

The role of innovation technology in developing solar energy technologies: challenges and future trends towards sustainable development (literature review)

College of Engineering Technology-Janzour, Faculty of Engineering – Alkhums- Elmergib
University- Technical College of civil Aviation & Meteorology – SBEAA, Technical College of civil
aviation & Meteorology_ SBAA General Department

Department of Mechanical and Industrial Engineering, Engineering, General Department
Hatem Mostafa Elwalwa, Fatema Husin Abdusalam Zarig, Murad Khaleel Husayn Murad,
Abdul Nasser Eyad Nashnush

hatemtomy1998@gmail.com, fhzarig@elmergib.edu.ly, muradmkm1@gmail.com,
nashnshnaser@gmail.com

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Abstract

This study aims to review and analyze the scientific literature related to solar energy and innovation technology, by focusing on recent developments in solar energy technologies and the role of technological innovation in improving the efficiency of solar systems and enhancing their contribution to achieving sustainable development. The study employed a literature review methodology, compiling scientific studies from reliable databases and academic sources, including Google Scholar, Research Gate, Scribd, and local journals such as Shrouss Journal and the University of Sirte Journal of Humanities, in addition to specialized scientific articles and reports relevant to the research topic. The studies were analyzed and compared according to technical criteria.

The review results showed that technological advancements in photovoltaic cells, concentrated solar power, storage systems, hybrid systems, and artificial intelligence technologies have significantly contributed to increasing the efficiency and reliability of solar energy production and reducing its costs. The studies also demonstrated that solar energy represents one of the most important sustainable alternatives to traditional energy sources, given its environmental and economic advantages, such as reducing carbon emissions and decreasing reliance on fossil fuels. Conversely, the review revealed the persistence of several challenges that limit the expansion of solar energy use. These include high initial investment costs, weak legislative and regulatory frameworks, limited supporting infrastructure, and the need to raise public awareness and enhance investment in research and development. The study emphasizes that achieving Maximizing the benefits of solar energy requires an integration of technological innovation, supportive policies, and a suitable investment environment, contributing to enhanced energy security and the achievement of sustainable development goals in the future.

Keywords: Solar energy, innovative technology, renewable energy, sustainable development, artificial intelligence, photovoltaic cells.

ملخص

تهدف هذه الدراسة إلى مراجعة وتحليل الأدبيات العلمية المتعلقة بالطاقة الشمسية وتقنيات الابتكار، مع التركيز على التطورات الحديثة في تقنيات الطاقة الشمسية ودور الابتكار التكنولوجي في تحسين كفاءة الأنظمة الشمسية وتعزيز مساهمتها في تحقيق التنمية المستدامة. استخدمت الدراسة منهجية مراجعة الأدبيات، حيث جُمعت الدراسات العلمية من قواعد بيانات ومصادر أكاديمية موثوقة، بما في ذلك Google Scholar و ResearchGate و Scribd، بالإضافة إلى المجلات المحلية مثل مجلة شروس ومجلة جامعة سرت للعلوم الإنسانية، فضلاً عن المقالات والتقارير العلمية المتخصصة ذات الصلة بموضوع البحث. وتم تحليل الدراسات ومقارنتها وفقاً لمعايير فنية. أظهرت نتائج

المراجعة أن التطورات التكنولوجية في الخلايا الكهروضوئية، والطاقة الشمسية المركزة، وأنظمة التخزين، والأنظمة الهجينة، وتقنيات الذكاء الاصطناعي، قد ساهمت بشكل كبير في زيادة كفاءة وموثوقية إنتاج الطاقة الشمسية وخفض تكاليفها. كما أوضحت الدراسات أن الطاقة الشمسية تُعد من أهم البدائل المستدامة لمصادر الطاقة التقليدية، نظرًا لمزاياها البيئية والاقتصادية، مثل خفض انبعاثات الكربون وتقليل الاعتماد على الوقود الأحفوري. في المقابل، كشفت المراجعة عن استمرار العديد من التحديات التي تحد من توسع استخدام الطاقة الشمسية. وتشمل هذه التحديات ارتفاع تكاليف الاستثمار الأولي، وضعف الأطر التشريعية والتنظيمية، ومحدودية البنية التحتية الداعمة، والحاجة إلى رفع مستوى الوعي العام وتعزيز الاستثمار في البحث والتطوير. وتؤكد الدراسة أن تحقيق أقصى استفادة من الطاقة الشمسية يتطلب تكامل الابتكار التكنولوجي، والسياسات الداعمة، وبيئة استثمارية ملائمة، بما يساهم في تعزيز أمن الطاقة وتحقيق أهداف التنمية المستدامة في المستقبل.

الكلمات المفتاحية: الطاقة الشمسية، التكنولوجيا المبتكرة، الطاقة المتجددة، التنمية المستدامة، الذكاء الاصطناعي، الخلايا الكهروضوئية.

1. Introduction

Renewable energy, particularly solar energy, is a key strategic pillar in the global transition towards more sustainable and efficient energy systems. This shift is driven by the ever-increasing demand for energy and the escalating environmental challenges associated with fossil fuel use, such as carbon emissions and climate change [4, 6]. Rapid technological advancements have significantly enhanced the performance of renewable energy systems by improving the efficiency of production, storage, and consumption, thereby increasing their competitiveness in the global energy mix [1].

In this context, solar energy has emerged as one of the most prominent and widespread renewable energy sources. This is supported by rapid technological advancements in photovoltaic cells, prediction algorithms, storage systems, and artificial intelligence, which have contributed to improved production forecasting accuracy, enhanced smart grid efficiency, and reduced energy volatility [2, 5]. Studies have also shown that integrating modern technologies with hybrid systems contributes to increased operational efficiency, lower costs, and enhanced grid stability, making solar energy a strategic option for securing the future of energy [5]. Despite these developments, technical, economic, and institutional challenges still hinder the widespread adoption of solar energy. These include high initial costs, weak infrastructure, a lack of legislative frameworks and investment support, and limited practical applications in some advanced sectors [7]. Furthermore, some studies indicate that the success of the transition to solar energy depends not only on technological advancements but also on public awareness, supportive government policies, and an improved investment climate [8].

Therefore, this study aims to shed light on the current state and evolution of solar energy technologies and their role in supporting sustainable development. It does so by analyzing previous literature that addresses the technical, economic, social, and political aspects, with the goal of highlighting research gaps and identifying future trends in this vital field.

2. Research Problem

Despite the rapid development of solar energy technologies and their increasing role in supporting the transition to sustainable energy systems, a clear gap exists between this technological advancement and the actual level of application of these technologies, especially in developing environments such as Libya [5, 7]. The adoption of solar energy continues to face a range of interconnected challenges, including technical challenges related to system efficiency, storage, and production forecasting; economic challenges linked to high initial costs and limited financing; and institutional challenges related to weak legislation and inadequate supporting infrastructure [5, 7]. Furthermore, the successful deployment of solar energy does

not depend solely on the technical aspect; it requires the integration of technological innovation, supportive policies, and community awareness [1, 8], which remains insufficiently integrated in many local contexts.

Therefore, the research problem lies in the lack of integration between the technical, economic, social, and institutional dimensions of solar energy technologies. This deficiency limits a comprehensive understanding of the current situation and affects the identification of actual challenges and future development prospects [1, 5, 7, 8].

3. Research Objectives

1. To analyze and evaluate current trends in solar energy research and technologies within the framework of the field's development.
2. To identify the most significant technical, economic, institutional, and social challenges facing the application of solar energy.
3. To highlight research gaps and propose future directions for developing the use of solar energy and enhancing its role in achieving sustainable development.

4. Research Significance

The significance of this study stems from the growing importance of solar energy as a leading renewable energy source capable of contributing to energy security and sustainable development, especially in light of the environmental and economic challenges resulting from excessive reliance on fossil fuels. The study is also significant in highlighting the role of innovative technologies in developing solar energy technologies, improving their efficiency, reducing their costs, and enhancing their reliability. Furthermore, this study provides a comprehensive overview of recent developments and research trends in the field of solar energy, while also highlighting the technical, economic, and institutional challenges facing its implementation. The study also serves as a scientific reference, compiling and analyzing the findings of previous studies in an integrated manner. This will help researchers and decision-makers understand the current state of solar energy and identify ways to promote its use, thereby supporting the achievement of sustainable development goals and to promote the transition to more efficient and sustainable energy systems.

5. Research Methodology

This study relied on studies published between 2020 and 2025, collected from academic databases such as Google Scholar, ResearchGate, and others, to ensure the accuracy and direct relevance of the information to the research topic.

This study employs a literature review methodology, analyzing and comparing a selection of previous scientific studies related to renewable energy technologies and solar power.

The methodology includes the following steps:

- Collecting peer-reviewed studies and research related to solar and renewable energy.
- Analyzing the scientific content of each study in terms of its objectives, methodology, results, and recommendations.
- Comparing the studies to identify similarities, differences, and research gaps.
- Drawing general conclusions that reflect the current state, challenges, and prospects of solar energy.

5. Theoretical Background

This can be divided into subheadings such as:

5.1 The Concept of Renewable Energy

Renewable energy is defined as energy derived from natural sources that are continuously replenished and do not become depleted with use at normal consumption rates, making it a sustainable alternative to traditional energy sources based on fossil fuels.

Several international organizations have provided definitions of renewable energy, most notably:

- The International Energy Agency (IEA): defines renewable energy as energy derived from continuously replenishing natural processes, such as sunlight and wind, which are replenished at a rate that exceeds or equals the rate at which they are consumed.
- The Intergovernmental Panel on Climate Change (IPCC): indicates that renewable energy is energy derived from renewable natural sources, whether solar, geophysical, or biological, and includes solar, wind, hydroelectric, biomass, geothermal, tidal, and wave energy. These sources can be converted into electrical or thermal energy using various technologies.
- The United Nations Environment Programme (UNEP) defines renewable energy as energy derived from natural resources that are replenished periodically at a rate faster than their consumption, and which does not depend on a limited or depletable supply. Its main sources include solar energy, wind energy, hydroelectric power, biomass energy, and geothermal energy [9].

5.2 The Concept of Solar Energy

Solar energy is one of the most important and abundant renewable energy sources in the world, as it relies on radiation from the sun that continuously reaches the Earth's surface. This energy can be utilized in many beneficial applications, such as producing thermal energy, instigating certain chemical reactions, and generating electricity, which is one of its most prominent uses today.

Solar energy is characterized by being a clean and environmentally friendly source, as its use does not produce polluting emissions or harmful environmental impacts like those resulting from traditional energy sources based on fossil fuels. Furthermore, its continuous availability and wide geographical distribution make it a strategic option for meeting the growing demand for energy. Therefore, expanding the use of solar energy and developing its technologies can significantly contribute to meeting the world's energy needs, reducing reliance on polluting traditional sources, and supporting sustainable development and environmental protection efforts [10].

5.3 Solar Energy Technologies (PV/CSP/Hybrid Systems)

There are numerous technologies for harnessing solar energy to convert solar radiation into usable energy. These are primarily classified into photovoltaic (PV) systems, concentrated solar power (CSP), and hybrid solar systems. These technologies are considered cornerstones of the renewable energy sector due to their role in increasing electricity production and reducing dependence on traditional energy sources.

Photovoltaic (PV) systems are the most widespread solar energy technology. They rely on solar cells made of semiconductor materials, such as silicon, to directly convert sunlight into electrical energy through the photovoltaic effect. These systems are characterized by their ease of installation and low operating and maintenance costs, making them suitable for residential, commercial, and industrial applications alike. [11]

Concentrated solar power (CSP) technology uses mirrors or lenses to focus sunlight and produce high temperatures. These temperatures are then used to heat special fluids, which in turn generate steam to power turbines and produce electricity. A key advantage of this technology is the ability to store thermal energy using molten salts. This allows for continuous electricity production even during periods of low solar radiation, thus enhancing the reliability of the electrical system [12].

In recent years, hybrid solar systems have emerged as a promising solution for improving the efficiency and stability of power generation. These systems combine multiple technologies or energy sources, such as photovoltaic and concentrated solar power systems, solar and wind power, or energy storage systems. This integration helps reduce production fluctuations and improve the continuity of electricity supply, making these systems a suitable option for supporting modern electrical grids and maximizing the utilization of renewable energy sources [13].

5.4 Challenges Facing Solar Energy Use

Despite the environmental and economic advantages that make solar energy one of the most important and widespread renewable energy sources, several challenges limit its complete adoption. Among the most prominent of these challenges is the intermittent nature of solar radiation. Energy production is affected by the absence of sunlight during nighttime hours or by reduced radiation intensity on cloudy and rainy days. Energy storage also represents a major technical challenge, necessitating the development of more efficient and secure storage technologies to ensure a continuous energy supply and promote reliance on solar systems in the future [7].

5.5 Technological Innovation in Solar Energy

Solar energy technologies have witnessed rapid advancements in recent years, contributing to increased efficiency and improved performance of solar systems, as well as reduced energy production costs. Key developments include improved solar cell efficiency and the emergence of new panel types, such as flexible and transparent panels, which have expanded the application of solar energy in smart buildings, transportation, and various electronic devices [14].

Concentrated solar power (CSP) technology has also witnessed significant advancements through improvements in solar radiation concentration systems and increased efficiency in converting thermal energy into electricity. Furthermore, the development of thermal storage technologies allows for continuous electricity production even after sunset, enhancing the reliability of these systems [15].

In the field of energy storage, modern technologies based on advanced batteries, such as lithium-ion and solid-state batteries, as well as thermal and hydrogen storage technologies, have emerged. These contribute to addressing the problem of fluctuations and inconsistencies in solar energy production, providing a more stable electricity supply [18].

Another important innovation is solar tracking systems, which automatically orient solar panels towards the sun during daylight hours. This increases the amount of radiation received and improves electricity production efficiency compared to traditional fixed systems [15].

Artificial intelligence and data analytics have also become essential tools in the development of solar energy systems. They are used for predicting energy production, managing electrical loads, early fault detection, and predictive maintenance, leading to improved operational performance and reduced maintenance costs [16]. Another promising modern trend is floating solar energy, which relies on installing solar panels on bodies of water such as lakes and dams. This reduces land consumption and improves panel efficiency due to lower ambient temperatures, in addition to contributing to reduced water evaporation rates [17].

These innovations confirm that technological development is a key factor in enhancing the efficiency and reliability of solar energy systems, thus supporting their expansion and strengthening their role in achieving sustainable development and future energy security.

5.6 The Role of Artificial Intelligence in Energy Technology Development

Artificial intelligence has become one of the most important modern tools contributing to accelerating innovation within the energy sector. Its ability to analyze massive amounts of complex data and discover new solutions and materials that may be difficult to access through traditional methods raises questions about the extent to which artificial intelligence can accelerate technological progress at rates exceeding previous expectations. While technological development has historically relied on predictable growth patterns, such as decreasing technology costs as its use and deployment increase, artificial intelligence is now opening new horizons for accelerating research and development processes. Its role is no longer limited to improving operational efficiency; it has expanded to support the discovery of new materials and technologies in the fields of renewable energy and energy storage. In the battery sector, AI applications have proven their ability to reduce the time and effort required to discover new,

high-performance materials. AI algorithms have been used to analyze millions of potential battery chemical compositions, contributing to the identification of promising materials that can improve the efficiency and performance of solid-state batteries. These technologies have also helped in discovering new electrode materials with properties suitable for developing future energy storage systems. [19] The impact of AI is not limited to battery technologies; it extends to other areas such as the development of biofuels and the improvement of green hydrogen production processes by helping to discover more efficient catalysts and materials than those currently used. AI also contributes to improving operations and maintenance processes by predicting failures and continuously analyzing system performance, leading to increased operational efficiency and reduced costs. Furthermore, the integration of AI with automation and robotics technologies has helped boost productivity and accelerate research and development within companies operating in the energy sector. This has been reflected in increased innovative activity, as studies have shown higher patent registration rates in companies that rely on artificial intelligence tools compared to others [19].

6. Review of Previous Studies

S. Manea's Study: This study examined the role of innovative technologies in developing the renewable energy sector in light of the global expansion in energy demand [1]. It focused on the contribution of modern technologies to improving the efficiency of renewable energy production, storage, and consumption. The study also demonstrated that adopting technological innovation has enabled renewable energy to increase its competitiveness and expand its share in the global energy market, in addition to improving the quality of energy supplied and providing technological solutions that facilitate production, storage, and consumption processes.

Y. F. Nassar et al.'s Study: This study aimed to evaluate the most suitable concentrated solar power (CSP) technologies for electricity generation in Libya, supporting the plan to increase the contribution of renewable energy to 30% by 2030 [2]. It compared five CSP technologies in 22 Libyan cities, using the cost of electricity production (LCOE) as a key indicator. The results showed that parabolic trough solar mirror technology was the most economically viable and least expensive among the technologies studied. The study also confirmed that using these technologies contributes to reducing carbon dioxide emissions and enhancing the sustainability of the energy sector in Libya.

The study by G. Anbalagan, P. Abirami, S. Balakrishnan, and B. Rajeswari: addressed the importance of solar energy as a leading renewable energy source in confronting the global energy crisis and the environmental problems associated with fossil fuel use, such as pollution, climate change, and greenhouse gas emissions [3]. It focused on reviewing the capabilities, advantages, and limitations of solar energy technologies, highlighting their role in supporting clean and sustainable electricity generation. The study also indicated that solar energy is among the most efficient and environmentally friendly renewable energy sources and that it holds promising future prospects in meeting the growing demand for energy and achieving sustainable development.

The study by E. Adepoju and A. Lawal: aimed to address the challenges of solar power outages and grid instability, which affect the reliability and expansion of renewable energy integration [4]. It focused on evaluating recent developments in photovoltaic systems, concentrated solar power, energy storage technologies, and intelligent grid control systems. The results showed that using smart inverters, artificial intelligence algorithms, and hybrid systems contributes to improving system efficiency and reducing energy production fluctuations. AI-powered solar energy prediction models achieved an accuracy of up to 95%, while hybrid systems increased operational efficiency by up to 25%. The study concluded that integrating modern technologies with supportive policies is crucial for promoting reliance on renewable energy and achieving more sustainable and resilient energy systems.

A study by M. Khaleel, A. Alsharif, I. I. Alzayani, and K. Imbay: addressed the importance of renewable energy in supporting economic, social, and environmental development, and its role in mitigating environmental problems resulting from reliance on traditional energy sources [5]. It also reviewed the most prominent recent developments and innovations in renewable energy technologies, emphasizing that expanding their use is a fundamental step towards achieving sustainable development. The study concluded that investing in and developing renewable energy technologies contributes to building a more sustainable and efficient energy future globally.

A study by A. A. H. Al-Rabib: The study examined the impact of developing solar energy technologies on achieving sustainable development, explaining that expanding the use of these technologies has contributed to reducing production costs and increasing the economic viability of solar energy [6]. It also emphasized that the future of solar energy depends on continuous technological development and policies that support innovation and reduce thermal emissions. The study indicated that achieving optimal utilization of solar energy requires a suitable legislative and investment environment, especially in Libya, where security and political instability and weak supportive policies and legislation are among the most prominent challenges hindering investment in and development of the renewable energy sector.

B. A. Aldeeb, M. Q. Bahmi, and W. A. Aldeeb's study: This study aimed to identify citizens' opinions on the future of solar energy in Libya, the level of awareness of its benefits, and the challenges of adopting it [7]. It relied on an electronic survey that included a sample of citizens in the western region during 2024. The results showed a lack of awareness of the existence of clear government plans for expanding solar energy, while most participants expressed their willingness to use it in their homes if appropriate incentives and support were provided. The study concluded that Libya has great potential to benefit from solar energy, but achieving this requires supportive policies, infrastructure development, increased community awareness, and encouraging investment in this sector.

7. Analysis and Discussion

Based on the literature review methodology, previous studies can be summarized, highlighting similarities and differences, as follows:

All studies agree that solar energy represents one of the most important strategic solutions for addressing the global energy crisis and reducing dependence on fossil fuels, with a pivotal role in achieving environmental sustainability and reducing greenhouse gas emissions. Most studies also concur that technological development, particularly in the areas of artificial intelligence, storage systems, and photovoltaic cells, is the key factor in improving the efficiency of solar energy production and enhancing its economic competitiveness.

In terms of comparison, some studies focused on the purely technical aspects, such as improving solar energy production forecasting using artificial intelligence and increasing the efficiency of smart grids. Other studies focused on evaluating and analyzing concentrated solar power technologies from an economic and environmental perspective to select the most suitable approach for implementation, especially in the Libyan context. Still other studies addressed the social and political dimensions, demonstrating that the successful implementation of solar energy depends not only on technology but also on public awareness, government policy support, the availability of infrastructure, and institutional stability. Some studies have shown that the solar energy sector faces common challenges, including high initial costs, low efficiency in some systems, a lack of legislative frameworks and investment support, and limited widespread practical application. Conversely, other studies have focused on the future opportunities offered by solar energy, such as gradual cost reductions, increased accuracy in production forecasting, and improved performance of hybrid systems.

8. Results

1. Studies have shown significant technological advancements in solar energy systems, particularly in improving efficiency and photovoltaic cell technologies. However, this progress is not matched by widespread adoption.
2. The results indicate a clear gap between technological advancements in solar energy and the level of practical application, especially in developing countries, due to several economic and institutional obstacles.
3. Studies have confirmed that economic challenges, primarily high initial costs and weak financing and support mechanisms, are among the most significant obstacles to expanding the use of solar energy.
4. The results show that institutional and legislative factors, such as weak supportive policies and the absence of clear regulatory frameworks, significantly impact the adoption and sustainability of solar energy projects.
5. Studies have indicated that the success of the transition to solar energy requires integration between the technical, economic and social aspects, as relying on the technical aspect alone does not achieve the required sustainability.

9. Recommendations and Future Vision:

First: Recommendations

1. Promote investment in modern solar energy technologies, especially those related to increasing cell efficiency and storage systems, with the aim of increasing production efficiency and reducing losses.
2. Work to reduce the initial costs of solar energy systems by providing financial incentives, government support, or partnerships with the private sector.
3. Develop legislative and regulatory frameworks to ensure a supportive and transparent environment for investment in solar energy projects.
4. Improving the electrical infrastructure to be more capable of absorbing and integrating renewable energy sources into the national grid.
5. Increase community awareness programs on the importance of solar energy and its role in achieving environmental and economic sustainability.
6. Encourage scientific research and applied studies that focus on local solutions that are appropriate to the climatic and economic conditions of each region.
7. Enhance the integration of technical, economic, and social aspects when planning solar energy projects to ensure their sustainability and long-term success.

Second: Future Vision

The future vision aims to enhance the role of solar energy as a primary and sustainable energy source by expanding its use and gradually integrating it into national electricity grids. This requires a shift from piecemeal solutions to comprehensive strategies based on technological innovation, institutional support, economic incentives, and enhanced public awareness. As smart energy storage and management technologies continue to advance, solar energy is expected to become a more efficient and reliable option, contributing to energy security and supporting long-term sustainable development goals.

10. Conclusion

This study concluded that solar energy has become a cornerstone of the transition to more efficient and sustainable energy systems, thanks to rapid technological advancements that have improved the performance and efficiency of solar systems and reduced their operating costs. The literature has shown that recent innovations in photovoltaics, concentrated solar power, storage systems, and artificial intelligence have significantly enhanced the reliability and competitiveness of solar energy within the global energy mix.

The study also highlighted that the challenges facing the solar energy sector are not limited to technical aspects but extend to economic, institutional, and social dimensions, necessitating

a comprehensive and integrated approach to address these challenges. In the Libyan context, the country's vast natural solar energy potential presents a genuine opportunity to achieve energy security and support sustainable development. However, realizing this potential requires developing supportive legislation and policies, improving infrastructure, encouraging investment, and raising public awareness.

Therefore, the future of solar energy hinges on countries' ability to effectively utilize technological innovation, provide a suitable regulatory and investment environment, and promote scientific research and continuous development. Continued advancements in solar energy technologies, energy storage technologies, and artificial intelligence are expected to contribute to increased reliance on solar energy in the coming years, making it one of the most important solutions for achieving sustainable development and ensuring energy security at both the local and global levels.

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