Integrated hybrid photovoltaic system for production, storage and use of electricity for energy-intensive processes

Konstantin Kostov,[1*], Krasimira Dimitrova[2]
Technical Universarity of Varna, Varna, Bulgaria[1,2]
kostov@meta8.bg[1]
krasimira.dimitrova@tu-varna.bg[2]

Abstract: *In today's global industrial environment, the need for sustainable, efficient, and energy-saving solutions for energy supply is more significant than ever and every enterprise that has adopted the policy of a green and low-carbon economy must seek such solutions. Enterprises must analyze their largest energy consumers and look for alternative options for generating and using "green energy". Photovoltaic systems are among the most common solutions, but their dependence on weather conditions requires integration with energy storage systems. This report presents a model and analysis of an integrated hybrid photovoltaic system with battery storage, designed to provide electricity for energy-intensive production processes under the conditions of the Bulgarian climate and electricity market.*
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1. Introduction

Sustainable development implies achieving an integrated balance between the three interrelated pillars of development – economic, social and environmental. In this context, sustainable development is seen as a process of harmonizing economic growth, social equality and the conservation of natural resources, with the aim of ensuring the long-term sustainability of human societies and ecosystems.

The growing urgency of climate change challenges, combined with the simultaneous need for energy security and economic stability, has raised heightened concerns about the future of energy sources.[6]

The use of renewable energy sources is becoming an increasingly important and responsible part of the fight against global challenges related to climate change, depletion of available natural resources and energy security both globally and in particular for manufacturing enterprises. Renewable energy sources such as solar, wind and hydroelectric energy provide sustainable alternative solutions to traditional coal and oil sources, which are the main generators of greenhouse emissions. Traditional energy sources must have a decreasing function and use at the expense of energy obtained from renewable energy sources. High-quality software solutions for monitoring energy consumption and, accordingly, planning energy consumption are also increasingly a priority part of the policies of modern enterprises. One of the priorities of the European Commission - the European Green Deal is the basis of this study in relation to the use of energy from alternative sources.[1] Business organizations are challenged to identify their environmental impacts in order to address environmental sustainability issues. [8]

By integrating alternative energy sources into energy systems, businesses can not only reduce their carbon footprint, but also increase energy independence and create new jobs in the field of green technologies. The wise use of alternative sources also helps to stabilize energy prices on international exchanges and to ensure access to electricity in remote and underserved areas, which is particularly important for economic development and social well-being. In the context of growing electricity consumption, the transition to sustainable use of alternative energy sources is becoming an indispensable part of energy production.

2. Purpose of the study

To develop and analyze a model of a hybrid photovoltaic-battery system, optimized to minimize energy losses and increase the efficiency of energy supply in industrial conditions in Bulgaria.

3. Research methodology

To achieve the goal of scientific research, it is necessary to solve the following research tasks:

1) To analyze the energy profile of a typical energy-intensive Bulgarian enterprise.
2) To determine the main sources of energy losses when using photovoltaic systems without storage.
3) To model a hybrid Photovoltaic battery (PV-battery) system with different combinations of parameters:
• Photovoltaic generator power,
• Battery capacity,
• Control algorithm.
4) To perform an energy and economic analysis to determine the optimal ratio between production capacity, investment and return.
5) To derive recommendations for parameterization and implementation of such systems in Bulgarian industrial enterprises.

To solve the tasks set to achieve the goal, literature review, engineering design and technical and economic analysis were used as research methods.

4. Economic, environmental and social advantages of using alternative energy

In 2015, United Nations (UN) Member States adopted 17 Sustainable Development Goals (SDGs) as part of the 15-year 2030 Agenda. They represent a blueprint for a better and more sustainable future, aimed at combating poverty, inequality, environmental problems and promoting peace and justice.[9], [11]

2025 marks the 10th anniversary of the adoption of the SDGs and the 10th edition of the Sustainable Development Report [9]. Produced by the SDG Transformation Center of Sustainable Development Solutions Network SDSN's, This report examines the progress made each year on the SDGs since their adoption by the 193 UN Member States and contains detailed country profiles, graphs, maps and analysis on each of the 17 goals. According to the Sustainable Development Report 2025, Bulgaria has an overall SDG index of 76.3/100, which places it in the middle of the EU ranking. (Fig. 1 and Fig. 2)

Fig. 1. Overall Performance and Average Performance by SDG. [9].

Fig. 2. SDG Dashboard and Trends. ***[9]****.*

The report shows that Bulgaria has a solid foundation and a full electricity supply, but the transition to clean energy and a low-carbon economy is too slow. Although the share of renewable energy sources is growing, the pace is not sufficient to reach the 2030 targets without accelerating the pace.

As countries around the world strive to achieve the 17 Sustainable Development Goals, society expects businesses to actively strengthen their sustainable practices and contribute to achieving net zero emissions.

The use of alternative energy in manufacturing plants is becoming increasingly relevant in the context of global efforts for sustainable development and minimizing carbon emissions. The use of "green" energy has some key advantages that are important for any enterprise:

• **Reducing energy costs** - Investing in alternative energy permanently reduces the cost of electricity, as the sources are free after the initial investment;
• **Cost optimization:** Alternative energy sources offer protection from fluctuations in traditional fuel prices and the electricity market, allowing businesses to more accurately plan electricity costs;
• **Reducing the carbon footprint** - Using alternative energy significantly reduces greenhouse gas emissions, which contributes to environmental protection and helps businesses prove their "green" policy of operating their organization;
• **Trust** - Businesses that implement sustainable energy practices build a better reputation and trust with their partners, customers and other related individuals and organizations;
• **Creating technological innovations** - Investing in the production and use of alternative energy stimulates innovation and the implementation of new technologies and software solutions.
• **Creating a competitive advantage:** Businesses that develop the use of alternative energy sources can be more attractive in the market to customers looking for sustainable solutions.
• **Use of external grant funding** - Companies have the opportunity to apply for various national programs for co-financing the production and storage of energy from renewable energy sources.

The use of alternative energy in manufacturing plants not only generates economic benefits, but also helps protect the environment and improves the image of companies in society. Businesses that invest in sustainable solutions will not only benefit from economic advantages, but will also play an active role in creating a cleaner and safer planet for future generations.

Electrical energy storage is recognized as a major technology with great potential for storing energy in a specific state, depending on the technology used. [4]

Financial profitability analysis is an essential topic for preliminary research and a key decision criterion in the design and construction of a photovoltaic system. [5]

5. Working principle of hybrid photovoltaic systems

Solar photovoltaic systems have become a reliable and sustainable energy source that meets the growing demand for electricity worldwide. The growing demand for clean energy has made this type of system an attractive option for electricity generation. [10]

Incorporating energy storage systems with solar photovoltaic systems is generating significant interest due to its ability to improve system flexibility, provide more reliable power supply, and optimize energy usage. [3], [6], [4] The use of solar energy, in particular by manufacturing enterprises, is the most affordable from an economic point of view. The technology for extracting and storing electrical energy from solar radiation is the most widespread and, accordingly, its price has been significantly reduced in recent years and is increasingly affordable for enterprises..

Photovoltaic technology is a method of directly converting sunlight into electricity using semiconductor materials. Solar panels, composed of photovoltaic cells, use sunlight to produce electrical energy. [4], [2]

Photovoltaic systems (PV- systems) with battery storage are increasingly being deployed in industrial plants with high energy consumption to reduce costs and increase energy independence. However, the efficiency of these systems depends on many parameters – installed power, battery capacity, inverter configuration, climatic conditions, load profile and control algorithm.

The main research problem is to identify the optimal parameters of the PV-battery system that minimize energy losses and maximize the usability of the produced energy under the conditions of the Bulgarian climate and industrial energy profiles..

On this basis, a local energy production system can be connected to existing infrastructure to become an energy generator.[7]

The hybrid photovoltaic system (Fig. 3) combines three main components:
• Photovoltaic generator (PV array) – converts solar radiation into electrical energy.
• Inverter-control unit – converts direct current (DC) into alternating current (AC) and manages the energy flows between the PV system, the battery and the grid.
• Storage system (battery module) – accumulates excess energy and provides power in the absence of sunlight or peak load.

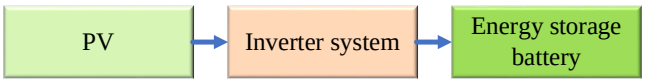

Fig. 3. Hybrid photovoltaic system

However, the size of the optimal system depends on many factors, such as meteorological data, load profile, battery size and price, feed-in tariffs, etc. [5]
A hybrid system can operate in several modes:
• Production and direct consumption – when there is sufficient solar radiation.
• Energy storage – when there is excess electricity production.
• Battery transfer to the load – during peak load or night mode.
• Grid exchange – when there is a shortage or excess of energy.
The integrated hybrid photovoltaic system with battery storage is an efficient and sustainable solution for providing electricity for energy-intensive production processes. The main advantages include:
• increased energy independence;
• stable power supply during peak loads;
• long-term economic and environmental benefits.

6. Development of a conceptual design for an integrated hybrid photovoltaic system

The development was made for the needs of a Bulgarian manufacturing company that manufactures metal structures and parts thereof.

The study examined a concrete case of providing an energy-intensive annealing process in the production of reinforcing steel wire to achieve greater elasticity of the material. This is a process of heating and controlled cooling of steel to reduce internal stresses, increase ductility, and improve the structure of the metal. This is done using an industrial electric furnace with top loading and a nominal power of 100 [kW/h].

Fig. 4 shows the schematic diagram of the wire annealing furnace. The company has undertaken to implement a program for maximum solar energy supply of the production process with this technology and for this purpose will use the available photovoltaic power plant with a capacity of 300 [kW/h] to meet the needs of this process. For this purpose, it has been calculated that the annealing system needs about 250 [kW] of electricity for the normal operation of the process.

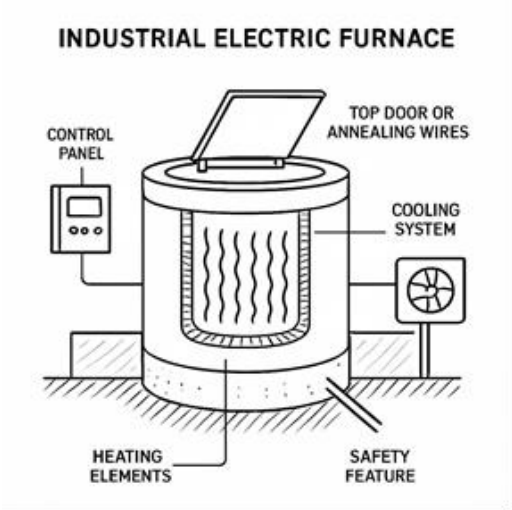

Fig. 4. Industrial annealing furnace

Table 1 shows the technological sequence of the process with data on the consumption of electricity for annealing wires with a material diameter of up to 4 [mm]. The table also shows that about 250 [kW] of electricity are required for one cycle. The company has built a photovoltaic power plant for electricity production with a capacity of 500 [kW/h]. This plant serves the entire production. In order to ensure the annealing process, the following work scheme has been made. Wire production is calculated in 6 working days and one day of maintenance. On the maintenance day, it is planned to temper the produced production that will be annealing. For this purpose, a hybrid system for storing electricity with digital control is being built, which is synchronized with the main inverter of the plant via software. It is planned that the batteries for wire production with a capacity of 300 [kW] will be charged with priority in order to ensure this production. The daily cost of wire production is between 200-300 [kW]. The hybrid system for the production, storage and consumption of photovoltaic energy takes into account the advantage of always keeping the batteries powered for wire production and then redirecting energy to other productions.

Table 1: *Wire annealing technology up to 4[mm] thick.*

Process	Temperature (°C)	Time (hours)	Energy consumed [kW/h]
Heating	до 800	2	180
Maintaining temperatures	800 - 900	1,00	60
Cooling	less than 100	1,00	10

As seen in Fig. 5, the photovoltaic installation can be used to support the overall energy system of the enterprise, both locally and with priority to individual nodes for planned energy consumption.

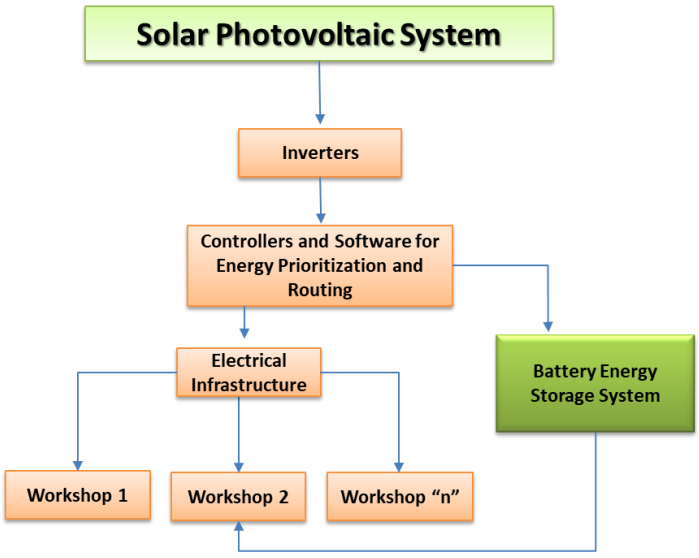

Fig. 5. Block diagram of photovoltaic infrastructure

The company plans to install a 500 [kW] photovoltaic power plant to cover part of its needs. In the first phase of the project, the installation of 303,3 [kW] photovoltaic panels is planned, and it will subsequently be upgraded to 500 [kW]. From an analysis of a 100 [kW] photovoltaic power plant in another base of the company, data on electricity production for one calendar year amounting to 106,875 [kW] is extracted. From this information, electricity production with a 300 [kW] power plant amounting to 320,000 [kW/year] is assumed. The average monthly yield is between 12,000 and 42,000 [kW] with a clear seasonality. This makes a daily yield between 400 and 1,400 [kW] on days with minimal sunlight and poor meteorological conditions and days with perfect conditions for solar energy production.

A battery system for electricity storage is also being designed for this system, to cover the production of wires and fibers. The batteries will have a total capacity of 303,08 [kWh].

7. Main components of the integrated hybrid photovoltaic system

Photovoltaic power plant with capacity 300,3 [kW] built from a photovoltaic panel SUN 66M-H8N – 550w, panel type - TOPCon HALF-CELL MONO PV MODULE

Inverters – Three Phase Hybrid Inverter+ Deye SUN- 50kw K-SG01HP3-EU – 6 pieces;

Total power battery system 303,08 [kWh]

Energy storage batteries - UZ Energy Power Lite 51.2V - 5.12kWh –59 pieces;

8. Investment costs for project implementation

Based on the current average price per kW of electricity consumed on the free market of 0,35 BGN excluding VAT, the following calculation can be made:

With an annual production of 320,000 kW x price of 0,35 BGN excluding VAT = 112,000 BGN per year, not taking into account the trend towards increasing electricity prices.

The price for delivery, installation and commissioning of the entire system is 450,000 BGN excluding VAT.

9. Return on investment

Return on investment: 440,000 / 112,000 = 3.93 years.

If the market price of electricity increases, which has been a constant trend in the last 2 reporting years, a return can be expected within 3,5 years.

The warranty period of the panels is 15 years, with the manufacturer giving 88% efficiency after 30 years.

The warranty period of the batteries is 10 years.

The warranty period of the inverters – 10 years.

The long warranty period of the system elements guarantees sustainable consumption of alternative energy.

10. Ecological effect

The implementation of a hybrid system with a photovoltaic installation and a battery group for energy storage has numerous positive environmental effects that would contribute to the sustainable development and implementation of a successful "green" practice in the company's energy management, such as:

• **Reduction of carbon emissions** - The use of solar energy instead of traditional fossil fuels significantly reduces emissions of CO2 and other greenhouse gases;

• **Sustainable resource management** - Solar energy is a renewable resource that is practically inexhaustible;

• **Efficient use of energy** - Batteries allow the storage of excess energy generated during sunny days, which ensures a stable and reliable supply during days with worse meteorological conditions;

• **Reduction of noise pollution** - Photovoltaic systems operate silently, compared to traditional generators operating on liquid, gaseous fuels and wind facilities, which create noise pollution;

• **Locations** – photovoltaic panels are located on a pitched roof and do not affect soils and biodiversity in any way.

11. Conclusion

The use of renewable energy sources and the implementation of hybrid energy systems to provide power at different stages of the production process represent a strategic step towards increasing the energy independence and environmental sustainability of enterprises. This approach creates the prerequisites for the production of products with "green production" certificates, which in turn improves the corporate image, increases competitiveness and provides access to new market segments in which consumers and business partners set high requirements for the use of energy produced entirely from renewable sources..

In recent years, there has been a growing trend towards the mass deployment of photovoltaic systems for electricity generation, which is an important step in the energy transformation process. The next stage in this transition is the effective management and integration of these systems through modern software solutions that allow for weather monitoring, energy consumption optimization, intelligent storage and use of accumulated energy at times of high market prices. This leads to better cost control, increased efficiency and a lower carbon footprint of production activities.

In a broader context, such technological and organizational solutions are fully consistent with Goal 7 of the UN Sustainable Development Goals – "Ensure access to affordable, reliable, sustainable and modern energy for all". They contribute both to increasing the share of energy from renewable sources and to improving the energy efficiency and sustainability of the industrial sector. The implementation of such systems not only supports the achievement of national and European goals for green transformation, but also strengthens the role of enterprises as active participants in the transition to a low-carbon and sustainable economy. In this sense, integrated energy management is a key tool for implementing the principles of sustainable development in the practice of modern industry. Despite the higher initial investment, the system is economically justified and guarantees a significant reduction in the carbon footprint of industrial production.

This publication presents the results of an actual scientific and practical study conducted within the framework of a scientific doctoral project PD9/2025, funded by the state budget - 2025 at the Technical University - Varna "Innovative solutions for sustainable business development in Bulgaria in the transition to a circular and low-carbon economy".

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