

Comparative analysis of solar energy and conventional energy sources in terms of efficiency and cost

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Abstract

The global demand for energy has increased significantly over the last few decades due to industrialization, urbanization, and population growth. Conventional energy resources such as coal, natural gas, and petroleum have historically dominated electricity generation because of their established infrastructure, reliability, and high energy density. However, growing concerns regarding environmental degradation, greenhouse gas emissions, and the depletion of fossil fuel reserves have accelerated the transition toward renewable energy technologies. Among the renewable alternatives, solar energy has emerged as one of the most promising and rapidly expanding sources of clean electricity generation (Kelvin Edem Bassey et al., 2024). This paper presents a comparative analysis of solar energy and conventional energy sources in terms of efficiency, operational performance, lifecycle costs, environmental impact, and long-term economic viability. The study evaluates photovoltaic (PV) and concentrated solar power (CSP) systems alongside conventional thermal power plants fueled by coal, natural gas, and oil (Hussain et al., 2024). The paper examines capital investment requirements, maintenance expenses, conversion efficiencies, operating costs, fuel dependency, and environmental externalities associated with each technology. A lifecycle assessment approach is applied to compare energy payback periods, levelized cost of electricity (LCOE), and sustainability indicators. The findings demonstrate that although conventional energy systems currently maintain advantages in dispatch reliability and initial energy conversion efficiency, solar technologies offer substantial long-term benefits due to declining installation costs, low operational expenses, minimal fuel requirements, and reduced carbon emissions (Hussain et al., 2024). The study concludes that continuous technological innovation, economies of scale, government incentives, and improvements in energy storage technologies are making solar energy increasingly competitive with traditional fossil-fuel-based electricity generation. The integration of solar energy into modern power systems can significantly contribute to energy security, environmental sustainability, and economic resilience.

Keywords: Solar Energy; Conventional Energy; Photovoltaic Systems; Renewable Energy; Efficiency Analysis; Lifecycle Cost Assessment; Sustainability; Energy Economics.

1 Introduction

Energy is one of the most critical drivers of economic development and industrial progress (Zhang et al., 2024). Modern societies rely heavily on stable and affordable electricity supplies for transportation, manufacturing, communication, healthcare, education, and domestic activities. Since the Industrial Revolution, conventional fossil-fuel-based energy systems have formed the backbone of global electricity production. Coal-fired power plants, oil refineries, and natural gas facilities have historically provided large-scale and dispatchable energy to support economic growth. Despite their significant contributions to industrial advancement, conventional energy systems are associated with several major

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challenges (University of East London, United Kingdom et al., 2023). Fossil fuel combustion releases large quantities of greenhouse gases, particularly carbon dioxide (CO₂), methane (CH₄), and nitrogen oxides (NO_x), which contribute to climate change and environmental degradation. In addition, conventional power generation leads to air pollution, acid rain, ecosystem damage, and public health concerns. Rising fuel prices and the finite nature of fossil fuel reserves have also raised questions regarding long-term energy security and economic sustainability.

Renewable energy technologies have emerged as viable alternatives to conventional energy systems (Solak & Irmak, 2023). Among these technologies, solar energy has received substantial attention because of its abundance, accessibility, and declining technology costs (Streimikiene et al., 2021). Solar radiation represents one of the largest energy resources available on Earth. Advances in photovoltaic materials, semiconductor manufacturing, and concentrated solar technologies have significantly improved the efficiency and affordability of solar electricity generation. Governments, industries, and international organizations are increasingly investing in solar energy infrastructure to reduce dependence on fossil fuels and meet climate targets (Ge et al., 2026). Solar installations have expanded rapidly in both developed and developing countries due to supportive policies, tax incentives, feed-in tariffs, and falling module prices. The transition toward solar energy is also supported by improvements in battery storage systems and smart grid technologies. However, important questions remain regarding the comparative efficiency and economic performance of solar energy relative to conventional energy sources. Conventional thermal plants generally achieve higher capacity utilization and can generate electricity continuously regardless of weather conditions. Solar energy systems, on the other hand, are intermittent and dependent on sunlight availability. Furthermore, solar installations often require significant upfront capital investment (Gayen et al., 2024). This paper aims to provide a detailed comparative analysis of solar energy and conventional energy systems in terms of efficiency and cost. The study examines the technical characteristics, operational performance, economic considerations, and environmental implications of both energy categories. By analyzing lifecycle costs and efficiency metrics, the paper seeks to evaluate the long-term competitiveness of solar technologies in the global energy market.

2 Literature Review

Research on renewable energy systems has expanded rapidly during the last two decades due to increasing environmental concerns and the urgent need for sustainable energy alternatives (Solak & Irmak, 2023). Numerous studies have compared renewable technologies with conventional fossil-fuel-based systems from technical, economic, and environmental perspectives. Early research primarily focused on the energy payback period and lifecycle energy consumption of photovoltaic systems. Studies demonstrated that modern solar panels can recover the energy consumed during manufacturing within a few years of operation, after which they continue generating net positive electricity for decades (Shamshad & Ur Rehman, 2025). Improvements in semiconductor materials, manufacturing processes, and module efficiency have further reduced the lifecycle energy demand of solar technologies. Several researchers have examined the levelized cost of electricity (LCOE) as a key indicator for comparing energy technologies (Sarker et al., 2023). LCOE represents the total lifecycle cost of a power generation system divided by its total electricity output over its operational lifetime. Conventional coal and natural gas plants historically exhibited lower LCOE values because of mature infrastructure and established supply chains (Farghali et al., 2023). However, declining solar panel prices and improvements in manufacturing efficiency have narrowed the cost gap substantially. Environmental studies have emphasized the ecological impacts associated with fossil fuel combustion (Salim et al., 2025). Coal-fired power plants are among the largest contributors to global carbon emissions and air pollution. Natural gas plants produce lower emissions than coal but still contribute significantly to greenhouse gas accumulation. Solar energy systems produce minimal emissions during operation, making them attractive for climate mitigation strategies. Recent literature has also explored hybrid energy systems that combine solar energy with battery storage, natural gas backup systems, or smart grid technologies (El-Araby, 2024). These integrated systems aim to overcome the intermittency limitations of solar power while improving overall system reliability. Technological advancements in concentrated solar power (CSP) have further expanded the potential of solar energy. CSP systems use mirrors or lenses to concentrate sunlight and generate thermal energy, which can then be converted into electricity using steam turbines. Thermal energy storage allows CSP plants to continue producing electricity after sunset, improving dispatch flexibility (Al-Suod et al., 2025). Despite the growing body of literature, comparative analyses that comprehensively evaluate both efficiency and cost across solar and conventional energy systems remain limited. Many studies focus primarily on either environmental benefits or economic feasibility without integrating both aspects into a unified framework. This paper addresses that gap by presenting a multidimensional comparative assessment of solar and conventional energy technologies.

2.1 Research Gap

Although numerous studies have investigated renewable energy technologies and conventional power generation systems independently, there remains a significant research gap in comprehensive comparative analyses that

simultaneously evaluate solar energy and conventional energy sources in terms of efficiency, lifecycle cost, environmental impact, and operational reliability. Many existing studies focus primarily on either technical efficiency or economic feasibility without integrating both aspects into a unified assessment framework (El-Araby, 2024). Furthermore, previous research often emphasizes photovoltaic (PV) systems while providing limited comparative evaluation of concentrated solar power (CSP) technologies alongside coal, natural gas, and oil-fired power plants. The influence of lifecycle assessment (LCA), including manufacturing, transportation, operation, and decommissioning impacts, is also insufficiently addressed in many comparative studies. Another important gap exists in the evaluation of long-term economic performance using standardized indicators such as the levelized cost of electricity (LCOE). Variations in fuel dependency, maintenance costs, and technological advancements are frequently analyzed separately rather than within a holistic comparative model. In addition, limited research has examined the combined effects of capacity factor, grid stability, intermittency, and energy storage requirements on the practical implementation of solar technologies in comparison with conventional systems. Environmental sustainability indicators, particularly lifecycle greenhouse gas emissions and energy payback periods, also require more integrated and updated investigation using recent industry and international energy agency data. Therefore, this study aims to bridge these gaps by conducting a comprehensive comparative analysis of solar energy systems and conventional energy sources based on technical efficiency, economic viability, environmental sustainability, and operational performance using lifecycle assessment and cost evaluation methodologies.

2.1.1 Research Questions

- How do solar energy systems, particularly photovoltaic (PV) and concentrated solar power (CSP), compare with conventional energy sources in terms of energy conversion efficiency?
- What are the differences in capital investment, operation and maintenance costs, and fuel dependency between solar energy systems and conventional power plants?
- How does the levelized cost of electricity (LCOE) vary between solar energy technologies and conventional energy generation systems over their lifecycle?
- What are the environmental impacts and lifecycle greenhouse gas emissions associated with solar energy systems compared to coal, oil, and natural gas power plants?
- To what extent do reliability, capacity factor, and grid stability influence the practical implementation of solar energy systems compared to conventional energy sources?

2.1.2 Research Objectives

- To evaluate and compare the energy conversion efficiency of solar energy systems (PV and CSP) and conventional energy sources.
- To analyze the economic performance of different energy technologies based on capital cost, operational cost, maintenance cost, and fuel dependency.
- To assess the levelized cost of electricity (LCOE) of solar and conventional energy systems using lifecycle cost analysis.
- To examine the environmental sustainability of solar and conventional energy technologies through lifecycle assessment (LCA), including greenhouse gas emissions and energy payback periods.

To investigate the reliability, capacity factor, and grid integration challenges of solar energy systems in comparison with conventional power generation technologies.

3 Methodology

The methodology of this study is based on a comparative analytical framework that evaluates solar energy systems and conventional energy sources using technical, economic, and environmental indicators.

3.1 Data Collection and Analysis

Secondary data were collected from scientific journals, government energy reports, industry databases, international energy agencies, and published lifecycle assessment studies. The analysis includes data related to: Photovoltaic (PV) systems, Concentrated Solar Power (CSP) systems, Coal-fired thermal power plants, Natural gas combined cycle plants, Oil-fired power stations.

4 Result and Discussion

A lifecycle assessment (LCA) approach is applied to evaluate the total environmental and economic impacts associated with each energy technology. The lifecycle stages include: Raw material extraction, Manufacturing and construction, Transportation and installation, Operation and maintenance, Decommissioning and disposal. The analysis incorporates both direct and indirect energy inputs associated with each technology.

4.1 Cost Evaluation

The cost analysis includes fixed and variable costs. Fixed costs primarily involve equipment manufacturing, land acquisition, and infrastructure development, while variable costs include fuel consumption, maintenance, labor, and operational expenditures.

The Levelized cost of electricity (LCOE) is calculated using the standard formula:

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t + Q_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

Where:

C_t = Capital cost in year t Q_t = Operation and maintenance cost in year t

F_t = fuel cost in year t E_t = electricity generated in year t r = discount rate n = project lifetime

This formula allows comparison of different energy technologies on a common economic basis.

4.2 Solar Energy Systems

Solar energy technologies convert sunlight into usable electricity or thermal energy. The two major categories of solar electricity generation are photovoltaic (PV) systems and concentrated solar power (CSP) systems.

4.3 Photovoltaic Systems

Photovoltaic systems generate electricity directly from sunlight using semiconductor materials such as silicon (Reda et al., 2024). When sunlight strikes the PV cells, electrons are excited and create an electric current.

4.3.1 Advantages of Photovoltaic Systems

Photovoltaic (PV) systems provide numerous advantages that make them one of the most attractive renewable energy technologies. During operation, PV systems produce minimal greenhouse gas emissions, significantly reducing environmental pollution and contributing to climate change mitigation. They also require low maintenance because of their simple design and limited moving components (Ahmed et al., 2024). Another important advantage is their modular and scalable installation, allowing systems to be deployed for small residential applications as well as large utility-scale power plants. In addition, solar energy reduces dependence on imported fossil fuels, thereby improving national energy security and economic stability. PV systems also have a long operational lifespan, typically lasting 25 to 30 years with consistent performance. Furthermore, solar panels operate silently, making them environmentally friendly and suitable for urban and residential areas.

4.3.2 Limitations of Photovoltaic Systems

Intermittent electricity generation, Dependence on weather conditions, High upfront capital costs, Requirement for energy storage systems, Large land area for utility-scale installations

4.4 Concentrated Solar Power Systems

CSP systems use mirrors or lenses to concentrate solar radiation and produce thermal energy. The heat generated is used to produce steam that drives a turbine connected to a generator.

4.4.1 *Types of CSP Technologies*

Concentrated Solar Power (CSP) technologies include parabolic trough systems, solar tower systems, Fresnel reflector systems, and dish-Stirling systems. These technologies use mirrors or reflectors to concentrate sunlight and generate thermal energy for electricity production with improved efficiency and storage capability.

4.4.2 *Advantages of CSP Systems*

Concentrated Solar Power (CSP) systems offer several significant advantages over many conventional renewable technologies. One of the major benefits of CSP is its thermal energy storage capability, which allows excess heat collected during sunny periods to be stored and used later for electricity generation. This storage feature enables CSP plants to provide dispatch-able electricity generation, meaning electricity can be supplied even during nighttime or cloudy conditions. Additionally, CSP systems achieve higher efficiency in sunny regions with strong solar irradiance, making them particularly suitable for desert and arid environments. The integration of thermal storage also helps reduce intermittency challenges commonly associated with renewable energy systems, thereby improving grid reliability and energy stability.

4.4.3 *Limitations of CSP Systems*

High infrastructure costs, Complex engineering requirements, Water consumption for cooling, Geographic limitations

4.5 **Efficiency of Solar Energy Systems**

The efficiency of solar systems depends on several factors, including panel technology, solar irradiance, temperature, and system design. Modern commercial photovoltaic panels typically achieve efficiencies between 18% and 24% (Razmjoo et al., 2021). Laboratory-scale technologies may exceed 40% efficiency under concentrated sunlight conditions. The power conversion efficiency of a solar cell can be represented as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Where:

η = efficiency P_{out} = electrical power output P_{in} = incident solar power

CSP systems may achieve thermal efficiencies ranging from 30% to 40%, depending on system design and thermal storage integration.

4.6 **Conventional Energy Systems**

Conventional energy systems rely primarily on fossil fuels such as coal, oil, and natural gas. These fuels are combusted to generate heat, which is used to produce steam that drives electricity-generating turbines.

4.7 **Coal-Fired Power Plants**

Coal remains one of the most widely used energy sources for electricity generation worldwide (Peter Efosa Ohenhen et al., 2024). Coal plants are capable of producing large amounts of continuous power and are often used as baseload generation facilities.

4.7.1 *Advantages of Coal Energy*

Conventional energy systems, particularly coal and natural gas power plants, offer several important advantages that have supported their widespread use for decades. One major benefit is the presence of well-established infrastructure, including extensive power plants, fuel transportation networks, and distribution systems. These systems are also capable of producing high power output, making them suitable for large-scale industrial and urban electricity demands. In addition, conventional power plants provide reliable electricity generation because they can operate continuously regardless of weather conditions or time of day. Another advantage is that fossil fuels may have relatively low fuel costs in certain regions where domestic reserves are abundant, contributing to affordable electricity production and stable energy supply.

4.7.2 Limitations of Coal Energy

High greenhouse gas emissions, Air pollution and particulate matter, Environmental degradation from mining, Ash disposal challenges, Water consumption Coal-fired plants typically achieve thermal efficiencies between 33% and 40%, although advanced ultra-supercritical plants may exceed 45% efficiency.

4.8 Natural Gas Power Plants

Natural gas combined cycle (NGCC) plants are among the most efficient conventional power generation technologies (Nguyen et al., 2025).

4.8.1 Advantages of Natural Gas

Natural gas power plants offer several advantages compared to traditional coal-fired systems. They generally achieve higher efficiency than coal plants, allowing more electricity to be generated from the same amount of fuel. In addition, natural gas produces lower carbon emissions and fewer air pollutants, making it a comparatively cleaner fossil fuel option. These plants also have fast startup capability, enabling them to respond quickly to changes in electricity demand. Furthermore, their flexible operation makes them suitable for supporting renewable energy integration and maintaining grid stability.

4.8.2 Limitations of Natural Gas

Dependence on fuel prices, Methane leakage concerns, Fossil fuel dependency, Infrastructure requirements. Combined cycle gas plants can achieve efficiencies above 60% under optimal operating conditions.

4.9 Oil-Fired Power Plants

Oil-fired power stations are generally used in regions with limited access to other fuel resources or for backup generation.

4.9.1 Advantages of Oil Energy

Oil-based energy systems provide several advantages that have supported their long-standing use in power generation and industrial applications. One of the primary benefits of oil is its high energy density, allowing a large amount of energy to be produced from a relatively small quantity of fuel. Oil-fired power plants are also capable of rapid electricity generation, making them suitable for meeting sudden increases in power demand and emergency backup supply. Additionally, the global oil industry benefits from well-established supply chains, including extensive transportation, storage, and distribution networks that ensure reliable fuel availability in many regions.

4.9.2 Limitations of Oil Energy

High fuel costs, Significant carbon emissions, Price volatility, Environmental pollution Oil-fired plants typically achieve efficiencies between 30% and 38%.

4.10 Comparative Efficiency Analysis

Efficiency is one of the most important indicators for evaluating energy systems. However, efficiency can be interpreted differently depending on the context.

4.11 Thermal Efficiency Vs Lifecycle Efficiency

Conventional fossil fuel plants generally exhibit higher direct thermal efficiencies because combustion processes release large amounts of concentrated energy. Combined cycle gas turbines can exceed 60% efficiency, significantly higher than most photovoltaic systems. However, solar energy systems demonstrate advantages when lifecycle efficiency and sustainability are considered. Solar technologies require no ongoing fuel extraction, transportation, or combustion during operation.

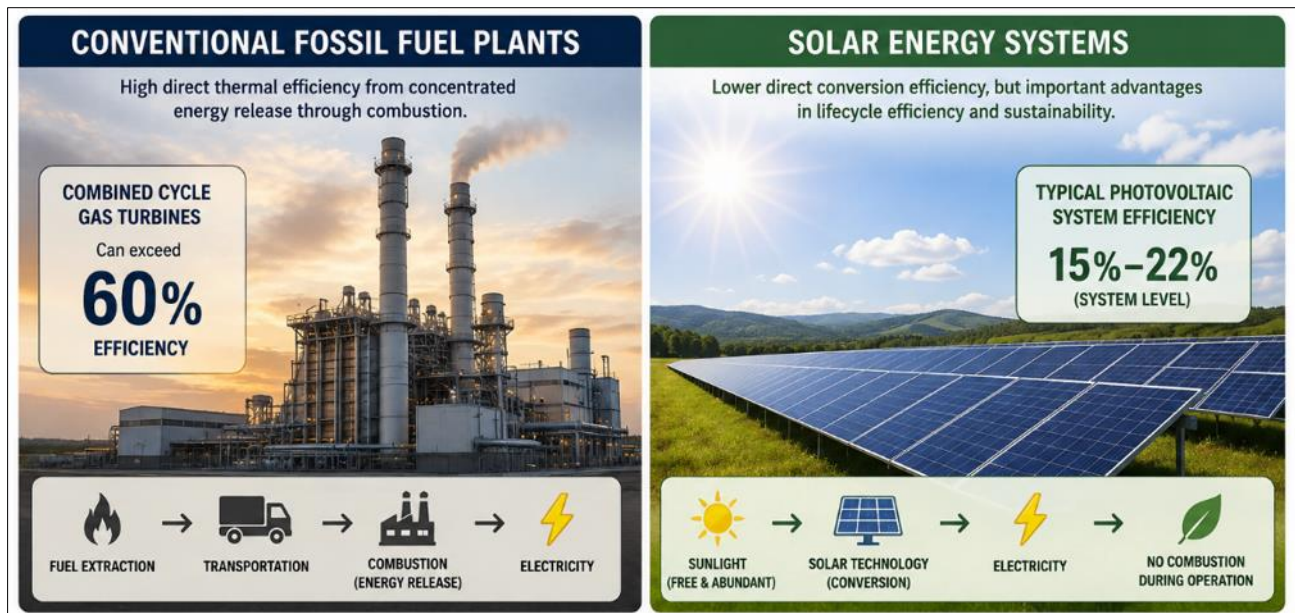


Figure 1 Thermal efficiency & lifecycle efficiency comparison

4.12 Capacity Factor Comparison

The capacity factor represents the ratio between actual electricity generation and maximum possible generation. Typical capacity factors include: Solar PV: 15%–30%, CSP with storage: 30%–45%, Coal plants: 50%–80%, Natural gas plants: 40%–70%.

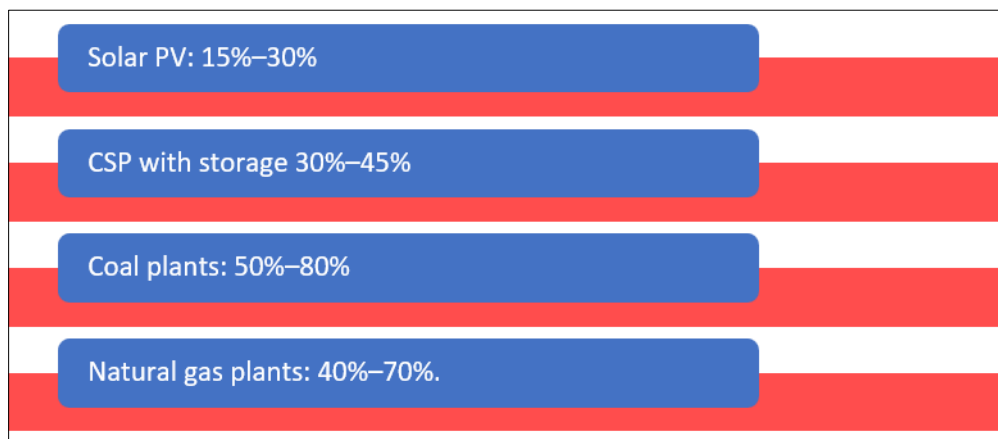


Figure 2 Capacity factor between actual electricity generation and maximum generation

The lower capacity factor of solar systems is primarily due to intermittency and dependence on daylight availability.

4.13 Energy Payback Period

The energy payback period measures the time required for an energy system to generate the amount of energy consumed during manufacturing and installation (Nassar et al., 2021). Modern photovoltaic systems typically achieve energy payback periods between 1 and 4 years, depending on technology type and geographic location. Since solar systems often operate for 25–30 years, they generate substantially more energy than they consume over their lifetime. Conventional power plants require continuous fuel inputs throughout their operational lifespan, resulting in ongoing energy consumption and emissions.

4.14 Reliability and Grid Stability

Conventional power plants provide dispatchable electricity generation and contribute to grid stability through controllable output. Solar energy systems are inherently variable because electricity generation depends on solar irradiance. Energy storage systems such as lithium-ion batteries, pumped hydro storage, and thermal energy storage are increasingly used to address solar intermittency challenges.

4.15 Comparative Cost Analysis

Cost remains one of the most critical factors influencing energy policy and investment decisions because it directly affects electricity affordability, infrastructure development, and economic sustainability. Governments and industries prioritize energy technologies that provide reliable power generation with lower long-term operational and maintenance expenses.

4.16 Capital Costs

Solar energy systems generally require higher upfront capital investment compared to conventional fossil fuel plants. Costs include: Solar panels or mirrors, Inverters and electrical equipment, Mounting structures, Grid interconnection infrastructure, Battery storage systems. However, solar technology costs have declined dramatically over the past decade due to mass production, technological innovation, and global competition. Conventional plants may require lower initial costs in some cases, but they involve substantial fuel infrastructure and transportation systems.

4.17 Fuel Costs

A major advantage of solar energy is the absence of fuel costs during operation. Sunlight is freely available and does not require extraction, transportation, or refining. Conventional power plants depend heavily on fossil fuel supplies, making them vulnerable to fuel price fluctuations and geopolitical instability.

4.18 Operation and Maintenance Costs

Solar energy systems generally have lower operation and maintenance costs because they contain fewer moving parts and require less routine servicing. Conventional thermal plants involve: Fuel handling systems, Boiler maintenance, Turbine servicing, Emission control systems, Cooling infrastructure. These components increase maintenance complexity and operational expenditures.

4.19 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity provides a comprehensive measure of electricity generation cost over the lifetime of a power system. Recent market trends indicate that utility-scale solar PV has become one of the most cost-competitive electricity generation technologies in many regions (Maradin, 2021). Declining solar module prices and improved manufacturing efficiency have significantly reduced LCOE values. In contrast, conventional energy systems face increasing costs associated with fuel procurement, carbon pricing, environmental compliance, and aging infrastructure.

4.20 External Costs

Conventional energy systems impose significant external costs on society that extend beyond direct electricity generation expenses. Fossil fuel combustion contributes to severe air pollution, leading to increased healthcare costs associated with respiratory and cardiovascular diseases. In addition, greenhouse gas emissions from conventional power plants accelerate climate change, causing long-term environmental and economic impacts. These systems also require costly environmental remediation efforts to address damage from mining, drilling, and industrial waste disposal. Furthermore, fossil fuel extraction and combustion contribute to ecosystem degradation by destroying natural habitats and reducing biodiversity. Water contamination from oil spills, coal ash disposal, and industrial wastewater further threatens public health and environmental sustainability. Solar energy systems produce substantially lower external costs because of minimal operational emissions.

4.21 Environmental Impact Analysis

Environmental sustainability has become a major consideration in global energy planning due to increasing concerns about climate change, resource depletion, and environmental degradation. Governments and energy organizations worldwide are focusing on cleaner and more sustainable energy solutions to reduce greenhouse gas emissions and minimize ecological damage. As a result, renewable energy technologies such as solar and wind power are gaining significant importance in achieving long-term environmental protection, energy security, and sustainable economic development.

4.22 Greenhouse Gas Emissions

Coal-fired power plants are among the largest contributors to global carbon dioxide emissions (M.Saleh & I.Hassan, 2024). Natural gas produces fewer emissions than coal but still contributes significantly to climate change. Solar energy systems generate very low operational greenhouse gas emissions. Lifecycle emissions are primarily associated with manufacturing, transportation, and installation processes.

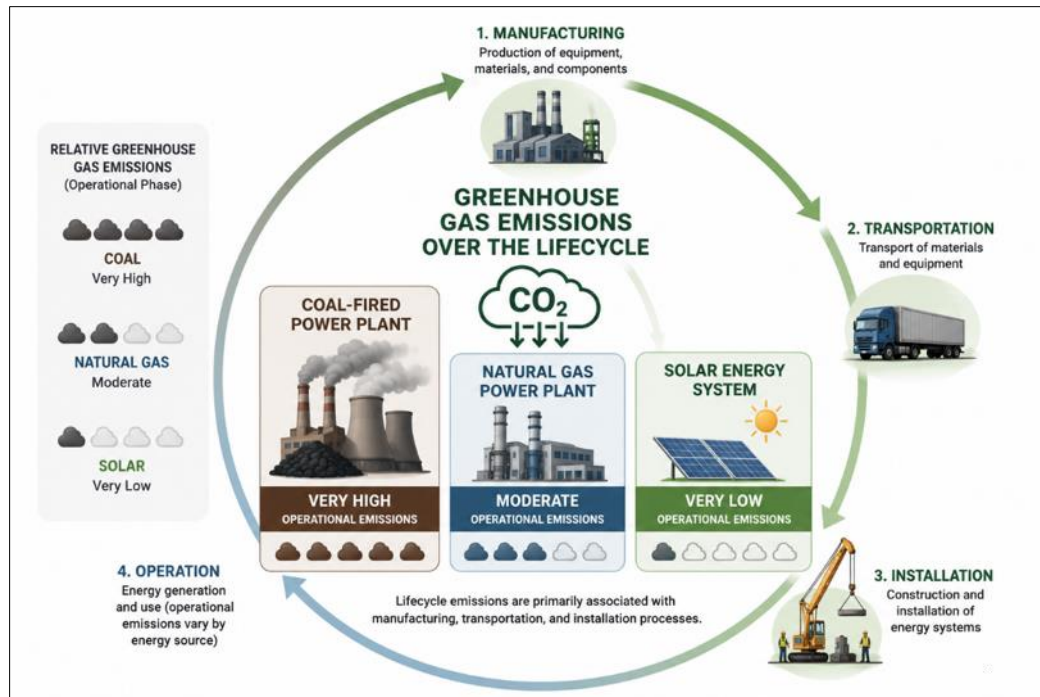


Figure 3 Greenhouse gas emissions cycle

4.23 Air Pollution

Fossil fuel combustion releases pollutants such as: Sulfur dioxide (SO₂), Nitrogen oxides (NO_x), Particulate matter, Mercury and heavy metals. These pollutants contribute to respiratory diseases, cardiovascular problems, and environmental degradation. Solar energy systems produce negligible air pollution during operation.

4.24 Water Consumption

Conventional thermal plants require large quantities of water for cooling purposes. Water scarcity concerns are becoming increasingly important in many regions. Photovoltaic systems require minimal water during operation, making them suitable for arid environments.

4.25 Land Use Considerations

Utility-scale solar farms require significant land area. However, solar installations can also be integrated into rooftops, parking structures, and urban infrastructure. Mining activities associated with fossil fuels often lead to severe land degradation and habitat destruction.

4.26 Economic and Social Implications

The transition from conventional energy systems to solar energy has important economic and social consequences.

4.27 Employment Opportunities

The renewable energy sector has become a major source of employment worldwide (Lu et al., 2021). Solar energy development creates jobs in Manufacturing, Installation, Maintenance, Research and development, Grid integration.

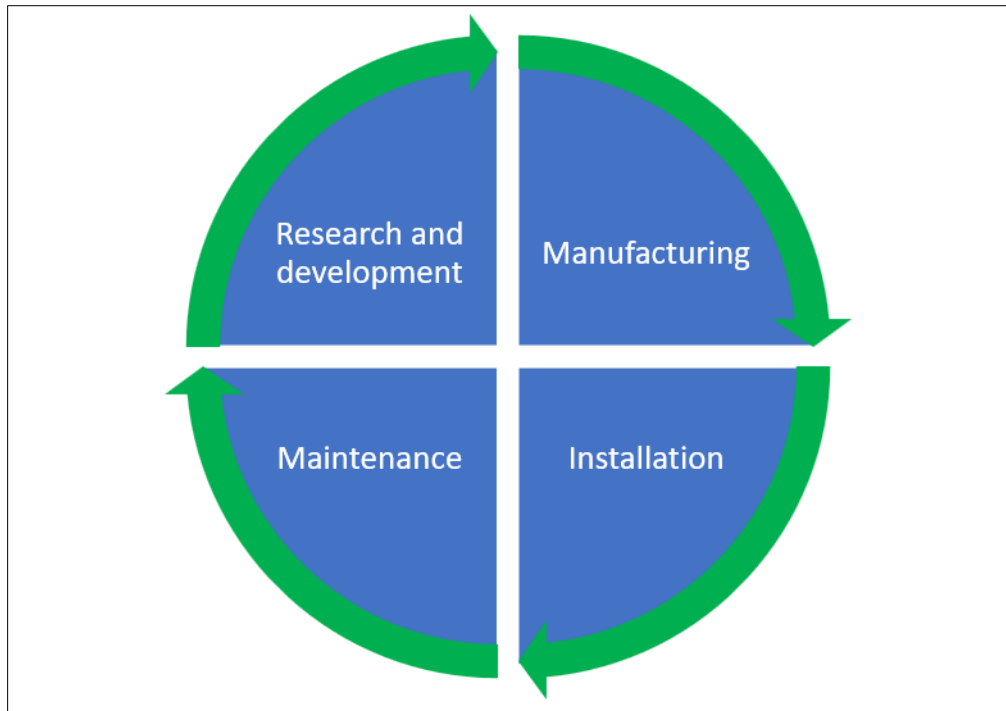


Figure 4 Employment opportunity in renewable energy sector

Conventional energy industries also provide employment but are increasingly subject to automation and environmental regulations.

4.28 Energy Security

Countries that rely heavily on imported fossil fuels face significant energy security risks due to geopolitical tensions and fluctuations in global fuel prices. In contrast, solar energy enhances energy independence because sunlight is locally available in most regions. Solar technologies are also highly effective for rural and remote electrification, as decentralized solar systems can supply electricity to communities without access to centralized power grids. Furthermore, because solar energy systems require no fuel and have relatively low operating costs, they provide greater long-term economic and price stability compared to fossil fuel-based power generation.

4.29 Challenges Facing Solar Energy

Despite its many advantages, solar energy still faces several significant challenges that limit its widespread adoption and efficiency. One of the major issues is intermittency, as solar electricity generation depends heavily on sunlight availability and weather conditions. Factors such as cloud cover, nighttime periods, and seasonal changes can significantly reduce power output. Another challenge is energy storage, since large-scale battery storage systems are still relatively expensive, although their costs are gradually decreasing with technological advancements. In addition, integrating large amounts of solar power into existing electricity networks requires substantial grid modernization, including the development of smart grid technologies and flexible demand management systems. Solar panel manufacturing also raises material supply chain concerns because it relies on resources such as silicon, silver, lithium, and rare earth elements, making sustainable sourcing and recycling strategies essential for long-term resource security. Furthermore, as solar installations continue to expand globally, recycling and proper end-of-life waste management of photovoltaic modules are becoming increasingly important to minimize environmental impacts and support sustainable energy development.

4.30 Future Prospects of Solar Energy

The future of solar energy appears highly promising due to continuous technological innovation and global policy support (Kiasari et al., 2024).

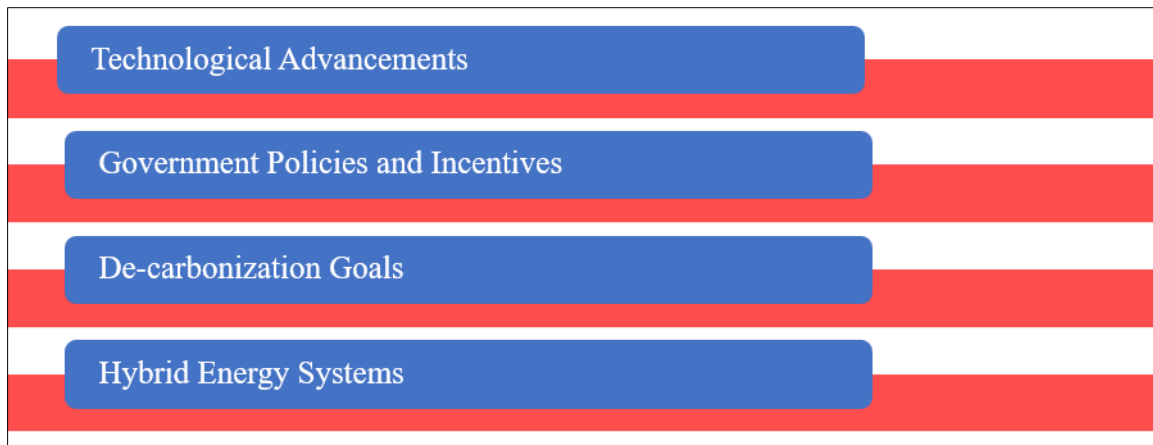


Figure 5 Future prospect benefits of solar energy

Future developments in solar energy are being driven by rapid technological advancements, supportive government policies, and global de-carbonization goals. Innovations such as high-efficiency solar cells, advanced battery storage, smart grids, perovskite technology, floating solar farms, and building-integrated photovoltaics are expected to improve performance while lowering costs. At the same time, government incentives and international climate commitments are accelerating renewable energy adoption. Future energy systems are also expected to integrate solar power with wind energy, hydrogen production, battery storage, and smart energy management technologies to create more reliable and sustainable power networks.

5. Conclusion

This paper has presented a comprehensive comparative analysis of solar energy and conventional energy sources in terms of efficiency and cost. Conventional fossil-fuel-based energy systems continue to provide reliable and dispatchable electricity generation with relatively high thermal efficiencies. Coal, natural gas, and oil have historically supported industrial development and global economic growth through established infrastructure and mature technologies. However, the environmental and economic limitations of conventional energy systems are becoming increasingly apparent. Fossil fuel combustion contributes significantly to greenhouse gas emissions, air pollution, climate change, and public health problems. In addition, dependence on finite fuel resources exposes economies to supply disruptions and price volatility. Solar energy technologies, particularly photovoltaic and concentrated solar power systems, offer substantial long-term advantages in sustainability, environmental protection, and energy security. Although solar systems often require higher initial capital investment and face intermittency challenges, declining technology costs and improvements in energy storage are rapidly enhancing their competitiveness. The analysis demonstrates that solar energy systems generally exhibit lower operational and maintenance costs due to the absence of fuel requirements. Lifecycle assessments further reveal that solar technologies produce significantly lower greenhouse gas emissions compared to conventional fossil fuel systems. While conventional energy sources currently maintain advantages in dispatchability and capacity utilization, continued technological advancements are narrowing the performance gap. Modern solar systems are becoming increasingly efficient, affordable, and scalable. The future global energy landscape will likely involve a gradual transition toward cleaner and more sustainable energy systems in which solar power plays a central role. Successful integration of solar energy will require investments in grid modernization, energy storage technologies, policy support, and international cooperation. Ultimately, the comparative evaluation indicates that solar energy represents one of the most promising solutions for achieving sustainable economic development, reducing environmental impacts, and ensuring long-term energy security.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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