frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 19 February 2025
DOI 10.3389/fenrg.2025.1540423

Check for updates

OPEN ACCESS

EDITED BY
Sudhakar Kumarasamy,
Universiti Malaysia Pahang, Malaysia

REVIEWED BY
Jorge Cunha,
University of Minho, Portugal
Slavica Prvulovic,
University of Novi Sad, Serbia

*CORRESPONDENCE
Anna Horzela-Miś,
✉ anna.horzela-mis@polsl.pl

RECEIVED 05 December 2024
ACCEPTED 28 January 2025
PUBLISHED 19 February 2025

CITATION
Horzela-Miś A and Semrau J (2025) The role of renewable energy and storage technologies in sustainable development: simulation in the construction industry.
Front. Energy Res. 13:1540423.
doi: 10.3389/fenrg.2025.1540423

The role of renewable energy and storage technologies in sustainable development: simulation in the construction industry

Anna Horzela-Miś[1]* and Jakub Semrau[2]

[1]Department of Management, Faculty of Organisation and Management, Silesian University of Technology, Gliwice, Poland, [2]Department of Logistics, Faculty of Organisation and Management, Silesian University of Technology, Gliwice, Poland

Introduction: The increasing demand for sustainable energy solutions has become crucial in addressing global environmental challenges such as climate change and resource depletion. As a significant energy consumer, the construction industry must explore renewable energy integration to enhance sustainability. This study investigates the role of photovoltaic (PV) systems and energy storage technologies in promoting sustainable energy use within a Polish construction manufacturing company.

Methods: A 26-year simulation was conducted to analyze the implementation of a PV system in an industrial setting. The study assessed energy savings, cost efficiency, and environmental benefits by modeling energy consumption, production, and storage dynamics. The financial feasibility of the investment was evaluated using key performance indicators such as return on investment, payback period, and levelized cost of electricity.

Results: The findings demonstrate that PV systems significantly reduce electricity expenses and reliance on grid power, achieving a payback period of approximately 9.4 years. The company has the potential to significantly reduce CO_2 emissions, contributing to environmental sustainability. The simulation further revealed that PV adoption enhanced energy independence, covering 53.3% of the company's energy needs while minimizing operational costs.

Discussion: The study highlights PV technology's economic and environmental benefits in industrial applications. Energy storage integration optimizes energy utilization, increasing efficiency and financial viability. These findings provide valuable insights for construction companies considering renewable energy investments. The broader societal advantages, including CO_2 reduction, improved public health, and regulatory compliance, underscore the importance of transitioning toward sustainable energy solutions.

KEYWORDS

efficiency, sustainable investments, photovoltaic systems, green technology, energy storage technologies

1 Introduction

The environmental issues confronting humanity in the 21st century demand immediate action (Zhang and Li, 2024). In recent times, crises like climate change, rapid global population growth (Uniyal et al., 2020), and shortages of land and water resources have become more severe (Colombi and D'Itria, 2023). Climate change, driven by the rise in global temperatures, poses a critical threat with far-reaching effects on ecosystems, communities, public health, and the world economy (Ghasemi et al., 2024). This phenomenon is primarily fueled by high levels of human-generated carbon dioxide, methane, and nitrous oxide in the atmosphere (Reidmiller et al., 2018; Allen, 2022). As a result, we are witnessing an increase in heat-related illnesses, accelerated ice melt, rising sea levels, disrupted ecosystems, compromised food production, more frequent and severe natural disasters, infrastructure damage, higher healthcare expenses, and growing water scarcity (Spellman and Bieber, 2016; Dincer and Ezzat, 2018).

Global energy consumption has been steadily increasing for decades (Rangarajan et al., 2024). Additionally, non-renewable fossil fuel reserves are steadily diminishing, and their continued use is further exacerbating climate change (Anghelache et al., 2023; Martins et al., 2019). The energy sector, which has traditionally depended heavily on fossil fuels, is now undergoing a significant transformation, marked by rapid technological advancements and the pursuit of innovative alternatives (Li et al., 2022). In recent years, global initiatives for a sustainable energy future have accelerated the advancement of renewable energy sources like offshore wind, solar photovoltaics (PVs), hydro, and geothermal energy (Yin et al., 2024; Gao et al., 2024). Renewable energy is increasingly becoming the top candidate to mitigate energy shortages (Upadhyay et al., 2024; Zemite et al., 2024). Renewable energy will continue to generate more electricity in the future as well (Rangarajan et al., 2024). These technologies facilitate the development of energy–prosumer settings and are in harmony with wider economic and regulatory schemes that promote the use of renewable energy. Their ability to satisfy and even surpass the energy requirements of industrial facilities, while maintaining economic feasibility, is especially noteworthy (Zemite et al., 2024).

In this context, the shift towards energy transformation appears unavoidable (Kurtyka, 2021; Marinina et al., 2022; Ponomarenko et al., 2021; Siontorou, 2023). The energy transition is a fundamental pillar of the sustainable development concept and a crucial factor in global efforts to lower GHG emissions (Postula et al., 2024). These emerging trends are reshaping energy production methods, with an emphasis on achieving low- or zero-emission outputs (Janik et al., 2018; Rymarczyk, 2020; Annamalai and Vasunandan, 2024). Notably, energy storage solutions are rapidly advancing, while the hydrogen economy and the growth of electromobility are projected to be key drivers of the economy as the energy sector evolves (Rossiter, 2019; Zhang and Li, 2024). However, it is crucial to recognize that even a complete transition may not fully address all environmental and social challenges within the anticipated timeframe and scale (White, 2020; Cotta and Domorenok, 2022; Wells et al., 2020). Despite these limitations, pursuing this transformation remains vital to securing a more sustainable future for upcoming generations.

Renewable energy sources are at the forefront of driving the global energy transition (Frankowski, 2017). Shifting to low- and zero-carbon energy represents a critical opportunity for societal advancement. The literature suggests that, in terms of analyzing factors influencing health, direct measures supporting energy transition through the adoption of renewable energy sources effectively enhance health policies (Mo et al., 2022; Karaaslan and Çamkaya, 2022; Buonocore et al., 2016).

The energy transition involves a gradual shift from traditional energy systems to new models focused on structural changes in energy production at global, national, and household levels (Smil, 2010). It serves not only as an environmental initiative (Miller et al., 2013) but also as a catalyst for economic and industrial growth, crucial for maintaining European leadership in sustainability and competitiveness (Młynarski, 2019). This transition reflects social demands for cleaner energy, economic pressures, and cultural shifts toward renewable resources (Herudziński, 2021). By aligning environmental protection with economic growth and industrial innovation, the energy transition aims to secure energy supply, enhance competitiveness, and achieve global sustainability (Hadžić et al., 2018). Key factors (Popkiewicz, 2016) include dwindling fossil fuel reserves, advancements in renewable technologies, rising social awareness (Manwell et al., 2009; Sheina et al., 2022), and the political will of leading nations like Denmark and Germany (Gu et al., 2023). Rapidly growing countries like China and some in Africa are also increasingly investing in renewable energy (Renna and Materi, 2021).

While the benefits of solar energy, including environmental advantages and energy independence, are well-documented, the literature also highlights significant hurdles to its adoption, particularly in the commercial and industrial sectors. High upfront costs and technological complexities remain key deterrents for investors (Gu et al., 2023). Despite the growing body of research on photovoltaic (PV) systems, there is a noticeable gap in studies that focus specifically on the economic feasibility and profitability of such investments over time. Existing research often lacks detailed analyses of the potential return on investment (ROI) and the time frame required for cost recovery, leaving companies uncertain about the long-term financial benefits of solar energy integration.

This paper addresses this gap by investigating the financial benefits of integrating solar energy into manufacturing enterprises within the construction industry. Using a 26-year simulation of photovoltaic (PV) system implementation, including energy storage technologies, this study demonstrates significant cost savings, enhanced energy independence, and long-term profitability. Furthermore, it highlights the advancements in solar energy technologies that enhance their viability and appeal, supported by studies validating their environmental and economic benefits. By providing practical benchmarks and insights, this research aims to support companies in overcoming the perceived barriers to adopting renewable energy solutions and to foster broader implementation of sustainable energy practices.

2 An overview of the literature

2.1 Photovoltaic

Renewable energy adoption in industrial settings is key to sustainable and self-sufficient energy solutions. Advances in solar (photovoltaic and thermal), wind, and micro-cogeneration systems enable on-site power generation (Solar Power Europe, 2023). These technologies support energy-prosumer environments, allowing buildings to generate power, contribute surplus electricity to the grid, and align with economic and regulatory frameworks. Countries like Latvia use net metering systems to balance on-site and grid electricity (Lebedeva et al., 2021). High-efficiency buildings are increasingly net energy producers, benefiting Europe's energy efficiency and sustainability goals. Despite this progress, research gaps exist in optimizing these technologies for smaller industries, which differ operationally and financially from residential or large-scale setups (Zemite et al., 2024).

Photovoltaic (PV) power is rapidly expanding globally, led by China. In 2023, China added 216.3 GW of new PV capacity, a 148% increase from 2022, with distributed PV set to exceed 500 GW by 2030 (Zhang et al., 2023; National Development and Reform Commission, 2022). Globally, PV installations reached 444 GW in 2023, with significant growth driven by China. The European Green Deal (EC, 2024c) pushes PV adoption in Europe, but widespread use introduces challenges like voltage regulation in distributed systems (Gao et al., 2024). Buildings in the EU account for 40% of energy consumption and 35% of greenhouse gas emissions (European Environmental Agency, 2024). The European Green Deal (EC, 2024a) and Renovation Wave (EC, 2024b) aim to enhance building efficiency and cut emissions by 55% by 2030. Decarbonizing buildings, including in Poland, is essential across sectors to reduce energy costs and increase sustainability (EC, 2024d). Despite the growing adoption of these technologies, research focusing on small-scale industries remains limited, highlighting the need for further study.

2.2 Energy storage technologies

Fossil energy consumption has risen due to population and industrial growth (Nejat et al., 2015). Integrating energy storage with renewables like wind and solar is key for reducing fossil fuel reliance and improving energy equity (Wu et al., 2023; Sterner and Stadler, 2019). Storage technology addresses renewables' intermittency and reduces costs (Kittner et al., 2017), supporting energy security, job creation (Ram et al., 2020), and system value (Lott et al., 2014). Global energy demand keeps increasing, driven by key sectors. Fossil fuels made up 85% of 2015s energy consumption (Padamurthy et al., 2024), In 2021, they accounted for around 80% of the world's primary energy supply, underscoring the continued reliance on oil, coal, and natural gas (IEA, 2022b). At the same time, global energy demand keeps growing; the International Energy Agency projects a rise of roughly 24% between 2021 and 2040 under its Stated Policies Scenario, driven by population growth, urbanization, and expanding industrial activity (IEA, 2022b). This growth highlights the need for alternative energy sources and better storage solutions as fossil fuels pose environmental risks like rising CO2 emissions (Padamurthy et al., 2024). Despite efforts, non-hydro renewables provided just 3.3% of global energy in 2015, projected to rise to 10% by 2035 (Padamurthy et al., 2024). Renewable energy sources—especially wind and solar—have shown notable growth, supported by decreasing costs and supportive policies. According to the International Renewable Energy Agency, the share of renewables in global electricity generation reached approximately 30% in 2021 when including hydropower, and is projected to rise further over the coming decades (IRENA, 2022). Advances in energy storage technologies—spanning lithium-ion batteries, pumped hydro, and emerging solutions such as hydrogen storage—are crucial for reducing the intermittency of renewables and ensuring a stable energy supply (IEA, 2022a; IRENA, 2022). Energy storage is now crucial for integrating renewables into modern industrial processes (Qays et al., 2020). Industries depend on storage systems to capture excess energy and ensure stable operations during low generation periods (Frate et al., 2021).

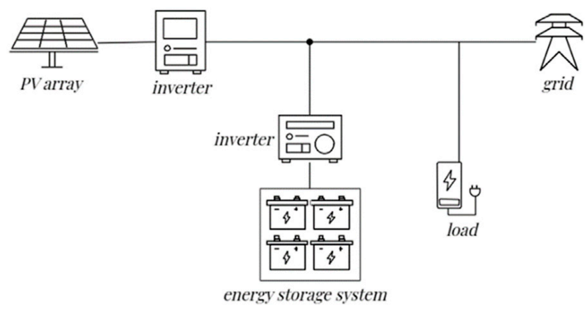

FIGURE 1
Schematic diagram of a typical PV energy storage access system. Source: (Gao et al., 2024).

Energy storage boosts independence, efficiency, and lowers emissions by reducing reliance on fossil fuels (Gschwind et al., 2015). It stabilizes renewable energy's variability, ensuring smooth industrial operations and grid reliability (Aghmadi and Mohammed, 2024). Advanced storage supports energy management strategies like demand response, reducing costs and optimizing resources (Ali et al., 2023). Continued policy support, robust investments, and international collaboration are essential to accelerate the transition toward a more sustainable and equitable energy future (IPCC, 2023).

Common storage technologies include flywheels, pumped storage, and electrochemical systems (Dincer and Ezzat, 2018). Lithium-ion and flow batteries are widely used in industries requiring frequent cycling or large-scale storage (Chaudhary et al., 2024). Thermal and compressed air systems also offer efficient solutions for specific industrial needs (Dincer and Erdemir, 2023; Olabi et al., 2021). Among these, electrochemical energy storage is the most widely adopted due to its quick response time and flexible configuration. The topology of a PV energy storage access system is illustrated in Figure 1.

Figure 1 illustrates a typical topology of a photovoltaic (PV) based energy storage system. The energy generated by PV modules is transferred to an inverter, which converts direct current (DC) into alternating current (AC) suitable for powering devices and feeding excess energy into the electrical grid. Surplus energy is stored in the energy storage system, allowing it to be used later during periods of higher demand. The energy storage system may include an additional inverter, enabling flexible energy management depending on the user's load requirements and grid conditions.

The choice of energy storage method typically depends on the specific application and various factors. These include the type of

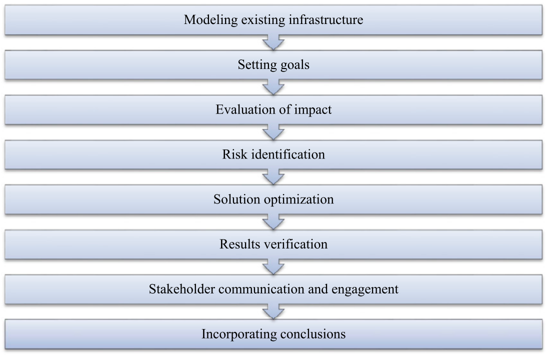

FIGURE 2
Steps in the process of simulating the implementation of renewable energy sources.

storage medium or material, the technique used, storage capacity, density, efficiency, and duration. Additional considerations are the rates of energy charge and discharge, the durability of the storage device, as well as initial and ongoing costs, and the environmental impact (Padamurthy et al., 2024).

3 Simulation of renewable energy deployment in construction sector

3.1 Methodology

Solar energy has emerged as a critical driver in the shift towards renewable energy worldwide, playing a major role in reducing energy consumption across various sectors (Vijayan et al., 2023; Huo et al., 2018). The building industry, responsible for a significant portion of global energy use and CO2 emissions (UNEP, 2021; IEA, 2020), is increasingly integrating solar technology to enhance energy efficiency and sustainability (Li et al., 2021; Muñiz et al., 2024). Solar panels, which generate clean electricity directly from sunlight, are transforming buildings by lowering grid dependency, cutting utility costs, and promoting energy independence through net metering (Skandalos et al., 2023; Calanter, 2015; Dai et al., 2022). Despite challenges like high initial costs and installation complexities, advancements in technology and economies of scale are making solar solutions more viable (Al-Radhi et al., 2023). Research highlights the environmental advantages of organic photovoltaic cells and silicon solar panels, emphasizing their lower environmental impact and contribution to reducing carbon emissions (Tsang et al., 2016; Oteng et al., 2023). As the global push for a green economy gains momentum, the construction sector's embrace of solar energy is pivotal in addressing climate change and achieving long-term sustainability.

In this research, the simulation of renewable energy sources in a construction manufacturing company involves modeling and analyzing various scenarios related to the adoption of new energy technologies and infrastructure. The company operates two production lines dedicated to manufacturing chemical products for construction, which are utilized in the execution of building projects. Additionally, the company maintains two storage

TABLE 1 Energy consumption of the company surveyed.

	Consumption		
Year 2021	17,435 kWh	Gross value	6466,55 EUR
Year 2022	20,607 kWh	Gross value	7740,06 EUR
Year 2023	**Consumption**	**Net value**	**Gross value**
January	2,710 kWh	890,61 EUR	1095,45 EUR
February	2,233 kWh	739,09 EUR	909,08 EUR
March	1968 kWh	665,24 EUR	818,24 EUR
April	1,640 kWh	562,07 EUR	691,34 EUR
May	1,290 kWh	454,23 EUR	558,70 EUR
June	1,197 kWh	432,72 EUR	532,24 EUR
July	997 kWh	360,42 EUR	443,31 EUR
August	1,384 kWh	464,58 EUR	571,44 EUR
September	1,500 kWh	503,52 EUR	619,33 EUR
October	1725 kWh	494,01 EUR	607,64 EUR
November	1,260 kWh	532,68 EUR	655,19 EUR
December	2,685 kWh	756,34 EUR	930,30 EUR
Total	21,189 kWh	6855,50 EUR	8432,27 EUR

warehouses to support its operations, alongside an administrative office that coordinates project management and business activities. This tool enables the simulation of the energy system's behaviour in response to changes such as the introduction of new energy sources, fluctuations in consumption, or shifts in market conditions. The process includes creating a model that incorporates factors like energy consumption, production, greenhouse gas emissions, weather conditions, energy prices, and regulations. Multiple simulations are then conducted to assess the impacts of these changes, including associated costs and benefits. Essentially, simulation serves as an analytical tool that provides companies with a deeper understanding of the effects of integrating renewable energy and supports more informed, data-driven decision-making. When simulating renewable energy implementation in a manufacturing company, focus on the key steps outlined in Figure 2.

The process of simulating the implementation of renewable energy sources begins with detailed modeling of the existing energy infrastructure, considering all production processes and energy consumption patterns (Kunatsa et al., 2024). Goals are then set, focusing on objectives like reducing greenhouse gas emissions, lowering energy costs, or enhancing energy independence. The potential impact on production processes, operational costs, energy balance, and efficiency is evaluated, followed by identifying risks such as supply instability or infrastructure adaptation needs. An optimization analysis is conducted to determine the most cost-effective, efficient, and sustainable solutions. The results are verified through simulations using historical data and forecasts related to energy consumption, prices, regulations, and technology. These findings are presented to stakeholders to gain support and engagement. Finally, the

TABLE 2 Investment cost estimate.

ID	Investment cost	
1	Net price	18497,65 EUR
2	Tax 23%	4254,46 EUR
3	Gross price of the entire investment	22752,11 EUR

conclusions are incorporated into the company's strategy to maximize the effectiveness and profitability of the renewable energy implementation. The calculations presented in this study were based on established methodologies and simulation tools widely employed in the evaluation of photovoltaic systems. Specifically, the simulation was conducted using PV*SOL, a leading industry-standard software that incorporates key factors such as the geographical location of the PV system, load profiles, and annual energy consumption. Additionally, the software considers detailed specifications of the PV modules, including manufacturer, model, orientation, and quantity, as well as the inverter's manufacturer.

The company under investigation is recognized as one of the leading manufacturers of construction materials in Poland, specializing in the development of innovative solutions for the construction sector. Its operations encompass the production of a diverse range of products, including mortars, adhesives, plasters, and other materials utilized at various stages of construction and building renovation. The company has established a strong reputation for the high quality of its products, which are distinguished by both their durability and exceptional technical properties, effectively addressing the increasingly stringent demands of the construction market. Furthermore, the enterprise is engaged in the production and distribution of construction materials for both domestic and international markets, offering a comprehensive portfolio of products that cater to different phases of construction and building modernization.

The electricity consumption over the past 3 years for the analyzed Polish manufacturing company in the construction industry has been presented in Table 1.

3.2 Results

In the surveyed company, there has been a noticeable trend of increasing electricity consumption by a few percentage points each year. This rise leads to higher maintenance costs across the organization, creating a need for efficient energy management and the exploration of alternative solutions, such as the adoption of renewable energy sources, to balance expenses. To better understand and address these growing costs, the company conducted a simulation on implementing renewable energy. This simulation allows for the prediction of the impact of rising electricity consumption and helps identify the most effective strategies for managing this issue.

Table 2 provides a cost estimate for the investment in a photovoltaic panel system for a manufacturing company within the construction industry. The table details the net cost of the photovoltaic panel installation along with the 23% value-added

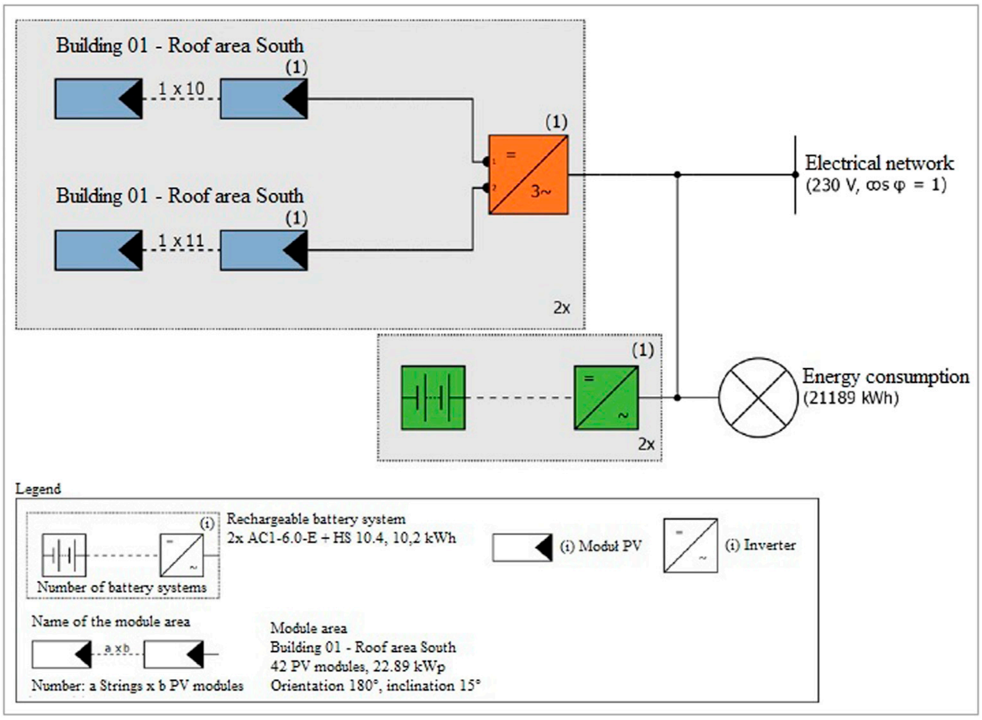

FIGURE 3
Technical diagram of the photovoltaic installation.

TABLE 3 Photovoltaic installation.

ID	Grid-connected photovoltaic installation (PV)	
1	PV generator power	22,89 kWp
2	PV generator area	108,5 m^2
3	Number of PV modules	42
4	Number of inverters	1

tax (VAT), ensuring a clear understanding of the total investment costs. By taking both of these values into account, the company can precisely estimate the overall cost of implementing the photovoltaic system and make informed financial decisions.

Figure 3 presents a comprehensive technical diagram of the photovoltaic installation, which also includes an energy storage system. This diagram provides detailed information on the electrical connections and all essential components, facilitating a thorough evaluation and implementation of the project. The inclusion of energy storage in the system enhances the overall efficiency and reliability of the installation. The detailed documentation ensures that the photovoltaic system can be effectively deployed in line with the planned specifications.

Table 3 presents basic data regarding the photovoltaic installation, including information such as the PV generator's power, its surface area, the number of photovoltaic panels, and the number of inverters. These key parameters allow for the evaluation of the system's performance, sizing of the photovoltaic system, and forecasting of investment profits.

The analysis of data related to the proposed photovoltaic installation provides a comprehensive understanding of its potential impact on the company's operations. This analysis enables the identification of several key indicators crucial for evaluating the efficiency and profitability of the system. First, by examining the energy produced by the installation, it is possible to estimate the amount of electricity generated over a specific period, which is essential for assessing potential savings and its impact on the company's energy balance. Additionally, analyzing the direct consumption of self-generated energy, the amount of energy returned to the grid, and the energy stored in the battery system allows for a thorough evaluation of the company's energy self-sufficiency and potential revenue from selling excess electricity back to the grid. The role of the energy storage system is also critical, as it enables the company to optimize energy usage by storing excess power for later use, reducing reliance on external electricity sources, and enhancing overall energy management. The share of self-consumption and the contribution of solar energy in meeting the company's demand are significant factors for understanding the role of renewable energy in its total energy requirements, which is important both economically and environmentally. Furthermore, the annual yield and efficiency coefficient serve as measures of the photovoltaic system's effectiveness and profitability, allowing for a comparison of actual performance with projections. Considerations such as reduced efficiency due to shading and the amount of CO_2 emissions that can be avoided highlight the system's operation under various environmental conditions and its environmental benefits through reduced greenhouse gas emissions.

TABLE 4 Simulation of plant operation PV.

ID	PV installation	
1	PV generator power	22,9 kWp
2	Annual yield	950,47 kWh/kWp
3	Performance ratio	85,2%
4	Reduction in yield due to shading	1,5%/Year
5	Energy produced by the PV system (AC grid)	21,890 kWh/Year
6	Own consumption of energy	6 730 kWh/Year
7	Charging the battery	5 163 kWh/Year
8	Energy returned to the grid	9 997 kWh/Year
9	Share own consumption of energy	54,1%
10	Avoidable CO_2 emissions	9 970 kg/Year

Simulation of the photovoltaic installation's operation, based on the previously mentioned data, allows for a comprehensive understanding of its functioning and efficiency. By utilizing the information provided in Table 3, various scenarios of the installation's operation under different weather and operational conditions can be modeled, enabling assessment of its production potential, impact on the company's energy balance, and estimation of savings and benefits associated with the implementation of renewable energy sources. The simulation has been presented in Table 4.

The parameters used in the simulation, were carefully selected based on widely accepted industry standards and relevant literature. These parameters ensure that the model accurately represents the operational conditions of photovoltaic (PV) systems in a manufacturing environment, particularly in Poland. The PV generator power was determined based on the company's energy requirements and available rooftop space for PV module installation. The chosen capacity balances the energy demands of the facility with the physical and financial constraints, ensuring sufficient electricity generation without overinvestment in unused capacity. The annual yield per kilowatt peak reflects the specific energy generation potential of the system, considering local climatic conditions and irradiance levels in Poland. This parameter was validated using PV*SOL simulation software, ensuring its accuracy for the geographic location. The performance ratio (PR) indicates the efficiency of the PV system, accounting for losses due to temperature, shading, and inverter performance (Gao et al., 2024; Skandalos et al., 2023). The value of 85.2% aligns with industry standards and empirical data for similar installations in Central Europe, making it a realistic and reliable choice for the simulation. A shading loss of 1.5% annually was included to account for potential partial obstructions from environmental or structural factors (Oteng et al., 2023; Zhang et al., 2023). This conservative assumption ensures that the analysis reflects real-world conditions, such as temporary shading from nearby objects or seasonal changes. This parameter represents the total annual energy output of the PV installation, providing a direct measure of the system's contribution to the company's electricity needs. It forms the basis for assessing cost savings, energy independence, and environmental benefits. The self-consumption rate highlights the extent to which the company can use the generated energy directly, reducing dependency on grid electricity. This parameter is critical for evaluating operational

TABLE 5 Potential electricity consumption scenario.

ID	Device	
1	Device	21,189 kWh/Year
2	Standby consumption (inverter)	133 kWh/Year
3	Total consumption	21,322 kWh/Year
4	Consumption covered by PV	6 730 kWh/Year
5	Consumption covered by the net battery	4 640 kWh/Year
6	Consumption covered by the network	9 952 kWh/Year
7	Solar energy's contribution to meeting demand	53,3%

efficiency and financial savings from reduced energy purchases. Energy stored in the battery supports load balancing and ensures energy availability during periods of low generation. This parameter was included to assess the benefits of integrating energy storage and its role in maximizing self-consumption. The amount of energy returned to the grid provides insights into potential revenue from feed-in tariffs and the system's contribution to the broader energy network. It also reflects the system's production surplus during peak generation. The self-consumption percentage demonstrates how effectively the company utilizes the generated energy on-site. This parameter is crucial for understanding the alignment of production and consumption profiles and for optimizing energy usage. Avoided CO_2 emissions quantify the environmental impact of transitioning to renewable energy. This metric underscores the sustainability benefits of the PV system, aligning with corporate social responsibility goals and regulatory requirements.

The data from Table 4 demonstrate that the photovoltaic system with a capacity of 22.9 kWp is an efficient solution, generating 21,890 kWh of electricity annually, of which 6,730 kWh is directly consumed by the company and 5,163 kWh is stored in batteries, collectively covering 54.1% of the company's energy demand. A surplus of 9,997 kWh is fed back into the grid, potentially generating additional financial benefits. This system also avoids the emission of 9,970 kg of CO_2 annually, significantly contributing to the company's sustainability goals. With a performance ratio of 85.2% and shading losses estimated at 1.5% per year, the installation is well-adapted to local conditions, ensuring stable energy cost savings and substantial environmental benefits.

The next step in the simulation involves presenting a potential scenario of electricity consumption for the past year, assuming the company had a photovoltaic installation in place. The analysis considers the total electricity consumption of 21,189 kWh, where standby consumption (inverter) accounted for 133 kWh. The photovoltaic installation covered 6,730 kWh, and an additional 4,640 kWh was supplied by the battery storage system. The remaining energy demand, totaling 9,952 kWh, was met by the electric grid. Solar energy contributed 53,3% to the total energy demand, underscoring the significant role of the photovoltaic installation in fulfilling the company's energy needs. This entire simulation step is detailed in Table 5.

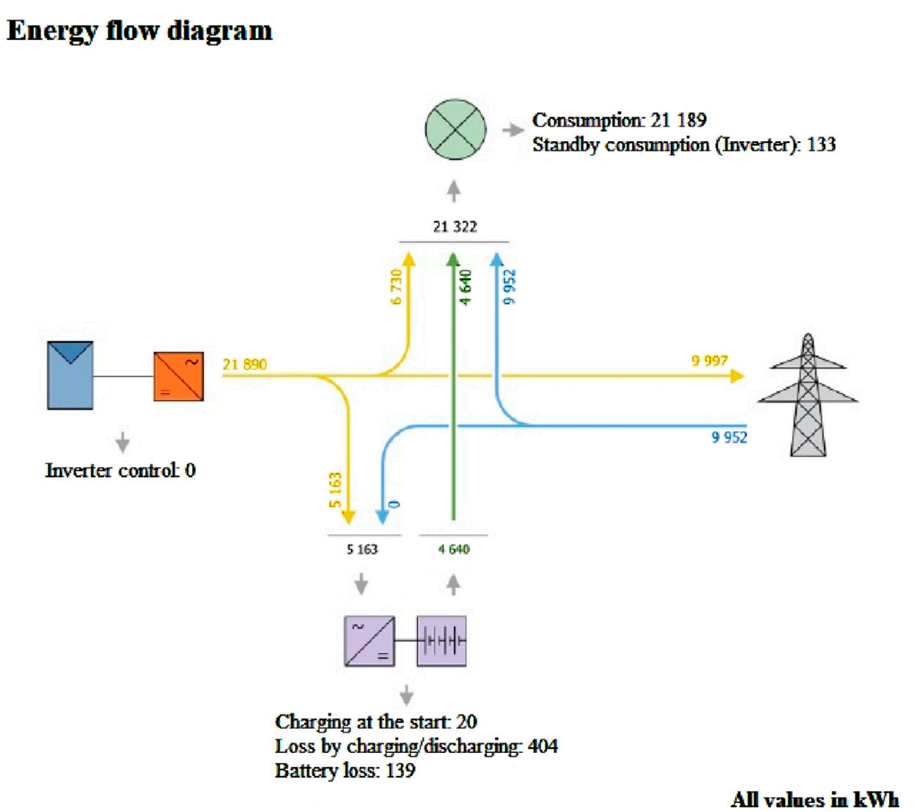

FIGURE 4
Energy flow diagram.

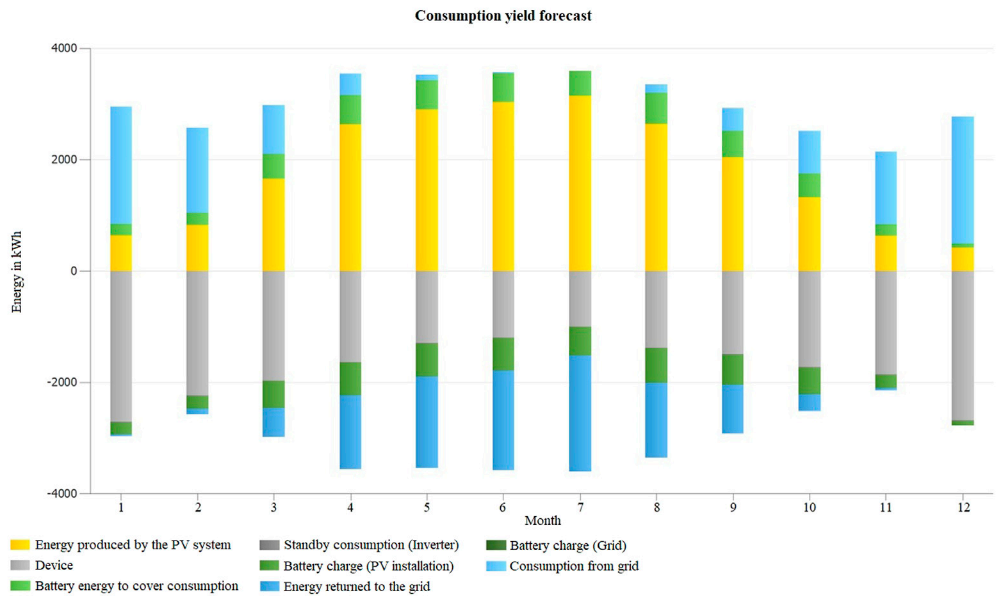

FIGURE 5
Functional forecast.

The energy flow diagram presented in Figure 4 visualizes the key processes of energy distribution within the manufacturing company, considering the photovoltaic installation and the energy storage system. The photovoltaic installation is capable of producing 6,730 kWh of electricity, which is used to meet various energy needs within the company. Additionally, 4,640 kWh of energy is supplied from the battery storage system, further contributing to the company's energy requirements. However, due to the variability of solar energy production, the company must also draw a portion of its energy from the electric grid to cover demand during periods of insufficient self-generation. This energy flow diagram helps to understand the role of the photovoltaic installation and the energy storage system in balancing the company's energy demand and its reliance on the electric grid.

Forecasting energy consumption and demand is essential for manufacturing enterprises, as it enables effective energy resource management and strategic planning. The annual energy consumption forecast, showed in a chart divided into 12 months, provides a detailed analysis of consumption trends and patterns throughout the year. The electricity consumption forecast was made by analyzing historical data from the enterprise, with particular emphasis on year-on-year consumption growth trends. The forecast methodology relied on statistical techniques, which allowed for the identification of patterns and dependencies in the historical consumption data. These trends were then extrapolated to predict future consumption. This figure includes eight key indicators: energy produced by the photovoltaic installation, energy consumption by the company's equipment, standby consumption, battery energy to cover consumption, battery charge (PV installation), energy returned to the grid, battery charge (grid), consumption from grid. The chart highlights the summer period as having the highest utilization of the photovoltaic installation due to favourable weather conditions typical in Poland. During this time, increased sunlight enhances the efficiency of electricity production by the photovoltaic panels, leading to a greater proportion of the company's energy demand being met through self-generation. By forecasting energy consumption and demand, companies can better prepare for variations in energy needs, optimize investments in energy infrastructure, and manage costs and energy efficiency throughout the year. This forecasting is presented in Figure 5.

The next step following the forecasting of energy consumption is analysing the utilization of solar energy by the company. Figure 6 provides a detailed monthly breakdown of this energy usage throughout the year. The chart highlights four key parameters: energy produced by the PV system, own consumption of energy directly, energy returned to the grid and battery charging. This detailed presentation allows for an in-depth assessment of how much of the generated solar energy is consumed by the company itself versus how much is transferred to the grid. This stage of analysis is essential for evaluating the efficiency and profitability of the photovoltaic installation, identifying areas for potential optimization, and making informed decisions about energy management.

The next important step is analyzing the profitability parameters of the photovoltaic installation. Table 6 presents key economic indicators that assess the investment's financial viability. The return on total expenditure stands at 10.31%, serving as a crucial indicator of long-term investment profitability. The cumulative cash flow of 67,195.95 EUR reflects a highly positive evaluation of the project's financial performance. The payback period of 9.4 years is a key metric, indicating the time required for the investment to generate sufficient returns to cover its initial cost. Additionally, the cost of electricity production at 0.08 EUR/kWh is a significant factor, allowing for comparison with other energy sources and assessing the competitiveness of the photovoltaic system in the energy market. These profitability parameters are essential for evaluating the solar energy investment and making informed strategic decisions for the company's growth. The calculated Levelized Cost of Electricity (LCOE) for the photovoltaic system

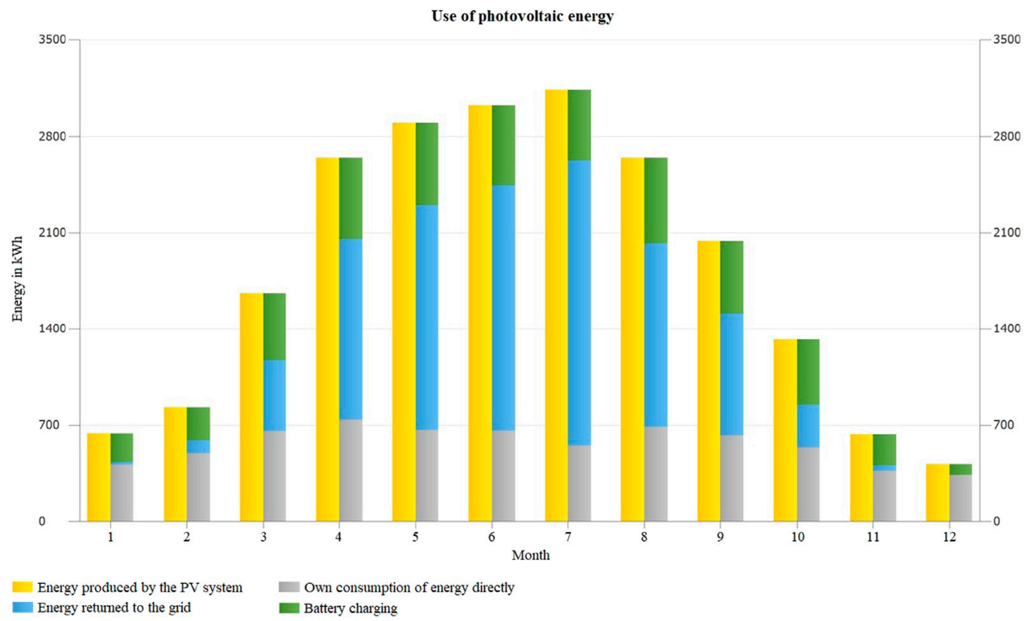

FIGURE 6
Use of photovoltaic energy.

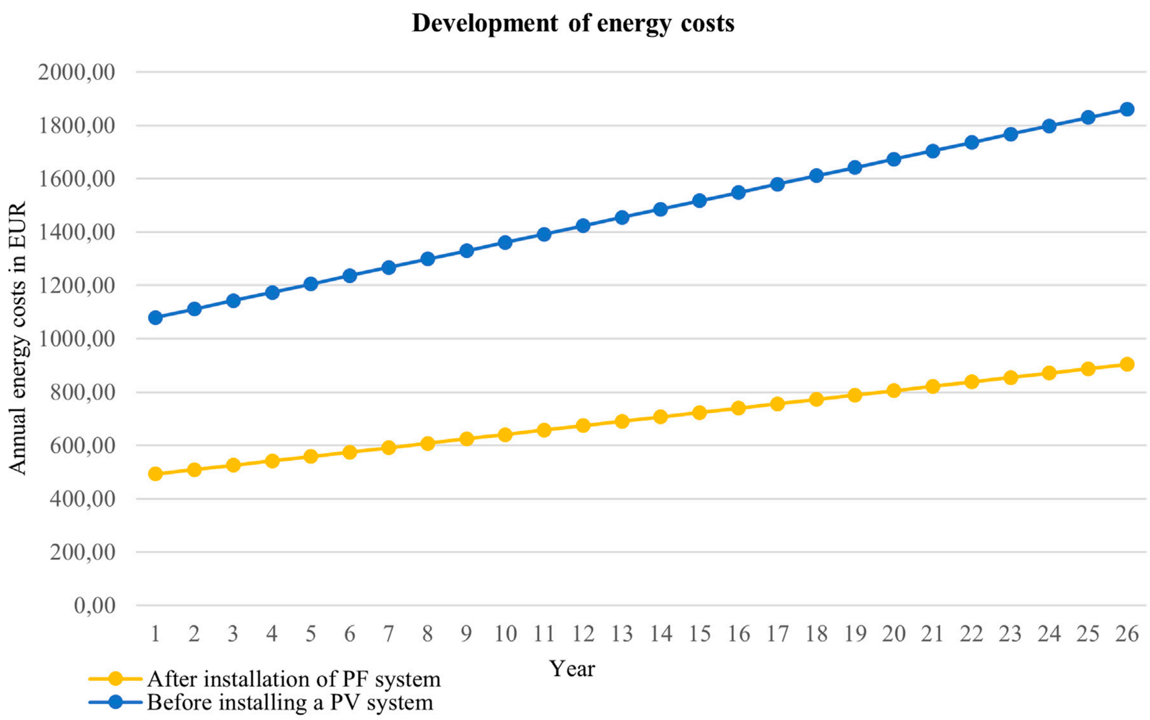

FIGURE 7
Development of energy costs.

is 0,08 EUR/kWh, assuming a 5% discount rate and annual operational costs at 1% of CAPEX. This value represents the total cost of electricity production over the system's 25-year lifespan, accounting for capital expenditures, operational expenses, and the time value of money.

Figure 7 presents a simulation of the development of energy costs over a period of 26 years, both before and after the installation of the photovoltaic system. It clearly indicates that after the implementation of the photovoltaic installation, the manufacturing company can significantly reduce its expenses on

TABLE 6 Profitability parameters.

ID	Profitability parameters	
1	Return on total expenditure	10,31%
2	Cumulative cashflow	67 195,95EUR
3	Depreciation period	9,4 Years
4	Levelized Cost of Electricity	0,08 EUR/kWh
5	Electricity generation costs	0,08 EUR/kWh

electricity during the analyzed period. This is a crucial reference point illustrating the benefits of employing renewable energy sources and can be a key factor in the company's investment decision-making process. Long-term analysis of energy costs before and after the installation of the photovoltaic system allows for a comprehensive understanding of the eco-nomic benefits associated with green technologies and their impact on the financial stability of the enterprise.

Figure 8 illustrates the cumulative cash flows over the review period. The data used in the simulation allows for an assessment of the project's profitability and determination of its long-term impact on the company's finances. Additionally, price degradation and escalation rates are applied monthly throughout the period under consideration. According to the data used in the simulation, these adjustments begin in the first year.

In summary, the financial analysis of the investment in the photovoltaic system demonstrates promising prospects for long-term profitability and financial savings for the Polish manufacturing company in the construction industry. At the end of the simulation the authors present a sensitivity analysis.

The sensitivity analysis of the investment in the photovoltaic system shows the key factors influencing the profitability and efficiency of the project. The results indicate that the most significant variables are the initial costs, electricity prices, energy production efficiency, storage capacity and regulatory changes. With a 20% increase in investment costs, the payback period is extended to about 11 years, which reduces the financial attractiveness of the project. On the other hand, a 20% reduction in costs, e.g., due to subsidies, shortens this period to 7.5 years, which significantly improves the return on investment (ROI). A 10% increase in electricity prices increases the savings from self-generation, shortening the payback period, while their decrease has the opposite effect. The efficiency of energy production plays a key role - its 10% reduction leads to greater dependence on the power grid and increases operating costs, while a 10% increase in efficiency improves energy self-sufficiency and project profitability. Changes in energy storage capacity by ±10% affect the energy independence of the household, which has a direct impact on the burden related to purchasing energy during peak periods. Changes in regulatory policy, such as the introduction of higher feed-in tariffs, significantly improve the attractiveness of investments by increasing revenues from energy fed into the grid. On the other hand, reducing subsidies or tax breaks significantly increases the effective cost of the installation, extending the payback period and reducing the investment potential. Figure 9 presents an analysis of the investment in a photovoltaic system, taking into account initial costs, energy efficiency, the impact of energy price changes and potential regulatory changes. The initial net price of the system is €18,497.65 (gross: €22,752.11) and the payback period is estimated at about 9.4 years at an energy generation cost of €0.08/kWh. The system generates 950.47 kWh/kWp per year, of which 6,730 kWh is consumed for self-consumption and 9,997 kWh is fed into the grid, reducing CO_2 emissions by 9,970 kg per year. Sensitivity scenarios consider various factors such as increases or decreases in installation

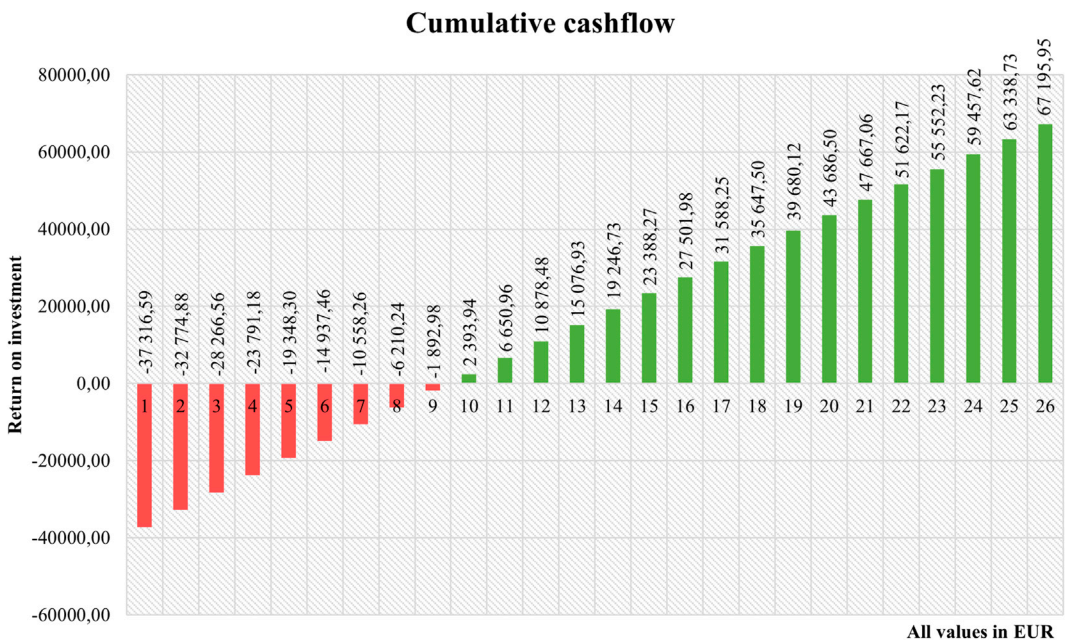

FIGURE 8
Cumulative cashflow.

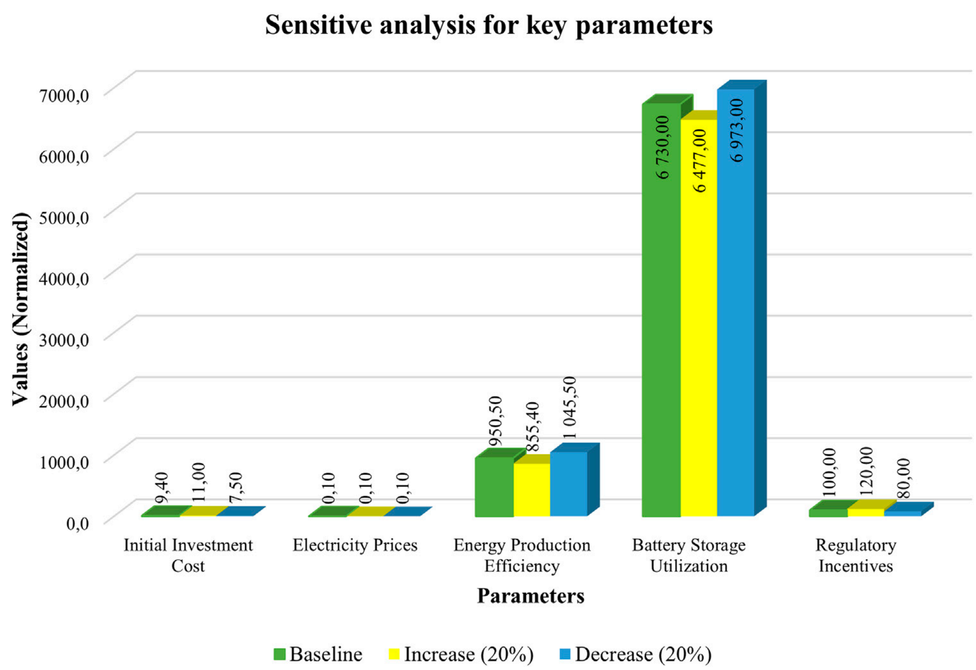

FIGURE 9
Sensitive analysis for key parameters.

costs (affecting the payback period from 7.5 to 11 years), changes in electricity prices (increasing or decreasing savings) and production efficiency (from 855.42 to 1,045.52 kWh/kWp per year). Also changes in energy storage capacity and regulations such as feed-in tariffs can significantly affect the project profitability. These results underline the need to monitor these parameters closely and optimize system configurations. Discusion and practical implications.

The analysis of electricity consumption and the proposed photovoltaic (PV) system for the surveyed Polish manufacturing company in the construction industry reveals several practical implications.

1. The continuous increase in electricity consumption over the past 3 years highlights the growing operational costs associated with energy use. Implementing a PV system offers a sustainable solution for mitigating these costs by generating on-site renewable energy, reducing dependency on grid electricity, and stabilizing energy expenses.
2. The financial analysis shows that the investment in PV technology is economically viable, with a projected payback period of 9.4 years. The return on total expenditure (10.31%) and cumulative cash flow forecast indicate substantial long-term profitability. For businesses in energy-intensive sectors, such as manufacturing, these savings can significantly enhance financial stability and competitive advantage.
3. The PV system is expected to cover 53.3% of the company's energy demand, with 54.1% of generated energy being directly consumed on-site. This degree of self-sufficiency reduces reliance on external energy sources, enhancing operational resilience, especially in times of energy price volatility.
4. The installation can help the company avoid approximately 9,970 kg of CO_2 emissions annually, contributing to the company's sustainability goals and compliance with increasingly stringent environmental regulations. Reducing greenhouse gas emissions also aligns with broader corporate social responsibility (CSR) objectives.
5. The incorporation of energy storage allows for better management of energy flows, enabling the company to store excess energy for use during peak demand or low sunlight periods. This maximizes energy utilization and reduces waste, leading to more efficient operations.
6. The detailed simulation and forecasting models provide valuable insights into energy consumption patterns throughout the year. This data-driven approach aids in long-term strategic planning, helping the company optimize its energy infrastructure and make informed decisions regarding further investments in renewable energy.
7. The analysis serves as a blueprint for future expansions or modifications. If energy demands increase or more stringent environmental regulations come into play, the company can scale the PV system or integrate additional renewable energy technologies seamlessly.
8. By stabilizing energy costs through renewable energy generation, the company can better predict and manage operational expenses. This predictability is crucial for budgeting and long-term financial planning, reducing exposure to energy market fluctuations.

4 Conclusion

The analysis of the proposed photovoltaic installation for the Polish manufacturing company in the construction industry reveals significant potential for energy savings and financial benefits over the long term. The data shows a consistent increase in electricity consumption over the past 3 years, highlighting the necessity for more efficient energy management. Implementing the photovoltaic system, as detailed in the simulation, would allow the company to generate a substantial portion of its energy needs internally, reducing dependency on external suppliers and stabilizing energy costs.

Key metrics from the study, such as a self-sufficiency rate of over 53% and a reduction in CO_2 emissions by nearly 10,000 kg annually, emphasize the environmental advantages of this transition. Additionally, the financial projections indicate a favorable return on investment, with a payback period of 9.4 years and a long-term savings potential of over 67,000 EUR. The analysis further highlights that after the initial investment, the cumulative cash flow steadily turns positive, demonstrating sustained profitability. The integration of energy storage systems further enhances operational efficiency by optimizing self-consumption and reducing the reliance on grid electricity during periods of low solar production. Moreover, the careful technical planning and expert consultation ensure that the photovoltaic system is tailored to the company's specific energy profile, maximizing its performance and return.

In conclusion, implementing a photovoltaic system is not only a viable strategy for reducing operating costs, but also consistent with sustainable business practices, offering long-term economic and environmental benefits. For the company studied, this investment represents a strategic step towards energy independence and resilience, with potential positive effects on both financial performance and environmental responsibility. For companies in similar industries, this case study serves as a practical example of how renewable energy investments can deliver both economic and environmental benefits.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AH-M: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. JS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. We agree.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aghmadi, A., and Mohammed, O. A. (2024). Energy storage systems: technologies and high-power applications. *Batteries* 10, 141. doi:10.3390/batteries10040141

Ali, Z. M., Calasan, M., Aleem, S. H. E. A., Jurado, F., and Gandoman, F. H. (2023). Applications of energy storage systems in enhancing energy management and access in microgrids: a review. *Energies* 16, 5930. doi:10.3390/en16165930

Allen, M. R. (2022). "IPCC framing and context," in *Global warming of 1.5 °C: IPCC special report on impacts of global warming of 1.5 °C above pre-industrial levels in context of strengthening response to climate change* (Cambridge, UK: Sustainable Development, and Efforts to Eradicate Poverty; Cambridge University Press), 49–92.

Al-Radhi, Y., Roy, K., Liang, H., Ghosh, K., Clifton, G. C., and Lim, J. B. P. (2023). Thermal performance of different construction materials used in New Zealand dwellings comparatively to international practice—a systematic literature review. *J. Build. Eng.* 72, 106346. doi:10.1016/j.jobe.2023.106346

Anghelache, C., Anghel, M. G., Iacob, S. V., Pârtachi, I., Rădulescu, I. G., and Brezoi, A. G. (2023). Analysis of the situation of renewable and non-renewable energy consumption in the European union. *Energies* 16, 1338. doi:10.3390/en16031338

Annamalai, S., and Vasunandan, A. (2024). Embracing intelligent machines: a qualitative study to explore the transformational trends in the workplace. *Central Eur. Manag. J.* 32 (3), 350–367. doi:10.1108/CEMJ-03-2023-0137

Buonocore, J., Luckow, P., Norris, G., Spengler, J. D., Biewald, B., Fisher, J., et al. (2016). Health and climate benefits of different energy-efficiency and renewable energy choices. *Nat. Clim. Change* 6 (1), 100–105. doi:10.1038/nclimate2771

Calanter, P. (2015). The main economic and environmental aspects relating to alternative technologies for the electricity production. *Qual. - Access Success* 16, 360–364.

Chaudhary, V., Pandit, M., Dubey, H. M., and Salkuti, S. R. (2024). Energy management in microgrid with battery storage system. 1, 23. doi:10.1007/978-3-031-18389-8_1

Colombi, C., and D'Itria, E. (2023). Fashion digital transformation: innovating business models toward circular economy and sustainability. *Sustainability* 15, 4942. doi:10.3390/su15064942

Cotta, B., and Domorenok, E. (2022). Catching up with the European union's recovery and resilience agenda: green transition reforms in the Italian national recovery and resilience plan. *Contemp. Ital. Polit.* 14, 424–440. doi:10.1080/23248823.2022.2126925

Dai, S. F., Liu, H. J., Yang, J. H., and Peng, H. Y. (2022). Wind loads on roof-mounted isolated solar panels of tall buildings through wind tunnel testing. *Sol. Energy* 231, 607–622. doi:10.1016/j.solener.2021.12.005

Dincer, I., and Erdemir, D. (2023). "Thermal energy storage systems," in *Book: solar ponds*. doi:10.1007/978-3-031-45457-8_2

Dincer, I., and Ezzat, M. F. (2018). Renewable energy production. *Compr. Energy Syst. Vol. 1-5* 3, V126–V207. doi:10.1016/B978-0-12-809597-3.00310-2

EC, (2024a). Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions—a renovation Wave for Europe: greening our buildings, creating jobs, improving lives, COM(2020) 662 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662 (Accessed on 25 August 2024).

EC (2024b). Delivering the European green deal. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#renovating-buildings-for-greener-lifestyles (Accessed on August 25, 2024).

EC (2024c). A European green deal: striving to Be the first climate-neutral continent. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (Accessed on August 25, 2024).

EC (2024d). Renovation Wave. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en (Accessed on August 25, 2024).

European Environmental Agency (2024). Greenhouse gas emissions from energy use in buildings in Europe. Available at: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-energy (accessed on August 25, 2024).

Frankowski, J. (2017). Transformacja energetyczna w polskiej gminie. Skutki polityki lokalnej opartej o odnawialne źródła energii na przykładzie Kisielic. *Pr. Geogr.* 149, 15–32. doi:10.4467/20833113PG.17.008.6924

Frate, G. F., Ferrari, L., and Desideri, U. (2021). Energy storage for grid-scale applications: technology review and economic feasibility analysis. *Renew. Energy* 163, 1754–1772. doi:10.1016/j.renene.2020.10.070

Gao, X., Zhang, J., Sun, H., Liang, Y., Wei, L., Yan, C., et al. (2024). A review of voltage control studies on low voltage distribution networks containing high penetration distributed photovoltaics. *Energies* 17, 3058. doi:10.3390/en17133058

Ghasemi, E., Azari, R., and Zahed, M. (2024). Carbon neutrality in the building sector of the global south—a review of barriers and transformations. *Buildings* 14, 321. doi:10.3390/buildings14020321

Gschwind, B., Lefevre, M., Blanc, I., Ranchin, T., Wyrwa, A., Drebszok, K., et al. (2015). Including the temporal change in PM2. 5 concentration in the assessment of human health impact: illustration with renewable energy scenarios to 2050. *Environ. Impact Assess. Rev.* 52, 62–68. doi:10.1016/j.eiar.2014.09.003

Gu, H., Liu, Y., Xia, H., Li, Z., Huang, L., and Zeng, Y. (2023). Temporal and spatial differences in CO2 equivalent emissions and carbon compensation caused by land use changes and industrial development in hunan province. *Sustainability* 15, 7832. doi:10.3390/su15107832

Hadžić, N., Kozmar, H., and Tomić, M. (2018). Feasibility of investment in renewable energy systems for shipyards. *Brodogradnja* 69 (2), 1–16. doi:10.21278/brod69201

Herudziński, T. (2021). Społeczna percepcja energetyki jądrowej w perspektywie procesów transformacji energetycznej w Polsce. *Człow. I Społeczeństwo T* LII, 251–265. doi:10.14746/cis.2021.52.13

Huo, T., Ren, H., Zhang, X., Cai, W., Feng, W., Zhou, N., et al. (2018). China's energy consumption in the building sector: a statistical yearbook-energy balance sheet based splitting method. *J. Clean. Prod.* 185, 665–679. doi:10.1016/j.jclepro.2018.02.283

IEA (2020). *Key world energy statistics 2020*. Paris, France: IEA.

IEA (2022a). *Global hydrogen review 2022*. International Energy Agency. Available at: www.iea.org.

IEA (2022b). *World energy outlook 2022*. International Energy Agency. Available at: www.iea.org.

IPCC (2023). *Climate change 2023: synthesis report*. Intergovernmental Panel on Climate Change. Available at: www.ipcc.ch.

IRENA, (2022). Battery storage for renewables: market status and technology outlook. *Irena. World energy transitions outlook 2023*. International Renewable Energy Agency. Available at: https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023 (Accessed on August 25, 2024).

Janik, W., Kaproń, H., and Paździor, A. (2018). Conditions for development of electricity production based on renewable energy sources. *Rynek Energii* (2), 22–27.

Karaaslan, A., and Çamkaya, S. (2022). The relationship between CO2 emissions, economic growth, health expenditure, and renewable and non-renewable energy consumption: empirical evidence from Turkey. *Renew. Energy* 190, 457–466. doi:10.1016/j.renene.2022.03.139

Kittner, N., Lill, F., and Kammen, D. M. (2017). Energy storage deployment and innovation for the clean energy transition. *Nat. Energy* 2 (9), 17125. doi:10.1038/nenergy.2017.125

Kunatsa, T., Myburgh, H. C., and De Freitas, A. (2024). A review on state-of-charge estimation methods, energy storage technologies and state-of-the-art simulators: recent developments and challenges. *World Electr. Veh. J.* 15, 381. doi:10.3390/wevj15090381

Kurtyka, M. (2021). Energetyka rozproszona jako element polskiej transformacji energetycznej. *Energ. rozproszona* (5-6), 7–13. doi:10.7494/er.2021.5-6.7

Lebedeva, K., Krumins, A., Tamane, A., and Dzelzitis, E. (2021). Analysis of Latvian households' potential participation in the energy market as prosumers. *Clean. Technol.* 3, 437–449. doi:10.3390/cleantechnol3020025

Li, X., Fang, Y., and Luo, F. (2022). A study on the willingness of industrial ecological transformation from China's zero waste cities perspective. *Int. J. Environ. Res. Public Health* 19, 9399. doi:10.3390/ijerph19159399

Li, Y., Wu, W., and Wang, Y. (2021). Global poverty dynamics and resilience building for sustainable poverty reduction. *J. Geogr. Sci.* 31, 1159–1170. doi:10.1007/s11442-021-1890-4

Lott, M. C., Kim, S. I., Tam, C., Houssin, D., and Gagné, J. F. (2014). *Technology roadmap: energy storage*. France: International Energy Agency IEA.

Manwell, J., McGowan, J., and Rogers, A. (2009). *Wind energy explained: theory, design and application*. New York: Wiley.

Marinina, O., Kirsanova, N., and Nevskaya, M. (2022). Circular economy models in industry: developing a conceptual framework. *Energies* 15, 9376. doi:10.3390/en15249376

Martins, F., Felgueiras, C., Smitkova, M., and Caetano, N. (2019). Analysis of fossil fuel energy consumption and environmental impacts in European countries. *Energies* 12, 964. doi:10.3390/en12060964

Miller, C., Iles, A., and Jones, C. (2013). The social dimensions of energy transitions. *Energy Res. and Soc. Sci.* 22 (2), 135–148. doi:10.1080/09505431.2013.786989

Młynarski, T. (2019). Unia Europejska w procesie transformacji energetycznej. *Krak. Stud. Międzynarodowe* 1, 31–44. doi:10.34697/2451-0610-ksm-2019-1-00

Mo, H., Jiang, K., Wang, P., Shao, M., and Wang, X. (2022). Co-benefits of energy structure transformation and pollution control for air quality and public health until 2050 in Guangdong. China. *Int. J. Environ. Res. Public Health* 14 (19), 14965. doi:10.3390/ijerph192214965

Muñiz, R., del Coso, R., Nuño, F., Villegas, P. J., Álvarez, D., and Martínez, J. A. (2024). Solar-powered smart buildings: integrated energy management solution for IoT-enabled sustainability. *Electronics* 13, 317. doi:10.3390/electronics13020317

National Development and Reform Commission (2022). *Renewable energy development plan for the 14th five-year plan; NDRC*. Beijing, China: National Development and Reform Commission.

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., and Abd, M. Z. (2015). A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). *Renew. Sustain. Energy Rev.* 43, 843–862. doi:10.1016/j.rser.2014.11.066

Olabi, A., Wilberforce, T., Ramadan, M., Abdelkareem, M. A., and Alami, A. H. (2021). Compressed air energy storage systems: componentsand operating parameters — a review. *J. Energy Storage* 34, 102000. doi:10.1016/j.est.2020.102000

Oteng, D., Zuo, J., and Sharifi, E. (2023). An evaluation of the impact framework for product stewardship on end-of-life solar photovoltaic modules: an environmental lifecycle assessment. *J. Clean. Prod.* 411, 137357. doi:10.1016/j.jclepro.2023.137357

Padamurthy, A., Vatala, M., V Ch, R. K., Santosh, P., Sheelwant, A., and Vemanaboina, H. (2024). A review on energy storage technologies: current trends and future opportunities. *J. Phys. Conf. Ser.* 2765, 012007. doi:10.1088/1742-6596/2765/1/012007

Ponomarenko, T., Marinina, O., Nevskaya, M., and Kuryakova, K. (2021). Developing corporate sustainability assessment methods for oil and gas companies. *Economies* 9, 58. doi:10.3390/economies9020058

Popkiewicz, M. (2016). *Rewolucja energetyczna. Ale po co?* Warszawa: Sonia Draga.

Postula, M., Kluza, K., Zioło, M., and Radecka-Moroz, K. (2024). Managing health through environmental policies. Analysis for European Union countries. *Central Eur. Manag. J.* 32 (1), 93–115. doi:10.1108/CEMJ-05-2023-0194

Qays, M. O., Buswig, Y., Hossain, M. L., and Abu-Siada, A. (2020). Recent progress and future trends on the state of charge estimation methods to improve battery-storage efficiency: a review. *CSEE J. Power Energy Syst.* 8, 105–114. doi:10.17775/CSEEJPES.2019.03060

Ram, M., Aghahosseini, A., and Breyer, C. (2020). Job creation during the global energy transition towards 100% renewable power system by 2050. *Technol. Forecast. Soc. Change* 151, 119682. doi:10.1016/j.techfore.2019.06.008

Rangarajan, S. S., Collins, E. R., and Senjyu, T. (2024). Grid forming inverter as an advanced smart inverter for augmented ancillary services in a low inertia and a weak grid system towards grid modernization. *Clean. Technol.* 6, 1011–1038. doi:10.3390/cleantechnol6030051

Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L., Maycock, T. K., et al. (2018). Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II; *U.S. Glob. Change Res. Program*: 1515p. doi:10.7930/NCA4.2018

Renna, P., and Materi, S. (2021). A literature review of energy efficiency and sustainability in manufacturing systems. *Appl. Sci. Switz.* 11 (16), 7366. doi:10.3390/app11167366

Rossiter, A. (2019). Energy saver: is your site ready for renewables? Several factors impact the demand and readiness of renewable energy sources for industrialuse. *Chem. Process.* 81 (11), 5–8.

Rymarczyk, J. (2020). Technologies, opportunities and challenges of the industrial revolution 4.0: theoretical considerations. *Entrepreneurial Bus. Econ. Rev.* 8 (1), 185–198. doi:10.15678/EBER.2020.080110

Sheina, S. G., Muhsin, M. D., and Girya, L. V. (2022). Use of renewable energy sources in extreme climatic conditions. *IOP Conf. Ser. Earth Environ. Sci.* 979 (1), 012190. doi:10.1088/1755-1315/979/1/012190

Siontorou, C. G. (2023). Fair development transition of lignite areas: key challenges and sustainability prospects. *Sustainability* 15, 12323. doi:10.3390/su151612323

Skandalos, N., Kapsalis, V., Ma, T., and Karamanis, D. (2023). Towards 30% efficiency by 2030 of eco-designed building integrated photovoltaics. *Solar* 3, 434–457. doi:10.3390/solar3030024

Smil, V. (2010). *Energy transitions. History, requirements, prospects*. Westport: Praeger.

Solar Power Europe (2023). A milestone year for renewable energy in europe—unveiling ember's electricity review. Available at: https://www.solarpowereurope.org/news/2023-a-milestone-year-for-renewable-energy-in-europe-unveiling-ember-s-electricity-review (Accessed on August 25, 2024).

Spellman, F., and Bieber, R. (2016). *The science of renewable energy*, 1–306.

Sterner, M., and Stadler, I. (2019). *Handbook of energy storage: demand, technologies, integration*. Berlin: Springer.

Tsang, M. P., Sonnemann, G. W., and Bassani, D. M. (2016). Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Sol. Energy Mater. Sol. Cells* 156, 37–48. doi:10.1016/j.solmat.2016.04.024

United Nations Environment Programme (UNEP) (2021). *2021 global status report for buildings and construction: towards a zero-emissions, efficient and resilient buildings and construction sector*. Nairobi, Kenya.

Uniyal, S., Paliwal, R., Kaphaliya, B., and Sharma, R. K. (2020). "Human overpopulation: impact on environment," in *Megacities and rapid urbanization: breakthroughs in research and practice* (Hershey, PA, USA: IGI Global), 20–30.

Upadhyay, S., Ahmed, I., and Mihet-Popa, L. (2024). Energy management system for an industrial microgrid using optimization algorithms-based reinforcement learning technique. *Energies* 17, 3898. doi:10.3390/en17163898

Vijayan, D. S., Koda, E., Sivasuriyan, A., Winkler, J., Devarajan, P., Kumar, R. S., et al. (2023). Advancements in solar panel technology in civil engineering for revolutionizing renewable energy solutions—a review. *Energies* 16, 6579. doi:10.3390/en16186579

Wells, P., Abouarghoub, W., Pettit, S., and Beresford, A. (2020). A socio-technical transitions perspective for assessing future sustainability following the COVID-19 pandemic. *Sustain. Sci. Pract. Policy* 16, 29–36. doi:10.1080/15487733.2020.1763002

White, D. (2020). Just transitions/design for transitions: preliminary notes on a design politics for a green new deal. *Cap. Nat. Soc.* 31, 20–39. doi:10.1080/10455752.2019.1583762

Wu, T., Wang, J.-W., Qu, S., Mi, Z., and Wei, Y.-M. (2023). Frontiers of energy storage technologies. *Int. J. Energy Res.* 2023, 1–14. doi:10.1155/2023/7138669

Yin, K., Xiao, Y., Shen, X., Zhu, Y., and Yang, Y. (2024). Review of photovoltaic–battery energy storage systems for grid-forming operation. *Batteries* 10, 288. doi:10.3390/batteries10080288

Zemite, L., Kozadajevs, J., Jansons, L., Bode, I., Dzelzitis, E., and Palkova, K. (2024). Integrating renewable energy solutions in small-scale industrial facilities. *Energies* 17, 2792. doi:10.3390/en17112792

Zhang, J., and Li, J. (2024). Revolution in renewables: integration of green hydrogen for a sustainable future. *Energies* 17, 4148. doi:10.3390/en17164148

Zhang, Z., Lyu, Q., and Zhang, J. (2023). Research progress and prospect of distributed PV power generation technology under the goal of emission peak and carbon neutrality. *Sol. Energy*, 17–21. doi:10.19911/j.1003-0417.tyn20211104.01