Solar energy systems: A critical review of technologies, applications, trends, and challenges

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Abstract

As a renewable source of power, solar energy has an increasingly important role to play in reducing greenhouse gas emissions and mitigating climate change. The paper explores the energy conversion principles, production capacity, technological developments, strengths, weaknesses, and the socio-economic impacts of solar energy. Technological developments including diverse PV systems, including monocrystalline, polycrystalline, thin-film, and emerging technologies like perovskite-silicon tandem cells which have helped propel solar power to the forefront of renewable energy and illustrate its potential to revolutionise electricity generation. There are many advantages to solar energy including sustainability, low environmental impact, decentralised energy production, and economic benefits, however, challenges such as intermittency, land use concerns, and high initial costs are important considerations. This paper also discusses global and national policy initiatives which underscore the commitment to a sustainable energy transition which are important given the enormous socio-economic benefits of solar energy which can help address inequality and support education, human rights, and healthcare.

Nomenclature

Abbreviations

BIPV	Building Integrated Photovoltaics
COP	Conference of the Parties
CSP	Concentrated Solar Power
c-Si	Crystalline Silicon
EU	European Union
GDP	Gross Domestic Product
GW	Gigawatt

IEA	International Energy Agency
PERC	Passivated Emitter and Rear Cell
PV	Photovoltaic
SDG	Sustainable Development Goal
SEIA	Solar Energy Industries Association
SWOT	Strengths, Weaknesses, Opportunities, Threats
TOPCon	Tunnel Oxide Passivated Contact
TW	Terawatt
UNDP	United Nations Development Programme

1. Introduction

Solar energy, often hailed as the ultimate renewable resource, has emerged as a critical player in the pursuit of sustainable and clean energy solutions on a global scale. This review paper will discuss solar energy in terms of its energy conversion principles and production capacity, current and recent developments in technology, overall strengths and weakness as an energy system, related energy policies and sustainability attributes and finally reflect on the role of solar energy in society.

2. Energy conversion principles

Radiating the light and heat which facilitates all life on Earth, as a main-sequence star, the sun releases its energy through nuclear fusion by converting hydrogen into helium at extremely high temperatures and pressures. The solar energy conversion into fuels or electricity utilises individual modules for light harvesting, water oxidation and proton reduction in a single device impersonating the natural photosynthesis process (European Commission, 2012) {1}.

As a result of the photovoltaic (PV) effect, light from the sun can be converted into electricity in photovoltaic (PV) devices via an electronic process in semiconductor material. As photons strike and ionise semiconductor material, outer electrons break free from atomic bonds in one direction creating an electrical current. Hirst (2012) {2} discusses the fundamental mechanisms behind this process and notes that a solar cell must possess two characteristics for PV conversion, firstly it must convert energy from the sun into chemical energy, electrons are excited into higher energy levels when light is absorbed which temporarily stores chemical energy, secondly it must have asymmetric electrical resistance, which generates an electric voltage and supply electrical work to a load resistance.

3. Energy production capacity

The energy production capacity of solar power has grown in recent years with solar energy harnessed through photovoltaic (PV) technology and concentrated solar power (CSP) systems, as a result it has emerged as a key renewable resource with the potential to revolutionise the way we generate electricity. According to the International Energy Agency (IEA) {3}, with a generation growth rate that matches the level forecast from 2023 to 2030 in the Net Zero Emissions by 2050 Scenario. solar PV generation had the largest absolute generation growth for all renewable technologies in 2022 increasing by 26 % to almost 1 300 TWh. In addition, the cost-effectiveness of PV as well as the expanding base of policy support in the EU, Chine, the US, and India should accelerate capacity growth and is on track.

Indeed, the solar energy market has grown rapidly on a global scale such as in the United States which has been supported by government incentives and decreasing costs as well as Germany which according to Chen et al (2019) {4}, has taken the lead in adopting solar energy adoption and more than 40% of the country's electricity coming from renewable sources, China has invested heavily in solar energy and is the largest producer of solar panels globally while India has increased solar energy usage looking to have 40% of energy generated from renewable sources by 2030. (Statista. 2023) {5}.

4. Technological developments

Rapid advancements in solar energy technology have transformed renewable energy and have involved innovations in photovoltaic systems, energy storage, and smart grid integration, with recent more developments focusing on next-generation cells, bifacial panels, flexible and printable cells, solar tracking, nighttime power plants, and transparent solar panels.

4.1 Current technology

Solar energy technology has experienced rapid changes which have helped transform renewable energy. The current state of solar technology reflects the interplay between innovations in photovoltaic (PV) systems, energy storage, smart grid integration, and novel applications in both urban and rural settings. These developments enhance the efficiency and cost-effectiveness of solar energy and support the transition toward sustainable and renewable energy sources.

As radiant light and heat from the sun, solar energy is typically harnessed through a number of technologies, the three principal methods used include solar photovoltaics (solar PV) that generate DC electricity as well as solar heating and cooling (SHC) for space or water heating and concentrating solar power (CSP) for electricity-generating power plants (SEIA) {6}.

According to Sustainable Energy Authority of Ireland (SEAI) {7}, there are several solar PV products available for a range of applications including solar panels on rooftops and in solar farms, Building Integrated Photovoltaics (BIPV) embedded in building materials such as roof tiles, glass or cladding and consumer electronics with integrated solar PV materials. Crystalline silicon (c-Si) solar cells are commonly used but are not 100% efficient, thin-film PV are more cost-effective but less efficient and concentrating PV arrays which use lenses and mirrors to reflect concentrated solar energy and need direct sunlight and tracking systems to be useful. SEIA also note the use of BIPV systems which forms the outer layer of a structure and can generate electricity for on-site use

Again, IEA {8} advise that crystalline silicon currently dominates the PV technology market share at 97% noting the recent move to more efficient monocrystalline wafers in 2022. In addition, a more efficient cell design (Passivated Emitter and Rear Cell [PERC]) has taken over while higher-efficiency cell designs (using TOPCon, heterojunction and back contact) expanded commercial production capturing more than a third of the market in the same year.

It's worth noting that there are several types of panels, each with their own benefits and challenges.

- Monocrystalline solar panels offer the highest power output with efficiency rates of up to 20%, they require less space than other panels due their high efficiency, have a long lifespan and often a 25-year warranty and perform well in low levels of light, however, they are the expensive panel on the market (EnergySage, 2023) (9}.

- Polycrystalline solar panels are more cost-effective; however, they are less efficient and take up more space than their monocrystalline counterparts and with sensitivity to higher temperatures typically have a s shorter lifespan market (EnergySage, 2023) (10}.
- Thin-film solar panels can offer an affordable alternative as it's simpler to produce than crystalline products and requires less material to produce, however, they have lower warranties, require a lot of space and typically are not suitable at the residential level.
- As the newest type of photovoltaic systems, amorphous solar cells have low efficiency rates at %, however, they are less costly to produce, have tolerance to heat and can generate energy even in low light conditions.
- Another new form of photovoltaic technology combines organic material which absorbs light which is converted into electrical energy using an inorganic semiconductor. More efficient than thin-film solar cells with rates up to 20%, they offer a more cost-effective alternative to traditional photovoltaic panels, however, they need further development before they are a practical alternative. (Ibn-Mohammed et al, 2017) (11).
- Telluride Solar Cell are a commonly used photovoltaic system consisting of a thin layer of cadmium and telluride which can be applied to substrates and require less materials than crystalline modules with efficiency rates up to 20%, however, they are poisonous to humans and their sensitivity to higher temperatures can significantly reduce lifespan (Scarpulla et al 2023) {12}.
- CPV/HCVP technologies use lenses or mirrors to concentrate sunlight onto solar cells and are extremely efficient, with rates up to 41%, however, they require tracking systems which require a lot of space and are less cost-effective given the materials involved in production (Xiao et al 2018) (13).

4.2 Recent technological developments

The solar energy sector has experienced significant technological development in recent years including the development of durable solar cells, solar panels that track the sun's movement, cells that can be printed onto surfaces and solar power plants that can work at night. This reflects the increasing commitment to efficient, flexible, and sustainable energy solutions.

1. **Next-generation photovoltaic cells**

   Recent breakthroughs in photovoltaic (PV) cells include the emergence of tandem solar cells which use several materials to absorb a greater spectrum of light and boost efficiency as well as perovskite-silicon tandem cells which can potentially provide opportunities for higher conversion efficiencies and providing a cost-effective and scalable solution.

2. **Bifacial solar panels**

   These solar panels can absorb sunlight from both sides of the module which increases the total energy generated. They are typically more durable than traditional panels and are particularly effective in areas with reflective surfaces with frameless modules also mitigating against potential-induced degradation (PID).

3. **Flexible and printable solar cells**

   Progress in materials science have resulted in flexible and printable solar cells which can be printed onto various flexible surfaces for use in unconventional environments and applications such as wearable solar devices and solar-integrated building materials.

4. **Solar tracking systems**

   Solar panels with solar tracking technology that follow the solar trajectory optimises energy capture and improves efficiency. Solar tracking systems can help enhance energy production and maximise the utility of available sunlight.

5. **Nighttime solar power plants**

   Innovations in energy storage and concentrated solar power (CSP) technologies have given rise to solar power plants that can operate during nighttime. These plants store excess solar energy generated during the day, allowing for continuous electricity production even in the absence of sunshine. This development addresses the challenge of intermittency associated with solar power.

6. **Transparent solar panels**

   Designed for integration into windows and building facades, transparent solar panels allow natural light to pass through while also capturing solar energy. This is an interesting development in terms of sustainable architecture in which buildings can generate electricity without compromising aesthetics or visibility.

5. Strengths and weaknesses

As the use of solar energy becomes increasingly popular, it’s important to consider not only it’s benefits in terms of low environmental impact and contribution to greenhouse gas emission reduction but also challenges related to intermittency and energy storage as well as concerns regarding land use and habitat disruption and the initial cost of implementation as discussed below.

5.1 Strengths

Given the magnitude and rapid rate of climate change depends “depend strongly on near-term mitigation and adaptation actions” (Intergovernmental Panel on Climate Change, 2022) {14}, the importance, and strengths of renewable sustainable alternatives to traditional fossil fuels can’t be understated. Indeed, with concerns around the effects of climate change and the interest in the development of renewable energy systems and more particularly with solar power technologies, it’s important to assess the environmental impact of any renewable technology to mitigate against any further degradation. (Hasanuzzaman and Kumar, 2020) {15}.

There are many advantages to using solar energy, as the International Energy Agency succinctly noted in 2011, solar energy technology is not only clean, inexhaustible, sustainable, and affordable but also increases a countries’ energy security through the use of independent indigenous resources, reduces pollution and lowers the cost of mitigating global warming resulting in enormous long-term benefits on a global scale.

1. **Renewable nature/sustainable**

   The Sun is an enormous source of reliable energy with the earth's surface receiving 1366 W/m2 of direct solar radiation, which decreases to a normal surface irradiance of approximately 1000 W/m2 (Dupont et al., 2020) {16} and therefore is at an environmental advantage to traditional energy sources and even other forms of renewable energy. Solar energy can help reduce greenhouse gas emissions and help communities through carbon sequestration. Unlike fossil fuel resources, solar energy provides a consistent and sustainable and almost limitless power source and overcomes concerns about resource depletion.

2. **Low environmental impact**

   The environmental impact of solar energy production is relatively low compared to non-renewable resources and contributes to reduced greenhouse gas emissions. PV systems have low carbon emissions, are not reliant on fossil fuels although they may be part of the manufacturing process and once installed provide a noise-free non-toxin emitting energy solution that is safe to the environment, however, the production of solar cells will have some health and environmental impacts which we will discuss.

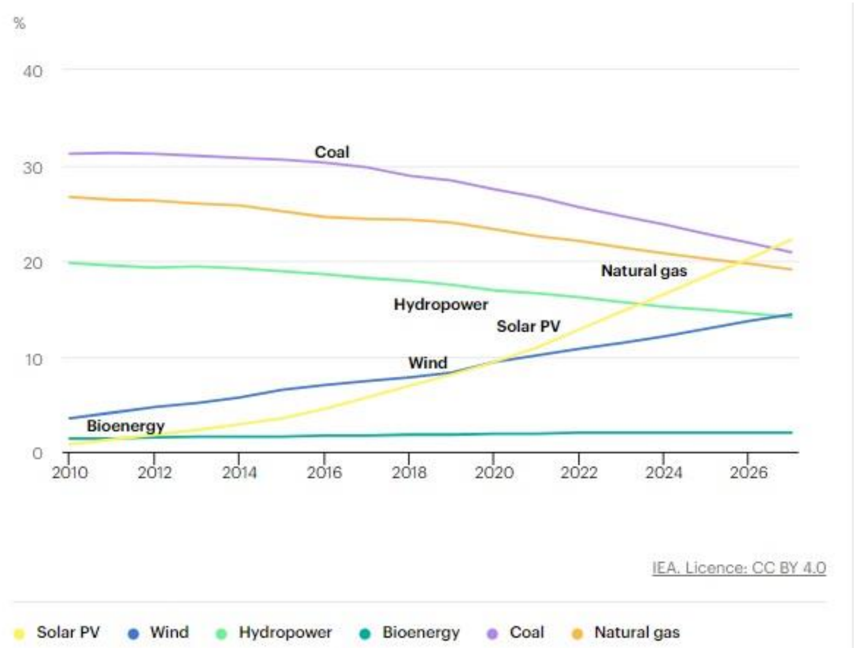
3. **Decentralised energy production and accessibly**

   Solar panels can be installed in remote areas which can help decentralise energy production while also reducing overall transmission losses. Amin (2020) (17} notes that renewable energy and more particularly solar photovoltaics (PV) are a relatively quick method for expanding access to electricity and providing individuals and groups with a degree of agency and autonomy in managing energy provisions and thus increase capacity building with the potential to create more democratic systems. Indeed, access to energy for lighting is a serious challenge in Africa with estimates suggesting that more than 50% of the 110 million -ff-grid households use kerosene lamps. The introduction of solar energy even in the form of solar lighting products can provide low-cost solutions. Furthermore, this facilitates energy independence removing dependence on third party suppliers, ownership increases engagement, empowers local communities and is a more sustainable form of energy management not only in terms of renewable energy but from a sociological perspective and has the potential to create a more just and egalitarian society.

4. **Low operating costs**

Once installed, the cost of operating solar systems as well as maintaining them is relatively low which contributes to their economic viability on a long-term basis. According to the IEA {18}, forecasts that cumulative solar PV capacity will triple and grow by almost 1 500 GW by 2027 with the installed power capacity of Solar PV's surpassing coal and natural gas. Although current investment costs are high as the result of commodity prices, they argue that utility-scale solar PV is the least expensive option for generating electricity in the most countries across the globe.

Share of cumulative power capacity by technology, 2010-2027



5. **Economic development**

Solar energy has the potential to be a highly cost-effective technique. As solar systems become becoming less expensive and more accessible, there is real potential for it to become a cheap energy and ultimately push economic growth and employment in the transport and agricultural sectors. Research has shown that a 1 GW solar power station can generate about ten times the amount of energy as a fossil fuel power plant although it would cost twice as much to develop.

5.2 Weaknesses

As noted, despite the myriad of benefits to solar energy, it is necessary to consider challenges which are unique in every implementation.

1. **Intermittency and energy storage challenges**

   The variability of sunlight and weather conditions lead to intermittent energy production, and therefore efficient energy storage solutions are required. In their assessment of the strength, weakness, opportunities, and threats (SWOT) of using solar energy, Guangal and Chala (2019) (19) note that since solar energy is limited to daylight hours, an energy storage system is necessary when there is insufficient stored energy or available sunlight This incurs additional costs which undermine the cost effectiveness of solar systems as a supply of constant energy where are limited by the capacity of the storage system.
2. **Land use and environmental concerns**

   As utility-scale solar energy (USSE) systems increase in size, greater consideration needs to be given to appropriate land use and according to Hernandez et al {20}, optimising land use efficiently is an ongoing challenge. As Sustainable Energy Authority of Ireland (SEAI) {21} note, while harnessing the solar energy and converting it to electricity is a cost-effective and viable process for producing pollution-free and sustainable power, to generate electricity at the scale to significantly reduce carbon emissions requires careful planning and considerations of land use as solar plant development require land grading and clearing much like traditional fossil fuel power plants and certain plants like concentrating solar power (CSP) need access to flat land. Consequently, siting a power plant is a challenging process that needs to assess current land usage and water rights white carefully considering local communities and conduct detailed environmental studies to assess impact and incorporate mitigation measures to minimise environmental impacts.

3. **High initial cost**

   Although the cost of solar energy installations decreases significantly over time, the initial costs of solar installations can be prohibitive. Furthermore, while there are enormous benefits as a result of installing solar systems, the initial investment cost is expensive and assessment of the final cost is challenging without assistance from the manufacturing company, however, these costs are often offset by government loans, tax exemptions and subsidies as governments work towards achieving international SDG and climate targets and significantly reduce the use of fossil fuels and this can helps to reduce the burden of the installation costs. (Guangal and Chala, 2019) {22}.

6. Solar energy policy

To mitigate the negative impacts on the environment of fossil fuels and prevent further degradation, many countries have pushed for a move to environmentally friendly renewable and sustainable energy alternatives and consequently have developed solar energy policies to support the shift away from fossil fuels. SolarPower {23} suggest that solar power is on track as 239 GW new solar were installed in 2022 surpassing the TW-scale and with 45% more solar power capacity than in 2021 forecasting the installation between 341 and 402 GW of solar globally in 2023.goes

6.1 Global pledge

More recently, the Global Pledge on Renewables and Energy Efficiency was launched at the World Climate Action Summit in Dubai 2023 with the COP28 Presidency and 118 countries. According to the European Commission (2023) {24}, the pledge originally proposed by the Commission President sets global targets to triple the installed capacity of renewable energy to at least 11 terawatts (TW) and double the rate of global energy efficiency improvements from 2% to 4% by 2030 to transition to a decarbonised energy system and continue to phase out fossil fuels.

6.2 National policies

Many countries have national policies on sustainable energy, for example, in Ireland, the Department of Communications, Climate Action and Environment (DCCAE) have implemented energy polices including Ireland's Transition to a Low Carbon Energy Future 2015-2030 to help deliver a more sustainable energy system (SEAI) {25}. In addition, according to the European Commission (2023) {26} the 2030 climate and energy framework include EU-wide targets and policy objectives for the period from 2021 to 2030, to reduce Greenhouse gas emissions: from 40% to at least 55% compared to 1990 levels, increase renewable energy: from 32% to 42.5% and shift the Energy efficiency target for final energy consumption: from 32.5% to 36% with an energy efficiency target for primary energy consumption: 39%. As the transition to clean energy transforms the global energy markets, the European Commission (2023) {27} released its Clean Energy Package with a focus on prioritising energy efficiency. Becoming a global leader in renewable energies and providing equitable benefits for all consumers.

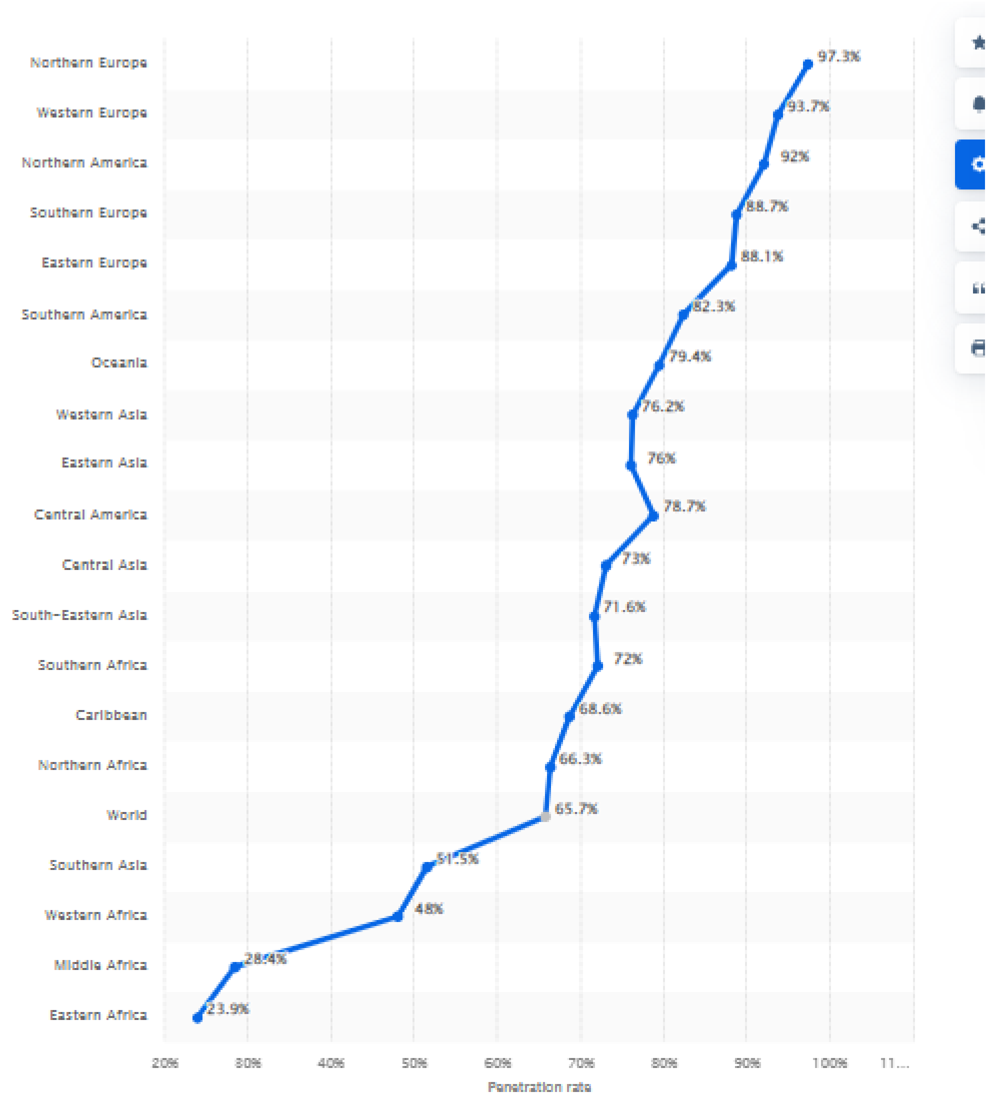
7. Sustainability and socio-economic benefits

According to Kusaya et al (2023) {28}, with a potential of 6500 TW to meet global energy needs, solar energy is one of the cleanest forms of energy and contributes significantly to sustainable development by reducing CO2 and SO2 emissions, attenuating the depletion of natural resources, facilitating energy security and independence, and enhancing the quality of water resources. In addition, solar energy is a virtually inexhaustible and relatively inexpensive energy source and is a natural alternative to carbon-intensive non-renewable energy and supports the Sustainable Development Goals.

One of the most important aspects of solar energy lies in it’s potential to reduce socio-economic inequalities and close the gap between advantaged and marginalised communities such as rural and urban populations in developing countries and between core and peripheral countries on a global scale thus supporting SDG 10 to reduce inequality between and within countries. For example, according to the International Telecommunication Union (ITU) {29}, 37 per cent of the global population (2.9 billion people), 96 per cent of which are from developing countries have never used the internet. Limited infrastructure and lack of access to electricity is a major contributory factor, however, solar powered devices can provide electricity in the absence of a grid connection.

Global internet usage

Statista: https://www.statista.com/statistics/269329/penetration-rate-of-the-internet-by-region



Internet access is also important for remote communities as it provides access educational resources thus supporting SDG 4 to ensure inclusive and equitable quality education and promote lifelong learning opportunities. Education is crucial in terms of capacity building and breaking the poverty gap and a sustainable way of improving living conditions and opportunities. It's also instrumental in reducing gender inequality by providing education resources to the female population, increasing employment opportunities and independence, and reducing the male-female gap.

In addition, solar energy can also support human rights by addressing food and water security using solar-powered irrigation systems instead of diesel-powered pumps. According to the United Nations Development Programme (UNDP) Cambodia {30}, the agricultural sector which accounts for

21 percent of Cambodia’s gross domestic product (GDP) and employs over 30 percent of the labour force is particularly vulnerable to climate change with reports estimates suggesting that 1 million hectares of rice fields from 2015–2019 have been damaged by drought with a loss of approximately US$100 million. As a result, UNDP are testing large-scale solar water pump system which provides water for irrigation during the dry season allowing farmers to plant rice or other crops for a second season while creating habitats for fish and water birds that facilitate subsistence fishing. Furthermore, large-scale solar water pumping can significantly reduce operation costs and the power from solar photovoltaic (PV) panels used for the pumps can also provide surplus electricity that can power small communities. Furthermore, with potential opportunities to invest in and own a share of solar installations, local communities gain control over energy resources and are empowered.

As a clean energy source which does cause air pollution, solar energy is also beneficial in terms of healthcare as it does not cause or contribute to respiratory health problems. From an operational perspective, it can also provide a reliable energy source for hospitals and clinics and as a relatively cheap energy solution, can also cut down on running costs.

8. Conclusion

In conclusion, solar energy stands at the forefront of the global transition towards sustainable and clean energy solutions and has a transformative role to play in society. This comprehensive review has explored solar energy's fundamental principles, energy production capacity, and the trajectory of technological developments. The strengths to solar power include low environmental impact, decentralised production, and economic benefits which support the SDGs and the 2030 Agenda. Furthermore, its low operating costs and economic benefits have the potential to reduce socio-economic inequalities and contribute to a more sustainable and equitable world. However, challenges such as intermittency, energy storage limitations as well as land use concerns, and the high costs of installation underscore the need for further research and the ongoing development of innovative solutions. Government policies are also important in helping to shape the future of solar energy adoption supported by global initiatives and national policies. As noted, the socio-economic benefits of solar energy are substantial ranging from facilitating internet access in remote areas to supporting education, gender equality, and addressing food and water security. Solar energy not only provides a clean and reliable energy source but also has the potential to empower communities, improve healthcare, and contribute to a more sustainable and just society. As countries work collectively to meet the SDGs and as societies seek to develop and prioritise sustainable practices, the importance of solar energy in creating a sustainable future for generations should not be underestimated.

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