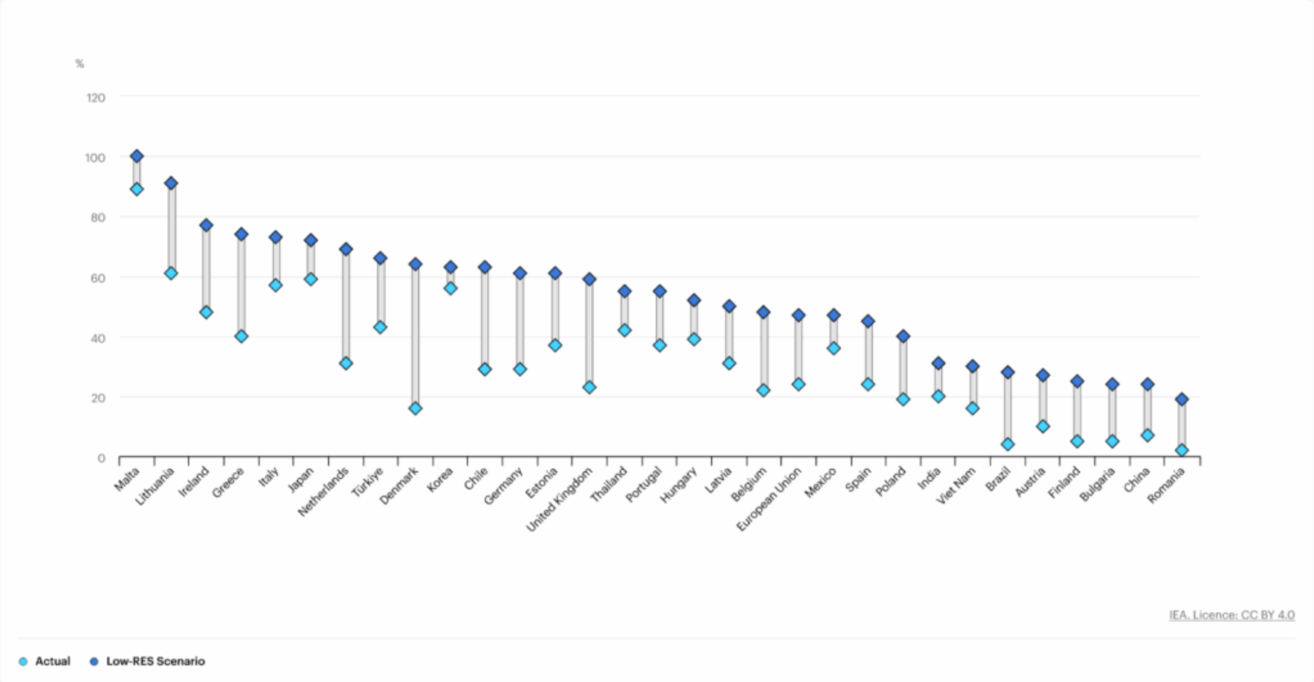
Figure 4. Renewable Capacity Growth and the Gap to Global Tripling, 2022-2030. Source: (IEA)

To facilitate this expansion, nations must mitigate regulatory uncertainty, shorten permission times, and enhance investment in grid infrastructure. Additional essential measures encompass enhancing flexibility to enable the incorporation of fluctuating renewables and mitigating financial risks.

This will assist nations in expediting their energy transition, yielding substantial economic, societal, and environmental benefits in the process. The IEA indicates that the implementation of renewable energy sources has substantially diminished fuel import requirements in numerous nations, hence improving energy diversification and security. The agency reports that, of the

2,500 GW of non-hydro renewable power capacity added worldwide since 2010, over 80% was implemented in nations dependent on fossil fuel imports. In the absence of these renewable contributions, total worldwide imports of coal and natural gas in these nations would have increased by 45% in 2023.

Consequently, nations have diminished coal imports by 700 million tonnes and natural gas imports by 400 billion cubic meters, resulting in an anticipated savings of USD 1.3 trillion since 2010. Countries such as Japan, South Korea, Thailand, India, and Vietnam have realised significant savings on fossil fuel imports by embracing renewable energy sources.



IEA. Licence: CC BY 4.0

Figure 5. Fossil Fuel Import Dependence of Electricity Supply, Actual and in Low-RES Scenario, 2023. Source: (IEA)

To secure the gains made thus far, Sonia Dunlop, CEO of Global Solar Council, emphasises the necessity for governments and business to expedite investments in solar, wind, and battery storage technologies. The expert asserts that this will guarantee the provision of clean, affordable, and reliable electricity to communities universally.

We are observing the initial indications of a significant turning point," stated Ember's Wiatros-Motyka. "With the declining costs of technologies, this is an opportune time to adopt the economic, social, and health advantages associated with enhanced solar, wind, and battery usage.

5.1Accessible Solar Resource

It is improbable that there was ever a period when mankind failed to comprehend and value the Sun's contribution to the survival of the human race. (Newton, 2015). The technical feasibility and economic viability of utilising solar energy are contingent upon the quantity of accessible sunlight (solar radiation) in the designated location for solar heaters or panels. This is occasionally termed the accessible solar resource.

Every region on Earth receives sunshine at least once annually. "Part of the year" denotes the period during which the northern and southern polar caps experience complete darkness for several months annually. The availability of sunshine is a crucial issue to consider when evaluating the use of solar energy.

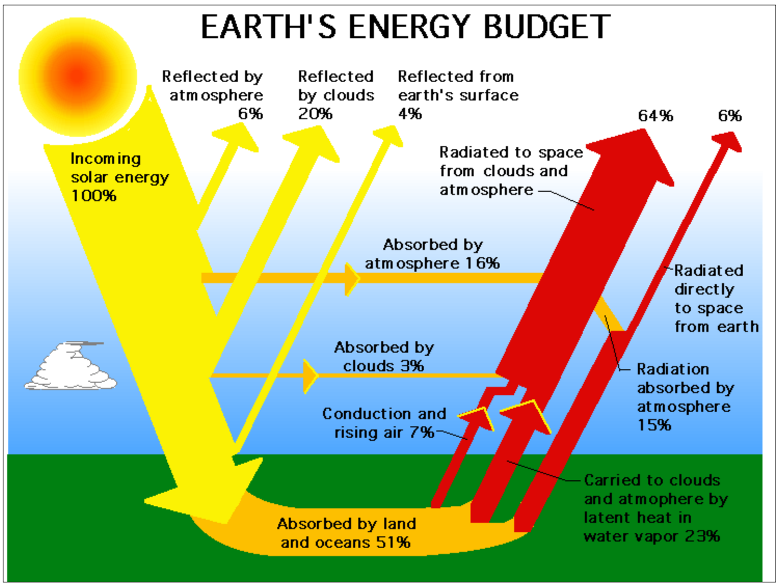


Figure 6. Earth s energy budget
(source, https://marine.rutgers.edu/cool/education/class/yuri/erb.html)

Several more aspects must be considered when assessing the feasibility of solar energy in a certain region. The following are:

a. Day and night result from the Earth's rotation, while seasons are attributed to the tilt of the Earth's rotational axis and its orbit around the sun, which is at an angle of 23°27'.

b. The Earth rotates around its axis, which extends through its north and south poles, completing a round from west to east each day. The Earth's rotation causes day and night, with a rotation of 15 degrees each hour. Furthermore, the Earth follows a somewhat eccentric elliptical orbit around the sun with each annual revolution. The Earth's axial tilt in relation to its orbit is consistently 23.5°. The Earth's revolution remains constant as the orientation of its spin axis consistently points towards the North Pole. Consequently, the earth's orbital position alters the angle of sunlight incidence, resulting in the variation of the earth's seasonal fluctuations.

c. At noon each day, the sun reaches its maximum elevation. In tropical low-latitude locations, specifically between the equatorial north and south latitudes of 23° 27', sunlight experiences two vertical occurrences annually, but at higher latitudes, the sun remains consistently near the equatorial direction. In the Arctic and Antarctic regions (located in the northern and southern hemispheres beyond 90° ~ 23° 27'), the sun remains below the horizon for an extended duration throughout winter.

5.2 Diffuse and Direct Solar Radiation.

As sunlight traverses Earth's atmosphere, a portion is absorbed, dispersed, and reflected. Sunlight consists of two components: direct sunlight and diffuse sunlight. Solar radiation traverses the atmosphere and reaches the Earth's surface, influenced by atmospheric air molecules, water vapour, and dust, which contribute to the absorption, reflection, and scattering of solar radiation. This process not only diminishes the intensity of the radiation but also alters its direction and spectral distribution. Consequently, the solar energy that ultimately reaches the ground is typically comprised of direct and diffuse components. Direct sunlight refers to radiation emanating directly from the sun without alteration in its trajectory; diffusion involves the reflection and scattering of solar radiation by the atmosphere, resulting in a change of direction. This phenomenon comprises three components: circumsolar scattering (light surrounding the sun), horizon circle scattering (light or darkness around the horizon), and additional diffuse radiation from the sky. Furthermore, the non-horizontal plane also captures the reflection of radiation from the earth. The total radiation or global sunlight is the aggregate of direct, diffuse, and reflected sunlight. It can depend on the lens or reflector to concentrate direct sunlight. A high condenser rate yields elevated energy density, but results in a loss of diffuse sunlight. A low condenser rate may also condense components of solar diffuse sunlight. Diffuse sunshine exhibits significant variability, and under cloudless conditions, it constitutes 10% of the total sunlight. When the sky is obscured by dark clouds and the sun is not seen, total sunshine is equivalent to diffuse sunlight. Consequently, a poly-type collector typically gathers energy at levels much beyond those of a non-poly-type collector. Reflected sunlight is typically feeble; but, over snow-covered terrain, vertical reflection can constitute up to 40% of the total sunshine.

5.3 Quantifying Sunlight and Solar Energy

Researchers quantify the solar irradiance present in particular locales throughout various seasons. They can thereafter assess the quantity of sunlight that reaches analogous places at the same latitude with comparable temperatures and conditions. Solar energy measurements are typically articulated as "total radiation on a horizontal surface" or as "total radiation on a sun-tracking surface". In this scenario, it is presumed that a solar panel is employed that automatically follows the sun's trajectory. The solar panel would be affixed to a tracking mechanism to maintain a perpendicular orientation to the sun throughout the day. This system is predominantly utilised in industrial environments, if employed at all.

5.4 Measurements of Solar Energy

Radiation data, which denotes the quantity of solar energy accessible at a specific place, for solar electric (photovoltaic) systems is often expressed in kilowatt-hours per square metre (kWh/m2). Direct measurements of solar energy can be articulated as "watts per square meter" (W/m^2) (https://www.energy.gov/eere/solar/articles/solar-radiation-basics). Radiation data for solar water heating and space heating systems is often expressed in British thermal units per square foot (Btu/ft^2).

6. PHOTOVOLTAIC MODULES

A solar panel is an apparatus that captures and transforms solar energy into electricity or thermal energy. Solar photovoltaic panels can be constructed to harness solar energy, which energises the atoms within a silicon layer situated between two protective panels. Electrons from these energised atoms generate an electric current, which can be utilised by external devices. Solar panels were utilised over a century ago for residential water heating. Solar panels may also be constructed using a uniquely curved mirror that focusses light onto an oil-filled tube. The oil subsequently warms and passes into a vat of water, causing it to boil instantaneously. Steam is generated and subsequently drives a turbine to produce power.

6.1 Mechanism of Solar Panel Functionality

The fundamental component of solar panels is pure silicon. When purified, silicon serves as an optimal neutral medium for electron transmission. Silicon, in its normal state, possesses four electrons but has the capacity for eight. Consequently, silicon can accommodate four additional electrons. When a silicon atom contacts another silicon atom, each atom acquires four electrons from the other. Eight electrons fulfil the atomic requirements, establishing a robust connection, however neither positive or negative charge is present. This substance is utilised in the fabrication of solar panel plates. The amalgamation of silicon with other charged components can potentially provide solar panels.

Phosphorus possesses five electrons available for donation to other atoms. The chemical combination of silicon and phosphorus yields a stable configuration of eight electrons together with an extra free electron. The silicon does not require the free electron; nonetheless, it cannot depart due to its link with the adjacent phosphorus atom. Consequently, this silicon and phosphorus plate is regarded as negatively charged.

A positive charge must also be generated for the flow of electricity. The amalgamation of silicon with an element like boron, which possesses just three electrons to contribute, results in a positive charge. A silicon and boron plate retains one vacancy for an additional electron. Consequently, the plate possesses a positive charge. The two plates are juxtaposed to form solar panels, with conductive wires interspersed between them.
http://www.articlesbase.com/technology-articles/solar-energy-basic-principles-649460.html

Photons strike the silicon/phosphorus atoms when the negative plates of solar cells are orientated towards the sun. The ninth electron is ultimately ejected from the outer shell. The positive silicon/boron plate autonomously attracts the electron into the vacant region of its outer band, preventing the electron from remaining free for an extended duration. As the sun's rays dislodge additional electrons, electricity is subsequently produced. When all conductive lines extract free electrons from the plates, sufficient electricity is created to power low-amperage motors or other electronic devices, although the output of a single solar cell is quite modest. When electrons are not utilised or dissipated into the atmosphere, they are returned to the negative plate, and the complete cycle recommences.

6.2 Solar Thermal Energy

sun thermal energy (STE) is a technology that captures sun energy for heating purposes. The US Energy Information Agency categorises solar thermal collectors as low, medium, or high temperature collectors. Low-temperature collectors are flat plates typically employed for heating swimming pools. Medium-temperature collectors, typically flat plates, are utilised for generating hot water for household and commercial applications. High-temperature collectors utilise mirrors or lenses to focus sunlight and are mostly employed for electricity generation. This differs from solar photovoltaic technology, which directly turns solar energy into electricity.

6.2.1 Low-Temperature Collector

Sunlight penetrates the windows and impinges upon the absorber plate, which subsequently heats up, converting solar energy into thermal energy. Heat is conveyed to the liquid flowing through pipes connected to the absorber plate. Absorber plates are typically coated with "selective coatings," which exhibit superior heat absorption and retention compared to standard black paint. Absorber plates are generally composed of metal, commonly copper or aluminium, due to their excellent thermal conductivity. Copper is costlier; yet, it exhibits superior conductivity and reduced susceptibility to corrosion compared to aluminium. In areas with average solar energy availability, flat plate collectors are typically sized at around one-half to one square foot per gallon of daily hot water consumption.

This method is primarily utilised in residential structures, where hot water demand significantly influences energy expenses. This typically refers to a scenario involving a sizable family or one where the demand for hot water is heightened owing to regular laundry activities.

Commercial applications encompass automotive washing services, military laundry operations, and dining businesses. The method can furthermore serve for space heating in off-grid buildings or in instances when utility power is prone to frequent interruptions. Solar water heating systems are likely to be economically advantageous for facilities with costly water heating operations or for establishments such as laundries or kitchens that want substantial volumes of hot water.

Unglazed liquid collectors are frequently employed to heat water for swimming pools. Due to the absence of high-temperature requirements, these collectors can utilise more economical materials like plastic or rubber. They do not necessitate freeze-proofing, as swimming pools are often utilised solely in warm weather or may be simply drained during colder conditions. Although solar collectors are most economically viable in sunny, temperate regions, they can be financially advantageous in nearly every location across the country and should be taken into account.

6.2.2 Elevated-temperature collector

To mitigate heat loss in flat-plate collectors and enhance collection temperature, the international community successfully developed vacuum tubes in the 1970s. The heat-absorbing element is encased in a high vacuum within the glass tube, significantly improving thermal efficiency. The assembly of multiple branch vacuum tubes shall form a vacuum tube collector, which is designed to enhance sunlight absorption; certain vacuum tubes are also equipped with reflectors at the rear. Vacuum collector tubes can be categorised into two main types: all-glass evacuated collector tubes (glass-U-tube vacuum collector tubes) and metal heat-pipe vacuum tubes (straight-through vacuum collector tubes and thermal storage vacuum collector tubes).

The condenser collector primarily consists of three primary components: the condenser, the absorber, and the tracking system. In accordance with the principle of distinction, condensers and condenser collectors can be classified into two categories: reflection and refraction condensers. Each category can further be subdivided into many types. To fulfil the demands of solar energy utilisation, such as streamlining tracking systems, enhancing reliability, and minimising costs through the development of condenser collectors in this century, various types of condenser collectors exist; however, their promotion is inferior to that of flat-plate collectors, resulting in a lower level of commercialisation. In reflecting concentrator collectors, the spinning parabolic mirror condenser (point focus) and the parabolic trough mirror condenser (line focus) are more commonly utilised. The former can become heated, while two-dimensional tracking is applicable; the latter can measure temperature, provided it is for one-dimensional tracking. The two types of condenser collectors were introduced at the beginning of this century and have undergone several enhancements over the decades, including the incorporation of reflective surfaces to enhance machining precision, the development of highly reflective materials, and the advancement of reliable tracking systems. Currently, these two varieties of parabolic trough collectors are fully equipped to satisfy diverse high-temperature solar energy utilisation demands; however, their elevated costs restrict broader application.

In the 1970s, the "compound parabolic concentrator mirror collector" (CPC) emerged on the international market. It comprises two parabolic mirrors; Concentrated Photovoltaic systems do not require solar tracking, merely seasonal changes, enabling them to gather sunlight and achieve elevated temperatures. The condensation rate typically remains below 10; when it falls below 3, it can be securely installed without requiring adjustments. At that time, many individuals highly regarded CPC, perceiving it as a significant advancement in solar thermal utilisation technology with potential for widespread application. Nevertheless, decades later, CPC has been utilised in only a limited number of demonstration projects and has not achieved widespread adoption like flat-plate collectors and vacuum tube collectors.

Other reflecting mirror concentrators include conical mirrors, spherical mirrors, bar mirrors, bucket-type trough mirrors, flat mirrors and parabolic mirror concentrators. Furthermore, a heliostat is utilised in a tower solar power plant. Heliostats have several flat or curved mirrors that, under computer control, direct sunlight to a single absorber, which can attain elevated temperatures and generate substantial energy.

The refraction theory of light allows for the creation of a refraction-type condenser. Certain individuals utilise a combination of lenses and flat mirrors to construct a high-temperature solar boiler. The glass lens is excessively heavy, the manufacturing process is intricate, and the cost is high, making it challenging to produce in larger sizes. Consequently, the refraction-type condenser is not a viable long-term solution. During the 1970s, the global advancement of big Fresnel lenses aimed to facilitate the construction of solar concentrating collectors. The Fresnel lens is a flat condenser lens that is lightweight and cost-effective, available in both spot and line focus configurations. It is typically constructed from plexiglass or other transparent plastics, but can also be produced from glass, primarily for use in solar concentrator power generation systems. The optical fibre condenser comprises fiber-optic lenses and optical fibres linked to solar composition, utilising an optical lens to focus light for office applications following fibre dispersion. The fluorescence condenser consists of a fluorescent pigment applied on a clear plate, often PMMA, which absorbs sunlight and certain fluorescent wavelengths within the absorption band, thereafter emitting fluorescence at a longer wavelength than the absorption band. Fluorescent emission undergoes total internal reflection at the edge face of the plate, attributable to the disparities between the plate and the surrounding medium. The condensation rate is contingent upon the ratio of flat area to edge area, achieving a ratio of 10:100 is feasible. This flat panel can capture sunlight from various angles and can also absorb diffuse light without necessitating solar tracking.

6.3 System Designs

The sun occupies several locations during the day. If the mirrors or lenses remain stationary, the focal point of the mirrors or lenses alters. Consequently, it appears imperative to implement a monitoring system that monitors the sun's location, while a solar tracker is merely optional for solar photovoltaics. The tracking method elevates expenses. Considering this, many designs can be identified based on their methods of concentrating light and tracking the sun's position.

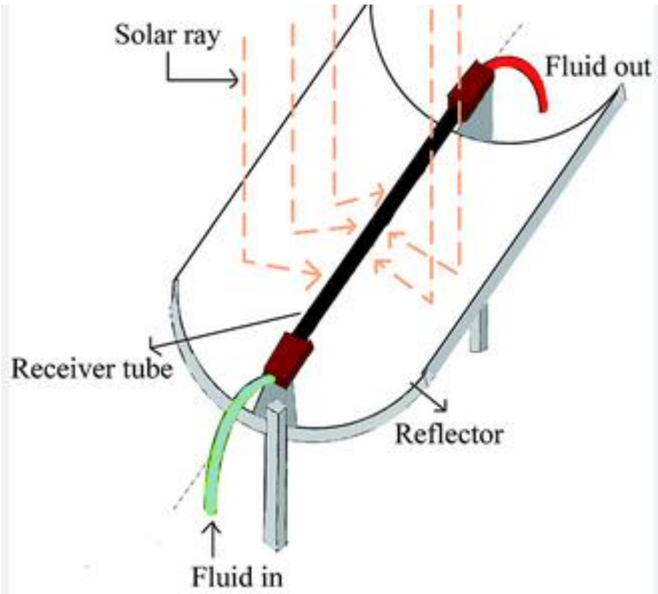


Figure 7. Illustration of a parabolic trough configuration.

A parallel shift in the sun's position relative to the receiver does not necessitate mirror adjustment.

6.3.1 Thermal Energy Storage.

2.3.1.1 Thermal energy storage.

The utilisation of sensible heat energy storage materials constitutes the most straightforward storage option. In practice, water, sand, gravel, and soil can be regarded as materials for energy storage, with water being utilised more frequently due to its superior heat capacity. During the 1970s and 1980s, the utilisation of water and soil for interseasonal storage of solar energy was documented. However, the material exhibits low sensible heat, which constrains energy storage capabilities.

6.3.1.2 Latent Heat Storage

Latent heat-storage units store thermal energy in a latent state by altering the phase of the storage medium. Relevant storage medium are referred to as "phase change materials" (PCM). Salts in crystalline form, such as sodium sulphate decahydrate, calcium chloride, and sodium hydrogen phosphate dodecahydrate, are typically utilised for low-temperature storage. We must address the cooling and layering challenges to maintain optimal operating temperature and service life.

The medium solar storage temperature typically exceeds 100°C; however, it is inappropriate for the medium temperature storage of the following materials:

- pressurized hot water,
- organic liquids,
- eutectic salt.

The temperature for solar heat storage typically exceeds 500°C. The specified materials, Liquid metal sodium and molten salt are presently undergoing evaluation for use in advanced nuclear reactor systems and concentrated solar power (CSP) plants that necessitate operation at exceptionally high temperatures. The exceptionally high temperature referenced (exceeding 1000°C) serves as a goal operating point for particular sophisticated designs.

6.3.2 Chemical and Thermal Energy Storage

Thermal energy storage employs chemical reactions to retain heat. It possesses the advantages of substantial heat capacity, compact volume, and lightweight characteristics. The byproducts of a chemical reaction can be stored independently for an extended duration. An exothermic reaction happens when required. It must satisfy the following conditions to utilise chemical reactions in thermal storage: high reaction reversibility, absence of secondary reactions, quick kinetics, ease of product separation, and stability retention. The reactant and consequent are non-toxic, non-flammable, exhibit a high heat of reaction, and are cost-effective. Certain chemical endothermic reactions may satisfy the aforementioned requirements. Utilise the endothermic pyrolysis reaction of $Ca(OH)_2$ to store and subsequently release heat as needed. The temperature for the dehydration reaction under high air pressure exceeds 500 degrees. Utilising sun energy to facilitate dehydration reactions is challenging. A catalyst can be employed to reduce the reaction temperature, although it remains significantly elevated. The heat reserve in chemistry is now being testing.

6.3.3. Thermal energy storage utilising plastic crystals

In 1984, the U.S. market introduced plastic crystal materials for residential heating. The technical designation of plastic crystal is Neopentyl Glycol (NPG); it shares similarities with three-dimensional periodic crystals, however its mechanical properties resemble those of plastic. It can store and release thermal energy at a constant temperature without relying on solid-liquid phase shift; instead, it utilises the solid-solid phase change within its plastic crystalline molecular structure to store energy. At a constant temperature of 44°C, plastic crystals absorb solar energy and store heat during the day, subsequently releasing it at night.

6.3.4 Solar Thermal Energy Storage Tank

A solar pond is a specific type of salt pond characterised by a gradient of salt concentration, utilised for the collection and storage of solar energy. Due to its simplicity, affordability, and suitability for large-scale applications, it has garnered significant attention. Subsequent to the 1960s, other countries commenced research on solar ponds, and Israel constructed three solar pond power stations.

6.4 Levelized Cost

Due to the absence of fuel utilisation in a solar power plant, the expenses primarily comprise construction costs, with little operational and maintenance costs. Provided that the plant's lifespan and the interest rate are known, the cost per kWh may be determined. This is referred to as the levelized cost. The initial stage in the calculation is to ascertain the investment required for the generation of 1 kWh annually. The information sheet for the Andasol 1 project indicates a total investment of 310 million euros for an annual production of 179 GWh. Given that 179 GWh equates to 179 million kWh, the investment per kWh of annual production is calculated as 310 / 179 = 1.73 euros. An other instance is the Cloncurry solar power station located in Australia. It generates 30 million kWh annually for an investment of 31 million Australian dollars. The cost is 1.03 Australian dollars for the generation of 1 kWh annually. This is considerably less expensive than Andasol 1, which can be partially attributed to the greater radiation in Cloncurry compared to Spain. The annual investment cost per kWh should not be conflated with the total cost per kWh during the whole lifespan of the plant.

Typically, the capacity of a power plant is designated, as exemplified by Andasol 1, which has a capacity of 50 MW. This figure is inappropriate for comparison because to variations in the capacity factor. A solar power plant equipped with heat storage can generate output post-sunset; however, this does not alter the capacity factor, it merely shifts the output. The average capacity factor for a solar power plant, influenced by tracking, shade, and location, is approximately 20%. Consequently, a 50 MW capacity power plant will generally yield an annual output of 50 MW x 24 hours x 365 days x 20% = 87,600 MWh/year, equivalent to 87.6 GWh/year.

While the investment for one kWh of annual production is appropriate for comparing the costs of various solar power plants, it does not provide the price per kWh. The method of financing significantly impacts the final price. Should the technology be validated, a 7% interest rate should be attainable. Nevertheless, for emerging technologies, investors want a much-elevated return to offset the increased risk. This substantially adversely impacts the price per kWh. Regardless of the financing method, a linear relationship consistently exists between the annual investment per kWh produced and the price of one kWh (excluding operational and maintenance costs). Consequently, if technological advancements result in a 20% reduction in investments, the price per kWh will similarly decrease by 20%.

In a financing scenario where funds are borrowed and repaid annually, resulting in a reduction of both principal and interest, the division factor can be calculated using the formula: (1 - (1 + interest / 100) ^ -lifetime) / (interest / 100). For a duration of 25 years and an interest rate of 7%, the division factor is 11.65. The investment for Andasol 1 was 1.73 euros; when divided by 11.65, this yields a cost of 0.15 euros per kWh. Incorporating a one cent operating and maintenance cost results in a levelized cost of 0.16 euros. Alternative funding methods, varied debt repayment strategies, differing life expectancies, and distinct interest rates may result in a substantially different outcome.

If the cost per kWh correlates with inflation, the inflation rate can be incorporated into the interest rate. If an investor deposits funds in a bank at a 7% interest rate, he is not adequately paid for inflation. Nevertheless, if the cost per kWh increases with inflation, he gets reimbursed and can incorporate a 2% adjustment (a standard inflation rate) into his return. The Andasol 1 facility is assured a feed-in tariff of 0.21 euros for a duration of 25 years. If this figure remains constant, it should be acknowledged that after 25 years of 2% inflation, 0.21 euro will possess a value equivalent to 0.13 euro now.

Ultimately, a delay exists between the initial investment and the commencement of electricity production. This enhances the investment with the interest during the period when the plant is inactive. The modular solar dish, together with solar photovoltaic and wind power, offers the benefit of initiating electricity production immediately upon completion of construction.

Considering that solar thermal power is dependable, capable of providing peak demand, and environmentally benign, a price of US$0.10 per kWh begins to be competitive. While a price of US$0.06 has been asserted with some operating expenses, a straightforward objective is to achieve an investment of 1 dollar (or less) for the production of 1 kWh annually.

6.5. Types of solar panels

Decades of study, labour, and innovation have resulted in a diverse array of solar panel types currently accessible in the market.

Table 1 presents an overview of the most prevalent and distinctive types of solar panels.

Table 1. Types of solar panels

Solar Cell Type	Efficiency-Rate	Advantages	Disadvantages
Monocrystalline Solar Panels (Mono-SI)	~20%	High efficiency rate; optimised for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels (p-Si)	~15%	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels (A-SI)	~7-10%	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan
Concentrated PV Cell (CVP)	~41%	Very high performance & efficiency rate	Solar tracker & cooling system needed (to reach high efficiency rate)

(source, https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels)

6.5.1 Methods for Classifying Various Types of Solar Panels

The utilisation of sunlight varies significantly between Earth and space, indicating that location is a crucial determinant in selecting among different types of solar panels. Differentiation among solar panels typically involves distinguishing between single-junction and multi-junction panels, as well as categorising them into first, second, or third generations. Single-junction and multi-junction panels are differentiated by the number of layers that capture sunlight, while generational classification emphasises the materials and efficiency of the various solar panel types.

The 1st Generation Solar Panels are conventional forms composed of monocrystalline silicon or polysilicon, widely utilised in standard environments.

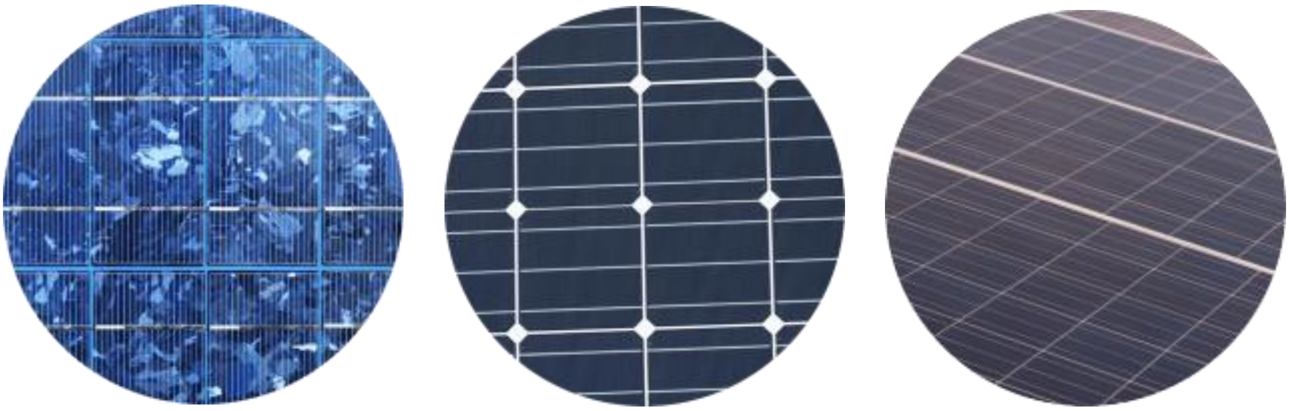


Figure 8. Types of Solar Panels
Monocrystalline (left), Polycrystalline (centre), Thin-Film Solar Cells (right) (source: https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels)

Monocrystalline Silicon Solar Panels (Mono-SI)
This category of solar panels, composed of monocrystalline silicon, represents the highest purity. They can be readily identified by their uniform black appearance and rounded edges. The great purity of silicon results in this type of solar panel achieving one of the highest efficiency rates, with the latest models exceeding 20%. Monocrystalline panels have superior power output, use little space, and has the longest lifespan. Consequently, they are the priciest among the group. Another advantage to consider is that they are generally less impacted by elevated temperatures in comparison to polycrystalline panels.

Polycrystalline Solar Panels (Poly-SI)
These panels can be readily identified due to their square shape, uncut angles, and blue, speckled appearance. They are produced by melting raw silicon, a procedure that is more expedient and cost-effective than that employed for monocrystalline panels. This results in a reduced end price, but also diminished efficiency (about 15%), less spatial efficiency, and a shorter lifespan due to greater susceptibility to elevated temperatures. The distinctions between monocrystalline and polycrystalline solar panels are minimal, and the selection will mostly depend on your particular circumstances. The initial alternative provides somewhat greater space efficiency at a marginally elevated cost, while the power outputs remain fundamentally equivalent.

Second Generation Solar Panels
These cells represent many forms of thin film solar cells, primarily utilised in photovoltaic power plants, integrated within buildings or smaller solar power systems.

Thin-Film Solar Cells (TFSC)
If you seek a more economical alternative, consider thin-film technology. Thin-film solar panels are produced by depositing one or more layers of photovoltaic material, such as silicon, cadmium, or copper, onto a substrate. These solar panels are the simplest to manufacture, and economies of scale render them more cost-effective than alternatives due to reduced material requirements for production.

They exhibit flexibility, which creates numerous potential for alternate applications, and are less susceptible to elevated temperatures. The primary concern is their substantial spatial requirements, rendering them often inappropriate for residential use. Furthermore, they possess the briefest guarantees due to their reduced lifespan compared to mono- and polycrystalline solar panels. Nevertheless, they may be a viable choice among the various forms of solar panels when ample space is accessible.

Amorphous Silicon Photovoltaic Cell (A-Si)

Have you ever utilised a solar-powered pocket calculator? Affirmative? You have certainly encountered these varieties of solar panels already. The amorphous silicon solar cell is primarily utilised in pocket calculators among the several varieties of solar panels. This solar panel employs a triple-layered technology, representing the pinnacle of thin-film varieties. In this context, "thin" refers to a thickness of 1 micrometre (one millionth of a metre). These cells exhibit a mere 7% efficiency, rendering them less effective than crystalline silicon cells, which achieve approximately 18% efficiency; however, the advantage lies in the relatively inexpensive cost of A-Si cells.

Third Generation Solar Panels

Third-generation solar panels encompass many thin-film technologies, the majority of which remain in the research or development stage. Some create energy utilising organic materials, while others employ inorganic compounds, such as CdTe.

Biohybrid Solar Cell

The Biohybrid solar cell is a form of solar panel currently in the research phase. An elite team at Vanderbilt University has made a discovery. The concept of the new technology is to leverage photosystem 1 to replicate the natural process of photosynthesis. It elucidates in greater depth the functioning of these cells. The materials utilised in this cell resemble those of conventional approaches; however, by integrating multiple layers of photosystem 1, the conversion of chemical to electrical energy is significantly enhanced, achieving efficiency levels up to 1000 times greater than first-generation solar panels.

Cadmium Telluride Photovoltaic Cell (CdTe)

This photovoltaic method employs Cadmium Telluride, facilitating the manufacture of solar cells at a comparatively low cost and resulting in a payback period of less than one year. Among all solar energy systems, this one necessitates the minimal water use for manufacturing. Considering the brief energy payback period, CdTe solar cells will minimise your carbon footprint.

The sole drawback of utilising Cadmium Telluride is its inherent toxicity when swallowed or inhaled. In Europe, this represents a significant obstacle, as numerous individuals express considerable apprehension regarding the technology underlying this form of solar panel (https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels).

Concentrated Photovoltaic Cell (CPV and HCPV)

Concentrated photovoltaic cells produce electrical energy in the same manner as traditional solar systems. Multi-junction solar panels exhibit an efficiency rate of up to 41%, the highest recorded among all photovoltaic systems to date. The designation of these CVP cells pertains to their exceptional efficiency relative to other solar panel types: they utilise curved mirror surfaces, lenses, and occasionally cooling systems to concentrate sunlight, thereby enhancing their performance.

Consequently, CVP cells have emerged as one of the most effective varieties of solar panels, with a performance and efficiency rate of up to 41%. The efficiency of CVP solar panels is contingent upon their orientation towards the sun at an optimal angle. A solar tracker within the solar panel is responsible for following the sun to achieve high efficiency rates (Misak et al., 2016).

7. APPLICATIONS OF SOLAR ENERGY

Solar energy, harnessed from the sun via solar panels, represents a recent endeavour of the "Going Green" movement aimed at establishing and sustaining renewable energy sources. Similar to any new home addition, there are initial expenses associated with the components and installation required to operationalise it (https://www.thespruce.com/top-solar-energy-uses-1152263).

7.1 Solar-powered Ventilation

Photo 1 Solar power ventilation
(source, https://eurzad.brodnica.pl/?d=118173634081890)

How would you prefer to utilise solar energy to operate bath fans, floor fans and ceiling fans in your residence? Fans are extensively employed within households to facilitate air circulation for comfort, humidity control and odour management. Consider the heating and cooling dynamics in your home and the potential reduction in utility expenses. Reflect on the number of ceiling fans that operate daily in your residence. Additionally, contemplate the frequency of bath fan usage throughout the day.

7.2 Utilise Solar Energy to Heat Your Swimming Pool

Figure 9. Swimming Pool Heating (Source: https://www.theengineeringchoice.com/what-is-solar-pool-heater/)

Swimming pools represent one of the paramount delights of summer for both children and parents. All are enthusiastic on the inaugural day of the pool's opening, except when the water temperature is excessively frigid for entry. To resolve that issue, you may incorporate a solar blanket that will heat the water, much to the satisfaction of all. This heating operates directly via the blanket, requiring no additional installations. However, if you choose to use a more advanced approach, simply install a solar hot water heating system. This system employs solar hot water heating panels affixed to your roof to capture solar energy, which is subsequently circulated to the pool. The pool temperature is elevated when water is gradually extracted, heated, and subsequently returned from the panels.

7.3 Solar energy has the capacity to heat water.

Figure 10. Solar Water Heaters Source: https://bluebirdsolar.com/blogs/all/solar-water-heater-the-smart-way-to-heat-water-using-the-power-of-the-sun?srsltid=AfmBOoolR4jVczOdCBhRL6j1PRkzIQZNtWk2yIb4WGYweiJVJ76Zr3zM

Have you contemplated the feasibility of utilising solar energy for water heating instead of relying on gas or traditional electric water heaters? I understand you can assert that acquiring all these components is necessary for this choice to function. Installation may be feasible for you or may not. Considering the expense, it may be prudent to retain your current option, correct?

Proceed with caution! Upon reflection, it is analogous to replacing an obsolete furnace, water heater, or air conditioning equipment. Replacing the unit may enhance efficiency by 15-30%, albeit this modification entails an initial expenditure. While the alteration will result in long-term financial savings, this should be evaluated over an extended timeframe.

7.4 Solar energy heating system

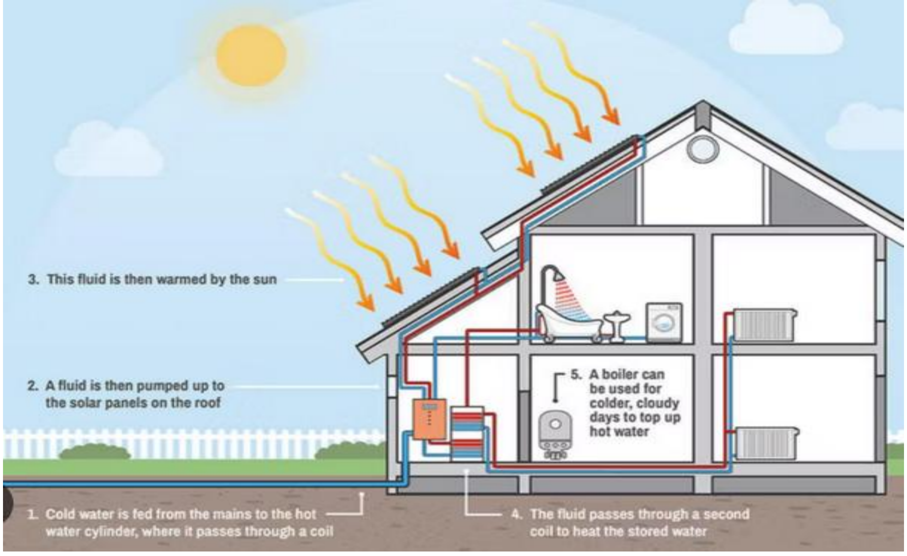


Figure 11. Solar heating system for roofs (source: https://www.screwfix.com/guides/heating-plumbing/renewable-heating/solar-water-heating-guide)

Solar heating is known as passive space heating, and in this instance, I will elucidate its functioning. A method involves utilising hot water heating in your residence, generated by sun-heated tubes on your roof, which are then pumped into your water heater (https://www.thespruce.com/top-solar-energy-uses-1152263).

The inclusion of a sunroom, termed a solar room, features an all-glass structure that permits sunlight to permeate and warm the space via a collector known as a transparent covering in the glass. Incorporating plants and rocks for aesthetic appeal will enable the rocks to absorb solar heat, which can subsequently be utilised to warm the room after sunset. Stored energy is advantageous and has numerous applications, such as batteries, for example.

7.5 Solar energy-powered pumps

Figure. 12 Solar Pump (Source: https://www.samkingpump.com/product/4spw4-3p-600w; https://www.whcsolar.cc/product/1100w-solar-surface-water-pump/)

In the two preceding illustrations, water was utilised for heating both water and your residence. To achieve that duty, you'll need to have a pump to circulate the water around. This pump would ordinarily connect to your home's power source, but let me give you this helpful suggestion. You can utilise solar energy to drive a DC motor that will slowly circulate the water throughout your home or in and out of your water heater. This way, the cost of the system is decreased further. Now, the naysayers may say fantastic, but what do we do when there is no sun? One way is to have conventional power run a pump when there is no sun. You can also have a battery backup system that can run the pump and the battery might be connected to a solar battery charger.

7.6 Solar energy for battery charging

Have you considered solar energy for charging batteries? These could be utilised to power sump pumps, hot water pumps, ceiling fans in your home, or lighting that id of DC nature. battery chargers are utilised in houses to charge all of those batteries used for video games and such as well. But most likely, if you have a reserve battery bank that is charged through the day while sunlight is present and is used for the nocturnal hours, you can see the benefits of that, right?

7.7 Use solar energy to power your home

Indeed, solar energy has the capacity to power your residence. The required system is not overly complex when reviewing the necessary equipment. Install solar panels to harness sunlight and transform it into electricity. Direct current (DC) power is transmitted to an inverter, which transforms it into alternating current (AC) power that operates your home. Utilising transfer switches and additional safety mechanisms, your clean, renewable energy source can supply power to your home, camper, cabin, tool shed, or any other structure.

7.8 Solar energy utilised for culinary purposes

Figure 14. Solar Stove & Solar PV Cook-stove:
Source: (https://www.engineeringforchange.org/solutions/product/solar-pv-cook-stove/)

This is universally relatable. Ultimately, sustenance is a must for everyone. The energy and resources expended on cooking may lead to unexpected utility expenditures. Utilising solar energy for cooking is far simpler than one might assume. We refer to it as thinking outside the box, or in this instance, cooking within a box. Envision utilising a solar oven for cooking rather than your traditional home appliance. Constructing one of these is a formula for great culinary endeavours on sunny days! Equipped with a box, pan, aluminium foil, a cooking bag, duct tape, styrofoam insulation and a thermometer, you will be able to cook promptly.

7.9 Photovoltaic Energy for Interior Illumination

Figure 15. Indoor Lighting (source: https://insolitehardware.com/product/baxton-50w-indoor-solar-light/)

Illumination throughout your residence is a universal necessity. The advent of LEDs (light emitting diodes) enables your home to provide ideal illumination with little energy consumption. These little electronic lights or light assemblies can be linked to a battery-operated system that harnesses solar energy during the day and utilises batteries at night. When sunlight is present, the battery charger replenishes the backup battery and powers the illumination. Subsequently, at night, the batteries activate and provide illumination in the absence of sunlight.

7.10 Utilisation of solar energy for outside illumination

Figure 16. Outdoor lighting (source: https://www.streetlights-solar.com/popularity-solar-outdoor-lighting-us.html)

If you share my preference, you appreciate returning home at night to the presence of security lighting and illuminated pathways. It not only provides a clear view of the walkway, keys, and entrance door, but also acts as a deterrent to intruders. Similar to a pole light, your entire yard can be illuminated at no cost. Indeed, solar lighting utilises solar panels to charge batteries during daylight, which subsequently power the lights at night.

7.11 Drawbacks of solar energy

Given the annual increase in electricity costs of 3%-5%, you might be contemplating alternate energy sources, such as solar power. However, prior to installing a solar system on your residence, several significant disadvantages must be considered. Given that solar power incurs the highest starting costs among all renewable energy sources, one may expect it to be highly effective. In actuality, solar panels exhibit low efficiency. In a prime location, achieving a conversion rate of 22% is fortunate, even with the most advanced and costly technologies accessible. Additionally, solar panels may be susceptible to damage from storms. In addition to the expense of repairing the solar panels, the damaged units must be managed and disposed of appropriately due to the hazardous substances contained within.

7.12 Geographical position and solar exposure

Your latitude significantly influences the effectiveness of solar power. Annual sunlight distribution varies by location, with solar power efficiency significantly diminishing as one move away from the equator. This indicates that inhabitants in regions such as Canada and Russia experience a solar disadvantage. In regions such as Hawaii, which experience an average of 277 days of rain and cloud cover annually, their proximity to the equator is inconsequential due to insufficient unobstructed sunshine reaching the surface.
http://waldenlabs.com/disadvantages-solar-energy

The effectiveness of solar energy is also influenced by the season. During the summer, you can produce more electricity than required due to the sun's proximity to your location. During winter, the sun's angle is more oblique relative to your position, resulting in insufficient electricity generation to meet your demands. Similar to all objects exposed to sunlight, solar panels will experience degradation due to ultraviolet radiation. Elements such as wind, hail, snow, debris, and temperature variations pose significant risks to solar panels.

7.13 Installation Zone

For homes seeking to install solar panels, the installation space is often not a significant concern, particularly as they are predominantly affixed to the roof. Nonetheless, large corporations aiming to generate substantial power will require an extensive installation area to ensure regular electricity supply. The largest solar farm, situated in Spain, spans over 173 acres and supplies energy to nearly 12,000 houses. That constitutes 173 acres of land that cannot be utilised for any other purpose, such as grazing livestock.
https://www.nachi.org/disadvantages-solar-energy.htm?loadbetadesign=0

7.14 Dependability

As solar energy is dependent on sunlight, electricity generation is not possible at night, necessitating the storage of surplus energy produced during the day or the connection to an alternative power source, such as the local utility grid. This indicates that you will incur additional expenses above the elevated price of the solar panels. Clouds and storms impede energy production by obstructing light rays that might otherwise be absorbed by the solar panel.

7.15 Ineffectiveness

The Qualitative Reasoning Group at Northwestern University indicates that the majority of residential solar panels convert merely 14% of their accessible energy into electricity. Contemporary solar panels, even at peak efficiency, convert merely 22% of available energy into electricity. The second rule of thermodynamics dictates that solar cells cannot achieve 100% efficiency. The optimal theoretical maximum efficiency is 85%, achievable with mirrors and motors that track the sun. The maximum theoretical efficiency for a non-tracking system is limited to 55%. This also applies to systems that monitor the sun under overcast conditions. While solar energy can still be harvested during overcast and rainy days, the effectiveness of the solar system diminishes. Solar panels rely on sunlight to efficiently collect solar energy. Consequently, several overcast, rainy days can significantly impact the energy grid. It is essential to consider that solar energy cannot be harvested at night. Conversely, if your water heating solution must operate at night or throughout winter, thermodynamic panels are a viable choice.

7.16 Environmental pollution and its consequences

Solar energy impactors can be temporally classified throughout the lifespan of a photovoltaic (PV) or concentrating solar power (CSP) system, from construction to decommissioning, and may exert one or more potential effects on the environment, eliciting various ecological responses. The technology, dimensions, and placement of solar energy infrastructure may affect biota and the environment in several manners. Integrated solar energy refers to energy that incurs no land-use or land-cover changes beyond those related to the extraction of raw materials and production processes. Consequently, it has negligible to no detrimental impacts on the ecosystem (apart from life-cycle emissions), resources (such as cultural assets), and legal rights, including the religious rights of indigenous populations. Integrated solar energy is systematically incorporated into components of the built environment in urban and suburban locales, such as commercial and residential rooftops, parking garages, and carports, in proximity to consumers. Despite its geographical dispersion, integrated solar energy presents significant solar energy potential, with estimates indicating that 20%–27% of all residential rooftop areas and 60%–65%

of commercial rooftops in the United States are suitable for photovoltaic and solar thermal systems. Conversely, displacive solar energy entails supplementary land-use or land-cover alterations, so diminishing biophysical capacity or enabling the depletion of other valuable resources (e.g., cultural) over the Earth's surface. These installations are generally ground-mounted and possess substantial capacity. They are frequently situated at considerable distances from demand loads and existing transmission infrastructure, necessitating extensive land area (i.e., installed capacity increases in tandem with land area) (Murphy-Mariscal Michelle L. et al., 2018).

7.17 Land Specifications

To satisfy anticipated energy consumption requirements by 2040, it is expected that almost 800,000 km^2 of extra land (with spacing), an area twice the size of California, will be impacted by carbon-intensive and renewable energy production. Ground-mounted solar energy necessitates substantial land areas to accommodate power plant infrastructure, mirrors and towers (e.g., CSP), and panels (e.g., PV), resulting in these installations frequently being located at considerable distances from urban population centres, where electricity consumption is highest. This may require supplementary transmission infrastructure (e.g., power line corridors, roadways, and substations) to convey electricity, hence extending consequences beyond the immediate footprint of the facilities (Murphy-Mariscal Michelle L. et al., 2018).

The environmental consequences of solar power include land and water use, pollution, habitat destruction, and the employment of very toxic substances in the manufacturing process.

Reflecting on the installation area, the land utilisation for solar fields might be extensive, and unlike wind power, co-utilization for agricultural purposes is not feasible. Solar power influences land utilisation concerning the extraction and manufacturing of materials required for photovoltaic output.

Solar panels include cadmium and lead, both of which are highly dangerous elements. Various harmful and hazardous substances utilised in solar panel production include gallium arsenide, copper-indium-gallium-diselenide, hydrochloric acid, sulphuric acid, nitric acid, hydrogen fluoride, 1,1,1-trichloroethane, and acetone. In the United States, manufacturers are mandated to ensure that certain high-value compounds are recycled instead than discarded. In nations like China, Malaysia, the Philippines, and Taiwan, where more than fifty percent of photovoltaics are produced, hazardous materials are being carelessly discarded in fields, contaminating the air, water, and land.

7.18 Costly energy storage

The major challenge in generating solar electricity on an industrial scale is widely regarded as the storage of substantial quantities of electrical energy. The existing battery storage systems for converting solar energy into electrical energy are prohibitively costly. Tesla has developed the Powerwall battery to accumulate solar energy for subsequent utilisation. Nonetheless, a 14kWh battery, priced at approximately $7,100 including installation, is quite costly. To provide one day's worth of backup electricity for a four-bedroom house, three Tesla batteries would be required, resulting in a substantial total cost.
$18,300.

7.19 Substantial upfront expenditure

The cost for average-sized systems generating between 4kW and 8kW of power ranges from $15,000 to $29,000. The expenses encompass solar panels, inverters, mounting gear, wiring, installation, permits, repairs, monitoring and maintenance, as well as supplementary operational and overhead costs.

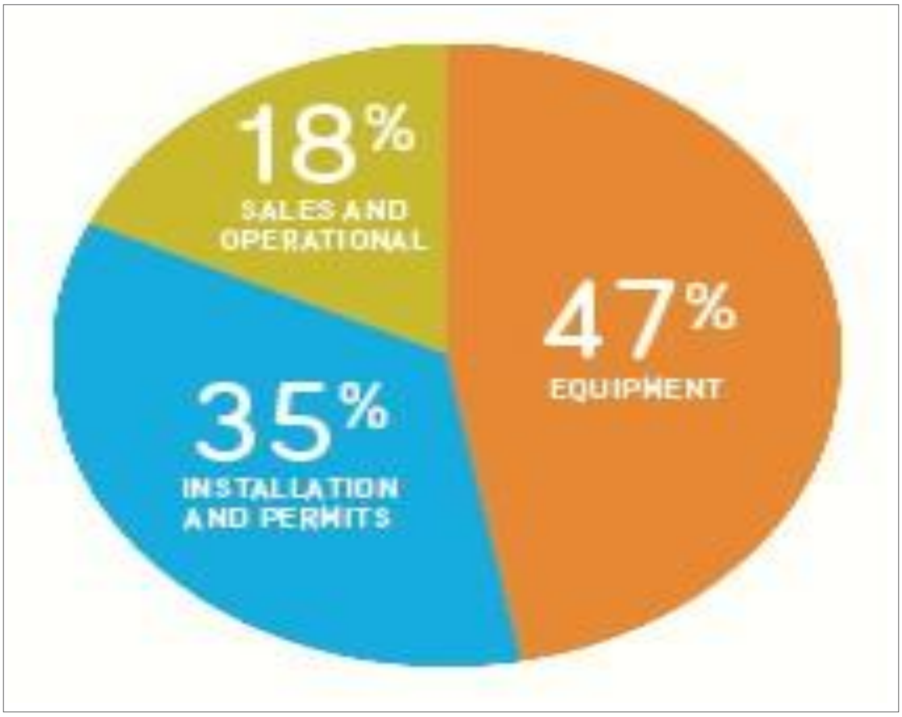


Figure 17. Percentages of measured costs of solar panels acquisition (source, https://www.sunrun.com/solar-lease/cost-of-solar)

Solar panels are quantified in watts and typically priced in dollars per watt. Not all panels possess the same quality, and their pricing reflects this disparity. Equipment expenses encompass solar panels, inverters, mounting hardware, and wiring; installation and permits include solar installation, supply chain logistics, permitting, and interconnection; sales and operational costs comprise monitoring and maintenance expenses, repairs, and supplementary operations and administrative expenditures. This does not encompass a battery storage system, which incurs an additional expense. Battery storage solutions are unnecessary if you want to meet your energy requirements by connecting to the local electricity grid.

Considering the expense of a battery storage system as previously outlined, the estimated total cost ranges from $33,300 to $47,300 to consistently provide sufficient energy, both day and night, for the typical four-bedroom residence. Depending on the climate and your geographical location, you may need to curtail usage and exercise greater frugality in your energy consumption.

Another aspect to evaluate regarding the initial expenditure is the payback period. For a $18,000 system, a payback period of 20 years is anticipated based on the savings generated by solar electricity. That is not particularly rational for the majority of individuals and their financial circumstances.

7.20 Financial Disadvantages

The primary drawback of solar energy is its economic feasibility. The semiconductor materials used in the production of solar cells are too costly to manufacture. Despite advancements in materials science and manufacturing techniques, the core methods remain prohibitively expensive. Less expensive solar panel materials are utilised in consumer electronics; nevertheless, they produce significantly lower power output compared to traditional photovoltaic cells.

Recent findings enable the utilisation of a broader spectrum of solar energy for power generation; nevertheless, these experimental materials still rely on costly crystal growth and doping techniques. Advancements in manufacturing remain some decades distant. For several decades, solar power producing facilities have functioned under government sponsorship, demonstrating that harnessing electricity from solar energy is technically feasible, albeit economically unviable, at least for the time being. These installations are situated in sparsely inhabited, arid areas that see nearly constant sunlight throughout the year. Extensive tracts of affordable land are necessary to house the solar panels and mirrors, necessitating the placement of these power plants at considerable distances from the sites of energy consumption. Costly transmission towers must bridge the gap between remote power sources and energy-consuming urban centres.

Notwithstanding the existing drawbacks of solar power, utilising the sun's free energy remains promise. As scientific advancements and manufacturing methods enhance the efficiency and reduce the cost of solar cells, solar power will emerge as a significant energy source for residential properties in the future.

8. CONCLUSION

The sun remains the most abundant, reliable, and long-lasting energy source available to humanity, and understanding its mechanisms—from nuclear fusion at its core to the dynamics of solar radiation reaching Earth—is fundamental to advancing modern energy systems. The scientific evolution from early misconceptions of chemical combustion and gravitational contraction to the correct explanation of nuclear fusion has enabled the development of sophisticated solar energy technologies capable of harnessing this immense resource. The proton–proton chain reaction, the transformation of mass into energy, and the binding energy of helium nuclei collectively illustrate the extraordinary physical processes that sustain the sun’s luminosity and ensure its stability over billions of years.

Solar energy technologies, particularly photovoltaic and solar thermal systems, translate the sun’s radiation into practical heating and electricity solutions. Advances in semiconductor engineering, thin-film materials, and high-efficiency concentrated PV systems demonstrate the vast potential of solar power as a cornerstone of global energy transformation. Meanwhile, thermal energy storage systems, including molten salts, phase-change materials, and emerging chemical storage pathways, address intermittency limitations and enhance the reliability of solar-driven electricity generation.

At the global scale, solar energy has become the fastest-growing renewable energy source, driven by declining costs, technological innovation, and urgent climate imperatives. Forecasts by international energy agencies demonstrate unprecedented expansion, with solar PV expected to dominate global renewable capacity additions through 2030. Nevertheless, challenges persist. These include land-use requirements, environmental impacts from manufacturing and disposal, supply chain concentration, energy storage costs, and the structural need for flexible, modernised power grids.

Despite these obstacles, ongoing research in materials science, energy storage, and solar fuels continues to improve efficiency, reduce economic barriers, and minimise environmental footprint. The exploration of advanced semiconductor structures, biohybrid photovoltaic systems, thermochemical storage cycles, and synthetic solar fuels holds promise for a future in which solar energy becomes not only a supplementary resource but a primary driver of global power systems.

Ultimately, solar energy stands at the intersection of scientific discovery, technological innovation, and environmental necessity. Its continued development is essential for meeting global energy demands, reducing dependence on fossil fuels, enhancing energy security, and mitigating the impacts of climate change. While considerable progress is still required to make solar power universally accessible, economically competitive, and environmentally sustainable, its potential remains unmatched. With sustained research, supportive policies, and strategic investments, solar energy will continue to shape the foundation of a cleaner, more resilient, and more sustainable global energy future.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

Bland Philip A., Moore Elaine A., Wright Ian, (2004), *An Introduction to the Solar System*, Cambridge University Press, ISBN 0-521-83735-9

Cahan David (editor), (2004), *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science*, California Studies in the History of Science Series, ISBN 978-052-0083-349

Dumiter, Aurelia Florina (2007), *Clima si topoclimatele orasului Oradea*, Editura Universitatii din Oradea, ISBN 978-606-10-0005-0

Dumitreanu Mihnea, (2017), *Valorificarea resurselor regenerabile de energie solară pentru producerea energiei verzi, prin realizarea unei capacităţi de producere a energiei electrice de 0,6 MW, pe panouri fotovoltaice, în comuna Oşorhei*, Projekt raport, Osorhei

Goga Nicu, (2010), *Sistemul solar, Astronomie prin exercitii si probleme*, Editura Revers, Craiova, ISBN 978-606-611-053-2

Green Simon F., Jones Mark H. (editors), (2004), *An Introduction to the Sun and Stars*, Cambridge University Press, ISBN 0-521-54622-2

Maican Edmond (2015), *Sisteme de energii regenerabile*, PrintechPublishing House, Bucharest, ISBN 978-606-23-0359-4

Misak Stanislav, Prokop Lukas (2016), *Operation Characteristics of Renewable Energy Sources*, Springer, ISSN 1865-3529

Murphy-Mariscal Michelle L., Grodsky Steven M., Hernandez Rebecca R., (2018), *Solar Energy Development and the Biosphere*, January 2018 DOI: 10.1016/B978-0-12- 811479-7.00020-8

Newton David E. (2015), *Solar Energy: A Reference Handbook: A Reference Handbook*, in Contemporary World Issues, Science, Technology and Medicine, ISBN 978- 1-61069-696-1

O'Keefe Maureen, Pike Katy, (2004), *The Sun's Energy*, Blake Publishing, ISBN 1- 86509-314-9

Severino Giuseppe, (2017), *The Structure and Evolution of the Sun*, Springer Publishing, XIV, ISBN 978-3-319-64961-0

Spohn Tilman, Breuer Doris, Johnson Torrence, (2014), *Encyclopedia of the Solar System*, third edition, Elsevier, ISBN 978-0-12-415845-0

Tiwari Gopal, Ghosal Madral K., (2005), *Renewable Energy Resources: Basic Principles and Applications,* Alpha Science International, ISBN 1842651250, 9781842651254

Tyson Neil deGrasse, (2017), *Moartea într-o gaură neagră și alte dileme cosmice*, Editura Trei, Bucuresti, ISBN978-606-40-0221-1

West Michael, (1993) *Solar Energy Basics ... and More*, University of Florida, Energy Extension Service, Cooperative Extension Service, Institute of Food and Agricultural Sciences, Fact Sheet EES-98

Xxx (2008), *Clima Romaniei*, Editura Academiei Romane, Bucuresti, ISBN 978-973- 27-1674

Bland, P. (2004). *Solar system: A very short introduction.* Oxford University Press.

Cahan, D. (2004). *Hermann von Helmholtz and the foundations of nineteenth-century science.* University of California Press.

Goga, N. (2010). *Thermal radiation and its applications.* Springer.

Green, M. A., Emery, K., Hishikawa, Y., & Warta, W. (2004). Solar cell efficiency tables. *Progress in Photovoltaics*, 12(5), 365–372.

GreenMatch. (2015). *Types of solar panels.* https://www.greenmatch.co.uk

International Energy Agency. (2024). *Renewables 2024: Global energy report.* IEA Publications.

Misak, S., & Prokop, L. (2016). High-efficiency concentrated photovoltaics. *Renewable Energy Journal*, 89, 161–169.

Murphy-Mariscal, M. L., et al. (2018). Solar energy development and ecosystem impacts. *Frontiers in Environmental Science*, 6(135), 1–14.

Newton, R. (2015). *The solar resource: A practical guide to solar radiation.* Academic Press.

O'Keefe, T., & Pike, R. (2004). *Solar thermal energy systems.* McGraw-Hill.

Severino, G. (2017). Nuclear fusion in stars: The proton–proton chain. *Astrophysical Reports*, 44(3), 233–251.

Tiwari, G. (2005). *Solar energy: Fundamentals, design, and applications.* Alpha Science International.

U.S. Department of Energy. (2021). *Solar radiation basics.* https://www.energy.gov

Walden Labs. (2021). *Disadvantages of solar energy.* http://waldenlabs.com

West, M. (1993). *Solar energy for a sustainable future.* MIT Press.

Online references

https://www.nachi.org/disadvantages-solar-energy.htm?loadbetadesign=0
http://waldenlabs.com/disadvantages-solar-energy/
https://www.sunrun.com/solar-lease/cost-of-solar
https://www.energy.gov/eere/solar/articles/solar-radiation-basics
(http://www.articlesbase.com/technology-articles/solar-energy-basic-principles-649460.html)
https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels
https://www.thespruce.com/top-solar-energy-uses1152263
https://marine.rutgers.edu/cool/education/class/yuri/erb.html
dgtat-dgtatamd.opendata.arcgis.com
https://www.gettyimages.com/
http://www.panourisolare-online.ro/pdf
http://www.douamaini.ro/