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Integrating Renewable Energy Solutions in Small-Scale Industrial Facilities

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Abstract: The purpose of this study was to analyze the economical suitability of numerous on-site renewable electricity generation technologies which were intended to be used in a recently built industrial facility designed and utilized as a warehouse. The facility was located in the vicinity of Riga, Latvia. Data were collected and calculations were performed within the scope of the project "Mitigating Energy Poverty through Innovative Solutions" as part of several planned activities to address the broad spectrum of energy poverty and self-reliance issues in both the residential sector and small-scale industrial facilities. During the project, evaluations of various renewable energy technologies, including PV installations, wind energy installations, battery storage solutions, and hybrid technologies, were carried out. The aim of these evaluations was to develop an electricity production–consumption model for efficient and cost-effective energy use and to reduce greenhouse gas emissions from the test facility. A model was created and subsequent research scenarios were developed based on a payback period instead of the net present value criterion. The project was carried out over several steps to develop a calculation methodology. The open access databases of energy resource providers were used to evaluate statistical data and make forecasts for the analysis of the electricity consumption of companies. MATLAB/Simulink 23/2 was used for the data analysis, and the H-TEC method was employed. This made it possible to modulate the required production capacity as the model allowed for the addition of new modules to modules already installed. The project results proved that despite high initial investment costs, renewable energy sources and efficient storage systems can provide cost-effective solutions and reduce dependence on fossil fuels in the long term.

Keywords: energy technologies; renewable electricity production; industrial buildings; cost effectiveness

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1. Introduction

The integration of renewable energy technologies into industrial infrastructures is increasingly becoming a focal point for achieving sustainable and autonomous energy solutions. This study focused its investigation within the rapidly evolving landscape of energy systems, transitioning from traditional centralized electricity generation to decentralized, consumer-driven models. This shift is especially relevant in the context of small-scale industrial facilities in which the potential for on-site renewable energy generation could lead to significant advancements in energy efficiency and reductions in greenhouse gas emissions.

The functionality and architecture of electricity systems have remained almost unaltered for many decades and are based on the principle of centralized electricity generation, transmission, and distribution, in which electricity producers and consumers occupying residential, commercial, and industrial real estate do not normally intersect. However, the gradual evolution of energy generation technologies has given consumers access to versatile options for on-site energy generation. In particular, solar power systems (including both photovoltaic (PV) and solar heating/cooling applications), wind energy installations, and micro-cogeneration systems have experienced rapid growth [1]. These technologies not only support the creation of energy–prosumer environments but also align with broader economic and regulatory frameworks that encourage renewable energy adoption. The potential for these technologies to meet and exceed the energy needs of industrial buildings while ensuring economic viability is of particular interest. This means that after only consuming electricity for decades, a variety of buildings have acquired the ability to also generate electricity for self-consumption, thus meeting the needs of their energy communities and transferring power directly to the grid. To balance on-site generation and the amount of electricity received from the grid, a net energy system (an energy-metering scheme) is employed in many countries, including Latvia, where its popularity has gained significant momentum in the residential sector [2]. In fact, with time and progress in on-site generation technology, some high-performance buildings have become permanent net generators with electricity production surpassing their own consumption. This is a desirable outcome for creating a more energy-efficient, cost-effective, and sustainable European real estate sector in the future [3–5]. Despite the growing implementation of such technologies, there remains a significant gap in the literature regarding their optimization and full potential within the specific context of small-scale industries. Previous studies often focused on residential or large-scale industrial applications, leaving a notable void in the research tailored to smaller industrial facilities with different operational dynamics and financial constraints.

Currently, in the European Union (EU), buildings are responsible for about 40% of energy consumption and 35% of greenhouse gas (GHG) emissions [6]. This covers the entire lifecycle of a building, which includes its construction, exploitation, renovation, and demolition stages. Consequently, in the context of the European Green Deal [7] agenda and the Renovation Wave initiative [8,9], one way to improve the energy performance of buildings and reduce their emission levels is to promote green and sustainable micro and on-site energy generation in all types of buildings and their complexes. Adopting a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net GHG emissions by at least 55% by 2030 compared to the levels in 1990 also creates an obligation for different groups of energy consumers, including the real estate and building sectors, to reduce their GHG emissions and significantly improve their energy efficiency to avoid GHG emission peak reoccurrences in the future [10].

In the Latvian building and real estate sector, a lifecycle-oriented decarbonization agenda is an obvious priority as well. This is because not only the residential sector but also other kinds of industries and businesses have shown an ever-growing interest in reducing their yearly energy expenses and achieving this goal in the most effective and sustainable way possible. One of these ways involves buildings producing electricity on site to meet their own energy needs and, if possible, feeding part of the generated electricity into the distribution grid [11].

At the end of 2023, more than 20,000 small-scale electricity producers with a total installed capacity of more than 560 megawatts (MW) were connected to the Latvian electricity distribution system, including solar and wind generators, small-scale hydroelectric power plants, micro-cogeneration systems, and biomass plants. In more than 99% of cases, clients chose to install a PV system as an electricity-producing scheme, and only less than 1% of cases adopted wind-powered microgenerators [12]. Similar trends in the domination of other small-scale electricity-production technologies in PV installation have also been observed [13] in Baltic countries in the EU context.

Last year, the relatively rapid development of on-site microgeneration continued, although its pace was slightly slower than in 2022, when an unprecedented PV installation peak was observed in Latvia. Almost 10,000 microgenerators with a total capacity of about

80 MW were installed and connected to the distribution system in 2022; a year later, this figure fell to 8000 microgenerators and a total installed capacity of about 70 MW. However, the total number of microgenerators connected to the distribution infrastructure exceeded 19,000 at the end of 2023, and their total production capacity reached 160 MW. A rapid increase in installation capacity was observed in the final months of the year, with the number of permits issued in December alone reaching 1300. This was most likely related to changes in the net accounting scheme—one can become a member until 30 April 2024 and use it until 28 February 2029, at which time it will be closed [14]. Last year, the average power of connected installations increased significantly; in 2022, the average installation power was approximately 85 kilowatts (kW), and in 2023, it reached 250 kW. The amount of solar generation produced and transferred to the distribution grid was approximately 128 gigawatt-hours (GWh). A year earlier, it was approximately 30 GWh, and in 2021, it was a meager 6.5 GWh [15].

Industrial real estate owners in Latvia are becoming increasingly interested in possibilities of generating electricity for local consumption on site, with or without the ability to feed the surplus into the distribution grid [16–18]. However, case studies are usually advised and are conducted prior to actual decision making in order to determine what kind of on-site electricity-generation installation or cascade of installations would provide the best solution for the objects in question [19,20]. One such object is a recently built industrial building, designed and used as a warehouse, that was evaluated as a potential on-site generation space within the project "Mitigating Energy Poverty through Innovative Solutions" [21]. This project was carried out in 2023 and combined scientific research achievements with practical application possibilities, with a focus on improving the energy efficiency and sustainability of industrial real estate. The aim of this project was to develop an electricity production–consumption model to ensure efficient and cost-effective energy use, thus reducing carbon dioxide (CO_2) emissions and promoting a greener and cleaner environment.

The scientific novelty of this research lies in its focused exploration of the integration of renewable energy solutions within the specific context of small-scale industrial facilities near urban centers, specifically by examining a case in Latvia. Unlike existing studies that often examined solar or wind energy in isolation, this study evaluated the combined effects of photovoltaic systems, wind energy installations, and battery storage solutions as a unified hybrid system. This holistic approach allowed for an in-depth understanding of how different technologies can complement each other to enhance energy reliability and efficiency in small-scale industrial settings. This research introduced a sophisticated model for predicting and optimizing the balance between energy production and consumption on site. This model incorporates real-time data analytics and simulations using MATLAB/Simulink, with a focus on the specific climatic and operational conditions of Latvia. It allows for more accurate forecasting and scenario planning, which are crucial for ensuring economic viability and sustainability. By integrating an economic analysis that responds to fluctuating energy prices and government incentives, this study provides a dynamic assessment of the cost-effectiveness of renewable installations. This assessment is novel in its application to small-scale industries, in which financial constraints are often more pronounced, as it offers a viable blueprint for decision making under varying economic conditions. This research extended the analysis of renewable systems to include broader sustainability metrics, such as a reduction in greenhouse gas emissions and alignment with EU energy policies. This comprehensive approach allowed for a detailed assessment of environmental impact, thus contributing to the policy discussion on energy strategies and climate action. In this research, the proposed energy solutions were not only developed but also tested in a real-world environment. This empirical testing provided critical data on the operational challenges and potential technological adjustments needed for optimal performance, thus contributing practical insights that are often missing in theoretical research.

This study aimed to fill a gap by providing a comprehensive analysis of the feasibility, challenges, and impacts of deploying renewable energy solutions in a recently constructed industrial warehouse in Latvia. By focusing on the specific needs and conditions of this scale and context, this research contributes to a more nuanced understanding of sustainable energy transitions in the industrial sector. These findings are expected to offer valuable insights into the practical implications of renewable energy technologies, thus providing a blueprint for their broader application across similar industrial settings. To achieve the set goal, the following research tasks were performed: an analysis of the energy consumption patterns of the test facility; the primary exclusion of the renewable technologies that were not economically or/and technically suitable for installation and use in the test facility; the identification and analysis of renewable technologies that were suitable for use in the test facility, with or without hybrid options; and an evaluation of the suitable technologies and their comparison with conventional energy applications available as baseload generators.

2. Materials and Methods

This project focused on the use of climate-efficient technologies that can significantly improve energy efficiency and reduce costs which, in the long term, could contribute to less dependence on fossil fuels and lay the foundation for more sustainable building operations.

This project's goal was to create a model of electricity consumption under energy market conditions on the basis of which a methodology for the evaluation of generation-related energy-efficient solutions could be developed for specific buildings. In order to achieve this goal, a case study object (test facility) was selected in collaboration with the project's industrial partner. The test facility was located near Riga and was a recently built industrial building designed and used as a warehouse. The square meterage of the facility's floor was 450 m^2 (see Figure 1).

Figure 1. The industrial building used as a test facility.

The test facility began its operations in April 2022 (Figure 1). Natural gas was used for heating, and electricity was provided via a distribution grid connection only. Alternative electricity supply technologies were evaluated for a period of time covering 1 year and 7 months, with final calculations and a summary of the results made in December of 2023. Due to the fact that daylight in the test facility was rather limited, the impact of daylight-saving measures on electricity consumption was not included in the project; however, for better-insolated objects, this measure should be taken into consideration.

The proposed method allowed all possible combinations of technical solutions for generation to be showcased based on their consumption patterns and their technical implementation constraints. It also enabled an assessment of the investment payback periods for each scenario. This approach allowed for a clear evaluation of all the options and the selection of the most suitable for investment, which was often not the most optimal.

To implement the proposed approach, a model was created. The main part of the model was the scenario generator—**5**. This component generated all the possible combinations of generation sources and storage—**4**—within the specified technical constraints—**1**. The electricity generation model represented the technical parameters and generated power of every type of generation for every hour based on metrological data. Technical limitations were applied to the installation of the generating capacity and battery storage as constraints. The electricity price—**2**—represented the Nord pool hourly electricity market prices for Latvia. The electricity transmission and distribution tariffs—**3**—represented the transmission and distribution system operators' tariffs. The investment costs—**6**—represented the investment costs of the generation equipment and the equipment installation. The warehouse model—**7**—represented the electricity consumption model (Figure 2).

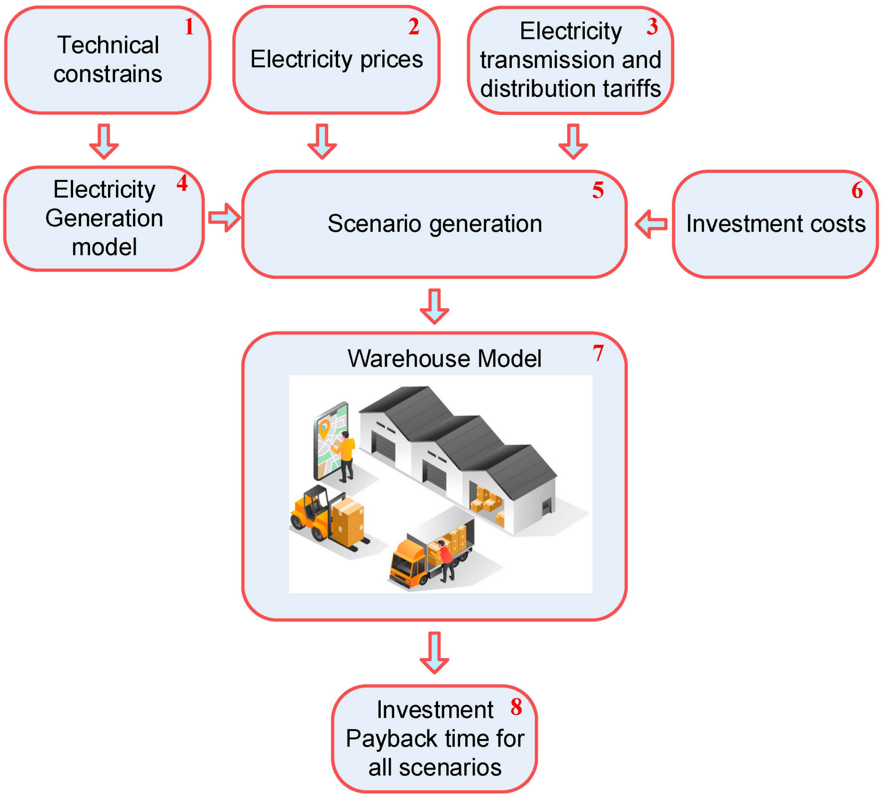


Figure 2. A visual representation of the investment payback period assessment for each scenario.

The output of the model in Figure 2 was an assessment of the payback (formula) period—**8**—for each scenario. At the request of the industrial partner, the net present value (NPV) criterion was abandoned and the payback period was used instead. This decision was primarily due to significant uncertainty regarding the bank interest rate.

$$PB = I/NCF$$

PB—payback period;
I—initial investment;
NCF—net cash flow per period.

$$I = Equipments\ costs + Instalation\ costs$$

$$NCF = \sum_{i=1}^{n}((PL_i - PN_i)(C_i + T_i + D_i) + PS_i(CS_i - T_i - D_i\ ))$$

PL—initial electricity consumption per hour;
PN—electricity from network per hour;

C—electricity market price, EUR/kWh;
T—transmission tariff per kWh;
D—distribution tariff per kWh;
PS—power sold to the network per hour;
CS—price for sold electricity, EUR/kWh.

The project was carried out in several steps to develop a calculation methodology. The open access databases of energy resource providers were used, for example, the electricity consumption database of the Latvian electricity distribution operator JSC, "Sadales tikls", was used in order to evaluate the statistical data and make forecasts for the analysis of the electricity consumption of companies. The participants in this project had access to scientific software, such as MATLAB/Simulink 2023, as well as the high-performance computing techniques necessary to both perform an assessment of the electricity consumption and self-generation and use the energy resource technologies. At the same time, it was possible to modulate the required production capacity using the H-TEC method as the model allowed for the addition of new modules to the modules already installed. The participants in this project also had access to pre-developed models which could be used to achieve the project's goal and allow the relevance of the input data, chosen criteria, initial assumptions, and constraints to be assessed.

Initially, data on the test facility's operation were collected. Electricity consumption data between 04.2022 and 12.2022 and between 01.2023 and 11.2023 are shown in Figures 3 and 4.

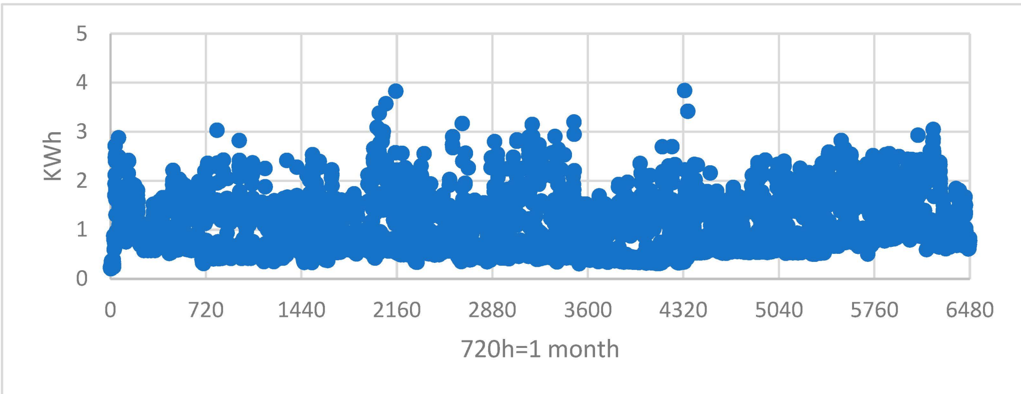


Figure 3. The test facility's electricity consumption data (04.2022–12.2022).

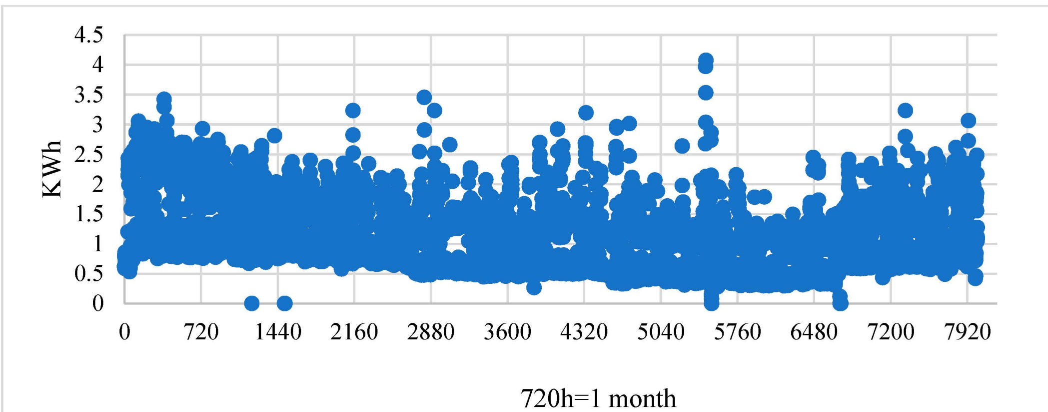


Figure 4. The test facility's electricity consumption data (01.2023–11.2023).

Changes in electricity prices were taken into consideration as well. In 2022, there was a significant increase in the price of electricity as well as an increase in the amplitude of price fluctuations (Figures 3 and 4). In turn, this increased the profitability of using on-site generation and storage technologies, as stated in [22].

Negative electricity prices occur during periods when the supply exceeds the demand and the grid is unable to store excess energy. With renewable energy sources such as wind and solar, which are intermittent and uncontrollable, there are times when more electricity is produced than is needed. During times of unusually low demand, such as overnight or during certain holidays, electricity consumption decreases, but if the generation remains constant or is unable to be scaled down accordingly, this leads to an excess in supply. However, the situation stabilized in 2023; therefore, using only historical data from 2022 to predict the profitability of various technologies would not be accurate. These price fluctuations are shown in Figure 5.

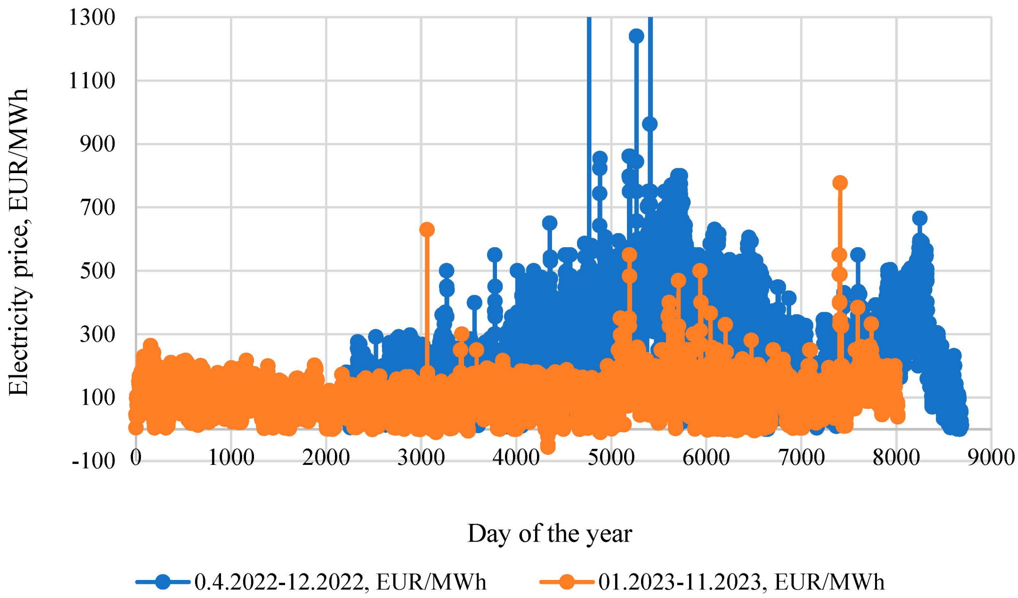


Figure 5. Electricity price fluctuations (04.2022–12.2022 and 01.2023–11.2023).

3. Results

During this project, several potential electricity-generation technologies were examined, namely hydrogen production with subsequent storage and conversion into electricity on demand; PV solar applications; wind energy applications (with a lithium-ion battery storage option); and diesel generation, which provided a price reference for the electricity generated from the other technologies on one hand and stable generation assurance on the other.

In 2022, the capital costs of hydrogen production facilities in Europe differed by technology. The cost for alkaline water electrolysis was around 1590 EUR/kW, while for proton exchange membrane electrolysis (PEMEL), it was around 1758 EUR/kW. The efficiency of hydrogen production largely depended on the cost of electricity, the necessary amount of capital investment, and the efficiency of the chosen electrolyzer [23–26]. The efficiency of the technologies decreased accordingly with the need to convert the hydrogen back into electricity, while the capital costs increased. Therefore, hydrogen technologies were found to be uncompetitive for the test facility and were not considered further. Hydrogen technologies could be economically justified for objects with more potential for local consumption and a larger installed capacity [27] of at least 1 MW and/or with the option of direct hydrogen consumption, which was not available in and around the test facility.

3.1. Solar PV Installations

The second technology option—lithium-ion batteries—was considered in relation to power-generation equipment. LiFePo4 batteries have an average market price of 400 EUR/kWh, and two battery usage strategies were reviewed within this project.

Exploring various energy storage techniques is essential for enhancing the flexibility and efficiency of renewable energy systems. Different storage technologies offer unique advantages and limitations based on their chemical properties, cost, durability, and efficiency. Flow batteries, especially vanadium redox flow batteries (VRFBs), are well suited to large-scale energy storage applications. They store energy in liquid electrolyte solutions that flow through electrochemical cells during charge and discharge cycles.

The role and characteristics of batteries, particularly lithium-ion batteries, in renewable energy systems are critical due to the ability of batteries to store energy efficiently. This is especially significant in industrial applications in which the balance between energy production, storage, and consumption directly impacts operational efficacy and cost-effectiveness. Lead–acid batteries are some of the oldest types of rechargeable batteries and are widely used for a variety of applications, including backup power and automotive systems. Nickel–cadmium (NiCd) and nickel–metal hydride (NiMH) batteries are two common types of nickel-based batteries. Other innovative storage technologies include solid-state batteries, supercapacitors, and lithium–sulfur batteries, with each promising improvements in safety, energy density, and longevity. Each storage technology offers distinct advantages and challenges, making each one suitable for specific applications. The choice of a particular technology often depends on the specific needs of the energy system, such as the capacity, discharge duration, environmental impact, installation space, and budget.

Lithium-ion batteries are composed of cells with an anode, a cathode, and an electrolyte that allows for ion transfer. When charging, lithium ions move from the cathode to the anode and vice versa during discharge, releasing energy stored in the form of electrical power. These batteries are favored in renewable energy applications due to their high energy density compared to other types of batteries. This means that they can store more energy for their size or weight, making them ideal for settings in which space or weight is a concern. Lithium-ion batteries typically offer high charge and discharge efficiencies that can exceed 90%. This high efficiency ensures minimal energy loss during storage and retrieval, thus enhancing the overall efficiency of the energy system. The aging of lithium-ion batteries is influenced by several factors, including the number of charge–discharge cycles, the depth of discharge, the operating temperature, and the rate of charge or discharge. Aging can result in a reduced capacity and efficiency over time. Monitoring the micro-health parameters of a battery involves examining the condition of the active materials and the electrolyte. These parameters provide insights into the internal health of a battery, allowing its lifecycle and efficiency in energy storage to be predicted. Changes in these parameters can indicate the onset of degradation processes such as electrolyte oxidation or electrode material fatigue. An accurate estimation of the SOC is crucial for optimizing a battery's performance and longevity. The SOC indicates the remaining capacity of the battery, which is essential for effective energy management. Temperature monitoring is equally important as extreme temperatures can accelerate aging and pose safety risks. Proper thermal management systems are required to maintain optimal operating temperatures for batteries. Lithium-ion batteries require integrated safety mechanisms to prevent conditions that could lead to thermal runaway, such as overcharging, short-circuiting, and extreme temperatures. This includes the use of management systems that can control charging rates and cutoffs as well as monitor cell voltages and temperatures. The lifecycle of lithium-ion batteries is an important consideration for their deployment in energy systems. Manufacturers and users must consider the end-of-life processes for these batteries, including recycling and disposal, to mitigate environmental impacts [28].

The first strategy is to store surplus electricity when electricity generation exceeds its consumption and make up the difference using the stored surplus when electricity consumption exceeds its generation. This proposed strategy was easy to implement using equipment for hybrid systems [29]. The second is the 24 h strategy, which can be used when the electricity wholesale market prices for the next 24 h are known. During the lowest price hours, electricity can be additionally stored from the grid, and during more expensive hours, it can be sold from the battery back to the grid [30]. However, this can only be achieved if the price difference is greater than the costs, which are subject to distribution and transmission tariffs. This proposed strategy can be easily implemented if a controller that reads prices from the Internet and prepares a charging–discharging schedule is also available.

PV modules for electricity generation in the test facility were also reviewed. In order to estimate the number and power of the PV modules to be installed, it was necessary to estimate the strength of the test facility's roof (Figure 6) with self-weight, snow load, and extreme snow load calculations [31,32]. The roof's busbars were surveyed with the aim of determining the technically possible increase in the loads on them.

Figure 6. The constructive elements of the test facility's roof.

The trusses, which were mainly made of steel U-profile elements, were tested in accordance with Latvian building regulations [33]. The load on the busbars was transferred through trusses at each nodal point on the top bar and at the mid-span of each top bar element as a concentrated load. It was not possible to check the composition of the roof; the roof covering was assumed from information provided by the test facility's owner. The PV modules were planned to be located only on one plane of the roof. When the control calculation for the trusses was carried out, it was determined that a complete analysis of the truss connections and welds was not possible; the control calculation was only performed for the carrying capacity of the truss grid and strip elements. The results of the performed calculations are shown in Figures 7–10.

Taking into account the sufficient bearing capacity of the truss strips and grid elements (Figures 7–10), the roof was allowed additional loading equivalent to 30 kg/m^2 on one plane.

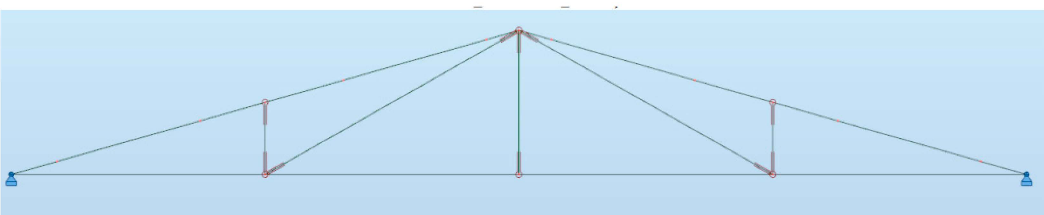


Figure 7. Calculation scheme.

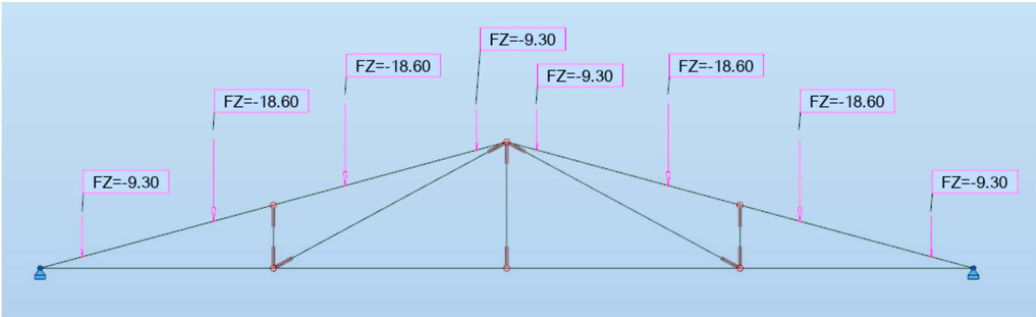


Figure 8. Snow load calculations (kN).

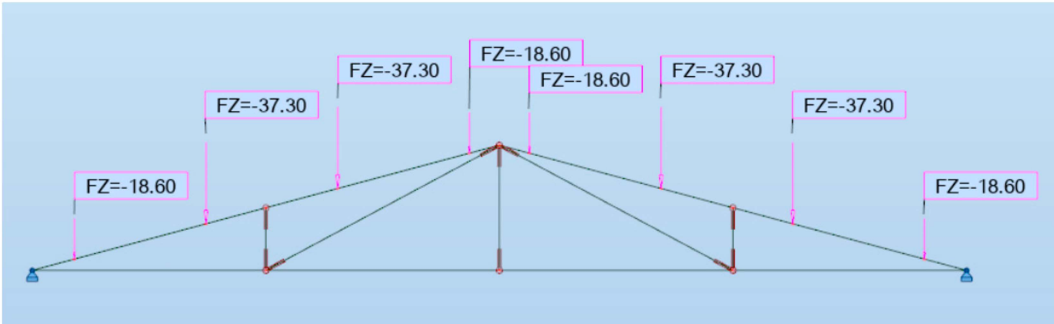


Figure 9. Extreme snow load calculations (kN).

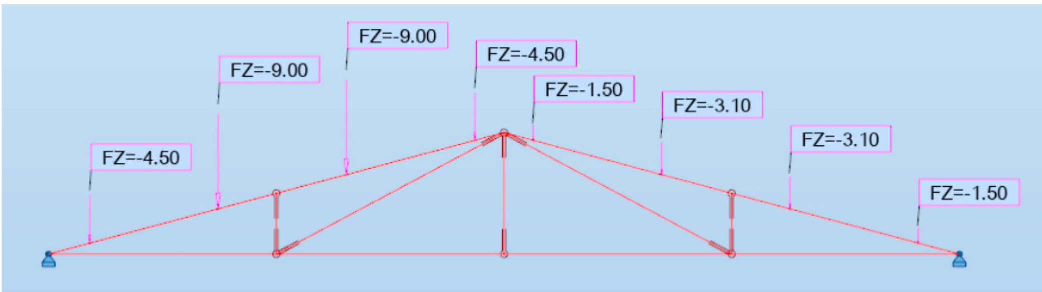


Figure 10. Self-weight load calculation (kN).

3.2. PV Solar and Energy Storage

After checking the durability of the roof, possible PV modules were selected. Since the PV modules were installed in a neighboring facility [34], the generation was interpolated to 1 kilowatt-hour (kWh) of installed PV panel capacity over the relevant period (Figure 11).

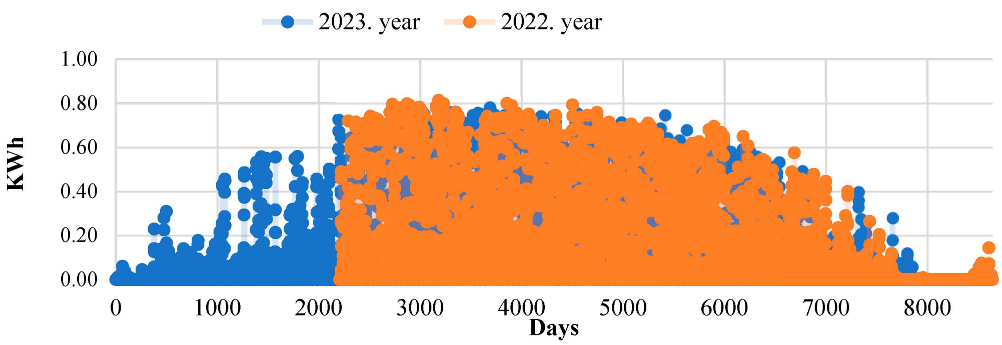
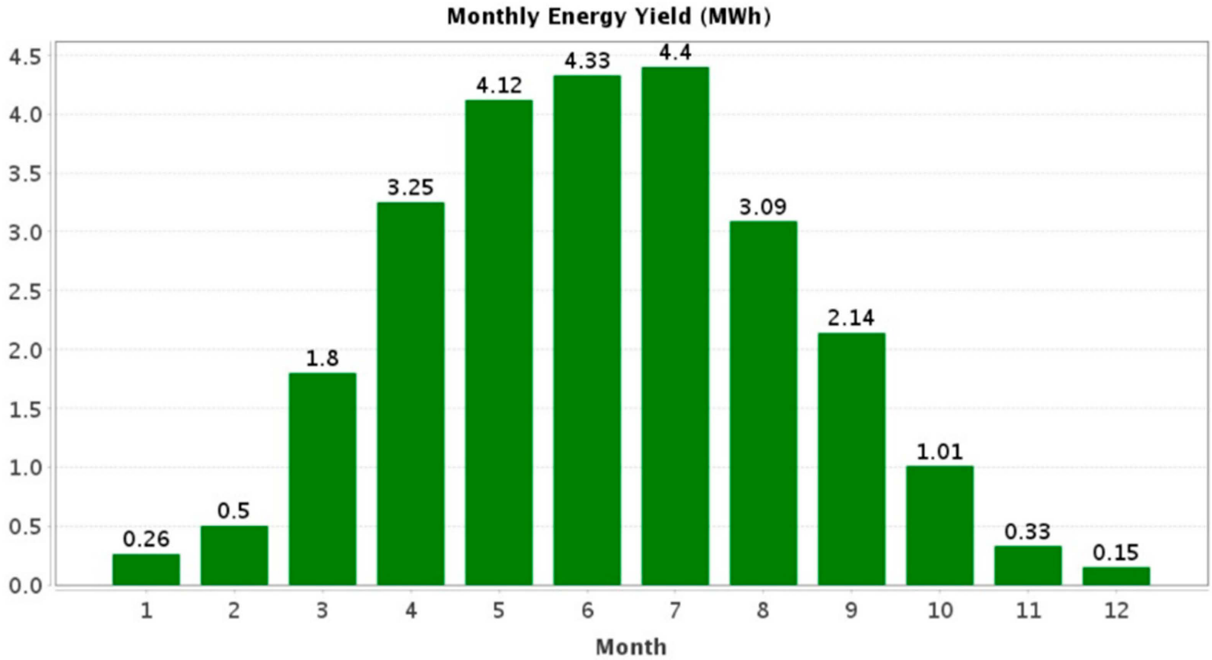


Figure 11. Interpolated generation to 1 kWh of installed PV panel capacity (2022–2023).

The maximum scenario included 75 PV modules with a peak power of 30.75 kW and an annual production of 25.38 megawatt-hours (MWh). The monthly energy generation patterns and technical specifications of the PV modules for the maximum scenario are shown in Figure 12.



	Number of PV Inverters	PV Inverter Rated AC Power	Total Number of PV Modules	Peak Power
PV Plant(6)	1	30.0 kW	75	30.75 kWp
Power Generation Unit	1	30.0 kW	75	30.75 kWp
Group1	1	30.0 kW	75	30.75 kWp

	DC Power Cable	AC Power Cable	Total
Power Loss under Rated Conditions	44.7W	68.17W	112.88W
Relative Power Loss at Rated Voltage	0.15 %	0.23 %	0.38 %
Cable Cross-sectional Area/Length	4mm^2/30.0 m	16mm^2/10.0 m	

Figure 12. Monthly energy generation patterns and technical specifications of PV modules (maximum scenario).

3.3. PV Solar and Energy Storage

In addition, other PV module scenarios with power ranges from 1 to 30 kW and battery power capacities from 0 to 10 kWh were considered as this hybrid solution is known to be one of the most sustainable to date [35,36]. In total, there were up to 330 possible scenarios for the solar–battery hybrid system alone. The calculation of the payback period is shown in Figure 12, where the battery capacity varies from 0 to 10 kWh. The PB2022 charts show the PB calculation using strategy 1 and the electricity prices in 2022. PB+2023 is the calculation using strategy 2 and the electricity prices in 2023. The PB of the PV modules, which was calculated for all the scenarios, is shown in Figure 13.

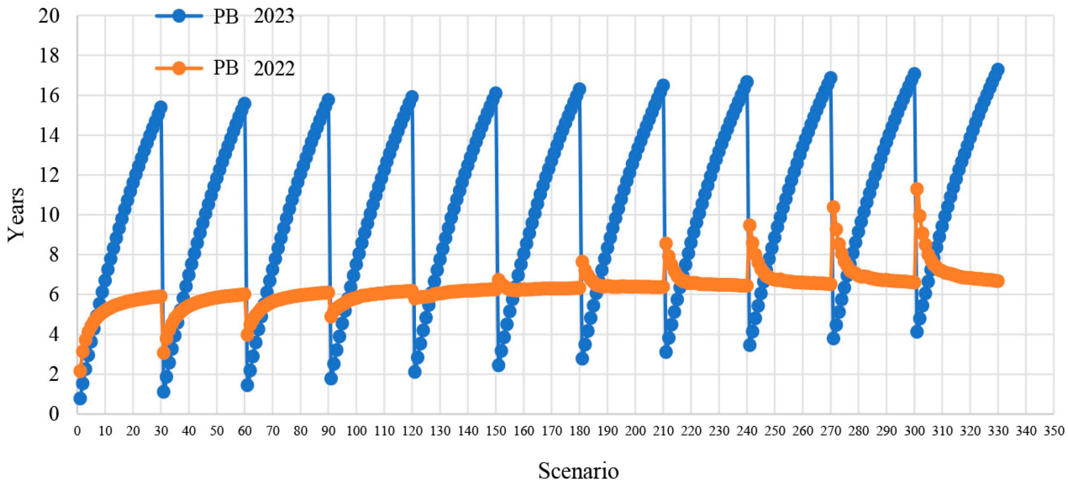


Figure 13. The NPV of the PV modules (all scenarios).

The payback period of the PV installation for all scenarios is shown in Figure 14, and the potential profit of the PV installation for all scenarios is shown in Figure 15.

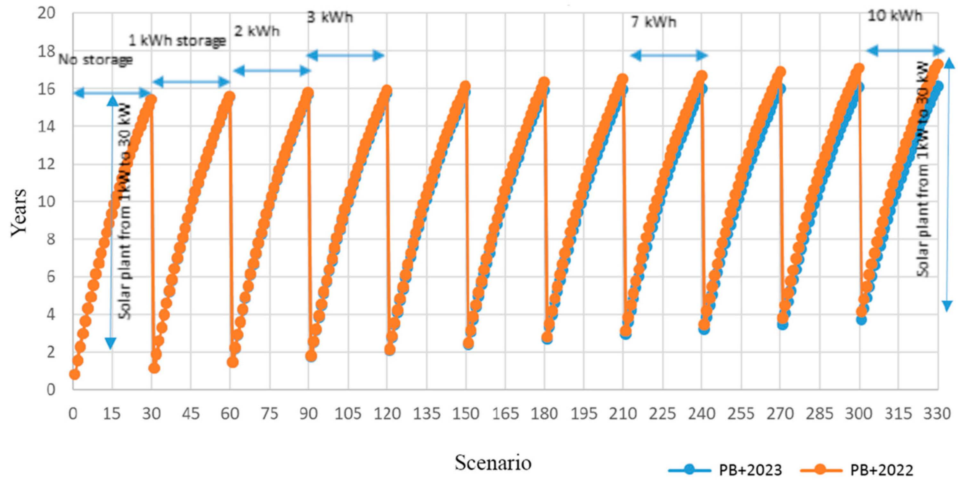


Figure 14. The payback period for the PV installation (all scenarios).

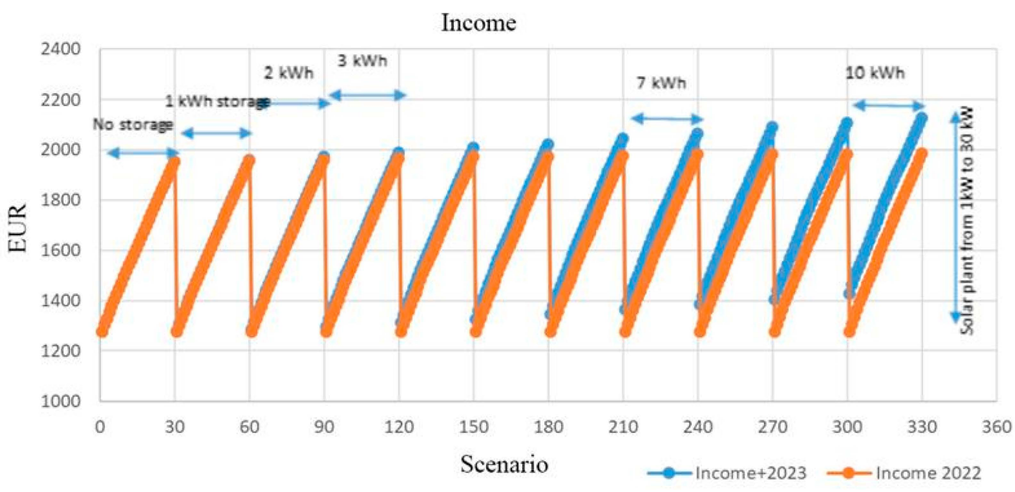


Figure 15. The potential profit of the PV installation (all scenarios).

The payback time of the PV modules was more than 16 years, so installing them with or without batteries would only be useful in a situation in which it is possible for the company to adjust its electricity consumption to the solar generation schedule.

3.4. Wind Energy Installations

In order to examine the maximum number of possible technologies, the possibility of on-site wind generation was also considered. This technology was included on the list as it is known that the production of electricity through wind energy installations in and around buildings is a potentially profitable and efficient way for a building to partially cover its energy demand [37]. The wind speed data used came from a nearby weather station, and based on the average wind speed, it was concluded that the most suitable type of wind turbine was a horizontal one due to the lower required minimum wind speed. In order to calculate the time ranges and the electricity generated, it was necessary to create a wind model. Average wind speed fluctuations in the direct vicinity of the test facility are shown in Figure 16.

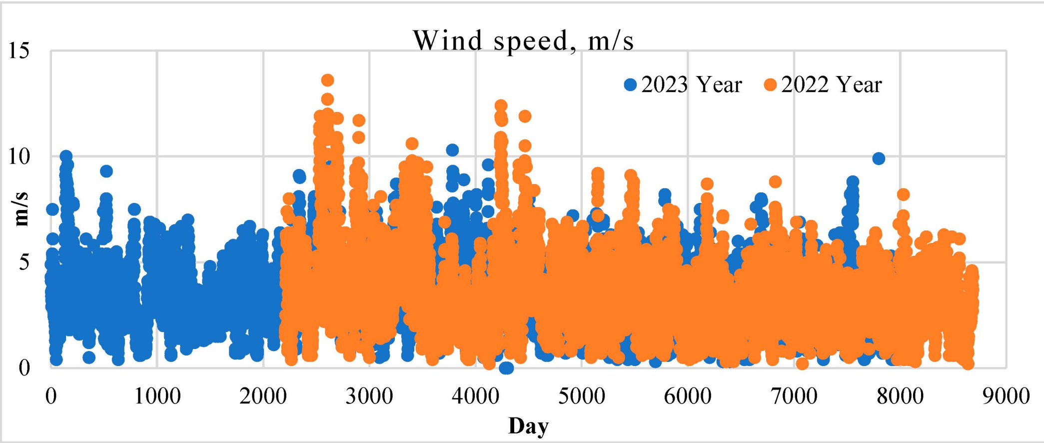


Figure 16. Average wind speed fluctuations in the direct vicinity of the test facility (04.2022–12.2023).

Due to the limited range and availability of wind turbines on the Latvian market and the price of wind-generation installations, the cost of wind generation was several times higher than that of the PV module cascade. GREEN AH-5KW PICTH distributor SIA "PLUS ENERGY GROUP", Rīga, Latvia horizontal wind turbines, which were available on the market and have an installed generation capacity of 5 kW, were chosen for this project's calculations. The selected wind turbine had a high safety rating and 24/7 continuous operation to ensure unattended operation in practically all weather conditions. The turbine's adjustability to wind speed fluctuations is shown in Figure 17.

The working wind speed range for the chosen generator was rather wide (2.0–60 m/s), and the effective operating time was as long as 30 years. Due to the use of an extruded aluminum profile for seamless monolithic construction, the turbine blades were resistant to thermal expansion caused by heat. White paint was applied to the turbines to reflect sunlight. The resistance class for the turbines was C5-M. The steel elements were galvanized and the aluminum elements were anodized to provide effective protection against corrosion. When installing the wind turbine, the grid wind inverter/distribution controller, independent brake system, and brake resistor unit were installed on the switchboard, which was located at the bottom of the steel mast. All the components of the equipment had a high protection class, which allowed it to work at lower temperatures. The potential health hazards caused by small wind turbines, as discussed in [38], were not included in the evaluation.

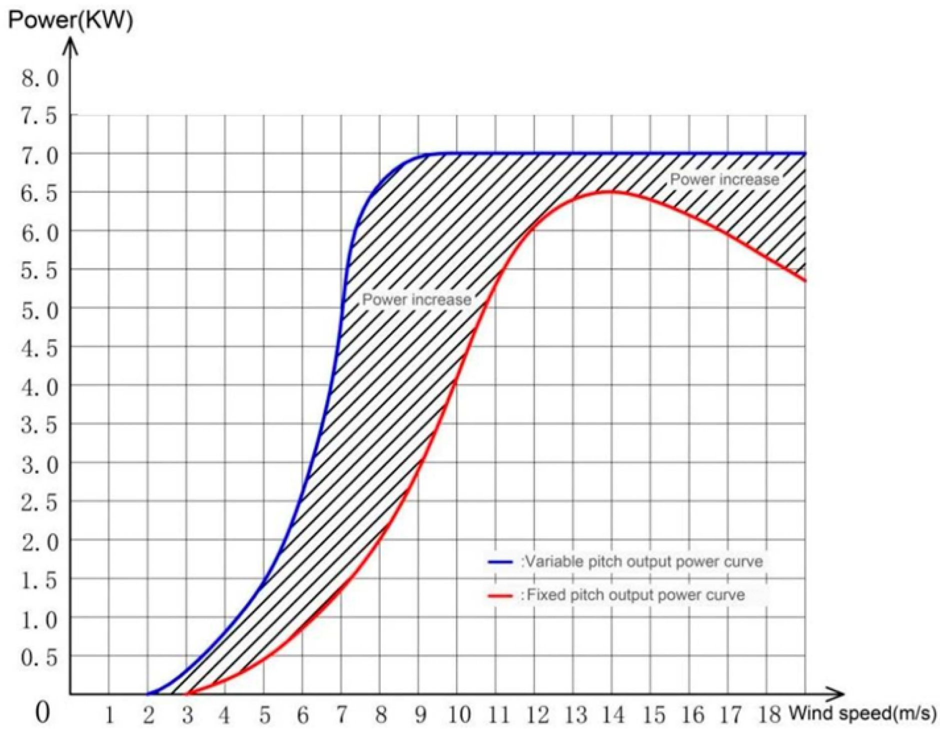


Figure 17. Primary technical characteristics of GREEN AH-5 kW and its adjustability to wind speed fluctuations.

Using the turbine passport data, the power characteristic curve was interpolated, and using the wind speed data, the possible electricity production in 2022 and 2023 was calculated as well.

The R^2 value for the relationship in Figure 18 between the wind speed and the power output in the dataset was approximately 0.354. This indicates that about 35.4% of the variability in the power output could be explained by the wind speed according to the linear regression model used here. These data serve as a baseline for wind-generation and energy storage research.

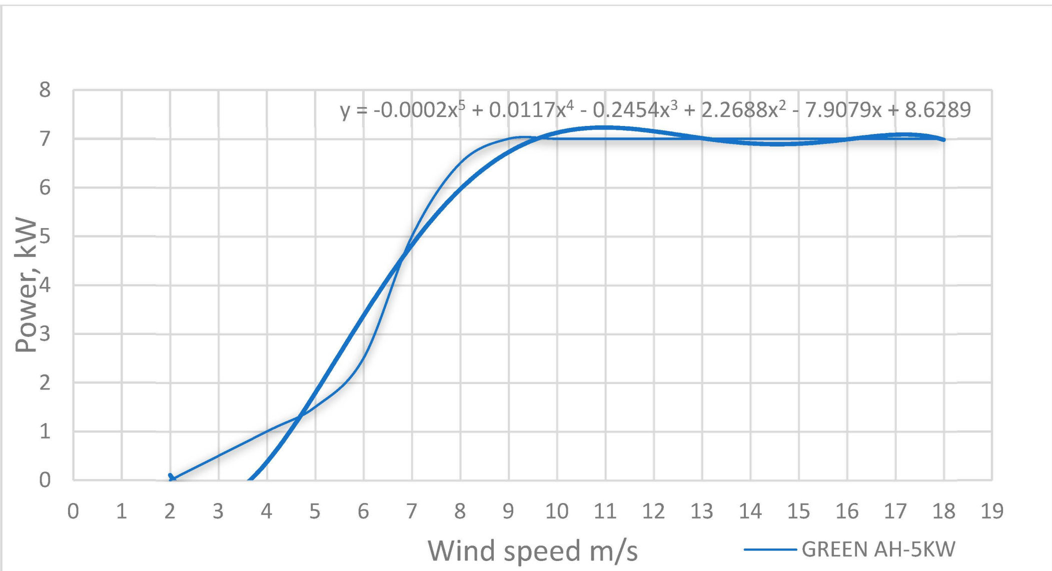


Figure 18. The power output of the turbine (kW) in relation to the wind speed (m/s).

The blue line represents the actual measured or calculated power output of the "GREEN AH-5KW" wind turbine at different wind speeds. The equation represents a polynomial fit to the data. Therefore, in the period of time between 04.2022 and 12.2022, 6.6 MWh of electricity was produced, and in the period between 01.2023 and 12.2023, approximately 7.1 MWh of electricity was produced, which would cost a total of EUR 2262 if sold on the electricity market.

3.5. Wind Generation and Energy Storage

Battery storage unit installation was also considered along with the wind turbine. In order to evaluate the efficiency of the investment, the payback period was calculated. The investment for the installation of a hybrid system with a wind turbine and battery storage was estimated at around EUR 30,000.

3.6. Comparative Conventional Energy Application

In order to conduct a proper analysis of the results in Figures 19 and 20, a conventional comparison technology was needed. The decision was made to consider an alternative option with a diesel generator capable of providing continuous power and replacing the grid-provided electricity during high-price periods. A 3 kW diesel generator was selected which was capable of providing the maximum load of the test facility all day long. The price of diesel fuel was selected as the minimum price available on the market (without VAT). The electricity prices in 2023 are shown in comparison to the diesel prices in Figure 21. "PB" and "NPV".

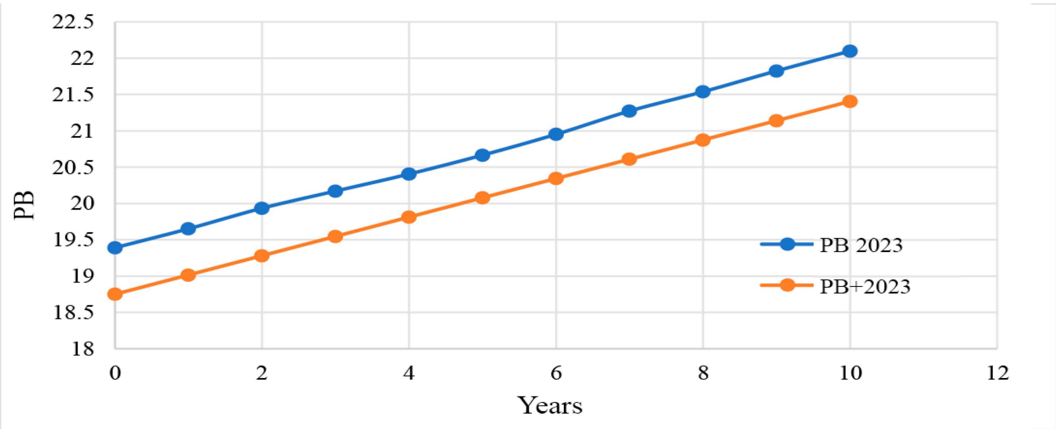


Figure 19. PB of wind turbine (2023).

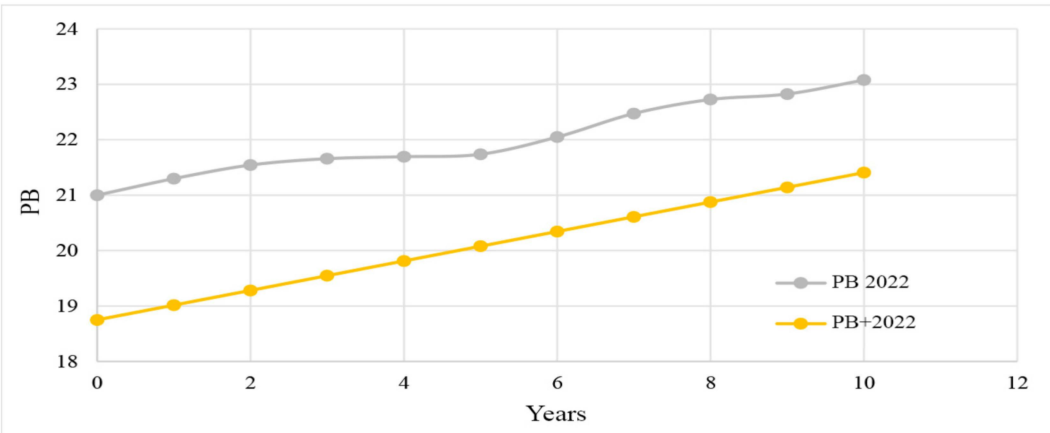


Figure 20. PB of wind turbine (2022).

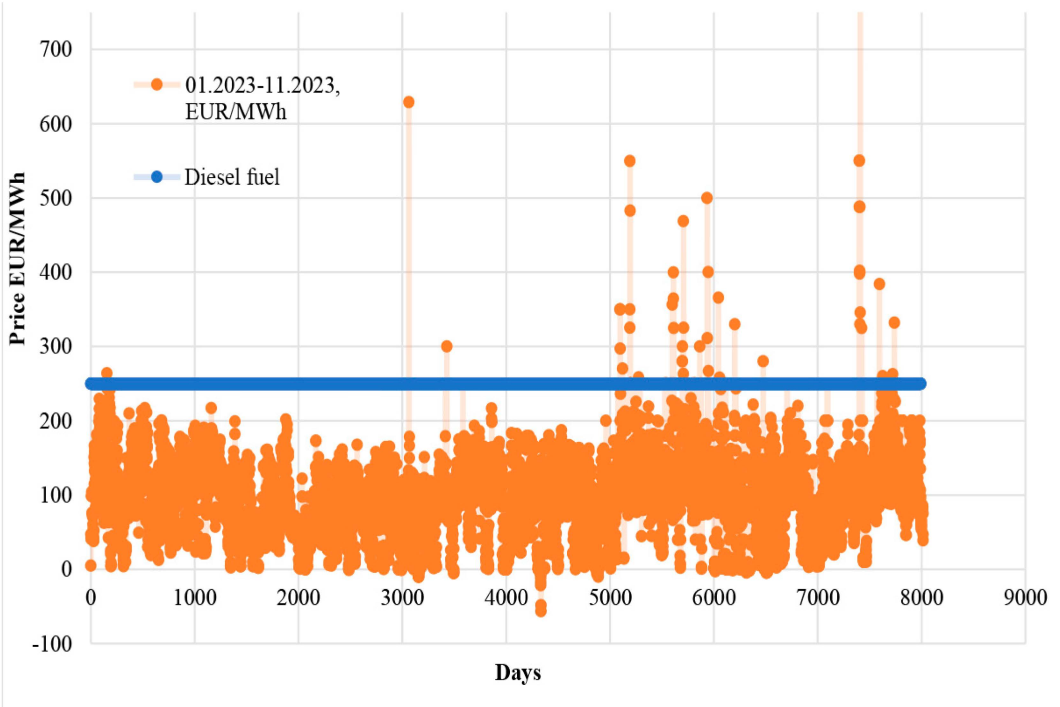


Figure 21. Electricity and diesel fuel price comparison (EUR/MWh).

During part of the time period, it was economically more profitable to operate a diesel generator; however, there were no considerable savings achieved, so the diesel generator was considered to serve only as a source of continuous power and not a provider of significant, long-lasting, and positive economic impact.

4. Discussion and Conclusions

The goal of this project was achieved, and the results can be regarded as an important step toward more efficient, environmentally friendly, and sustainable use of electricity in the industrial real estate sector of Latvia. The results not only promote the convergence of scientific knowledge and innovation but also provide real, practical solutions that can significantly improve on-site energy generation and consumption at the industrial prosumer level.

This project included research on and an evaluation of various hybrid energy technologies, including lithium batteries, solar panels, and wind generators. Different scenarios were analyzed to determine which solutions were the most cost-effective and sustainable. A methodology for evaluating the energy-efficient solutions was successfully developed, and electricity consumption and on-site generation options were also developed.

This project proved that despite initial high investment costs, renewable energy sources and efficient storage systems are cost-effective and can reduce dependence on fossil fuels in the long term.

On a wider scale, however, the project's commercialization potential was dependent on external factors such as market trends, competition, and the regulatory environment. If market trends indicate an increasing demand for sustainable and efficient energy technologies, the commercialization potential of the project could increase accordingly. In addition, if there were regulatory incentives or support programs to promote the implementation of sustainable technologies in industry, this could increase the project's partners' interest in the wider dissemination of its results.

The practical results of this project include, but are not limited to, the following:

- The collection and analysis of data on the test facility's energy consumption, generation potential, and costs;

- An extensive analysis of various hybrid energy technologies, including PV modules, wind turbines, and lithium-ion batteries, to identify the most efficient and cost-effective options for the test facility;
- The calculation of models and simulations;
- The creation and testing of a prototype which demonstrated a cost-effective solution for energy production and consumption;
- The performance of a detailed cost–benefit analysis to ascertain the cost-effectiveness of the solution based on investments, operating costs, and savings.

It is also important that industrial building owners and operators consider several additional criteria to ensure sustainable and efficient energy use in their facilities:

- The efficiency of the energy production and consumption of different technologies must be evaluated, taking into account the specific needs and operating mode of the building;
- The initial investment and expected payback period should be considered, as well as possible savings in the long term;
- The potential of technologies to reduce CO_2 emissions and their impact on the environment as a whole should be a priority, as should the use of renewable energy sources on site;
- The ease with which the chosen technologies can be integrated into the existing infrastructure and necessary system modifications should be considered;
- Opportunities to adapt electricity consumption to the mode of operation of the renewable energy sources used should be considered in order to maximize their potential, reduce costs, and minimize the need to use battery storage options;
- Renewable-energy-generation-based hybrid technologies should be considered to ensure stability and security in the energy supply, as well as to ensure adequate reserve systems;
- National and international regulatory acts, subsidies, and support programs that may affect the choice and implementation of technologies should be examined;
- Future technological trends and innovations that could introduce significant changes in energy production and consumption, as well as possible future modernizations, should be taken into account.

Carefully evaluating these criteria and combining them with scientifically based conclusions would help promote more efficient and sustainable energy use in industrial buildings, which is essential in the context of both economic and environmental protection.

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