IMPLEMENTATION OF A SOLAR–HYDRO HYBRID SYSTEM FOR POWERING WATER PUMPS IN A SUSTAINABLE AGRICULTURAL FARM

IMPLEMENTAREA UNUI SISTEM HIBRID SOLAR-HIDRO PENTRU ALIMENTAREA POMPELOR DE APĂ ÎNTR-O FERMĂ AGRICOLĂ SUSTENABILĂ

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ABSTRACT

In the context of rising electricity costs and the increasing impact of climate change, modern agriculture faces major challenges in ensuring reliable water and energy resources, particularly in isolated rural areas. Irrigation systems require a secure and continuous energy supply; however, access to the electrical grid is often limited or unstable. The aim of this paper is to analyze, size, and evaluate the energy, economic, and environmental performance of a hybrid solar–hydro energy system designed to supply water pumps in an organic agricultural farm. The methodology includes mathematical modeling of the system components, simulation of system operation in the MATLAB/Simulink environment, and performance analysis based on a real case study—the EcoVerd organic farm. The results demonstrate that the hybrid system, consisting of a 4.8 kW photovoltaic installation, a 1.5 kW micro-hydropower unit, and a 9.6 kWh energy storage system, fully meets the energy demand of a 2.2 kW irrigation pump. System implementation leads to an approximately 95% reduction in energy costs, annual savings of up to €3,885, a payback period of less than four years, and the avoidance of approximately 1.8 tons of CO_2 emissions per year.

REZUMAT

În contextual creșterii costurilor energiei electrice și al accentuării efectelor schimbărilor climatice, agricultura modernă se confruntă cu dificultăți majore privind asigurarea resurselor de apă și energie, în special în zonele rurale izolate. Sistemele de irigați necesită o alimentare energetic sigură și continuă, însă accesul la rețeaua electric este adesea limitat sau instabil. Scopul acestui articol este analiza, dimensionarea și evaluarea performanțelor energetice, economice și de mediu ale unui sistem energetic hibrid solar–hidro destinat alimentării pompelor de apă într-o fermă agricolă ecologică. Metodologia include modelarea matematică a componentelor sistemului, simularea funcționării acestuia în mediul MATLAB/Simulink și analiza rezultatelor pe baza unui studiu de caz real – ferma ecologică EcoVerd. Rezultatele obținute demonstrează că sistemul hibrid, compus dintr-o instalație fotovoltaică de 4.8 kW, o microhidrocentrală de 1.5 kW și un sistem de stocare de 9.6 kWh, asigură integral necesarul energetic al unei pompe de 2.2 kW pentru irigații. Implementarea sistemului conduce la o reducere de aproximativ 95% a costurilor energetice, economii anuale de până la 3.885 €, o perioadă de amortizare sub 4 ani și evitarea emisiilor de circa 1.8 tone CO_2 pe an.

INTRODUCTION

The integration of renewable energy sources in agriculture has become increasingly important in recent years, driven by the need to reduce environmental impact, increase farm-level energy autonomy, and ensure long-term economic sustainability (*ASAS, 2021*). Agricultural systems rely on several forms of renewable energy, of which the most relevant are solar, wind, hydro, biomass, and geothermal resources (*IRENA, 2020*).

Solar energy is widely used through photovoltaic (PV) systems for powering irrigation, lighting, and auxiliary equipment, as well as through solar-thermal systems for water heating in greenhouses and livestock shelters (*FAO, 2020*). Wind energy remains relevant in rural areas, particularly for water pumping and small-scale electricity production.

Hydropower, especially micro-hydropower, is suitable for farms located near flowing water sources, enabling both water pumping and electricity generation in off-grid settings. Biomass resources—such as crop residues, manure, and agro-industrial waste—can be converted into biogas or solid biofuels, supporting heating and combined heat and power applications. Geothermal energy represents an additional sustainable option for heating greenhouses, livestock buildings, or climate control systems.

The adoption of renewable energy systems in agriculture is associated with several advantages, including reduced operational costs, improved energy independence, decreased greenhouse gas emissions, and enhanced environmental sustainability. However, the implementation of such systems also presents challenges, such as high initial investment costs, variability of natural resources, and the need for adequate technical expertise and supporting infrastructure.

In the context of increasing water scarcity, irrigation remains one of the most energy-intensive processes in agriculture. Thus, the development and optimization of renewable-based pumping systems has become a priority, particularly for small and medium-sized farms operating in off-grid or partially electrified areas. Recent studies highlight the growing interest in hybrid renewable energy systems that combine complementary energy sources to ensure higher reliability, reduced intermittency, and improved overall efficiency in agricultural applications (*Li et al., 2017; Angadi et al., 2021*).

Considering global trends towards decarbonization and resilience in food production systems, hybrid solar–hydro energy solutions represent a promising direction for sustainable agricultural water management. This paper positions itself within this international research context by analyzing, modeling, and evaluating the performance of a hybrid solar–hydro energy system for water pumping in an ecological vegetable farm, thereby providing both a practical case study and a methodological framework that will be further detailed in the subsequent sections of the article.

The specific objective of this study is to design, model, and evaluate a hybrid solar–hydro energy system for powering irrigation water pumps in an off-grid ecological vegetable farm, with a focus on energy autonomy, system reliability, and techno-economic performance.

The original contribution of this work lies in the integrated assessment of a real-world case study, combining detailed system sizing, dynamic simulation in MATLAB/Simulink, and a comprehensive analysis of energy efficiency, economic viability, and environmental benefits. Unlike existing studies that often address hybrid systems at a conceptual or regional level, this paper provides a practical, replicable methodological framework for implementing solar–hydro pumping solutions in small and medium-sized agricultural farms with limited access to the electrical grid.

MATERIALS AND METHODS

In the context of climate change and rising energy prices, modern agriculture needs efficient and sustainable solutions (*GreenFarmCluj, 2021*). Water pumping is one of the essential activities on agricultural farms, especially for irrigation, but energy consumption can be significant. Implementing hybrid energy systems *(Ciupercă, 2022*), solar–hydro, represents a viable, economically efficient (*Pătrăucean, 2020*) and environmentally friendly alternative to traditional power supply from the electrical grid or fossil-fuel generators.

The need to implement a solar–hydro hybrid system for powering water pumps (*Grundfos Romania, 2025*) on an agricultural farm is justified by the following factors:

• Limited access to the electrical grid in many agricultural areas.
• High costs of fossil fuels.
• The need for continuous operation of irrigation systems.
• Availability of natural resources: sunlight and flowing water (stream, canal, river).
• The need to protect the environment and reduce the carbon footprint.

The objectives of implementing a solar–hydro hybrid system are:

• To ensure continuous water pumping on the farm using 100% renewable energy.
• To reduce conventional energy consumption by at least 80–90%.
• To achieve investment payback within a maximum of 5–7 years.
• To demonstrate the applicability of hybrid energy systems in rural areas.

Description of the solar–hydro hybrid system for pump supply

The system consists of two main renewable energy sources:

a) Solar component

• Photovoltaic (PV) panels of 3–5 kW, optimally oriented southwards.
• MPPT controller (*Priyadarshi et al., 2020*).
• Optional battery storage (*Bamisile et al., 2024*).

b) Hydro component

• Micro-hydroturbine (Pelton, Francis, Kaplan – depending on head and flow rate).
• Guided channel or water intake from the river.
• The generated electrical energy is supplied either directly to the irrigation pump or stored in the battery system.

c) Management system

• Hybrid inverters with automatic switching.
• Level, pressure, and humidity sensors.
• Submersible or surface electric pumps (2–3 kW).
• Buffer tank + drip/sprinkler irrigation.

Figure 1 shows the schematic diagram of the hybrid energy system.

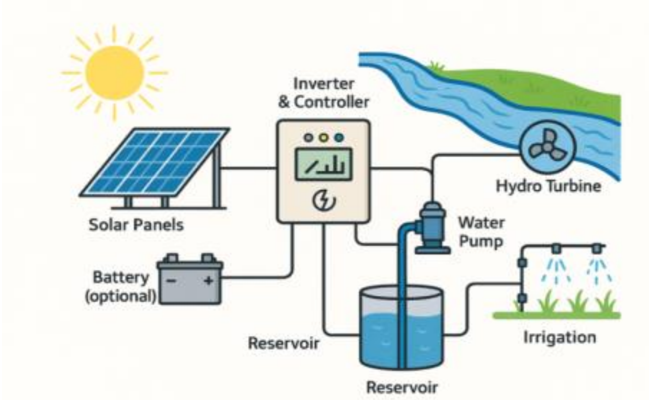

Fig. 1 - Schematic diagram of a hybrid energy system for powering water pumps on an agricultural farm

Advantages and benefits of the solar–hydro hybrid system

Economic:

• Reduced long-term costs.
• Elimination of diesel fuel use.
• Possibility of accessing funding (AFIR, PNRR).

Technical:

• Continuous power supply (solar during the day + hydro at night).
• Automated system with minimal maintenance.
• Long service life: 20–25 years.

Ecological:

• Zero CO_2 emissions.
• No noise or thermal pollution.
• Increases farm sustainability.

Solar systems are widely used (*Cristea et al., 2024; Li et al., 2017*), but hybrid systems are becoming necessary for irrigation (*Angadi et al., 2021*). The optimization of hybrid system sizing and performance evaluation is an active research topic (*Li et al., 2020*).

Challenges in implementation

• Reduced water flow during dry periods.
• High initial investment costs.
• Need for technical expertise.
• Water intake authorization requirements.

Case Study – EcoVerd Organic Farm

The farm is located in Alba County, Ighiu commune, covering 5 hectares, with two greenhouses of 500 m² each. Available natural resources: a stream with a flow rate of 12–15 l/s and solar exposure >1450 kWh/m²/year.

Figure 2 presents an overview of an organic farm.

Fig. 2 - Overview of the EcoVerd organic vegetable farm

Table 1 includes the farm specifications.

Table 1

Ecological farm specifications - EcoVerd

Characteristic	Specifications
Total area	5 hectares
Main crops	Tomatoes, cucumbers, lettuce, peppers
Crop type	In the open field and in the solarium
Solariums	2 × 500 m², passive heating and ventilation
Ecological certification	ECOCERT certificate
Market	Local markets, weekly subscriptions, direct deliveries

The previous system used a 5 kW diesel pump (3 L/h), which caused issues related to cost, pollution, and reliability.

The implemented hybrid system includes the following components:

- Solar panels: 12 × 400 W = 4.8 kW
- Francis micro-hydropower unit: 1.5 kW
- Hybrid inverter: 5 kW
- Batteries: 4 × 12 V, 200 Ah (~9.6 kWh)
- Electric pump: 2.2 kW (4 m³/h)
- Automated sensors
- Drip + sprinkler irrigation

Automation features: automatic PV/hydro switching, reservoir level control, SMS/email alerts.

Objective: continuous irrigation operation using renewable energy.

Table 2 presents the hybrid system components.

Table 2

Composition of the solar-hydro hybrid energy system

Component	Technical specifications
Photovoltaic panels	12 pieces × 400 W = 4.8 kW installed
Solar mounting structure	Aluminum, with fixed angle of 30°
MPPT controller	80a, inverter compatible
Hybrid inverter	5 kW, with automatic solar/hydro switching
SHP	Pelton turbine, 1.5 kW, 230 V, three-phase
Batteries	4 × 12V, 200Ah (buffer storage for 3 hours)
Submersible pump	2.2 kW, flow rate 4 m³/h, delivery head: 50 m
Water tank	10,000 l, PVC supply pipes
Irrigation system	Automatic trickle and sprinkling (soil/moisture sensors)

The implementation stages are shown in Table 3.

Table 3

Stages of a hybrid solar-hydro energy project for pumping water on a vegetable farm

Stage	Estimated duration
Field study and stream level	1 week
Technical design	2 weeks
Equipment purchases	2 weeks
Solar system installation	1 week
Micro-hydropower plant installation	2 weeks
Pump and automation installation	1 week
Testing and commissioning	3 days

Operating conditions

- Annual solar irradiation: 1450 kWh/m²/year
- Diurnal profile: maximum at 12:00–14:00
- Stream flow rate: decreases to 8 L/s during dry periods
- Average temperature: 12–28°C
- Seasonal water demand: 25–40 m³/day

Equations used in the design of the hybrid system

Hydraulic turbine power – P_{hyd}

$$P_{hyd} = \eta_t \cdot \rho \cdot g \cdot Q \cdot H \tag{1}$$

where: η_t is the turbine efficiency, considered to be 70%; ρ is the water density, taken as 1000 kg/m³; Q is the turbine flow rate, considered to be 12 L/s; H is the turbine head, considered to be 20 m. The hydraulic turbine power P_{hyd} as a function of the flow rate Q is often modeled as follows:

$$P_{hyd}(Q) = \begin{cases} 0, & Q < Q_{min} \\ k(Q - Q_{min}), & Q_{min} \le Q \le Q_{nom} \\ P_{nom}, & Q > Q_{nom} \end{cases} \tag{2}$$

where: Q_{min} – the minimum flow rate at which the turbine begins to produce energy; Q_{nom} – the nominal flow rate of the turbine; P_{nom} – the nominal power of the turbine; k – the slope of the linear segment (usually derived from the nominal power value).

Figure 3 shows a typical P_{hyd}–Q curve for a 1.5 kW Francis turbine.

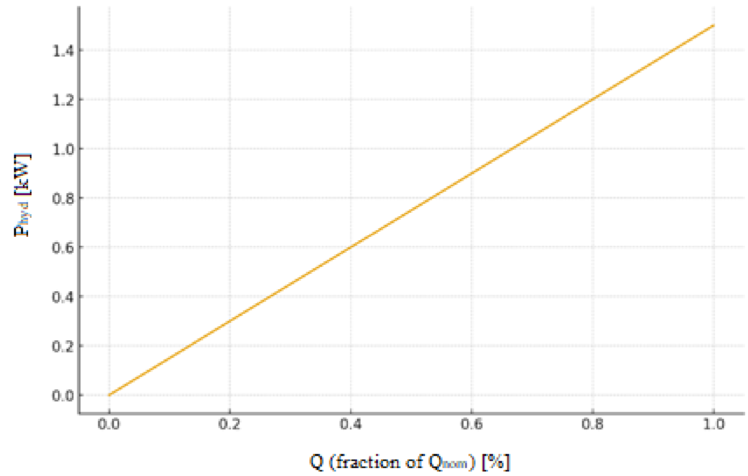

Fig. 3 – P_{hyd}–Q curve for a 1.5 kW Francis turbine

Figure 4 shows a typical efficiency curve for a 1.5 kW Francis turbine.

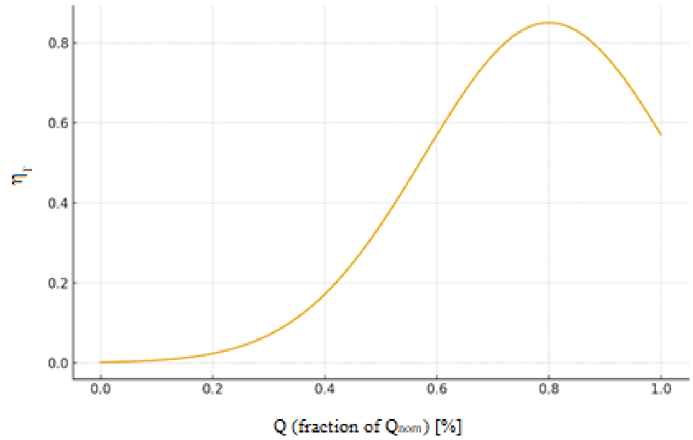

Fig. 4 – Efficiency curve for a 1.5 kW Francis turbine

The seasonal variation of the stream flow rate is given by the following formula:

$$Q(t) = Q_{med} + \Delta Q \sin\left(\frac{2\pi t}{T_{an}}\right) \tag{3}$$

where: Q(t) is the instantaneous flow rate (at time *t*); Q_{med} is the annual average flow rate; ΔQ is the amplitude of the seasonal variation; the term $\sin\left(\frac{2\pi t}{T_{an}}\right)$ represents the sinusoidal variation and models the annual periodicity of the flow rate, ranging between –1 and +1, i.e., between the minimum and maximum values.

Photovoltaic production

$$P_{PV}(t)=G(t)\cdot A_{PV}\cdot\eta_{PV}\cdot\eta_{inv} \tag{4}$$

where: $P_{PV}(t)$ is the photovoltaic power produced at time t (W); G(t) is the solar irradiance at time t on the module surface (W/m²); A_{PV} is the total active area of the photovoltaic panels (m²); η_{PV} is the efficiency of the photovoltaic panels (18%); η_{inv} is the inverter efficiency (96–98%).

Battery model

$$SOC_{t+1} = SOC_t + \frac{\eta_{ch} P_{ch} - \frac{P_{dis}}{\eta_{dis}}}{E_{bat}} \tag{5}$$

where:

SOC_t, SOC_{t+1} — state of charge at time t and t+1, η_{ch} — charging efficiency (typical values: between 0.90 and 0.99); η_{dis} — discharging efficiency (typical values: between 0.90 and 0.99); P_{ch} — charging power at step t ($P_{ch} \geq 0$); P_{dis} — discharging power at step t (power delivered by the battery to the load, $P_{dis} \geq 0$); E_{bat} — energy capacity.

SOC limits: SOC ∈ [0.20; 0.95]

Efficiencies: PV: 18%, inverter: 96–98%, batteries: 90–95%, Francis turbines: 70%.

Justification for System Sizing

Motivation for power selection:

• Photovoltaic nominal power 4.8 kW
  → ensures pump operation for 2–4 hours under moderate sunlight
  → equivalent to 22–26 kWh/day in summer
• Francis-type micro-hydroturbine 1.5 kW
  → continuous operation 24 h
  → daily energy: 1.5 × 24 = 36 kWh/day
• Batteries with 9.8 kWh capacity
  → pump operation for ~2 hours in the absence of both sources
• 5 kW inverter
  → oversized for the pump's consumption peaks

MATLAB/Simulink Model Architecture

Simulation model includes:

Modeled blocks:

- PV generator (5-parameter mathematical model)
- Francis turbine with performance curve
- Battery (SOC, efficiencies, limits)
- DC/AC inverter
- Load (electric pump + consumption curve)
- Hybrid control algorithm

Model inputs:

- Hourly irradiance (24h vector)
- Stream flow (seasonal vector)
- Panel temperature
- Irrigation schedule

Boundary conditions:

- SOC ≥ 20%
- P_{hyd} ≥ 0.7 kW for stable operation
- Q – minimum flow 8 l/s
- P_{PV} ≥ 250 W for MPPT activation
- Pump starts only if reservoir < 80%

Hybrid Control Algorithm

Simplified logic flow:

- If P_{hyd} ≥ 1 kW → turbine powers the pump.
- If P_{PV} ≥ 700 W → surplus charges the batteries.
- If both sources are active → hydro has priority.
- If SOC < 20% and P_{hyd}< 0.7 kW → pump stops.
- If reservoir > 95% → saving mode.

Key Parameter Analysis:

- River flow variation ±30%
- Seasonality of irrigation demand
- Panel orientation losses ±15°
- Battery efficiency sensitivity
- Pump consumption variation 1.5–2.5 kW

RESULTS

Estimated results to be obtained following the implementation of a hybrid solar-hydro energy system for pumping water in an organic vegetable farm:

Given / derived inputs

- Current electricity bill (before): ≈ €100 / month
- Electricity bill (after): ≈ €5 / month
- Monthly energy cost reduction: €95 / month → €1,140 / year.
- Annual renewable energy produced:7,000 kWh / year.
- Implied avoided cost ≈ €1,140 / 7,000 kWh = €0.16286 / kWh.
- Max daily pumping (design): 30,000 l/day.
- CO_2 reduction: ≈ 1.8 t CO_2 / year.
- Stated payback (target): ~ 5 years.

An economic calculation of the payback period for the EcoVerd organic farm — which implements a hybrid solar-hydro system for water pumping — is presented in Table 4.

Table 4

Economic calculation of the solar-hydro hybrid energy system for water pumping

Element	Cost (€)
Panels and structure	3,500
Inverter and controller	1,200
SHP	2,800
Batteries	1,600
Pump and irrigation system	1,200
Installation and design	1,000
Total investment cost	**11,300 €**

Estimated annual savings

a) Current costs without the hybrid system:

• Water pumping using a diesel generator (~3 liters/h).

• ~5 hours of pumping/day × 6 months/year (agricultural season) → ~900 hours/year of pump operation.

Fuel cost:

• 3 l/h × 900 h = 2,700 liters of diesel/year

• 2,700 l × 1.55 €/l = ~4,185 €/year

b) Costs with the hybrid system:

• Minimum maintenance (panel cleaning, turbine check): ~100 €/year

• Batteries: replacement every 8 years (~200 €/year amortized)

Annual net savings:

4,185 € − 100 € − 200 € = ~3,885 €/year

Payback period calculation

• Total investment: 11,300 €

• Annual net savings: ~3,885 €

Simple payback period:

11,300 € / 3,885 €/year ≈ 2.9 years

Conservative scenario (less favorable conditions)

• Savings reduced by 20% (less sun / lower water flow → auxiliary energy needed).

• Annual net savings: ~3,100 €/year

Conservative payback:

11,300 € / 3,100 €/year ≈ 3.6 years

Other indirect savings

• Increased agricultural productivity (more efficient irrigation)

• Elimination of interruption risks (avoiding production losses)

• Reduction of generator maintenance costs

Table 5 presents the economic indicators of the solar-hydro hybrid system implemented at the EcoVerd organic farm.

Table 5

Calculation of economic indicators

Indicator	**Estimated value**
Total investment	11,300 €
Annual net savings	~3,885 – 3,100 €
Amortization	~2.9 – 3.6 years
System life span	20 – 25 years
Savings for 20 years	~75,000 €

More realistic scenarios (include annual O&M = 2% of CAPEX)

Table 6 presents four CAPEX examples and the resulting net annual cash flow and payback when annual O&M = 2% of CAPEX is included.

Table 6

CAPEX examples and the resulting net annual cash flow and payback

CAPEX (€)	Annual O&M (2%)	Net annual saving = 1,140 − O&M (€)	Payback (years) = CAPEX ÷ Net annual saving
5,700 (baseline)	€114	€1,026	5.56 years
8,000 (small system)	€160	€980	8.16 years
15,000 (mid-range)	€300	€840	17.86 years
30,000 (larger system)	€600	€540	55.56 years

Other economics & environmental indicators (annual)

Value of produced renewable energy: 7,000 kWh × €0.16286 = €1,140 (matches annual saving).

CO_2 avoided: ≈ 1.8 t CO_2 / year.

Daily pumping capacity (theoretical design max): 30,000 l/day → ~ 10,950,000 l/year.

Estimate water cost saved per liter, is done by dividing the annual energy savings by the annual volume pumped: €1,140 ÷ 10,950,000 l ≈ €0.000104 / l (≈ €0.104 per 1,000 l).

A comprehensive evaluation of the economic, operational, and environmental effects resulting from the implementation of the hybrid solar-hydro energy system at the EcoVerd organic vegetable farm is summarized in Table 7.

The results highlight significant improvements in energy efficiency, resource availability, production stability, and environmental performance. Beyond the immediate financial benefits, the system contributes to long-term sustainability by reducing the farm's carbon footprint, improving irrigation reliability, and enhancing the farm's market differentiation through strong ecological branding.

Table 7

The impact of implementing the hybrid solar-hydro energy system on the activity of the EcoVerd organic vegetable farm

Domain	Concrete impact
Energy costs	Approx. 95% reduction compared to the previous diesel-generator-based system; operating expenses become highly predictable due to free solar energy; reduced dependency on fuel price fluctuations.
Water availability	Ensures continuous daily pumping capacity (~30,000 liters); increased reliability of irrigation during peak demand; improved water management across seasons.
Crop productivity	15–20% increase due to optimized and consistent irrigation; improved plant health and reduced crop stress during dry periods; higher uniformity of yields.
Environment	1.8 tons of CO_2 emissions avoided annually; elimination of noise pollution from diesel generators; zero risk of oil or fuel leaks; reduced ecological footprint of the farm's operations.
Public image / marketing	Adoption of a "zero-carbon" energy label enhances brand credibility; attracts environmentally conscious consumers and business partners; strengthens the farm's position in premium organic markets.
Operational reliability (added)	Reduced downtime related to generator failure; lower maintenance requirements; improved energy autonomy, especially in remote areas.
Long-term financial impact (added)	Short payback period due to savings on fuel and maintenance; increased farm resilience to market and energy-price volatility; overall improvement in profitability.

Analyzing the data in Table 5, 6, 7 it can be concluded that the hybrid solar-hydro system for water pumping on an agricultural farm is profitable, sustainable, and contributes significantly to the long-term economic stability of the farm.

The implementation of the hybrid solar–hydro system at the EcoVerd farm demonstrates clear economic and environmental advantages compared to diesel-based pumping. Annual savings of up to €3,885 lead to a significantly reduced payback period (below 3 years), which is notably shorter than the 5-year payback typical for similar renewable energy systems in agriculture.

Beyond direct financial benefits, the system ensures:

- improved water availability,
- increased crop productivity (15–20%) due to optimized irrigation,
- elimination of noise and oil leakage risks,
- avoidance of approximately 1.8 tons of CO_2 emissions per year.

The design, optimal sizing, and simulation of the solar–hydro hybrid energy system intended for water pumping at the EcoVerd ecological farm were carried out using a software program developed in MATLAB, in accordance with methodologies presented in the literature (Amusan et al., 2024; Nekkache et al., 2018; Bakır et al., 2023; Poompavai et al., 2019).

The MATLAB simulation aimed to evaluate the performance of the hybrid solar–hydro energy system with battery storage, used to power a 2.2 kW submersible pump in an ecological agricultural setting. The energy model includes the following main components:

- Photovoltaic (PV) panels of 4.8 kW — sized to cover the pump's consumption during periods of high solar irradiance.
- Francis-type hydro turbine of 1.5 kW — responsible for generating a stable energy output, depending on the available water flow rate and head.
- Li-ion battery system of 9.6 kW — used for storing surplus energy and compensating for production deficits during periods of low solar or hydro resource availability.
- Load — represented by the 2.2 kW submersible pump used for crop irrigation.
- Energy management unit — manages energy flows between the renewable sources, the battery, and the load, and implements decision algorithms for charging and discharging (*Bakır et al., 2023; Poompavai et al., 2019*).

The MATLAB model simulated the hourly dynamics of the system, including energy generation, consumption, battery state of charge (SOC), and energy losses. The simulation can be extended to 24 hours or multiple days by integrating real solar irradiance data, water flow rates, and equipment efficiencies.

Figure 5 presents the results of the MATLAB simulation of the hybrid solar–hydro energy system with battery storage used for water pumping in an ecological farm.

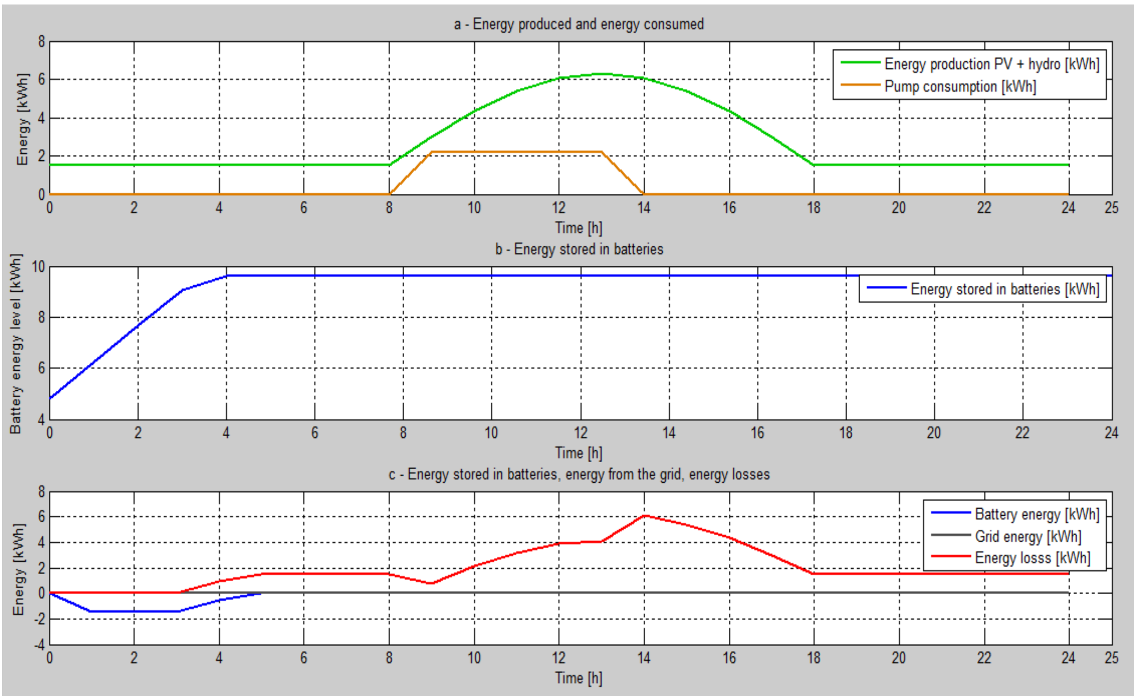

Fig. 5 – Simulation of the solar–hydro hybrid energy system with battery storage for a 6-hour operating period in an agricultural farm

Figure 6 shows the simulation results of a solar energy system with battery storage used for water pumping, implemented in the same ecological farm.

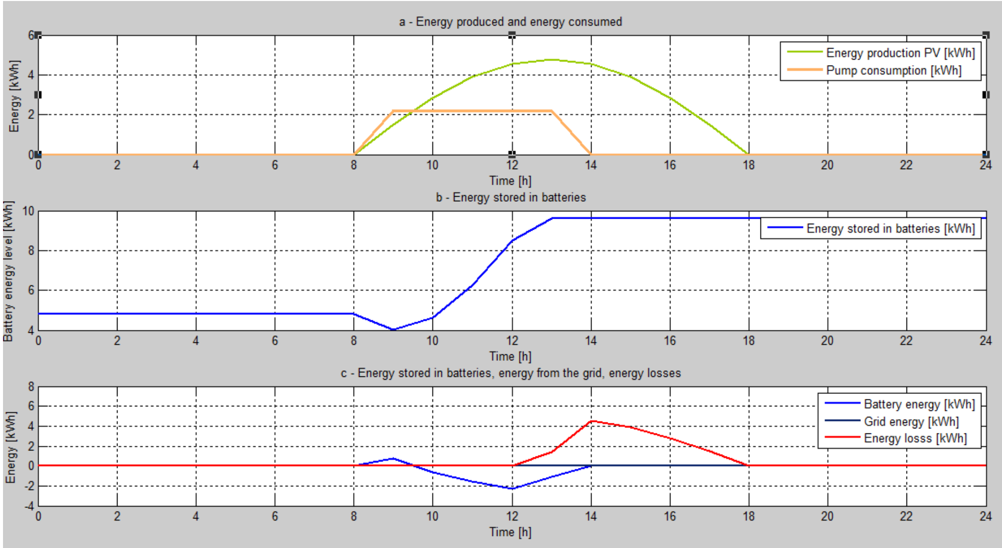

Fig. 6 – Simulation of the solar energy system with battery storage for a 6-hour operating period in an agricultural farm

Analysis of Figures 5 and 6 indicates that the hybrid energy system produces sufficient energy in both scenarios. Figures 5c and 6c reveal the presence of energy surpluses (energy losses). In the first scenario, the generated energy is sufficient to meet the consumption without requiring battery discharge. In the second scenario, the batteries are used only for a short period, between 08:00 and 09:30, until photovoltaic production exceeds the irrigation system's energy demand.

The MATLAB program enables the modeling of generated energy, consumption, and storage system behavior in simulations covering 24 hours or multiple days. The model presented is a basic one, with the possibility of extension through the integration of real meteorological data or component efficiencies.

Figure 7 presents the simulation of an extended scenario in which the daily irrigation duration increases from 6 to 8 hours. In this case as well, the energy generated by the solar–hydro hybrid system fully covers the demand, with a maximum surplus occurring around 15:00, when the pump is turned off.

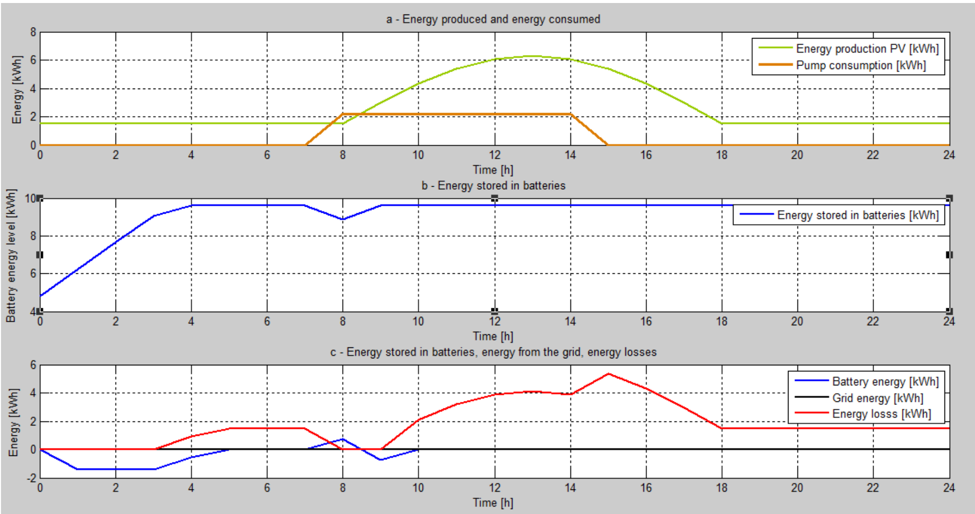

Fig. 7 – Simulation of the solar–hydro hybrid energy system with battery storage for an 8-hour operating period in an agricultural farm

The simulation results confirm that the photovoltaic system ensures the energy required for pump operation, while the hydro turbine and batteries serve as a backup solution for periods with insufficient solar radiation.

For the hourly energy balance, the following assumptions were considered: photovoltaic production reaches its maximum between 11:00 and 12:00; hydro production is constant at 1.2 kW (approx. 80% of capacity); pump consumption is constant between 08:00 and 15:00; battery values are positive during charging and negative during discharging; SOC is limited between 20% and 90%.

Table 8 presents the hourly energy balance for pump operation between 08:00 and 15:00.

Table 8

Hourly energy balance of the hybrid energy system for water pump operation for 8 hours

Ora	PV (kW)	Hydro (kW)	Consumption (kW)	Battery (kW)	Surplus (kW)	Deficit (kW)	Battery SOC (%)
0	0	1.2	0	0	1.2	0	0.5
1	0	1.2	0	0	1.2	0	0.5
2	0	1.2	0	0	1.2	0	0.5
3	0	1.2	0	0	1.2	0	0.5
4	0	1.2	0	0	1.2	0	0.5
5	0	1.2	0	0	1.2	0	0.5
6	0	1.2	0	0	1.2	0	0.5
7	0	1.2	0	0	1.2	0	0.5
8	0.96	1.2	2.2	-0.04	0	0	0.5
9	2.4	1.2	2.2	1.4	0	0	0.64
10	3.84	1.2	2.2	2.84	0	0	0.88
11	4.32	1.2	2.2	0.2	3.92	0	0.9
12	4.8	1.2	2.2	0	3.84	0	0.9
13	4.32	1.2	2.2	0	3.32	0	0.9
14	3.36	1.2	2.2	0	2.36	0	0.9
15	1.92	1.2	2.2	0	0.92	0	0.9
16	0.48	1.2	0	0	1.68	0	0.9
17	0	1.2	0	0	1.2	0	0.9
18	0	1.2	0	0	1.2	0	0.9
19	0	1.2	0	0	1.2	0	0.9
20	0	1.2	0	0	1.2	0	0.9
21	0	1.2	0	0	1.2	0	0.9
22	0	1.2	0	0	1.2	0	0.9
23	0	1.2	0	0	1.2	0	0.9

Figure 8 shows the evolution of battery SOC during the 8-hour operating interval.

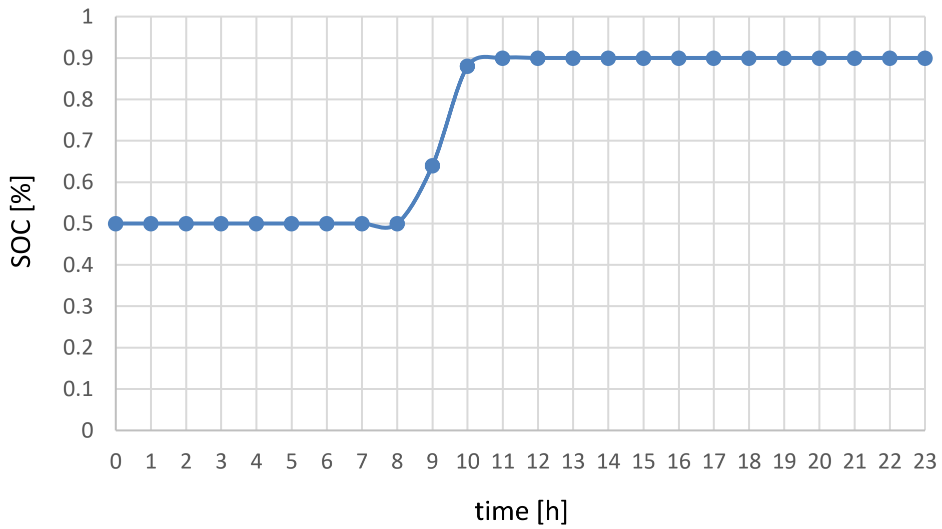

Fig. 8 – Battery SOC evolution for an 8-hour pumping interval

Analysis of the data in Table 8 shows that no energy deficit occurs; on the contrary, the system generates a total surplus of 37.6 kW, of which a maximum of 9.6 kW can be stored in the battery. In this scenario, photovoltaic contribution is 71%, and hydro contribution is 29%. In the absence of solar radiation, the pump could be supplied by the hydro turbine and battery.

A third scenario was also analyzed, based on modified assumptions: PV production decreases by 10%; hydro production is constant at 1 kW (approx. 67% of capacity, with a flow rate of 8 L/s); the pump operates between 08:00 and 17:00 (drier period); SOC is maintained between 20% and 90%. The results are shown in Table 9.

Table 9

Hourly energy balance of the hybrid energy system for water pump operation (10-hour operating period)

Ora	PV (kW)	Hydro (kW)	Consumption (kW)	Battery (kW)	Surplus (kW)	Deficit (kW)	Battery SOC (%)
0	0	0.8	0	0	0.8	0	0.5
1	0	0.8	0	0	0.8	0	0.5
2	0	0.8	0	0	0.8	0	0.5
3	0	0.8	0	0	0.8	0	0.5
4	0	0.8	0	0	0.8	0	0.5
5	0	0.8	0	0	0.8	0	0.5
6	0	0.8	0	0	0.8	0	0.5
7	0	0.8	0	0	0.8	0	0.5
8	0.86	0.8	2.2	-0.54	0	0	0.49
9	2.16	0.8	2.2	0.76	0	0	0.57
10	3.46	0.8	2.2	2.06	0	0	0.76
11	3.88	0.8	2.2	2.48	1.14	0	0.9
12	3.02	0.8	2.2	1.62	1.62	0	0.9
13	2.06	0.8	2.2	0.66	0.66	0	0.9
14	1.38	0.8	2.2	-0.02	0	0	0.89
15	0.86	0.8	2.2	-0.54	0	0	0.83
16	0.28	0.8	2.2	-1.12	0	0	0.71
17	0	0.8	2.2	-1.4	0	0	0.56
18	0	0.8	0	0.8	0	0	0.64
19	0	0.8	0	0.8	0	0	0.72
20	0	0.8	0	0.8	0	0	0.80
21	0	0.8	0	0.8	0	0	0.88
22	0	0.8	0	0.2	0.6	0	0.90
23	0	0.8	0	0	0.8	0	0.90

Figure 9 presents the SOC evolution for this scenario.

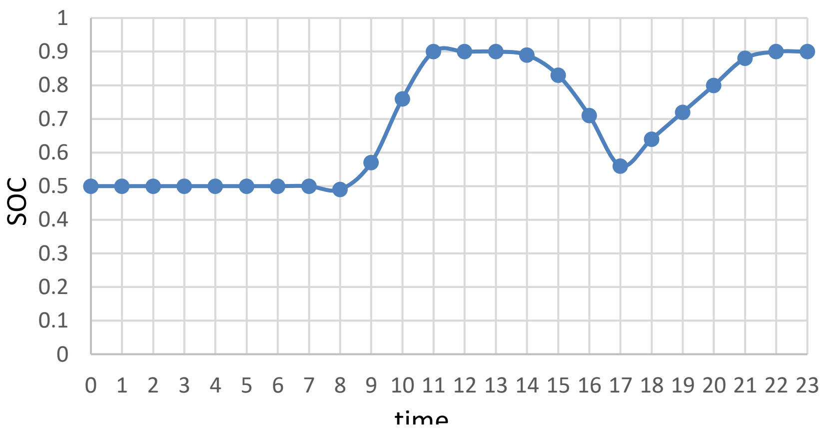

Fig. 9 – Battery SOC evolution for a 10-hour pumping interval

Analysis of Table 9 shows that no energy deficit occurs in this scenario either. The total surplus is approximately 15.2 kW, of which up to 9.6 kW can be stored in the battery. The photovoltaic contribution is 69%, and the hydro contribution is 31%.

Based on the comparison of the results obtained in the three scenarios, the following conclusions can be drawn:

• The solar–hydro hybrid system provides superior energy stability due to the constant output of the Francis turbine.

• The batteries undergo fewer charge–discharge cycles, which increases their lifespan and reduces operating costs.

• The hybrid system yields a higher energy surplus, owing to the hydro contribution.

• The risk of supply interruptions is reduced, as the hybrid system ensures continuous load supply even under low solar irradiance conditions.

CONCLUSIONS

The implementation of the solar–hydro hybrid system at the EcoVerd farm demonstrates that the intelligent integration of renewable energy sources is a viable, efficient, and sustainable solution for small and medium-sized farms in Romania. The combination of solar and hydropower ensures continuous and stable energy supply for water pumping, significantly reducing dependence on fossil fuels and on the conventional electrical grid.

The results obtained show that the hybrid system provides:

- continuous energy availability, due to the constant output of the hydraulic turbine and the high daily contribution of the photovoltaic panels;
- high economic efficiency, with annual savings of up to €3,885 and a payback period below 3 years, considerably shorter than that of conventional renewable energy systems;
- a 15–20% increase in crop productivity, enabled by reliable, uninterrupted irrigation;
- a reduced environmental impact, through the elimination of diesel consumption, the avoidance of approximately 1.8 tons of CO_2 emissions per year, and the removal of noise pollution and fuel leakage risks;
- enhanced operational reliability, thanks to decreased downtime and fewer charge–discharge cycles for the batteries, supported by the steady hydro contribution.

The MATLAB simulations confirmed the accuracy of the system sizing and its ability to fully meet the pump's energy demand under various scenarios (6–10 hours of irrigation, fluctuations in solar irradiance and water flow). The modeling results highlighted the clear advantages of the hybrid configuration over a solar-only system, particularly in terms of energy stability and reduced battery stress.

Considering the demonstrated energy, economic, and ecological performance, the solar–hydro hybrid system represents a replicable solution for mountainous and sub-mountainous regions of Romania, where both water resources and solar potential are available. The EcoVerd organic farm thus becomes a concrete example of best practice in sustainable agriculture, offering a scalable model for modern water and energy management in agricultural operations.

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