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POWERING GREENHOUSES WITH PHOTOVOLTAICS AND BATTERY PACKS IN SOUTHERN BULGARIA

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Abstract

The integration of photovoltaic (PV) technologies into greenhouse structures represents a promising approach to achieving sustainable agricultural production while reducing dependence on fossil-based energy. This paper presents a comprehensive analysis of a photovoltaic greenhouse concept designed to operate as an energy hub by combining semi-transparent PV modules, battery energy storage systems (BESS), and auxiliary loads such as irrigation pumps and electric vehicle (EV) chargers. Performance simulations and literature data are used to evaluate the seasonal energy autonomy of the system and its operational impact on both food production and energy management. Results indicate that the inclusion of battery storage significantly enhances self-sufficiency, increasing summer energy autonomy from approximately 24% to 43% and winter autonomy from 69% to over 81%. These findings demonstrate the dual role of photovoltaic greenhouses: providing controlled environmental conditions for crops and serving as distributed renewable energy generators. The study underlines the potential of PV-greenhouse systems as scalable solutions for sustainable agriculture, energy transition, and climate change mitigation.

Keywords: photovoltaic greenhouse, semi-transparent PV, battery storage, energy autonomy, sustainable agriculture, energy hub.

OVERVIEW OF CLIMATIC CONDITIONS IN SOUTHERN BULGARIA (SUNSHINE)

Southern Bulgaria is characterized by a mild continental climate and high sunshine, which is favorable for photovoltaic (PV) systems. The average annual duration of sunshine in the southern regions reaches 2100–2500 hours, with the highest value recorded in the city of Sandanski – about 2500 hours per year. This corresponds to a significant resource solar energy: the average annual total solar radiation in Bulgaria is ~1517 kWh/m², while in the South-East and South-West regions (including the southern parts of the country) it reaches ~1650 kWh/m² per year. In practice, this means that Southern Bulgaria has a solar potential comparable to that of Southern European countries [1].

In the summer months, conditions are particularly suitable: sunshine reaches 11–12 hours per day in July and August, and the solar energy intensity around noon exceeds 0.75 kW/m². The winter months are less sunny (e.g. December around 50 kWh/m² per month), but still provide a valuable resource for generating electricity. The warm climate of Southern Bulgaria reduces the need for heavy heating compared to more northern regions, which further supports the efficiency of greenhouse systems. The higher sunshine directly translates into more yield from photovoltaics, making the region extremely suitable for solar installations.

Estimated monthly PV electricity production (Southern Bulgaria). Figure 1 presents the estimated monthly electricity production from a 100 kW photovoltaic

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system, illustrated by turquoise columns. Electricity generation reaches its highest levels during the summer months (June–August) and decreases significantly during winter. This seasonal variation reflects the influence of solar irradiation and sunshine duration on photovoltaic electricity production.

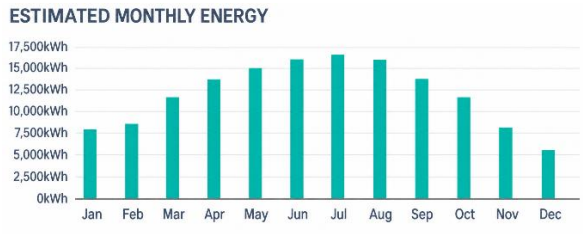


Fig. 1. *Estimated monthly electricity production of a 100 kW photovoltaic system in Southern Bulgaria*

The abundance of solar energy in Southern Bulgaria creates excellent conditions for the implementation of photovoltaic systems in agriculture. Solar panels can achieve high productivity – about 1300–1500 kWh per year from each installed kWp with optimal orientation and inclination. This means that a system with a peak power of 1 kW can generate over 1,300 kWh of electricity per year under Southern Bulgarian conditions. Compared to the national average (~1100–1420 kWh/kWp per year), the southern regions have ~10–15% higher yields. These high levels of sunshine and radiation provide a stable and predictable basis for the efficient operation of PV systems throughout most of the year, which is key to the energy security of greenhouses [2].

TECHNICAL SPECIFICATIONS OF PHOTOVOLTAIC PANELS AND BATTERY SYSTEMS FOR MEDIUM-SIZED GREENHOUSES

Photovoltaic panels (modules): Modern greenhouse installations usually use monocrystalline silicon panels with high efficiency (20–22%). Monocrystalline modules have the advantage of higher efficiency and better performance at high temperatures compared to polycrystalline ones. The typical power of a single panel today is 400–600+ Wp, an example is the YINGLI Solar YL410D-37e model with a peak power of 410 W and an efficiency of over 21%. It is made of 108 monocrystalline cells (PERC technology), at a voltage of 30.95 V and a current of ~13.3 A, with a size of ~1.72×1.13 m and a weight of ~21.5 kg. Another example of a high-efficiency module is the Trina Solar Vertex series – panels with a cell size of 210 mm and a power of 500–660 W at an efficiency of ~21.6%. Such high-power modules reduce the number of panels needed and save space, which is important for limited areas such as greenhouse roofs.

the durability of the panels is also important for greenhouse conditions. Models with a robust construction (e.g. glass-glass lamination) are recommended, resistant to moisture, hail, dust and ammonia fumes from fertilizers. The panels of the German company Solarwatt have double-sided tempered glass and half-cut PERC cells, which are resistant to ammonia, salt fog and snow load. They retain their durability in the aggressive greenhouse environment. Also, double-sided (bifacial) panels are increasingly used, which can capture reflected light inside the greenhouse. With proper integration, partially transparent or reduced-density panels even act as shading, improving the microclimate (reducing overheating) and simultaneously generating energy [3].

Battery systems (accumulators): For energy storage at night or in cloudy weather, the implementation of battery blocks is used. There are several types of batteries, but the main ones for PV systems are lead-acid (incl. AGM and gel) and lithium-ion (Li-ion) batteries. Lead-acid batteries (traditional or AGM/gel) are cheaper initially, but have a shorter life – about 500 full discharge cycles for maintenance-free AGM/gel batteries (≈1–3 years of intensive use). They allow a depth of discharge of up to ~50%, above which they wear out quickly. At the same time, lithium-ion batteries (most often

lithium iron phosphate – LiFePO4) provide 3000–5000 cycles at 80–90% depth of discharge. This means 10+ years of operation with daily charge/discharge – a key advantage that justifies their higher price. For example, a 5 kWh Li-ion module can withstand ~4000 cycles, while a lead-acid module with the same capacity can withstand ~1800 cycles. Lithium batteries also have a higher energy density (more compact) and high charge/discharge efficiency (>95%). Table 1 summarizes some characteristics:

Table 1. *Comparison of battery technologies for PV systems*

Battery type	Typical cycles (up to 80% discharge)	Usable capacity (DoD)	Advantages	Disadvantages
Lead-acid (FLA)	~300–500 full cycles	~50% (recommended)	Low cost; surge resistant	Short life; requires maintenance (topping up)
AGM / Gel (VRLA)	~500–1000 cycles	~50–70%	Maintenance-free; longer life than FLA	Higher price than FLA; average life
Lithium-ion ($LiFePO_4$)	~4000+ cycles	90%+	Long life; deep discharge; compact	High initial price

The choice of battery depends on the needs: if the greenhouse aims for complete autonomy, reliable Li-ion batteries will be preferred, despite the larger investment, due to their long life and lower cost per cycle. If the system is hybrid with the grid, a smaller lithium module can be combined (to cover evening peaks) or even rely entirely on the grid at night and save battery costs. It is important that the battery has a capacity that covers the greenhouse's nighttime consumption (e.g. lighting and circulation), as well as a reserve for a few cloudy hours. A commonly used indicator is the C10 capacity, corresponding to a 10-hour discharge - for example, a 100 Ah battery at 48 V (4.8 kWh) should be able to deliver ~0.48 kW stably for 10 hours. Modular lithium batteries from companies such as Pylontech, Tesla Powerwall, LG Chem are increasingly popular in greenhouse systems, which allow expansion to tens of kWh. As an example, a 4.8 kWh (48 V) lithium battery is available on the Bulgarian market for ~3,000 BGN, while a lead-acid unit with a similar usable capacity would be around 1,500–2,000 BGN, but with a much shorter service life.

In addition to panels and batteries, key components are solar inverters (DC/AC converters) and charge controllers. In stand-alone systems, hybrid inverters or a combination of an MPPT solar controller and a standalone inverter are used. Inverters must be sized for the maximum consumption – for example, a 20 kW load requires a ~25 kVA inverter for reliability. Modern inverters have an efficiency of >96% and built-in protection. For higher capacities (over 30–50 kW), several three-phase inverters connected in parallel are often used, which allows modularity and redundancy. Manufacturers such as SMA, Fronius, Huawei, Victron offer industrial solutions adapted to agricultural conditions (dust and high temperature resistant) [4].

INSTALLATION MODELS – AUTONOMOUS, HYBRID, WITH/WITHOUT GRID INVERTER

In practice, several basic models for integrating photovoltaics into the greenhouse are applied:

- Autonomous system (off-grid): The greenhouse is powered entirely by the PV array and batteries, without connection to the power grid. During the day, the panels directly cover the consumption and charge the batteries, and at night and in the absence of sun, the batteries take over the power supply. An autonomous inverter is used, which synthesizes its own AC network for consumers. The advantage is complete energy independence and avoidance of electricity costs from the grid. The disadvantage is the high investment costs for

large-capacity batteries and the need for precise sizing so that the greenhouse does not remain without power. An example of an autonomous system is a family farm in Vratsa with a 30 kWp photovoltaic power plant and lithium-ion batteries, which is not connected to the grid and independently powers 13 greenhouse tunnels - fans, lighting, pumps, etc. During the day, the PV panels there charge the batteries, which take over the load during the dark hours. This shows that even medium-sized farms can successfully operate off-grid with good planning.

- On-grid system without batteries: Here, the photovoltaics are connected to the electrical grid via a grid-tie inverter. During the day, solar energy powers the greenhouse, and the excess is fed into the grid (sold or exchanged under a net metering scheme). At night or in case of a shortage, the greenhouse automatically draws power from the grid. This solution eliminates the need for an expensive battery pack and allows for the efficient use of 100% of the energy produced. These grid-connected systems are the most common in greenhouses, as they provide reliability (the grid serves as a backup) and cost savings. Installing an on-grid PV system requires coordination with the energy distribution company and a two-way electricity meter. In Bulgaria, the connection process is relatively simple for installations under 30 kW of installed capacity, and from 2023, rooftop PV up to 20 kW for self-consumption can be built without a building permit - only with a notification regime. For larger capacities (>30 kW), a standard connection and licensing procedure is required, but if the energy is used for own needs (not for purely commercial sale), the licensing regime is simplified (no license is required for production up to 5 MW for own needs).
- Hybrid system (combined): This is the most flexible option – the photovoltaic installation is connected to the grid and has a battery bank. Solar energy is used as a priority, the batteries store the surplus for the evening hours, and in case of shortage, the grid serves as a backup. The hybrid model guarantees uninterrupted power supply – critical for sensitive equipment (e.g. automation, heating). Modern hybrid inverters can automatically switch modes and optimize energy flows. For example, on a sunny day the battery is fully charged, after which the surplus goes to the grid or is limited, and when the power supply stops (accident) the inverter switches the greenhouse to emergency battery power mode (UPS function). The hybrid system combines the advantages of both approaches – security and economy, but is more expensive than the purely grid-based one due to the cost of the batteries and the more complex inverter. This model is suitable for farmers who want to minimize their dependence on electricity companies, but still have a reserve in case of unforeseen situations.

In all models, it is important to integrate the system with the specific needs of the greenhouse. For example, if the farm has a diesel generator, it can be combined with PV in a hybrid system as an additional backup during particularly long periods without sun. Also, the physical placement of the panels in relation to the greenhouse varies: for large areas, ground-mounted PV arrays are often built next to the greenhouse, while for small and medium-sized greenhouses, the panels can be mounted on the roof or even used as a roof structure. If the greenhouse is smaller, it is sometimes more efficient to place the panels on the ground close to it (on a shed or structure) so as not to overshadow the plants inside. For larger greenhouses, there are practices to mount the panels higher above the structure (on a separate supporting frame), which provides diffused light for the crops below. In some cases, mobile (solar tracking) systems or translucent panels, specially designed for agrivoltaic purposes, which allow some of the light to pass through to the plants, are also applied.

In conclusion, the choice between an autonomous, grid-connected or hybrid configuration depends on the following factors: the availability and reliability of the

electricity grid in the area, the desired level of energy independence, the farm budget and risk tolerance. Medium-sized farms often choose a hybrid approach – a PV system with grid connection for selling surplus and a small battery reserve for critical consumers, which optimizes both costs and security of supply [5].

ENERGY NEEDS OF AN AVERAGE GREENHOUSE AND SYSTEM SIZING

The energy needs of a greenhouse depend on its size, type of crops and the degree of automation. The main consumers include: heating/cooling, artificial lighting, ventilation, irrigation (pumps) and auxiliary equipment (automation, fertilizer dispensers, CO_2 generators, etc.). An average-sized greenhouse (e.g. 1000 m² area) with year-round vegetable cultivation may have an annual consumption of around 150,000 kWh of electricity. This figure varies greatly - a greenhouse for seedlings only (without fruiting) or with minimal heating will consume less, while a modern glass greenhouse with intensive artificial lighting (e.g. for tomatoes or flowers in winter) can exceed 200,000 kWh/year for 0.1 ha of area.

To properly size a PV system, an energy audit of the greenhouse is required, covering the following: (1) hourly and seasonal consumption profile, (2) peak loads (kW) and simultaneity, (3) critical consumers that should not lose power. Based on this, the necessary sizes of solar generation and batteries are determined. A common approach is to design a system that covers at least 100% of the average daily consumption during the least sunny period to ensure self-sufficiency. For example, if the greenhouse consumes an average of 410 kWh per day (150,000 kWh/year), a PV array can be targeted that provides ~410 kWh on a December day. Since December has ~2.5–3 hours of sunshine per day (50–60 kWh/m² per month), a 100 kWp installation would generate about 200–250 kWh on a clear winter day, which is ~50–60% of the needs, and the rest must come from the grid or batteries. In summer, the same 100 kWp system will produce much more – up to ~700–800 kWh per day, allowing for surplus for sale or battery charging.

A practical example of calculation is given by the company Miilkiia: for a greenhouse with a roof area of 1000 m², if 70% of the roof is covered with panels (700 m²), with an average solar irradiation of 4 kWh/m²/day and an efficiency of the panels of 20%, the daily production would be ~560 kWh. For a year, this equates to ~204,400 kWh, which fully covers consumption of 150,000 kWh and leaves a surplus of ~54,000 kWh for sale to the grid. Of course, this is an idealized scenario (assuming that the entire area can be used and the sunlight is constant). In real conditions, losses of ~10–15% are reported (from temperature effects, dust, non-ideal orientation, shading, etc.), so for 150 MWh of annual consumption, about 150–170 kWp of installed PV capacity in Southern Bulgaria may be needed.

The size of the battery pack is mainly determined by the desired autonomy (how long the greenhouse can operate without sun). If the goal is to fully cover the night consumption, the night load must be calculated. For example, in a 1000 m² modern greenhouse, only supporting heating and minimal lighting can operate at night, say 20 kW on average for 12 hours = 240 kWh. For such a scenario, a battery of ~250 kWh (for example 5 modules of 50 kWh) would be needed, which is a significant expense. Therefore, a compromise is often made in hybrid systems – the battery is sized to cover the most important consumers (lighting, control systems) and an automatic reduction of the load at night is provided (the temperature can drop by several degrees if there is no external power supply, etc.). In autonomous systems, however, the batteries must cover the full load for at least 1–2 days, plus a reserve for periods of cloudiness. The rule of 3 days of autonomy at 50% discharge is often applied – that is, a battery with a

capacity equal to three times the daily consumption, which at 410 kWh/day is about 1230 kWh. This naturally makes the system extremely expensive and explains why most farms choose grid connection instead of mainly batteries.

Energy management: To make optimal use of solar energy, it is advisable to plan energy-intensive processes in the greenhouse for daytime hours. For example, irrigation pumps and fans can be started around noon, when the PV system provides maximum power. Numerous studies have shown that ventilation and humidification are most often operated when the sun is at its strongest, which is why their consumption can be directly absorbed by the photovoltaics. This reduces the required battery capacity - they mainly provide nighttime lighting and heating, while daytime peaks are absorbed by the sun. New energy management systems (EMS) allow for intelligent management - for example, if the batteries are charged, excess energy can be fed to additional water heaters or directed to the grid. There is some flexibility in greenhouse production - some processes (such as heating) have thermal inertia and can be temporarily reduced until the sun rises without harming the plants. It is this flexibility that should be used to reduce peak system loads [8].

In summary, sizing a PV system for a greenhouse includes: (a) calculating the annual and peak consumption, (b) determining the required PV power to cover daily needs for most of the year, (c) determining battery capacity according to the desired autonomy, (d) ensuring sufficient inverter capacity against peaks. Table 2 presents sample component sizes for different consumption levels [6].

Table 2. *Comparison of battery technologies for PV systems*

Annual greenhouse consumption	Required PV power (Southern Bulgaria)	Batteries (Li-ion) for 8 hours of autonomy	Example configuration
50,000 kWh (small greenhouse)	~40 kWp	~100 kWh (e.g. 2×50 kWh modules)	40 kW panels + 2×25 kW inverters, 2×50 kWh $LiFePO_4$
150,000 kWh (average, 1000 m^2)	~120 kWp	~300 kWh	120 kW panels + 3×40 kW inverters, 6×50 kWh $LiFePO_4$
300,000 kWh (large, 1–2 ha)	~250 kWp	~600 kWh	250 kW panels + 5×50 kW inverters, 12×50 kWh $LiFePO_4$

COST ANALYSIS: INVESTMENT, RUNNING COSTS, MAINTENANCE, SAVINGS AND PAYBACK PERIOD

Initial investment costs: The cost of building a photovoltaic system depends on the scale, type of components and complexity of the installation. By 2025, a complete PV installation for business customers (including panels, inverters, structures, labor) costs approximately 800–1200 EUR/kWp (1500–2400 BGN/kW) for higher capacities, without batteries. For example, a 100 kW system would be around 150–200 thousand BGN. The largest share of the costs is the solar panels (20–30%) and the batteries, if included. Lithium-ion batteries add approximately 700–1000 BGN per kWh capacity, so a 200 kWh battery pack can reach 150–200 thousand BGN by itself. Table 3 gives an example of the cost distribution for a hybrid system with batteries:

Table 3. *Example of investment cost distribution for a hybrid PV system*

Component	Share of total value (example)
PV modules (panels)	25%
Battery system (Li-ion)	35%
Inverters, controllers, electrical panels	15%
Assembly structures, labor, design	25%

Example of investment cost breakdown. The four main components are shown: photovoltaic panels, battery modules, power electronics (inverters, controllers) and costs for installation, structures and other activities. In a hybrid system, batteries can form the largest share of the budget (30–40%), while in a grid-connected system without batteries, panels and inverters dominate.

It is important to note that the prices of PV technologies have dropped significantly over the past decade – according to industry data, with panel prices 30–40% lower than 10 years ago. At the same time, the price of electricity from the grid is increasing, which makes investing in photovoltaics increasingly profitable. According to analyses, such an investment for business purposes is fully paid off in 6–10 years under current conditions. This means that after this period, the saved electricity costs cover the initial investment, and the system continues to generate free energy for another 15–20 years (the typical life of panels is 25+ years, of inverters 10–15 years, of batteries 10+ years for li-ion or ~5 years for AGM).

Running costs and maintenance: Photovoltaic systems are characterized by low operating costs. The panels have no moving parts and require only periodic cleaning (washing off dust and adhering dirt 1–2 times a year) and inspection of the wiring. In areas with higher rainfall, rain naturally cleans the modules, but in greenhouses, dust and limescale deposits from irrigation may require manual washing of the panels, for example with soft water or washing robots. Inverters and electrical panels should be inspected for overheating of connections and their cooling fans renewed as necessary (replacing filters, if applicable). Battery systems, especially lithium ones, require an environment free from extreme heat - an air-conditioned cabinet or room is recommended to operate at <30°C for maximum life. If lead-acid batteries are used, they should be regularly checked and recharged/balanced, as deep discharge shortens their life drastically.

Running costs are mainly limited to monitoring and spare parts. According to operators, annual maintenance is less than 1% of the investment – for example, for a 100 kW system ~1000–1500 BGN/year, which covers inspections, cleaning and possible replacement of a small percentage of defective modules or electronics. Some farmers with solar greenhouses report that their actual cost is only the labor for periodic inspections, as serious damage is rare. Inverters often have a 5–10 year warranty, panels – a 10 year product warranty and 25 years for performance (over 80% of the nominal value by the 25th year). This means that after the system is paid off, electricity costs practically disappear, replaced only by minor maintenance costs. An additional economic plus is the extension of the life of the equipment – for example, if the solar system directly powers fans during the day, this reduces grid consumption and, accordingly, possible peak power tariffs.

Savings and return: The main savings come from the saved electricity bills. For agricultural enterprises, the price of electricity is on the free market - in 2024, the average price for business customers in Bulgaria was about 0.155 USD/kWh (~0.27 BGN/kWh). At this level, if a greenhouse consumes 150,000 kWh/year, the annual electricity cost would be ~40,500 BGN. A 120 kW PV system with a 200 kWh battery can cover ~80% of this consumption, saving about 32,000 BGN per year (the remaining 20% is taken from the grid at night or in winter days). Thus, an investment of ~300,000 BGN would pay off in ~9–10 years at these prices. However, if electricity prices increase (as they did in 2022), the payback period will be even faster – for

many projects, the period has dropped to 5–7 years. According to a study by NREL (USA), a typical photovoltaic greenhouse can pay for itself in 6–10 years. Bulgarian sources also indicate a range of 6–7 years for full payback under current conditions and government incentives. This is an extremely short period compared to the life of the systems – after payback, the farmer secures at least another decade of free electricity, which directly translates into profit and competitive advantage (lower cost of production).

Example of return on investment over time. The graph shows the accumulated cash flow (costs saved minus investment) over the years for a PV system. At the beginning (year 0) an investment is made (-100 notional units). Each year the solar system saves, for example, 15 units of electricity bills. The line crosses zero around year 6.5–7 – there the investment is paid off, after which the accumulated value becomes positive (the system starts to "make money"). This illustration corresponds to a payback period of ~7 years, in line with real projects (6–10 years). After the payback, the annual savings directly increase the farm's profit.

In addition to direct savings, we should also mention indirect financial benefits: protection from future increases in electricity prices (energy independence acts as a hedge), the possibility of selling surplus (income), increasing the value of the property/farm with available RES infrastructure, as well as improving the sustainable image of the production (which can be used in marketing). Some retail chains and end customers give preference to agricultural products grown with renewable energy in the context of the "green transition". All these factors contribute to solar greenhouses being not only environmentally friendly, but also economically beneficial in the long term [7].

TAXATION, GOVERNMENT SUBSIDIES AND INCENTIVES IN BULGARIA

Tax regime for PV systems: In Bulgaria, photovoltaic systems for own use are not subject to additional taxes on the energy produced. If the farm uses solar electricity for its own needs, this simply reduces its costs and does not generate taxable income. However, if the farm sells electricity to the grid (e.g. surplus), the income generated is subject to standard taxation. The farmer can choose whether to sell as an individual or as a company. In the case of a company, the income from the sale of electricity increases the profit, which is taxed at 10% corporate tax. The company can use a VAT tax credit for the purchased equipment (which effectively reduces the investment by 20% when registering under the VAT Act). If it sells as an individual, it also owes income tax (a flat tax of 10%), but the need to keep accounts as a commercial company is avoided. In many cases, for small systems up to ~30 kW, farmers choose the simpler regime (as an individual), and for larger projects they register a separate company for the photovoltaic plant in order to be able to recover VAT and account for expenses.

It is important to note that electricity producers for own consumption are exempt from excise duty. In Bulgaria, there is an excise duty on electricity, but it applies only to licensed producers with capacities above 5 MW, which is not the case for greenhouse installations. Also, from 2023, the requirement for a construction permit for small rooftop PV systems up to 20 kW for own needs was abolished - which significantly reduced the administrative burden. Of course, the obligation to connect to the grid (when there is one) remains in accordance with the established procedure - a notification is submitted to the electricity distribution company, which inspects the

grid and within 30 days approves the connection conditions for systems up to 10.8 kW (with a simplified procedure). For systems above 30 kW, a standard project and connection contract are required, and for the sale of all energy - registration as an electricity trader. But rural farms are usually mainly interested in reducing their own bills, so they implement projects up to several hundred kW and use 80–100% of the energy for their own needs, without becoming large electricity traders.

Government subsidies and incentives: In recent years, there has been significant support for the implementation of renewable sources in agriculture, mainly through European programs. At the time of writing (2025), several initiatives are active:

• Rural Development Programme (RDP): In 2023–2024, targeted admissions were opened under sub-measures 4.1 and 4.2, aimed at investments in renewable energy for agricultural holdings and processing enterprises. A budget of BGN 52.8 million was provided under sub-measure 4.2 (for processing and marketing), with financial assistance covering up to 50% of the eligible costs for RES systems. Investments in installations for the production of energy from RES for own needs, including photovoltaics, and local energy storage facilities (batteries) are eligible. Projects of greenhouses and enterprises from sensitive sectors (fruits, vegetables) are evaluated as a priority, which precisely includes vegetable greenhouses. In practice, an average farmer can apply with a project (e.g. 200 kW panels + 200 kWh battery ~ 500 thousand BGN) and receive a 50% grant (grant ~ 250 thousand BGN), which drastically reduces the return on investment period.

• National Recovery and Resilience Plan (NRRP): Under the NRRP, the Ministry of Energy opened procedures for financing photovoltaic power plants with batteries for business needs. One of the procedures (BG-RRP-4.032) was aimed at building solar installations between 30 kW and 1 MW, mandatorily combined with a storage battery (with a capacity of 1.5 kWh for every 1 kW installed). Financing under this measure covers up to 70% of the project cost (max. EUR 1 million grant). Many companies and agricultural cooperatives applied at the end of 2022 and 2023, and by 2024, hundreds of projects had been approved. For farmers, this was a golden opportunity to practically build PV systems almost for free (with a 70% grant), which explains the boom in projects - according to ESO data, ~1000 MW of new RES capacity was introduced in the country in 2024. It should be noted that these programs have deadlines and specific requirements, but the trend is for support to continue in the coming years, as Bulgaria has national targets for the share of renewable energy and decarbonization.

• Other incentives: Some local initiatives and commercial banks also offer more favorable conditions for "green" investments. For example, the Bulgarian Development Bank (BDB) launched a credit line in 2025 to finance photovoltaics for municipalities and businesses with preferential interest rates. Commercial banks such as Raiffeisenbank and ProCredit Bank have specialized products for RES, which often include consultations and a grace period until the project is implemented. Tax breaks such as accelerated depreciation of the investment (for companies – under the CITA) are also a form of incentive: photovoltaic facilities can be depreciated by up to 50% per year, which reduces taxable profit in the first years.

In summary, currently the combination of European subsidies and cost savings makes the implementation of PV and batteries very profitable for the agricultural sector. An entrepreneurial farmer can benefit from 50–70% grant funding, and the rest of the investment can be repaid through savings on bills within 5–7 years. This is also the reason why many solar greenhouses are already operating successfully in our country – state

policy stimulates this transformation, and market conditions (high energy prices) further justify it economically [7].

PRACTICAL EXAMPLES (CASE STUDIES) FROM SOUTHERN BULGARIA

In Bulgaria, the implementation of photovoltaics in agriculture is gaining popularity, with real examples of working solar greenhouses. In Southern Bulgaria - especially in traditional greenhouse regions - several pilot projects are already operating:

- Solar greenhouses in Plovdiv and Stara Zagora regions: According to industry publications, several photovoltaic greenhouses have been successfully built in the Plovdiv region (Thracian Lowland) and around Stara Zagora. They have systems in the range of 100 to 500 kWp, which provide a significant portion (at least 60–70%) of the energy for their operation. Typically, such complexes also include battery storage systems to ensure constant power supply around the clock. For example, data has been published for a greenhouse near the town of Parvomay (~1 ha area) with installed 200 kW panels and a 300 kWh lithium battery, covering about 80% of the farm's annual needs (the rest is mainly winter gas heating). Another example is a rose greenhouse in Stara Zagora, which combines a 100 kW rooftop PV system with a small wind turbine, as well as a diesel generator for backup - indicative of a hybrid approach that increases reliability.
- Versol Farm, Lik village, Vratsa region: Although not in Southern Bulgaria, this case study is very instructive. The Versol organic farm (described in Agri.bg) has 3 decares of greenhouses, powered by an autonomous 30 kWp photovoltaic power plant with batteries. The system was implemented with the help of RDP projects and also includes solar collectors for hot water and automation software. The farm is not connected to the national grid – the entire complex (greenhouses, warehouses, irrigation) is powered by the sun and rainwater. During the day, 30 kW panels directly power the drip irrigation, fans and lighting, while also charging lithium-ion batteries. At night, the batteries (charged to full capacity during the day) cover the needs. This allows year-round cultivation of organic vegetables without the use of diesel generators or mains electricity, which significantly reduces costs and carbon footprint. The Versol case study shows that even in Northern Bulgaria (where the sunshine is slightly lower) it is possible to operate completely autonomously, as long as the system is properly sized and combined with eco-practices (in this case – thermal collectors, water tanks for heat, etc.). This gives confidence to farmers in the southern parts that their projects would be even more successful given the better solar resource.
- Greenhouses in Dobrich (Northeast) and Sliven region: According to the newspaper "Bulgarian Farmer", in addition to Southern Bulgaria, there are solar greenhouses in Dobrudzha, Sliven and Pleven regions. In Dobrich, several vegetable growers have built PV systems of ~50 kW on the roofs of their greenhouses, which power heating fans in the winter and help with lighting. In Sliven (village of Zhelyo Voyvoda), a farm is mentioned that uses solar panels for irrigation - apparently a photovoltaic pumping system, drawing water from a borehole for the flower greenhouses. These examples, although geographically scattered, show a common trend: farmers understand the potential of the sun not only to grow crops, but also to save them costs, and are investing in agro-photovoltaics, often with the help of programs and consulting services.
- International experience relevant to Southern Bulgaria: In Spain – a country with a climate similar to ours – there are successfully operating projects such as “Solar Cucumber” – a 100 kW solar installation powers a complex of cucumber greenhouses, fully covering their needs. We have similar sizes and climatic conditions in our country (e.g. the semi-mountainous regions of Petrich, Sandanski). In Greece, a number of greenhouse farms also install PV sheds, which helps them with the frequent

summer heat (they provide shade) and power surges. These examples confirm that the technology has been tested and works – not only in the laboratory, but also in real farms, without hindering yields, on the contrary, it even stimulates them through a better microclimate.

The practical cases point to several key conclusions: First, photovoltaics can be successfully integrated into different types of greenhouses – polyethylene tunnel, glass, Gothic, etc., as long as the structure is reinforced for the additional weight of the panels. Second, farmers often start with a small system and upgrade it – e.g. first 30 kW, then expand to 60 kW, as they see the effect on their bills. Third, synergy is important: in most cases, PV systems are part of a comprehensive package of energy efficiency measures – greenhouse insulation, thermal screens, water-saving technologies. This maximizes the benefits of solar energy.

Last but not least, practical experience shows that solar greenhouses improve profitability. According to calculations in European reports, the implementation of PV can save 25–40% of the greenhouse's energy costs, and individual farmers in our country speak of an even greater effect after the increase in electricity prices in 2022. This, combined with subsidies, makes the payback periods short and encourages more and more farmers to consider switching to photovoltaic power supply [7].

CONCLUSION

Powering greenhouses with photovoltaic systems and battery units in Southern Bulgaria is emerging as a promising solution, uniting the environmental and economic goals of modern agriculture. Thanks to the excellent climatic conditions (high sunshine) and the development of PV technologies, medium-sized agricultural enterprises can significantly reduce their energy costs and dependence on the grid. The technical analysis showed that there are suitable panels with high efficiency, reliable lithium batteries and flexible installation models (autonomous, hybrid) that can meet the specific needs of greenhouses. Calculations of energy needs and sizing prove that even with significant consumption, the solar system can be designed to cover the main share of the load, especially if daily processes are synchronized with energy production. The financial analysis highlighted a return within 6–10 years without subsidies and even faster with grant funding – which, supported by the current RDP schemes and the Recovery Plan, makes the investment even more attractive.

Real examples from the country – in Plovdiv, Stara Zagora, as well as similar attempts abroad – demonstrate that solar greenhouses are not an experiment, but a working model with measurable benefits: a 25–40% drop in energy costs, a more stable microclimate for plants (thanks to the shading from the panels and uninterrupted power supply) and lower carbon emissions. From a business strategy perspective, a medium-sized agricultural enterprise with solar power increases its competitiveness – it is less vulnerable to fluctuations in electricity and fuel prices, can boast of "green" production (which adds value to end users) and in the long term saves funds that can be reinvested in expanding its activities.

Of course, the success of such projects also depends on good planning and management. Farmers need to consult with specialists when designing the systems, make the most of available subsidies and integrate photovoltaics as part of an overall energy efficiency strategy (insulation, modern climate control technologies, etc.). But the trend is clear: the future of greenhouse production is closely linked to renewable energy. Southern Bulgaria with its sun has every chance to be a leader in this transition – transforming traditional greenhouses and greenhouses into high-tech, energy-independent and sustainable farms that produce ecologically clean food at a lower cost and with the environment in mind.

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