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Review Article

Clean energy supply chain and carbon reduction solutions: The effects of renewable energy technologies on carbon neutrality

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ABSTRACT

This study examines the role of the clean energy supply chain in carbon reduction and the contribution of renewable energy technologies in achieving carbon neutrality goals. The potential of renewable energy sources such as solar, wind and biomass to reduce fossil fuel dependency and their advantages for environmental sustainability were evaluated. The findings show that solar energy is the most effective energy source with near-zero carbon emissions, wind energy stands out with its low cost advantage, and biomass energy has significant potential despite its limited environmental impacts.

In order to effectively manage the energy transition processes, it is necessary to develop renewable energy infrastructures, implement national and international policies and incentive mechanisms, invest in technological innovations and raise awareness in the society. Adopting a strategic approach, taking into account local energy resources and conditions, plays a key role in achieving carbon neutrality goals.

In conclusion, renewable energy technologies offer innovative solutions that support both environmental and economic sustainability. In this context, the transformation of energy systems and the dissemination of clean energy sources have a strategic importance in combating climate change and reducing global carbon emissions.

Keywords: Biomass energy; Carbon neutrality; Energy transition; Renewable energy sources; Sustainable energy systems

1. Introduction

The global energy sector is undergoing a profound transformation process within the framework of combating climate change. The intensive use of fossil fuels has accelerated global warming by increasing carbon dioxide (CO_2) emissions in the atmosphere. This has made the development and application of renewable energy sources a strategic necessity [1,18]. Renewable energy sources such as solar, wind, biomass, and hydropower not only provide environmental sustainability with low carbon emissions, but also support economic and social development goals [9,12].

Some studies in the literature in terms of Renewable Energy, Environmental and Economic Dimensions, Renewable energy systems offer significant potential to reduce the environmental impacts of energy production and accelerate energy transition processes. [13] stated that solar energy plays a critical role in the global energy transition with near-zero carbon emissions. This is supported by the findings of [17] on the carbon reduction potential of solar energy in developing countries. Wind energy is increasingly preferred in power generation with the advantage of low cost [14]. [12] have shown that wind energy can be used as a facilitator in the production of carbon-neutral hydrogen. However, [8] emphasized that the efficiency of wind turbines is greatly influenced by geographical and climatic factors. Biomass energy, on the other hand, contributes to the circular economy and provides a balance between waste management and energy production. However, [3] stated that biomass fuels are not carbon-neutral, certain emissions may occur in

their production process. [16] highlighted the potential of biomass gasification technologies to reduce these emissions.
In terms of Challenges Encountered in the Energy Transition Process, some studies in the literature show that the energy transition brings not only technological but also economic and political challenges. Especially in developing countries, renewable energy projects are often slow due to lack of financial resources and infrastructure deficiencies [17,15]. However, international collaborations and financial incentives have the potential to accelerate the energy transition process [2,4]. For example, innovative energy policies in Finland are considered as a model for achieving carbon neutrality [5]. In countries such as China, integrating solar and wind energy is emerging as an effective strategy to reduce carbon emissions [14,18].
Some studies in the literature in terms of Innovative Approaches in Energy Systems, Innovative technologies increase the applicability of renewable energy systems and reduce energy production costs. [11] stated that advances in energy storage systems have increased the efficiency of solar and wind energy. [20] state that biomass gasification technologies offer a solution in hydrogen production. In addition, the use of multiple energy systems increases the security of energy supply and allows costs to be optimized [4,12] drew attention to the role of hybrid energy systems in achieving carbon-neutral goals.
Purpose of the Study: It aims to examine the effects of renewable energy sources on carbon neutrality. The study will evaluate the economic and environmental benefits of solar, wind and biomass energies and analyze the challenges encountered in energy transition processes and innovative strategies to overcome these challenges. In addition, developments in the energy supply chain and the effects of international collaborations on energy systems will be discussed.

2. Material and Methods

This study was conducted on the basis of a literature review assessing the carbon reduction potential of the clean energy supply chain. Various academic sources, reports, and international research have been used to analyze the contributions of renewable energy technologies, especially solar, wind, and biomass sources, to carbon neutrality goals. These researches cover the environmental and economic impacts of each energy source, its capacity to provide sustainability, and its application areas.
In this study, existing literature reviews on clean energy supply chain and carbon reduction solutions are compiled and analyzed. The research process includes the following steps:
Literature Review: The study started with a review of academic articles, industry reports, and policy documents examining the potential of renewable energy technologies to reduce carbon emissions. These resources include important work on the energy transition, carbon neutrality goals, and sustainability of energy systems.
Data Collection: Comprehensive data on renewable energy systems were collected. This data includes models and analyses that demonstrate the potential of solar, wind and biomass energy to contribute to carbon neutrality goals. The data generally covers energy production capacity at the global level, emission reduction impacts and economic analysis.
Data Analysis: The data obtained from the literature were examined with quantitative analysis methods to evaluate the carbon reduction capacity of renewable energy sources. Analyses were made on the application examples of solar, wind and biomass energy and their integration into energy systems. In addition, the potential of these technologies in terms of economic sustainability has been evaluated by taking into account the cost-effectiveness and efficiency parameters.
Carbon Neutrality Strategies: Another objective of the study was to analyze the proposed strategies to achieve carbon neutrality goals. Policy and technology-based strategies in the literature were compared with roadmaps to carbon neutrality. Innovative approaches to reducing carbon emissions are discussed with application examples, especially in developing countries [19,10].
Renewable Energy Policies and Implementation: The study also discusses policy recommendations and successfully implemented examples that promote the renewable energy transition around the world. In particular, analyses were conducted on the consistency of carbon emission reduction targets between countries and how energy policies can be integrated into these targets [2,7].
This study took a review approach based on secondary data analysis. The findings and data in the literature were analyzed in a qualitative manner and the carbon reduction potential, economic efficiency and impact on environmental sustainability of each energy source were compared. The analysis of the data was supported by an extensive literature to understand how terrestrial variables and technological advances interact. The processes of contributing to the carbon neutrality goals of renewable energy systems were evaluated by associating each system with local practices.
This study adopts a systematic literature review approach to evaluate the potential of renewable energy Technologies namely solar, wind, and biomass in contributing to carbon neutrality. The methodology consists of the following components:

2.1 Research design

A qualitative and semi-quantitative framework was employed, based on a comprehensive content analysis of

peer-reviewed articles, international reports, and policy documents published between 2010 and 2024. The review focused on the environmental and economic impacts of renewable energy technologies and their integration into clean energy supply chains.

2.2 Inclusion criteria

Sources were selected based on the following criteria:

- Direct relevance to carbon neutrality or renewable energy transition
- Published in reputable journals or institutional reports
- Availability of quantitative data or modeling outputs (e.g., CO_2 reduction percentages, cost metrics)
- Focus on solar, wind, or biomass technologies

2.3 Data sources

The main databases searched included ScienceDirect, Scopus, Web of Science, and Google Scholar. Keywords used included: *"renewable energy", "carbon neutrality", "solar energy cost", "wind energy integration", "biomass sustainability"*.

2.4 Analysis framework

The selected studies were coded based on:

- Type of renewable energy
- Technological readiness level
- Reported emission reduction percentages
- Associated economic parameters (cost reduction, LCOE)
- Geographical implementation (developed vs. developing countries)

2.5 Visualization and comparative evaluation

Two comparative bar-line charts (Figures 1 and 2) were constructed using Microsoft Excel and OriginPro, based on averaged or commonly reported values across the selected studies. These visualizations illustrate:

- Emission reduction potentials (%)
- Cost reduction potentials (%)
- Efficiency metrics of each energy system (%)

2.6 Limitations

The study is limited to secondary data and does not include primary empirical measurements. Future studies may expand on this framework by incorporating life cycle assessment (LCA) or techno-economic modeling.

3. Results and Discussion

Analysis of the potential of renewable energy sources to contribute to carbon neutrality goals has revealed the environmental and economic impacts of various energy systems. The solar, wind and biomass energies included in the study offer significant advantages in terms of their potential to reduce carbon emissions. Solar Energy: Solar energy works with high efficiency, especially in hot climate regions, and makes a great contribution to zeroing carbon emissions. Studies show that solar energy has a high potential to zero CO_2 emissions, and this technology is widely used around the world. [13,14]. Wind Energy: Wind energy similarly helps to reduce carbon emissions at low costs. The power generation of wind turbines is resistant to a variety of climatic conditions, but local wind speeds and topographical factors can affect this efficiency. Wind energy has great long-term energy efficiency potential, especially for onshore wind farms [12,16]. Biomass Energy: Biomass energy is a method used to produce energy from organic waste, contributing to the carbon cycle and providing a great opportunity to establish zero-carbon emission systems. However, some carbon emissions generated during biomass energy production can limit the environmental impact of this technology. [11,6].

The most important factor in contributing to the carbon neutrality goals of renewable energy systems is the type of technology used as well as the application area. Solar and wind energy are characterized by low operating costs and high efficiency rates. However, although biomass energy is a less common resource, it holds an important place in terms of environmental sustainability. However, the emissions generated during the processing and use of biomass are among the disadvantages of this technology.

The capacity of all three forms of energy to contribute to carbon neutrality goals may vary depending on local conditions. In this context, it is critical for countries to consider local energy resources when determining their energy policies. Studies show that solar and wind power are more broadly applicable, but biomass may be limited to more specific geographic areas [8,9]. As a result, the implementation of renewable energy systems is directly related not only to technological developments, but also to the promotion of carbon emission reduction targets at the national and international level. To achieve carbon neutrality goals, the energy transition must be supported by strategic planning.

Figure 1 visualizes the carbon emission reduction and cost reduction potential of solar, wind and biomass energies. Using two y-axes, it shows both the carbon emission reduction rate and the cost reduction rate on the same graph.

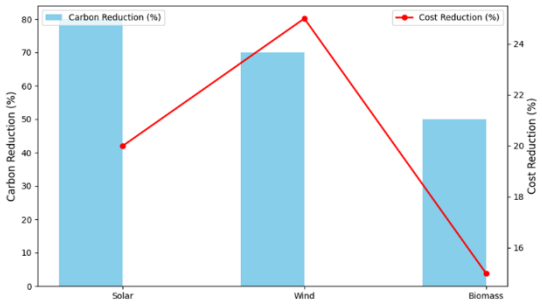

Fig.1. Carbon emission reduction and cost reduction potentials

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Figure 1 illustrates the carbon emission reduction and cost reduction potentials of solar, wind, and biomass energy sources. The blue bars represent the percentage of carbon emissions reduced by each energy type, while the red line shows the associated cost reduction potential.

- Solar energy demonstrates the highest carbon emission reduction potential at 80%, indicating its critical role in decarbonization strategies. However, its cost reduction effect is moderate at 20%, largely due to high initial investment costs.
- Wind energy achieves a 70% reduction in emissions and leads in cost reduction with 25%, highlighting its economic advantage in large-scale deployments, especially in regions with consistent wind patterns.
- Biomass energy shows the lowest performance in both categories, with 50% emission reduction and 15% cost reduction. This reflects the challenges associated with fuel processing and logistics, especially in less developed areas.

These results suggest that solar and wind energy are highly effective for carbon mitigation, while biomass requires targeted optimization to reach similar sustainability levels.

Figure 2 highlights that renewable energy sources offer significant economic gains as well as environmental benefits. In particular, solar energy is the most effective in reducing carbon emissions, while wind energy comes to the fore in terms of cost reduction.

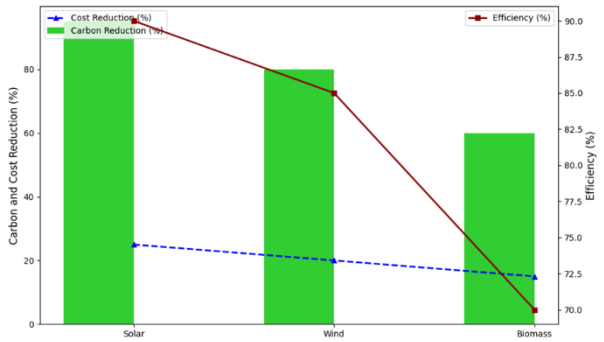

Fig. 2. Carbon emission reduction, cost reduction and efficiency

Figure 2 presents a comprehensive comparison of renewable energy sources in terms of carbon emission reduction (green bars), cost reduction (blue dashed line), and overall system efficiency (red solid line).

- Solar energy stands out with 95% carbon reduction and the highest efficiency level (90%), making it the most environmentally sustainable option. It also offers a 25% cost reduction, indicating improved affordability over time.
- Wind energy shows 80% carbon reduction, 85% efficiency, and 20% cost reduction. Although slightly less efficient than solar, it remains cost-competitive and flexible in diverse climates.
- Biomass energy, while achieving 60% carbon reduction and 70% efficiency, trails in all categories. This indicates that its benefits are context-specific and require careful management of supply chains and emissions during fuel processing.

Overall, solar energy emerges as the most balanced and effective technology across all performance indicators, while wind energy excels in cost savings. Biomass, despite its potential in rural or off-grid applications, requires more sustainable and efficient deployment models to remain viable in long-term carbon neutrality strategies.

The chart compares the environmental benefits and economic gains of renewable energy sources, as well as their efficiency. Solar energy performs best in terms of carbon emission reduction and efficiency, while wind energy achieves the highest rate of cost reduction.

Renewable energy sources are considered a key tool in achieving global carbon neutrality goals. This study analyzes the potential of renewable energy technologies such as solar, wind, and biomass to reduce carbon emissions and their economic impact on energy systems. The findings reveal that renewable energy systems offer environmentally and economically sustainable solutions, but the challenges encountered in this process need to be addressed in terms of policy, technology and financing.

In terms of the Potential of Solar Energy, it stands out among renewable energy sources with near-zero carbon emissions. [13] stated that solar energy plays a leading role in the global energy transition and has the potential to zero carbon emissions. These findings are in line with the work of [14] showing the effects of solar energy applications in China on carbon reduction. However, the initial investment costs of solar panels, energy storage challenges, and infrastructure deficiencies in developing countries are important factors limiting the spread of this technology [17]. [11] emphasize that nanotechnological innovations in solar energy technologies increase efficiency and reduce costs. In addition, [17] stated that solar energy systems have the potential to increase energy supply security, especially in developing countries. However, inadequacies in energy storage systems are still seen as an obstacle to the global spread of solar energy.

Wind Energy: In terms of Economic and Environmental Advantages, it stands out as a low-cost renewable energy source. [12] emphasize that wind energy plays a facilitating role in the production of carbon-neutral hydrogen and has great potential in the integration of energy systems. [14] stated that wind energy offers an effective solution to carbon reduction with low operating costs. However, [8] state that the performance of wind turbines is greatly affected by geographical and climatic factors, which limits the viability of wind energy. [9] suggest that these limitations can be

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overcome with smart energy management systems. In particular, the use of hybrid energy models is considered a promising strategy to increase the efficiency of wind energy [13].

Biomass Energy: In terms of Opportunities and Limitations, it plays an important role by contributing to the circular economy through the conversion of organic waste into energy. However, [3] stated that biomass fuels are not completely carbon-neutral and certain carbon emissions may occur in their production process. [16] state that biomass gasification technologies play a key role in reducing these emissions and increasing the efficiency of biomass energy. [8] highlight that biomass is an important tool in increasing energy access, especially in rural areas. However, large-scale use of this energy source may conflict with other sustainability goals, such as food security and land use [20]. Therefore, biomass production processes need to be optimized and supported by sustainable agricultural practices.

In terms of Integration of Multiple Energy Systems, it increases the security of energy supply and optimizes costs by integrating different renewable energy sources [4]. Such systems offer an effective solution, especially in the stabilization of variable energy sources such as solar and wind energy [15]. [18] stated that multiple energy systems should be supported by carbon trading mechanisms, and these systems play a strategic role in achieving carbon neutrality goals.

In terms of policies and international cooperation, the expansion of renewable energy sources should be supported not only by technological innovations, but also by effective policy mechanisms. [5] highlight that Finland's innovative energy policies have set a successful example in achieving carbon neutrality goals. [2] suggest that energy transition processes in developing countries should be supported by international cooperation and financing mechanisms.

In particular, carbon trading is an important tool in enhancing the economic sustainability of renewable energy systems [18,11] stated that carbon trading contributes to cost-effectiveness analyses in energy systems.

In developing countries, biomass energy is often seen as a practical solution for decentralized energy production, especially in rural areas lacking grid access. However, several challenges hinder its full-scale implementation:

- Technological Barriers: Outdated combustion techniques result in inefficient energy conversion and air pollution. Modern gasification and pyrolysis systems remain underutilized due to high initial costs and lack of technical expertise.
- Logistical Challenges: Collecting and transporting biomass feedstock in geographically dispersed regions is costly and labor-intensive.
- Environmental Trade-offs: Large-scale biomass cultivation may compete with food production and lead to deforestation or land degradation if not managed sustainably.
- Policy Gaps: Many developing countries lack clear regulatory frameworks and incentive mechanisms to support biomass integration into their national energy mix.

To overcome these obstacles, targeted investments in sustainable agricultural practices, decentralized energy infrastructure, and capacity-building programs are needed. International cooperation and technology transfer mechanisms can also accelerate the development and adoption of clean biomass technologies in low- and middle-income countries.

Renewable energy sources are indispensable in achieving global carbon neutrality goals. However, in order to use these resources effectively, factors such as technology development, financing and policy mechanisms need to be handled together. Solar, wind and biomass energies can play an important role in this transformation, with their own advantages and limitations.

4. Conclusion

In this study, the effects of the clean energy supply chain on carbon reduction and the potential of renewable energy sources in achieving carbon neutrality targets were evaluated. The findings show that renewable energy sources such as solar, wind, and biomass play a critical role in reducing fossil fuel dependency and are essential for environmental sustainability.

- Solar energy stands out with its high efficiency and near-zero carbon emissions, especially in hot climatic regions. This source is one of the most powerful alternatives in terms of its potential to zero carbon emissions.
- Wind energy is attracting attention as an effective tool to reduce carbon emissions at low costs. However, local wind speeds and geographical factors can affect the effectiveness of this technology.
- Although biomass energy contributes to the carbon cycle, it has limitations in terms of environmental sustainability due to some carbon emissions generated in production processes.

This study reveals that renewable energy sources not only offer environmental benefits but also provide economic sustainability. However, in order to achieve carbon neutrality goals, energy transition processes need to be supported by strategic planning at the national level.

- Development of Renewable Energy Infrastructures: The installation and integration of solar and wind energy systems should be encouraged. These systems can

significantly reduce carbon emissions, especially in regions with high dependence on fossil fuels.

- Policy and Incentive Mechanisms: Policies such as tax breaks, subsidies, and investment incentives that support the renewable energy transition should be implemented. This will accelerate the energy transition and make it easier to achieve carbon neutrality goals.
- Technological Innovations: Priority should be given to research and development that will increase the efficiency of technologies such as solar panels and wind turbines. In addition, innovative processing techniques should be developed to minimize the carbon emissions of biomass energy.
- Education and Awareness-Raising: Training programs should be organized to raise awareness in society about the importance of renewable energy sources and carbon neutrality goals.
- International Cooperation: Since reducing carbon emissions requires a global effort, cooperation and information sharing between countries should be encouraged. For example, successful energy transition strategies can guide other countries.
- Assessment of Local Conditions: When determining energy policies, the unique geographical and economic conditions of each country or region should be taken into account.

In line with these recommendations, it will be possible to expand renewable energy systems and achieve carbon neutrality targets. In this process, long-term planning and adopting a multi-stakeholder approach are of great importance.

Acknowledgment

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research.

Conflict of interest

There is no conflict of interest.

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