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Design of a hybrid renewable energy installation with energy storage for a selected farm

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Abstract

The growing demand for energy and the diminishing resources of non-renewable energy materials present a significant challenge that necessitates the development of innovative and environmentally friendly energy sources, as well as efficient methods for its storage. The advancement of such technologies will contribute to reducing the costs of electricity and heating, while simultaneously minimizing the negative environmental impacts of human activity. This will also enable sustainable development in both urban and rural areas, improving their energy independence. In this context, the present study has developed a project for a hybrid photovoltaic installation integrated with an energy storage system, tailored to the specific needs and energy requirements of an agricultural farm. The primary objective of the proposed installation is to reduce electricity costs by utilizing a ground-mounted photovoltaic system to power a heat pump. Excess thermal energy will be stored in a thermal buffer, while surplus electrical energy will be stored in batteries. This solution allows for a more efficient utilization of available energy resources and enhances the energy autonomy of the farm.

Keywords

Photovoltaic effect, solar Energy, energy storage

Introduction

Since the dawn of civilization, humanity has relied on renewable energy sources as the foundation of its survival and development. Biomass combustion, one of the earliest sources of thermal energy, was widely used in daily life. Similarly, wind energy, recognized as a multifunctional power source, was employed in various domains—from propelling sailing vessels and transporting water to higher agricultural areas to driving mechanical windmills. In the early stages of technological advancement, these windmills were equipped with vertical rotation axes, which were eventually replaced by more efficient designs featuring horizontal drive shafts (Jastrzębska, 2009).

The analysis of photovoltaics in the context of its physical operating principles acknowledges that this energy originates from an external source—the Sun—which emits virtually unlimited energy resources. However, it is important to note that solar radiation reaches only the portion of the Earth's surface facing the Sun, leading to the periodic nature of energy production, which is limited to the diurnal cycle (Krawiec, 2010; Klugman-Radziemska, 2011). Additionally, the intensity of this process varies depending on the time of day and the geographical location of the installation, reflecting differences in solar irradiation across various regions of the world.

The photovoltaic effect was first observed in 1839 by Alexandre Edmond Becquerel. However, the commercial application of this technology became feasible only after World War II, following technological breakthroughs in electronics and semiconductor materials. In its early phase, photovoltaics found primary applications in the space and military sectors, where it was used to power satellites due to its independence from terrestrial resources (Jaeger-Waldau, 2020; Scafetta and Willson, 2014).

Despite its successes, the development of photovoltaic technology faced significant limitations in the second half of the 20th century, driven by the increasing demand for monocrystalline silicon, a fundamental material in the electronics industry (Sibiński and Znajdek, 2016). It was not until the relocation of silicon production technologies, including the vacuum-based Czochralski method, to China that photovoltaics entered a phase of rapid growth, accelerating significantly in the first two decades of the 21st century (Pietruszka et al., 2014).

Each phase of dynamic technological advancement becomes the subject of intensive scientific research and engineering efforts, as was the case with photovoltaics. The outcomes of these efforts have resulted in new technologies that have significantly improved energy conversion efficiency in monocrystalline cells. A notable achievement was the development of a relatively inexpensive method for producing polycrystalline silicon, which is widely used in photovoltaic cell manufacturing. Furthermore, semiconductor research has led to the development of innovative materials applied in solar cell production. Of particular interest is thin-film technology, which requires up to one hundred times less material than traditional silicon cells. The last decade has seen the introduction of cost-effective materials such as perovskites and polymers, which offer a promising alternative to conventional solutions (Drabczyk, 2014; Beaucarne et al., 2012; Minami, 2005).

The rapid expansion of the photovoltaic sector and research advancements in this field often outpace formal educational processes, necessitating the frequent publication of new scientific materials that serve as a vital source of knowledge for a broad audience. In this context, it is worth highlighting the contributions of Prof. Jan Stopczyk, who conceptualized and developed the philosophy of the prosumer—a unit that simultaneously acts as both a producer and consumer of electricity on a micro-scale. The scale of this concept, encompassing millions of prosumers, is of crucial importance in the context of national energy systems (Skibowski and Mroziński, 2012).

In light of the above, the objective of this study is to develop a design for a hybrid photovoltaic installation with an energy storage system tailored to the energy needs of an agricultural holding. This installation aims to reduce costs associated with electricity consumption by utilizing a ground-mounted photovoltaic system to power a heat pump. Excess thermal energy will be stored in a thermal buffer, while surplus electrical energy will be stored in batteries, optimizing the utilization of available energy resources.

Literature Review

In the first half of the 20th century, despite initial experiments, interest in the utilization of solar energy remained marginal. This phenomenon was largely due to the dominance of fossil fuels, which featured relatively low production costs and high availability, reducing the demand for alternative energy sources. As a result, research on solar-based technologies remained on the periphery of mainstream energy development for a long time. Only from the 1950s onward did systematic scientific and technological research on solar energy begin to develop, facilitated by the growing recognition of its potential as an alternative energy source (Soga, 2006; Luque and Hegedus, 2014; Szymański, 2013).

The primary catalyst for this growth was the intensive research conducted at the time by academic institutions, including prestigious universities such as Yale University and the Massachusetts Institute of Technology (MIT). These institutions, regarded as pioneers in this field, undertook extensive research on innovative solutions for designing flat-plate solar collectors, advancing photochemistry, and integrating solar energy into heating systems, including building heating applications (Aouaj et al., 2009). Furthermore, parallel research efforts were underway in countries such as the USSR and India, focusing not only on solar energy conversion technologies but also on their implementation in various industrial sectors and communities with limited access to conventional energy sources (Mohamed et al., 2009).

At the same time, numerous symposia and scientific conferences were organized, serving as platforms for knowledge exchange among researchers and institutions worldwide. These events, supported by international organizations such as UNESCO and the United Nations (UN), aimed to promote and disseminate the development of solar energy technologies. However, the primary factor stimulating intensified research and development efforts in this field was the global energy crisis of 1973 (Way et al., 2019; Banyamin et al., 2014). This event exposed the vulnerability of dependence on traditional energy sources and drew international attention to the urgent need to seek alternative and more efficient methods of energy generation. The energy crisis mobilized governments and research institutions, leading to a significant increase in investments and the stimulation of work on new solar technologies (Cleary et al., 2018).

The year 1955 marked a milestone in the development of industrial photovoltaic systems when the Western Electric Company initiated attempts to commercialize silicon-based photovoltaic cell production technology. The pioneering applications of this technology were initially focused on powering equipment used in space research, laying the foundation for the development of photovoltaics in extreme conditions. Over time, further research and development efforts enabled silicon-based technologies to achieve the required efficiency parameters, making their application viable not only in the space sector but also in industry and everyday use, eventually becoming an integral part of a sustainable energy system (Pluta, 2008).

The chronology of key events in the development of photovoltaics in the United States includes several groundbreaking moments that significantly contributed to the commercialization of photovoltaic technologies. A notable example is the invention of the photovoltaic cell in Bell Laboratories in the early 1950s, which served as the starting point for the advancement of solar energy conversion technologies. In 1958, through the initiative of the U.S. government, photovoltaic cells were first deployed in space, powering satellites and proving their reliability under extreme conditions (Wojciechowski, 2016; Namysłowska-Wilczyńska et al., 2016; Mirek, 2016). Further advancements in photovoltaic technology followed the 1973 energy crisis, when interest in photovoltaics as an alternative energy source on Earth began to grow rapidly.

During the 1970s, research intensified on integrating photovoltaic cells into building structures. Government programs, such as those initiated by the U.S. Department of Energy, aimed to develop technologies enabling the implementation of photovoltaic systems in residential and commercial buildings, as well as strategies for integrating photovoltaics with existing power grids. One of the significant milestones of this period was the introduction of tax incentives for photovoltaic investments and funding for research through federal programs, which allocated billions of dollars toward advancing this technology (Svazas et al., 2019; Tvaronavičienė et al., 2018; Stavytskyy et al., 2018).

Breakthroughs also occurred in the early 1980s when the first thin-film photovoltaic cells with efficiency exceeding 10% were developed. Simultaneously, the cost of photovoltaic modules dropped below $10 per watt-peak, which played a crucial role in their commercialization and market availability. Moreover, the construction of the first photovoltaic power plants, such as the one completed in Carissa Plains in 1985, marked a significant step toward the large-scale production of electricity using photovoltaic cells.

In the 1990s, intensive efforts were undertaken to increase photovoltaic cell efficiency, leading to further technological breakthroughs. Collaboration between public and private institutions laid the foundation for the mass production of photovoltaic systems, including the development of technological infrastructure (Krupa and Soliński, 2012). A landmark achievement came in 1992 when the University of South Florida developed thin-film cells with an efficiency of 5.9%, representing another step toward enhancing photovoltaic technology (Wojciechowski, 2008; Parau et al., 2014).

In 2000, the United States launched the Solar 2000 project, which aimed to promote and implement renewable energy technologies, with a particular emphasis on solar energy. The primary objective of this initiative was to achieve a total installed capacity of 1,400 MW, with 900 MW to be generated from photovoltaic installations in the United States, and the remaining 500 MW planned for installation in other countries (Jastrzębska, 2013).

Over the past two decades, solar energy has emerged as one of the fastest-growing sectors of the global economy. The industry's average annual growth rate has exceeded 35%, an exceptionally impressive figure in the context of renewable energy technology development. The expansion of photovoltaic module production and installation is often compared to the early-stage growth of the microelectronics industry, highlighting the rapid pace of technological advancement (Eltawil et al., 2010; Yao et al., 2020).

Alongside the information technology and biotechnology sectors, photovoltaics is now one of the most dynamic segments of the modern economy. Even in 2006, when the global photovoltaic market faced a temporary shortage of silicon, significantly more photovoltaic systems were installed compared to previous years. This resilience to market crises underscores the strong growth trend and increasing maturity of this technology (Zagrajek et al., 2020).

Recent interdisciplinary studies highlight the growing role of digital technologies and decision support systems in sustainability and energy planning. Gavurova et al. (2025) developed a hybrid model for assessing the socio-economic impact of digital transformation, offering insights transferable to energy system design. Similarly, Gavurova and Polishchuk (2025) applied fuzzy logic for inclusive planning, while Moravec et al. (2025) explored algorithmic personalization and media literacy – factors relevant for shaping user behavior in adopting solar technologies. These studies underline the importance of digitalization and user-centric approaches in advancing photovoltaic development.

Considering conservative forecasts of the photovoltaic market's growth rate, which predict an average annual increase of 25%, it is estimated that by 2030, the value of the global semiconductor industry associated with the photovoltaic sector will exceed €175 trillion (Khaboot et al., 2019). This technological progress is driven by continuous improvements in photovoltaic panel efficiency, increasing investment levels, and growing political and economic support for green technologies. Consequently, solar energy is gaining significance as a crucial element in the global energy transition toward sustainable development.

Research Methods

This study employed advanced research methodologies utilizing Sunny Design software, developed by SMA Solar Technology AG, which serves as a key tool for designing, simulating, and analyzing the performance and operation of photovoltaic (PV) systems. The objective of the study was to conduct a detailed evaluation of the efficiency, performance, and profitability of photovoltaic installations under various system configurations, taking into account diverse external and technological factors.

The first stage of the study involved an in-depth analysis of the functionalities provided by Sunny Design, which enables the modeling and simulation of PV system operations based on specific location, meteorological, and technological parameters. This stage involved an examination of the software's capability to create dedicated site profiles, incorporating meteorological data such as solar irradiation, air temperature, humidity, and other environmental variables that directly influence PV panel efficiency. Additionally, this phase utilized both local databases and external data sources integrated through the software, allowing for a more precise representation of actual conditions in the analyzed locations.

The next step in the research process involved conducting operational simulations of photovoltaic installations designed in various configurations, including:

1. A grid-connected PV installation,
2. A grid-connected PV installation with self-consumption capability,
3. An off-grid PV installation,
4. A hybrid PV installation.

The simulations, conducted using Sunny Design's modeling capabilities, allowed for the estimation of electricity production under various meteorological conditions and time periods. As a result of these simulations, it was possible to determine the impact of key system parameters, such as the type of PV modules, inverters, and battery charge controllers, on the total energy output.

Another crucial element of the study was the detailed financial analysis of photovoltaic systems. To assess profitability, the study examined potential savings from electricity generation and revenue opportunities from selling surplus energy to the power grid. The Sunny Design software facilitated a comprehensive economic analysis of the investment, considering:

- Initial investment costs,
- Operational and maintenance costs,
- Government subsidies,
- Electricity tariff fluctuations,
- Other economic factors influencing the financial feasibility of photovoltaic technologies.

Due to the specific requirements of the software used in this study, only components offered by SMA Solar Technology AG were incorporated, including inverters, battery charge controllers, and monitoring systems. This constraint ensured consistency and compatibility within the modeled PV installations. Furthermore, an analysis was conducted on how the selection of different SMA components influenced the overall efficiency and profitability of the designed photovoltaic systems.

To evaluate simulation results and compare different scenarios, advanced statistical analysis methods were applied, including:

- Calculation of mean values,
- Standard deviations,
- Comparative assessment of nominal efficiency across different installation configurations.

Special attention was given to analyzing the impact of meteorological data variability and technological parameters on the overall efficiency and profitability of photovoltaic systems.

System Design

The design of a hybrid renewable energy system integrated with an energy storage solution for a selected agricultural holding is based on a location near Szczecin, allowing for precise assessment of the system's energy efficiency based on the region's solar irradiation characteristics. The proposed photovoltaic (PV) installation will be a ground-mounted system, oriented southward at a 37° tilt angle, which represents the optimal inclination for maximizing energy yields.

The primary objective of the system is to significantly reduce the farm's overall energy consumption, resulting in operational cost savings. Consequently, it is essential to obtain detailed data on the farm's annual energy consumption, encompassing both the residential building and the agricultural production facilities. A summary of energy consumption for the year 2023 is presented in Table 1 below.

Table 1: Energy Consumption in 2023

Date	**Consumption [kWh]**		
	Household [kWh]	**Farm [kWh]**	**Total [kWh]**
01.05.2022 - 31.05.2022	205	0	205
01.06.2022 - 30.06.2022	205	1042	1247
01.07.2022 - 31.07.2022	210.5	1271	1481.5
01.08.2022 - 31.08.2022	210.5	1107	1317.5
01.09.2022 - 30.09.2022	264.5	1061	1325.5
01.10.2022 - 31.10.2022	264.5	902	1166.5
01.11.2022 - 30.11.2022	1129	862	1991
01.12.2022 - 31.12.2022	1701	984	2685
01.01.2023 - 31.01.2023	1734	998	2732
01.02.2023 - 28.02.2023	1526	508	2034
01.03.2023 - 31.03.2023	1267	508	1775
01.04.2023 - 30.04.2023	830	698.5	1528.5
01.05.2023 - 31.05.2023	411	698.5	1109.5
Total [kWh]	9958	10640	20598

Source: Own elaboration.

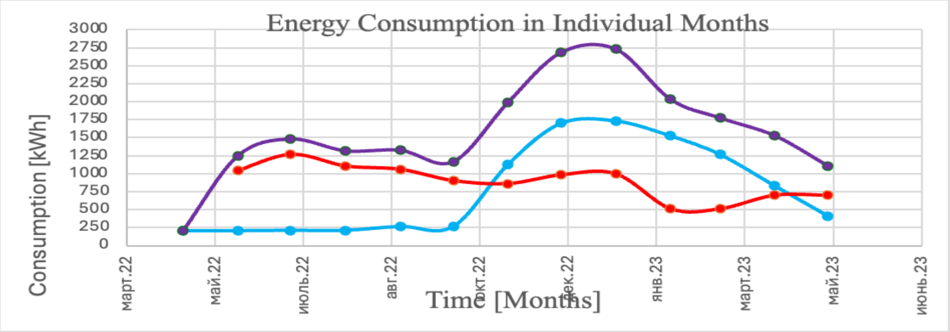

Fig. 1: Monthly Energy Consumption. The blue color indicates household energy consumption, the red color represents farm energy consumption, and the purple color represents total energy consumption. Source: Own elaboration.

Based on the analysis of monthly energy consumption in the agricultural holding for the year 2023, a graph was created to illustrate the disparities in energy demand between the residential building and the production facilities. The graph highlights that the energy requirements of these two areas are not aligned. By summing the energy consumption for both segments, it is possible to determine the total energy demand for each month of the year.

Since the proposed installation is not intended to provide full energy independence from the distribution grid, the system's capacity has been designed to maximize the utilization of generated energy during non-heating months. It is important to note that from late autumn to early spring, the performance of a photovoltaic system is significantly reduced, necessitating a higher system capacity to meet the increasing energy demand during this period.

Based on the energy consumption analysis and the simulation results conducted using Sunny Design, it was determined that the proposed photovoltaic installation will consist of 30 solar panels, each with a capacity of 545

Wp, resulting in a total peak power of 16.35 kWp. It is estimated that this system will be capable of generating approximately 17,270 kWh of electricity per year. However, due to seasonal variations in energy demand, it will not be possible for the farm to consume all the generated energy directly.

To increase self-consumption of the energy produced by the photovoltaic installation, the system design incorporates an energy storage solution that includes both electrical and thermal storage. Additionally, a heat pump has been integrated into the system to enhance on-site energy consumption. These solutions contribute to reducing costs associated with purchasing electricity from the grid, and the resulting savings can be converted into long-term economic benefits.

Components of the Photovoltaic System

1. **Photovoltaic Modules:**
    - Type: Monocrystalline, PERC technology, half-cut cells.
    - Nominal power: 545 Wp (Standard Test Conditions - STC).
    - Operating parameters under NOCT (Nominal Operating Cell Temperature):
        - Maximum power: 412 W.
        - Open-circuit voltage: 46.55 V.
        - Voltage at maximum power: 39.20 V.
        - Short-circuit current: 11.13 A.
        - Current at maximum power: 10.51 A.
        - Efficiency above 20%.
        - Annual degradation rate: 0.55%.
2. **Mounting Structure:**
    - Type: Ground-mounted, free-standing, dual-support, corrosion-resistant coating.
    - Layout: Two rows of 15 modules.
    - Tilt angle: 37° facing south.
3. **Inverter:**
    - Type: Three-phase.
    - Rated power: 15 kW.
    - Maximum supported PV module power: 22.5 kWp (STC).
    - Maximum input voltage: 1000 V.
    - Nominal input voltage: 580 V.
    - Minimum input voltage: 150 V.
    - Initial input voltage: 188 V.
    - Rated output current: 21.7 A.
    - Maximum output current: 36.6 A.
    - Nominal AC voltage: 230 V / 400 V.
    - Grid frequency: 50 Hz.
    - Maximum efficiency: 98.2%.
4. **Solar Cables:**
    - Cross-section: 4 mm².
    - Material: Tinned copper conductors.
    - Insulation: Halogen-free material.
5. **Heat Pump (Air-to-Water):**
    - Type: Monoblock.
    - Heating capacity range: 3.10 kW to 8.90 kW.
    - Power supply: 230 V / 50 Hz.
    - Maximum input power: 3.0 kW.
    - Maximum input current: 13.5 A.
    - Operating temperature range: -25°C to 40°C.
6. **Thermal Buffer:**
    - Equipped with a domestic hot water coil and a central heating coil.
    - Capacity: 200 L.
    - Maximum stored water temperature: 95°C.
7. **Energy Storage System:**
    - Type: Lithium iron phosphate ($LiFePO_4$).
    - Capacity: 15 kWh.
    - Nominal voltage: 600 V (for three-phase system).
    - Maximum output power: 5 kW.
    - Control module: With display.

- Operating temperature range: -10°C to 55°C.

The above system parameters constitute integral components that enable the efficient collection, storage, and utilization of renewable energy from photovoltaics and heat from the heat pump in the heating cycle, while ensuring high efficiency and long-term durability of the components.

To conduct a detailed comparison of the economic efficiency of photovoltaic system investments, four different system variants were developed. The objective of this approach is to highlight the differences in energy yields, initial costs, payback periods, and potential profits generated by each solution. All analyzed installations will be equipped with identical components and will generate a similar amount of electricity. However, the key factor affecting the investment profitability will be the presence of batteries and the heat pump with a thermal buffer, which modify the self-consumption rate of the energy produced. This factor has a direct impact on the overall efficiency of the photovoltaic system and the investment payback period.

It is essential to note that in the variant with the heat pump, the total annual energy consumption increases to approximately 24,000 kWh, as the current heat source is not included in the analyzed system and the heat pump serves as an additional heating method.

By comparing the amount of energy used for self-consumption versus the energy fed into the grid, it will be possible to estimate the self-consumption rate. Since the amount of energy generated by the PV panels remains the same across all variants, it will be possible to determine which variant utilizes the generated energy most efficiently in different months, allowing for a precise assessment of investment profitability in the context of seasonal fluctuations in energy demand.

Results

In the context of promoting solutions such as photovoltaic installations and addressing their high costs, numerous financial instruments have been developed to support consumers in adopting this technology. Consequently, the cost estimate for a photovoltaic installation, in addition to accounting for the full costs of purchasing and installing the system, also includes potential financial support in the form of grants available for agricultural holdings. Examples of such grants include:

Agroenergia – a subsidy program covering up to 20% of installation costs, with a maximum support limit of PLN 25,000. This funding is intended for the purchase and installation of photovoltaic systems with a capacity of up to 50 kW.

Stop Smog – a program offering subsidies of up to 70% of installation costs, with a maximum support amount of PLN 53,000. This grant covers expenses related to the installation, connection, and commissioning of micro-scale photovoltaic systems.

These financial mechanisms aim to reduce the cost barrier associated with implementing renewable energy technologies in the agricultural sector, thereby increasing their accessibility and practical adoption.

Table 3: Photovoltaic Installation Cost Estimate

Photovoltaic Installation	Price (PLN)	Quantity	Cost (PLN)	Cost (EUR)
Mounting structure	8,586.00	1	8,586.00	1,908.00
Photovoltaic modules	540.00	30	16,200.00	3,600.00
Inverter	13,950.00	1	13,950.00	3,100.00
Cables	3.40	100	340.00	75.56
Other components	10% of investment value	–	3,907.60	868.36
Labor	30% of investment value	–	11,722.80	2,604.06
Total	54,706.40		54,706.40	12,146.98
Agroenergia subsidy	43,765.12		43,765.12	9,705.58
Stop Smog subsidy	16,411.92		16,411.92	3,646.90

Source: Own elaboration.

Table 4: Photovoltaic Installation Cost Estimate with Heat Pump

Photovoltaic Installation with Heat Pump	**Price (PLN)**	**Quantity**	**Cost (PLN)**	**Cost (EUR)**
Mounting structure	8,586.00	1	8,586.00	1,908.00
Photovoltaic modules	540.00	30	16,200.00	3,600.00
Inverter	13,950.00	1	13,950.00	3,100.00
Heat pump	17,398.35	1	17,398.35	3,866.30
Thermal buffer	3,890.00	1	3,890.00	864.44
Cables	3.40	100	340.00	75.56
Other components	10% of investment value	–	6,036.44	1,343.65
Labor	30% of investment value	–	18,109.31	4,024.18
Total	84,510.09		84,510.09	18,734.72
Agroenergia subsidy	67,608.07		67,608.07	15,024.01
Stop Smog subsidy	31,510.09		31,510.09	7,002.23

Source: Own elaboration.

Table 5: Cost Estimate of a Photovoltaic Installation with Energy Storage

Photovoltaic Installation with Energy Storage	**Price (PLN)**	**Quantity**	**Cost (PLN)**	**Cost (EUR)**
Mounting structure	8,586.00	1	8,586.00	1,908.00
Photovoltaic modules	540.00	30	16,200.00	3,600.00
Inverter	13,950.00	1	13,950.00	3,100.00
Energy storage	32,219.85	1	32,219.85	7,157.75
Cables	3.40	100	340.00	75.56
Other components	10% of investment value	–	7,129.59	1,585.46
Labor	30% of investment value	–	21,388.76	4,753.05
Total	99,814.19		99,814.19	22,179.87
Agroenergia subsidy	79,851.35		79,851.35	17,746.97
Stop Smog subsidy	46,814.19		46,814.19	10,402.93

Source: Own elaboration.

Table 6: Cost Estimate of a Photovoltaic Installation with Energy Storage and Heat Pump

Photovoltaic Installation with Energy Storage and Heat Pump	**Price (PLN)**	**Quantity**	**Cost (PLN)**	**Cost (EUR)**
Mounting structure	8,586.00	1	8,586.00	1,908.00
Photovoltaic modules	540.00	30	16,200.00	3,600.00
Inverter	13,950.00	1	13,950.00	3,100.00
Heat pump	17,398.35	1	17,398.35	3,866.30
Thermal buffer	3,890.00	1	3,890.00	864.44
Energy storage	32,219.85	1	32,219.85	7,157.75
Cables	3.40	100	340.00	75.56
Other components	10% of investment value	–	9,258.42	2,055.09
Labor	30% of investment value	–	27,775.26	6,166.67
Total	129,617.88		129,617.88	28,792.86
Agroenergia subsidy	104,617.88		104,617.88	23,235.08
Stop Smog subsidy	76,617.88		76,617.88	17,017.0

Source: Own elaboration.

A key piece of information for the investor is the estimation of the approximate payback period of the investment, the time frame in which the investment will begin generating profits, and the magnitude of these profits, particularly in the case of installations that yield savings through reduced energy consumption. These savings are considered direct profits resulting from the implementation of the investment.

Despite energy price fluctuations, the presented graph does not account for these variations, instead relying on a fixed energy price and annual energy consumption of the household. This method of presentation is used to evaluate the investment's profitability, demonstrating its economic viability regardless of potential changes in electricity prices. In the event of rising energy prices, the installation will generate even greater savings, thereby shortening the payback period and increasing the overall financial gains achieved.

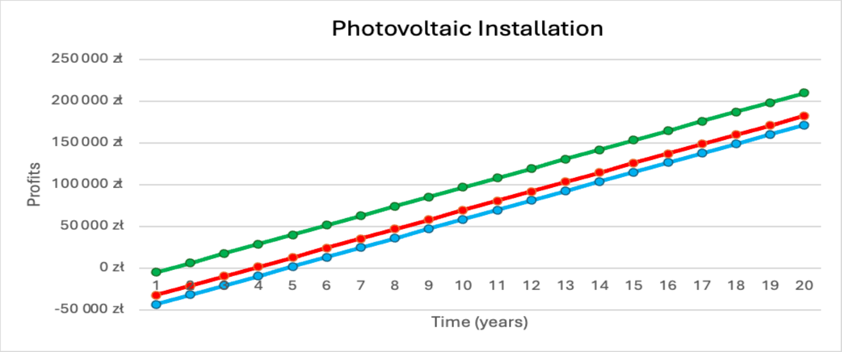

Fig. 2: Payback Period of the Photovoltaic Installation. The blue color represents the scenario without subsidy, the red color represents the Agroenergia subsidy, and the green color represents the Stop Smog subsidy. Source: Own elaboration based on Sunny Design.

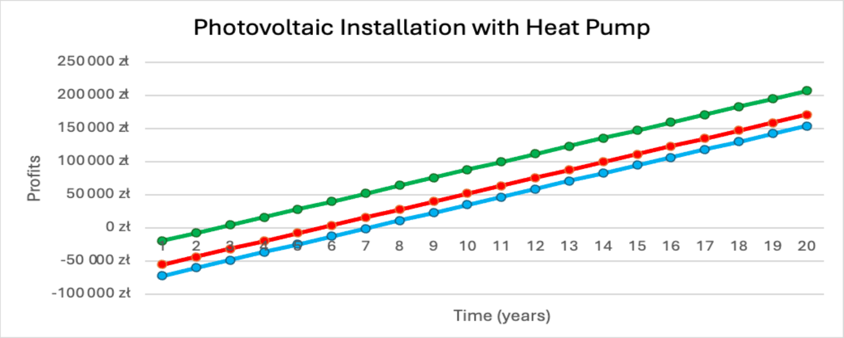

Fig. 3. Payback Period of the Photovoltaic Installation with Heat Pump. The blue color represents the scenario without subsidy, the red color represents the Agroenergia subsidy, and the green color represents the Stop Smog subsidy. Source: Own elaboration based on Sunny Design.

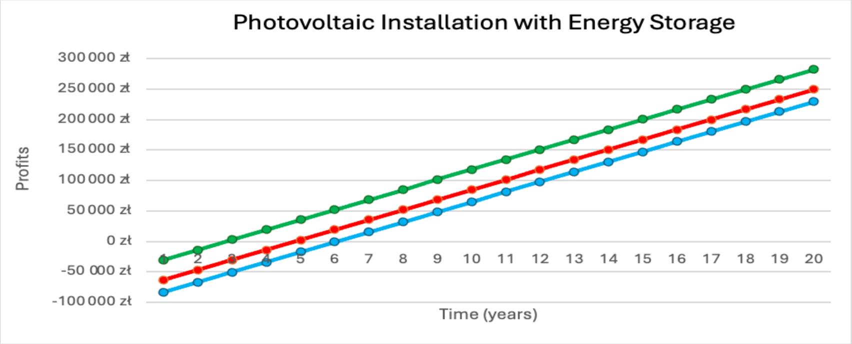

Fig. 4. Payback Period of the Photovoltaic Installation with Energy Storage. The blue color represents the scenario without subsidy, the red color represents the Agroenergia subsidy, and the green color represents the Stop Smog subsidy. Source: Own elaboration based on Sunny Design.

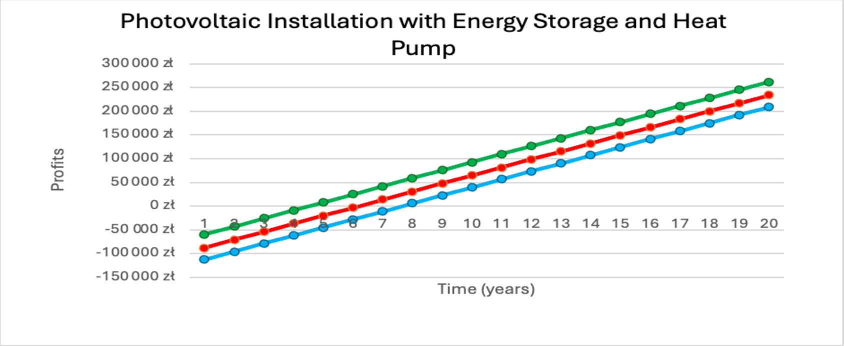

Fig. 5. Payback Period of the Photovoltaic Installation with Energy Storage and Heat Pump. The blue color represents the scenario without subsidy, the red color represents the Agroenergia subsidy, and the green color represents the Stop Smog subsidy. Source: Own elaboration based on Sunny Design.

Summary

After analyzing various photovoltaic installation variants, it can be concluded that such systems generate significant savings, particularly during the summer months. During this period, the demand for energy used for heating decreases, and the extended availability of solar energy enables photovoltaic modules to produce a higher amount of electricity, allowing for greater self-consumption. In contrast, during colder months, energy demand increases, especially for thermal energy, while the energy generated by photovoltaic panels decreases, necessitating energy drawn from the power grid.

Photovoltaic installations with energy storage and hybrid systems, which combine energy storage with a heat pump, demonstrate the highest efficiency. The key factor in this efficiency is the role of the energy storage system, which significantly increases self-consumption, enabling the use of stored energy even after sunset, when photovoltaic production declines.

Standalone photovoltaic installations, although less efficient than systems with energy storage, offer a favorable cost balance due to lower investment costs and reduced maintenance requirements. The analysis indicates that the least favorable option is a photovoltaic installation with a heat pump but without energy storage. This is due to the high initial costs, which do not significantly improve self-consumption compared to a traditional photovoltaic installation, as well as higher operational costs resulting from the increased energy demand of the heat pump.

Despite the high investment costs, the optimal solutions are photovoltaic installations with energy storage and hybrid installations (photovoltaics, energy storage, and heat pump). Thanks to available subsidies, these solutions can significantly reduce construction costs and shorten the payback period. The future increase in electricity prices suggests that such investments can yield substantial long-term financial benefits in the form of energy savings.

Conclusions

- Hybrid photovoltaic systems represent a high initial-cost investment that generates significant economic benefits over the long term by reducing electricity costs.
- Financial support through subsidies significantly reduces the initial installation cost, resulting in a shorter payback period and enhanced economic efficiency of the investment.
- Integrating the photovoltaic system with energy storage increases self-consumption of electricity, thereby reducing operating costs and accelerating the payback period of the investment.
- The use of heat pumps in hybrid photovoltaic installations also enhances self-consumption by increasing electricity demand, thereby lowering overall energy costs and reducing dependence on external energy sources.
- Hybrid photovoltaic systems with energy storage and heat pumps demonstrate significantly higher economic efficiency than traditional photovoltaic installations, generating greater savings and long-term financial returns.
- Agricultural holdings exhibit a specific and uneven energy consumption profile, which must be considered when designing renewable energy systems to optimize energy efficiency.
- Investing in hybrid photovoltaic systems is particularly cost-effective for agricultural holdings, as their increased energy demand coincides with peak photovoltaic production periods, resulting in substantial savings and profits over time.

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