# Enhancing Renewable Energy Power Generation through the Exploration of Laser Technology

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# Enhancing Renewable Energy Power Generation through the Exploration of Laser Technology

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## Abstract

This research aims to investigate the utilization of laser technology in improving the performance of power generation systems from renewable energy sources, focusing on solar, wind, hydropower, and biomass energy. A literature review and comprehensive analysis were conducted using a descriptive and synthetic data analysis method. The discussion results indicate that laser technology can significantly contribute to the utilization of renewable energy. In solar power generation systems, laser technology enhances solar radiation absorption in solar thermophotovoltaics applications and flexible solar panel designs. In wind power generation systems, laser technology is employed in long-range wind flow measurement using LiDAR, wind turbine load validation, and improving wind turbine control. In hydropower generation systems, laser technology protects and monitors water turbine blades to prevent erosion and damage. In biomass power generation systems, laser technology is employed for chemical element detection in the energy conversion process and analysis of biomass properties. In conclusion, using laser technology in power generation from renewable energy sources offers significant potential for enhancing efficiency, performance, sustainability, and environmental friendliness.

Keywords: laser technology; renewable energy; power generation; efficiency sustainability

## I. Introduction

In an era increasingly conscious of sustainability and environmental protection, renewable energy has become a primary focus in meeting global energy needs (Jaiswal et al., 2022). Compared to conventional energy sources such as fossil fuels, renewable energy offers various advantages. Renewable energy sources such as solar, wind, water, and biomass are unlimited natural resources that can be sustainably utilized without diminishing their potential. In recent decades, technological advancements have played a crucial role in advancing the use of renewable energy. Innovations continue to emerge in the field of renewable energy, including efficiency improvements, cost reductions, and the development of supportive infrastructure (Gielen et al., 2019). Alongside these technological advancements, integrating renewable energy into the global energy system is increasingly feasible, contributing to source diversification and reducing greenhouse gas emissions (Pupo-Roncallo et al., 2019).

One technology that has experienced rapid progress is laser technology. Laser technology has various applications in different fields, including developing power generation systems from renewable energy sources (Gupta & Carlson, 2015). The unique properties of lasers, which can produce concentrated and focused beams of light, provide an intriguing potential for enhancing performance and efficiency in various sectors, including power generation. In the realm of renewable energy, laser technology can significantly improve the efficiency and performance of power generation from renewable energy sources.

The utilization of laser technology in power generation systems from renewable energy sources has become an exciting area of research. Laser technology is employed for various purposes, such as enhancing the efficiency of solar panels (Desta et al., 2016), monitoring and protecting turbines (Schuerhoff et al., 2015), as well as analyzing the properties of biomass in biomass power plants (Zhang et al., 2020). Laser technology is also used to detect and monitor chemical elements in energy conversion in biomass power plants (Viljanen, 2019). These research findings provide valuable insights into the potential of laser technology in enhancing the performance of renewable energy power generation systems. However, a comprehensive literature review on using laser technology in power generation systems from renewable energy sources still needs to be completed. Through this literature review, the recent progress in the use of laser technology in various aspects of power generation from renewable energy sources and the benefits and potential offered by this technology can be identified.

Therefore, this research aims to investigate the potential of laser technology in enhancing the performance and efficiency of power generation systems from renewable energy sources. This review article will explore the utilization of laser technology in power generation from renewable energy sources, including solar energy, wind energy, water energy, and biomass energy. A deeper understanding of the potential of laser technology is hoped to promote the development of more efficient, sustainable, and environmentally friendly renewable energy power generation systems.

## II. Methodology

This research used a comprehensive literature review and analysis approach to address the formulated research objectives. This approach involved a thorough literature review on using laser technology in power generation from renewable energy sources. This method allowed for a deep understanding of the applications of laser technology and the benefits that have been achieved.

The data used in this study were obtained through extensive literature searches on the internet. The primary data sources included scientific journals, conference proceedings, research reports, and other relevant, reliable sources of information related to the use of laser technology in renewable energy-based power generation. The data was searched through academic databases and scientific information search platforms, including Google Scholar (Ma'arif et al., 2022). Strict inclusion and exclusion criteria were applied in selecting relevant and high-quality data sources, such as scientific articles published in English or Indonesian, articles published after 2015, and articles focused on discussing the use of laser technology to enhance the performance of power generation systems from renewable energy sources.

Data analysis in this study was conducted through descriptive and synthesis methods. The data collected from various literature sources were systematically analyzed to identify patterns and significant findings related to using laser technology in renewable energy-based power generation. Relevant and significant information was extracted from the identified literature and presented comprehensively in this review article.

## III. Results and Discussion

This study aims to investigate the utilization of laser technology in enhancing the performance and efficiency of power generation systems from renewable energy sources. Several relevant previous studies have been conducted and presented in Table 1, providing a solid foundation for this research. The potential and benefits offered by laser technology in energy conversion technologies derived from renewable energy sources were identified through a review of previous research. Additionally, this study seeks to understand the contribution and role of laser technology in optimizing sustainable power generation.

Table 1. Summary and mapping of previous research

| Resources & Technology | Laser Function | Description | References |
|---|---|---|---|
| Solar: Solar Panels | Optimization in the manufacturing of solar panels | Laser technology creates and manipulates patterned structures that enhance solar radiation absorption in applications such as solar thermophotovoltaics and solar thermal applications with flexible designs and desired features. | (Khodasevych, et al., 2015) |
| | | Focused femtosecond laser beams are directed into encapsulating materials to modify their optical constants, reducing the optical shadowing of front-side metal metallization in solar cells and improving their optical performance. | (Peharz, et al., 2015) |
| | | Laser technology creates new back-reflector architectures with micro-structured light scattering features, enhancing light absorption in thin-film solar cells and improving cell efficiency. | (Desta, et al., 2016) |

| Resources & Technology | Laser Function | Description | References |
|---|---|---|---|
| Wind: Wind Turbine | Optimization and monitoring of wind turbine performance based on LiDAR | Laser technology is used for long-range wind flow measurements using LiDAR, providing more accurate and representative measurements of wind flow patterns and optimizing wind turbine performance. | (Borraccino, 2017) |
| | | Laser technology in LiDAR is used to measure vertical wind speed data and several parameters relevant to wind turbine development, offering reliable evaluation in a more effective and cost-efficient manner. | (Li & Yu, 2017) |
| | | Laser technology is employed for wind turbine load validation using LiDAR-based wind data acquisition. Wind measurements and wind turbine load estimations are performed aerodynamically without meteorological masts. | (Dimitrov, et al., 2019) (Goit, et al., 2019) |
| | | Laser technology is used to compare wind speed and wind direction measurements against existing indicators on LiDAR-based wind turbines, yielding accurate correction coefficients. | (Wang, et al., 2023) |
| | | Laser technology is employed to evaluate wind gust severity using LiDAR methods, identifying threats and taking preventive measures to avoid high loads on wind turbines. | (Bos, et al., 2016) |
| | | Laser technology is utilized to enhance wind turbine control with LiDAR as an additional sensor, enabling the development of novel control techniques to reduce structural loads and enhance energy production. | (Scholbrock, et al., 2016) |
| | Detection of defects and damages in wind turbine blades | Compact laser shearography systems are developed for on-site robotic inspection of wind turbine blades to detect subsurface defects and damages in composite materials. | (Li, et al., 2021) (Li, et al., 2020) |
| | | Laser technology is used to develop continuous line thermography techniques capable of visualizing rotating wind turbine blade damages using non-contact methods, spatially non-scanning data acquisition, and intuitive data interpretation. | (Hwang, et al., 2017) |
| Water: Water Turbine | Monitoring and protection of water turbine blades | Laser technology protects low-pressure steam turbine steel blades from water droplet erosion through automated laser treatment and erosion protection techniques, improving blade resilience and lifespan. | (Schuerhoff, et al., 2015) |
| | | Laser technology is utilized to restore turbine blade tips through metal deposition processes, optimizing restoration methods to increase lifespan and reduce maintenance costs. | (Ciappi, et al., 2021) |
| | | Comparison between laser technology and digital photogrammetry in scanning the geometry of water turbine blades to determine deviations between the two methods. | (Nedelcu, et al., 2020) |
| Biomass | Improving the efficiency of the pyrolysis and gasification process | Laser technology is used to develop faster and more advanced pyrolysis and gasification processes to produce fuel-grade bioenergy, biogas, and biochar more effectively and efficiently. | (Tursunov & Dobrowolski, 2015) |
| | Detection of chemical elements in the energy conversion process | Laser technology serves as an online diagnostic tool for monitoring high-temperature chemical reactions in biomass combustion, including temperature, oxygen, and crucial elements in biomass thermal conversion, using techniques such as Collinear Photofragmentation and Atomic Absorption Spectroscopy (CPFAAS) and Microwave-Assisted Laser-Induced Breakdown Spectroscopy (MW-LIBS). | (Viljanen, 2019) |

| Resources & Technology | Laser Function | Description | References |
|---|---|---|---|
| | Analysis of biomass properties | Laser technology is employed to enhance the quantitative analysis of coal properties using laser-induced breakdown spectroscopy (LIBS), including proximate analysis (calorific value, ash content, volatile matter) and ultimate analysis (carbon and hydrogen content). | (Zhang, et al., 2020) |

## 1. Utilization of Laser Technology in Solar Power Generation

Solar power generation is one of the most promising renewable energy sources in addressing energy challenges and the negative impacts of fossil fuel usage. In efforts to optimize the efficiency of solar power generation, the utilization of laser technology to enhance the performance of solar panel modules, as seen in Table 1, has been the focus of research.

One benefit of laser technology in the fabrication of solar panel modules is its ability to create and manipulate patterned structures that enhance solar radiation absorption in applications such as solar thermophotovoltaics and solar thermal applications with flexible designs and desired features (Khodasevych et al., 2015). In this research, lasers are used to create patterned structures specifically designed to enhance light absorption efficiency by solar cells. Solar panel modules can generate more electrical energy with increased solar radiation absorption.

Furthermore, laser technology has also been used to modify solar cell encapsulation materials by focusing femtosecond laser beams into the materials (Peharz et al., 2015). In this research, femtosecond laser beams are utilized to modify the optical constants of the encapsulation materials, which in turn reduces the optical shadowing caused by front-side metal metallization in solar cells. By reducing this optical shadowing, light absorption by solar cells can be enhanced, thereby improving their optical performance and increasing the efficiency of solar energy conversion to electricity.

Studies have shown that laser technology can create new back-reflector architectures with micro-structured light-scattering features (Desta et al., 2016). These structures enhance light absorption in thin-film solar cells, which typically have lower efficiencies than crystalline silicon solar cells. By improving light absorption, the efficiency of thin-film solar cells can be increased, thereby enhancing the energy output of solar panel modules.

Overall, the use of laser technology in the fabrication of solar panel modules in solar power generation has significant potential in optimizing the efficiency and performance of solar cells. By creating and manipulating patterned structures, modifying the optical constants of encapsulation materials, and creating new back-reflector architectures, laser technology can enhance light absorption, reduce optical shadowing, and improve solar energy conversion efficiency to electricity. Laser technology can contribute significantly to developing more efficient and sustainable solar power generation systems.

## 2. Utilization of Laser Technology in Wind Power Generation

### 2.1. Optimization and Monitoring of Wind Turbine Performance Based on LiDAR

Wind power generation has become a popular renewable energy source in efforts to reduce carbon emissions and enhance energy sustainability. Laser technology has been employed to optimize and monitor the performance of wind turbines using Light Detection and Ranging (LiDAR) systems. Various previous studies have been identified, as seen in Table 1.

Laser technology in LiDAR allows for more accurate long-range wind flow measurements, better-representing wind flow patterns, and optimizing wind turbine performance (Borraccino, 2017). By measuring vertical wind speed data and potential parameters for wind turbine development, laser technology in LiDAR provides effective and cost-efficient evaluations (Li & Yu, 2017). This allows wind power developers to make better decisions regarding wind turbine location and configuration.

Furthermore, laser technology is utilized for wind turbine load validation through LiDAR-based wind data acquisition (Dimitrov et al., 2019) (Goit et al., 2019). This method enables wind measurements and wind turbine load estimations using aerodynamic principles without meteorological masts. It helps reduce the cost and complexity of load measurements, thereby enhancing wind turbine monitoring efficiency.

The use of laser technology in LiDAR methods is also employed to compare wind speed and wind direction measurements against wind turbine indicators, resulting in accurate correction coefficients (Wang et al., 2023). This data is crucial for optimizing wind turbine placement and adjusting operations based on prevailing wind conditions.

Wind gust telemonitoring and controlling city monitoring analogy is utilized to identify threats and take preventive measures to avoid high loads on wind turbines (Bos et al., 2016). Using LiDAR methods, the severity level of wind gusts can be evaluated more accurately, enhancing the reliability and safety of wind turbine operations.

Finally, laser technology enhances wind turbine control by incorporating LiDAR as an additional sensor (Scholbrock et al., 2016). This enables the development of new control techniques that can reduce structural loads on wind turbines while increasing overall energy production.

Overall, using laser technology in LiDAR systems for wind turbine optimization and monitoring in wind power generation has provided significant benefits. By providing more accurate measurements, effective evaluations, gust severity monitoring, and improved wind turbine control, laser technology helps enhance the efficiency and performance of wind turbines in generating renewable energy. Further advancements in this technology will continue to contribute significantly to developing more efficient and sustainable wind power generation systems.

### 2.2. Detection of Defects and Damage in Wind Turbine Blades

Another benefit of laser technology in Wind Power Generation is the monitoring and detection of defects and damage in wind turbine blades, which is crucial for ensuring wind turbines' ongoing operation and reliability. Previous research has demonstrated these benefits, as shown in Table 1.

One application of laser technology is the development of compact laser shearography systems used for on-site robotic inspection of wind turbine blades (Li et al., 2021) (Li et al., 2020). This system aims to detect subsurface defects and damage in the composite materials used in wind turbine blades. By utilizing laser technology, inspections can be conducted efficiently and accurately without dismantling the wind turbine blades. This helps save time and costs in maintenance while ensuring the quality and reliability of wind turbines.

Additionally, laser technology has been used to develop continuous line thermography techniques for detecting damages in rotating wind turbine blades (Hwang et al., 2017). This method utilizes non-contact laser technology to visualize real-time wind turbine blade damage. The thermographic data obtained provides information about abnormal temperature changes, indicating the presence of damages or defects in the blades. With intuitive data interpretation, this method enables wind power operators to identify damages and take necessary preventive actions quickly.

Using laser technology to detect defects and damage in wind turbine blades in Wind Power Generation is essential in ensuring ongoing operation sustainability and enhancing wind turbine reliability. With compact laser shearography systems and continuous line thermography techniques, the detection of subsurface defects, composite material damage, and abnormal temperature changes can be identified more efficiently and accurately. This contributes to timely maintenance and improves the reliability and performance of wind turbines. Further developments in the utilization of laser technology will continue to enhance defect monitoring in wind turbine blades in the future.

## 3. Utilization of Laser Technology in Hydropower Generation

Hydropower generation is an essential renewable energy source in meeting global electricity demand. In efforts to monitor and protect the blades of water turbines in hydropower generation, laser technology has been utilized and discussed in previous research, as seen in Table 1.

The utilization of laser technology in blade protection has been studied to safeguard low-pressure steam turbine blades from water droplet erosion (Schuerhoff et al., 2015). Erosion protection and automated laser treatment techniques are employed to enhance the durability and lifespan of turbine blades. By employing this technology, turbine blades can be protected from erosion caused by water droplets, extending their lifespan and reducing maintenance costs.

In addition to protection, laser technology has been used to restore water turbine blade tips through metal deposition techniques (Ciappi et al., 2021). Optimal restoration of turbine blade tips can be achieved using metal deposition methods assisted by laser technology. This increases the lifespan of turbine blades, reduces maintenance costs, and optimizes the overall performance of hydropower generation.

Furthermore, a comparison between laser technology and digital photogrammetry is conducted to scan water turbine blade geometries (Nedelcu et al., 2020). This research aims to identify deviations between the two technologies and evaluate their accuracy and efficiency. By comparing laser technology and digital photogrammetry, monitoring and scanning water turbine blade geometries can be conducted more effectively and accurately.

Using laser technology to monitor and protect water turbine blades in hydropower generation provides significant benefits. Protection against water droplet erosion and restoration of turbine blade tips using metal deposition technology extend the lifespan and reduce maintenance costs. Meanwhile, the comparison between laser technology and digital photogrammetry in scanning water turbine blade geometries aids in the monitoring and evaluating of blade conditions with higher accuracy. Further developments in the utilization of laser technology are expected to contribute positively to hydropower generation's performance and sustainability.

## 4. Utilization of Laser Technology in Biomass Power Generation

Biomass Power Generation using pyrolysis and gasification processes is a promising solution for generating electricity from renewable biomass sources. Biomass-derived from tourism waste and solid waste (Aridito & Ma'arif, 2019) (Ma'arif, 2019) (Ma'arif & Wardoyo, 2020); agricultural waste (Ma'arif et al., 2016) (Syamsiro et al., 2020), and traditional market waste (Ma'arif et al., 2019) have been identified as viable biomass sources for Biomass Power Generation. Utilizing this biomass as fuel in pyrolysis and gasification processes offers a solution for waste utilization and contributes to environmentally friendly renewable energy production.

In Biomass Power Generation, gasification technology has been identified as suitable for converting biomass into electricity, particularly in remote areas (Ma'arif, 2023). Research has shown that gasification technology can be implemented on both large and small scales, including combined heat and power applications, biomass and coal co-firing gasification, and combined heat and power units driven by gas turbines (Beenackers & Maniatis, 1998). Recent advancements in biomass gasification have shown progress in utilizing syngas for heat and power generation, hydrogen production, and liquid fuel synthesis (Wang et al., 2008). Additionally, various biomass conversion methods, including high-temperature gasification and combustion, have been explored and demonstrated the suitability of different methods for various types of biomass (Dahlquist, 2013). This opens opportunities for efficiently utilizing various biomass types in Biomass Power Generation.

Overall, Biomass Power Generation utilizing pyrolysis and gasification processes presents a promising solution for generating electricity from biomass. Various biomass sources such as tourism, agricultural, and traditional market waste can be used as fuel in Biomass Power Generation. The development of gasification technology on both large and small scales, along with the increased utilization of syngas and biomass conversion methods, provides a bright prospect for developing sustainable and environmentally friendly Biomass Power Generation. In efforts to improve the efficiency of the pyrolysis and gasification processes in Biomass Power Generation, laser technology has been the focus of previous research, as shown in Table 1.

### 4.1. Enhancing the Efficiency of Pyrolysis and Gasification Processes

Laser technology's use to develop pyrolysis and gasification processes aims to produce biofuel energy such as biogas and biochar more effectively and efficiently (Tursunov & Dobrowolski, 2015). Laser technology is used to optimize the pyrolysis and gasification reactions by influencing the energy and matter interactions at the molecular level. Process efficiency can be improved with faster and more advanced laser technology, resulting in more usable energy obtained from the biomass utilized.

The utilization of laser technology in Biomass Power Generation not only enhances process efficiency but also helps reduce emissions and environmental impacts. The temperature and duration required in the pyrolysis and gasification processes can be better controlled by employing more advanced laser technology. This impacts the improved efficiency of biomass conversion into energy and reduces greenhouse gas emissions and other pollutants.

### 4.2. Detecting Chemical Elements in Energy Conversion Processes

In Biomass Power Generation, detecting and monitoring chemical elements in the biomass-to-electricity conversion is vital in ensuring operational efficiency and sustainability. Laser technology has been used as an online diagnostic tool to monitor high-temperature chemistry in biomass combustion in Biomass Power Generation (Viljanen, 2019). Methods used include Collinear Photofragmentation and Atomic Absorption Spectroscopy (CPFAAS) and Microwave-Assisted Laser-Induced Breakdown Spectroscopy (MW-LIBS). With the assistance of laser technology, temperature, oxygen, and crucial elements in the thermal conversion of biomass can be monitored in real-time and with accuracy. This enables Biomass Power Generation operators to optimize conversion process conditions, identify potential issues, and take necessary actions to enhance efficiency.

Laser technology's detection of chemical elements in Biomass Power Generation offers significant benefits. Monitoring high temperatures and chemical composition allows Biomass Power Generation operations to be controlled more effectively. Accurate knowledge about the chemical conditions in biomass energy conversion processes allows for precise adjustments in terms of temperature, oxygen ratios, and other vital parameters. In the long run, this can lead to increased operational efficiency and sustainability of Biomass Power Generation.

### 4.3. Analyzing Biomass Properties Using Laser Technology

A deep understanding of the properties of the biomass utilized is crucial in ensuring the efficiency and sustainability of Biomass Power Generation operations. Using laser technology in analyzing biomass properties involves using laser-induced breakdown spectroscopy (LIBS) to enhance quantitative analysis (Zhang, et al., 2020). This technology enables proximate and ultimate analyses of biomass. Proximate analysis includes measuring calorific value, ash content, and volatile content in biomass, while ultimate analysis involves measuring carbon and hydrogen content. Using laser technology, biomass property analysis can be conducted more rapidly, accurately, and non-destructively.

The utilization of laser technology in analyzing biomass properties in Biomass Power Generation offers significant benefits. With improved quantitative analysis, Biomass Power Generation operations can be optimized based on precise biomass characteristics. Information on calorific value, ash content, volatile content, carbon content, and hydrogen content in biomass assists in appropriate fuel planning, conversion processes, and operational control. A better understanding of biomass properties can enhance the efficiency and sustainability of Biomass Power Generation operations.

In further developments, laser technology in Biomass Power Generation holds great potential for enhancing efficiency, controlling chemical elements, and understanding biomass properties. Advanced laser technology improves biofuel energy production, such as biogas and biochar, and drives the development of sustainable Biomass Power Generation. On the other hand, laser technology is used as an online diagnostic tool for monitoring chemical elements, ensuring efficient biomass-to-electricity conversion. The utilization of LIBS in analyzing biomass properties enables optimal utilization of biomass in electricity conversion. Developing biomass analysis methods using laser technology will optimize Biomass Power Generation operations towards improved efficiency, sustainability, and environmental friendliness.

## IV. Conclusion

Based on the exposition and discussion of previous research, laser technology holds great potential for enhancing power generation performance from renewable energy sources. In solar energy, laser technology has been utilized to create and manipulate patterned structures on solar panels, improving sunlight absorption and enhancing the optical performance of solar cells. Furthermore, laser technology has been employed for load validation and control in wind turbines using LiDAR, which aids in improving the efficiency and monitoring of wind turbines. Additionally, laser technology has been utilized to protect and monitor water turbine blades to prevent erosion and damage. Moreover, laser technology has been used to detect chemical elements in the energy conversion process of biomass power generation, enhancing the understanding of biomass properties and ensuring better conversion efficiency.

Overall, using laser technology in renewable energy sources significantly enhances the performance and efficiency of power generation. Laser technology aids in improving sunlight absorption in solar panels, optimizing wind turbine operations, protecting and monitoring water turbines, and analyzing biomass properties. Further development in the utilization of laser technology is expected to drive the more efficient, sustainable, and environmentally friendly use of renewable energy sources.

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