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A technical-economic analysis regarding the efficiency of a photovoltaic system with energy storage in accumulator batteries compared to injection into the national energy system

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Abstract. The introductory part of the article presents the regulatory framework from Romania and European Union regarding photovoltaic systems implementation. Then, the paper displays aspects of the on-grid and off-grid photovoltaic systems, their general arrangements, costs, advantages, and disadvantages. The article is concluded with a comparative efficiency study of the two systems. These photovoltaic systems can be easily adapted for use in the naval domain, and they fulfil the European Union's 'green deal' requirements related to emissions.

Keywords: renewable energy, photovoltaic, system, on-grid, off-grid

1. Introduction

The paper proposes a technical and economic analysis concerning the storage of electricity produced by a photovoltaic system in electrochemical batteries with lithium compared with the injection of the same electricity into the National Energetic System.

Due to the unprecedented evolution of the renewable energy domain and frequent changes in the legislative framework at the national level, the paper is instead a picture of the situation in Romania at the end of March 2023.

The paper's first section proposes a short analysis of the regulatory framework and the situation of photovoltaic systems in Romania till the end of March 2023. The next part of the paper is dedicated to a short characterization of the on-grid systems followed by off-grid counterparts. At the same time, the concluding chapter draws a comparison between the two systems.

Based on their previous work and relevant literature review, the authors consider the green energy topic a hot point on the political agenda regarding the already visible effects of climate change and the synergic efforts to cut emissions [1].

2. Method

The paper presents state of the art regarding the production of electricity from photovoltaic means along with the legal framework in the field, describe the on-grids versus off-grid photovoltaic systems with their pros and cons, and culminate with a comparison from the technical and economic point of view between the storage into batteries and injection of the energy into National Energetic System (N.E.S).

2.1 The Romanian situation regarding photovoltaic systems and the regulatory system in the field

Briefly, the National Energetic System consists of producers (thermoelectric, hydropower, nuclear plants, wind turbines, photovoltaic panels sites, biomass or hydrocarbon-based plants) connected to the transport network (in Romania managed by S.C. Transelectrica S.A.), area distribution network and consumers. In most developed countries, electricity production is mainly centralized [2].

During the last years, along with the development and dropping of the costs of renewable energy plants (wind turbines but especially photovoltaic), consumers have had the opportunity to produce a portion of the necessary energy locally. Due to consumption fluctuations but mainly due to intermittency of energy sources, sometimes the production is below the consumption needful and at other times above it. In the classical situation, when the production exceeds the consumption, the lack of a storage system, and the excess is not used, so it is lost. Due to this, the regulatory framework was established, which regulates the situation when a consumer can inject electrical energy into the distribution network to where he is connected. Of course, the injection of energy is done with a proper and agreed on installation to avoid system perturbations; the system is synchronized with the national network through a bidirectional counter. This type of consumer is named PROSUMER (PROducer - conSUMER) [3].

The Romanian prosumers' regulatory framework can be found in [4]. The latest change is the Order 95/2022 of the Chief of the National Regulatory Authority in the Field Energy, which amends the order of the same authority no. 15/2022, Methodology for establishing the rules for the sale of electricity produced in power plants from renewable sources with an installed electrical power of no more than 400 kW per place of consumption belonging to prosumers.

Any consumer has the right to ask to inject the surplus of electricity coming from renewable sources into the national network. After approving the contract and establishing the project, the consumer can sign an additional contract to sell the surplus at the same price he buys the energy except for the energy distribution cost. Though the price of energy is the same, the transport bears a series of additional costs like excise duty, taxes, subscription, services, and green certificates, e.g., In the case of a domestic consumer with energy provider SPEEH (Hidroelectrica S.A.) about one-third of costs is the effective cost with active electric energy. In conclusion, as financially the bills for buying and selling are equal, a consumer has to inject 3 kWh for each single kWh bought, and if the price of active energy is more excellent, considering the same tax system, is the case of non-domestic consumers, this fraction can be almost two or less. As for now, the prosumers do not pay any tax for the injected energy. Providers can pay the difference between consumed and injected energy in 24 months.

One provider (Cooperativa de Energie) was a benchmark indicator from the DAM (Day-Ahead Market) energy trading market in RON / MWh. This provider pays one month after the injection of the energy for the subunit ratio and sells it for a supra unitary report of DAM [5, 6].

DAM is mainly higher at the European level as we get farther from the North Sea seaside and the Atlantic Ocean. The production of energy from renewable sources backed by a developed transport network of electric energy can reduce energy costs. On 30th March 2023, within Iberic Peninsula, the price was 31 EUR/MWh, in France, Netherlands, Germany, and Denmark 81 – 83 EUR /MWh, while in Romania and Bulgaria 109 EUR/MWh [7]. Hydropower storage is the solution for the fluctuations of wind or solar power. This situation rarely happens as in Romania, the prices are smaller than in the west of Europe, mainly during days with more extensive wind power production.

As an aftermath of the Russian Federation – Ukraine conflict, the prices in Romania were capped at 1.3 RON /KWh or 260 EUR/MWh for domestic and industrial consumers [8]. The government budget supports the difference between the price from the provider and the capped budget.

Romania has a series of programs ongoing, like photovoltaic panels, heat pumps, replacing the old domestic electric appliances with new ones that are more effective from an energetic point of view, and thermal isolation of the buildings. Currently, a public debate on a new guide to budget for the installation of photovoltaic panels managed through Environment Fund Administration. Through this program, there are budgeted grants with values up to 20,000 RON for photovoltaic systems of at least 3 kW, and the prosumer contribution is ten percent of the grant value. Within the program, the provision states that excess energy is injected into the national network [9].

This year, Romania took the measure of reducing the VAT to 5% for photovoltaic panels and heat pumps.

We presented a snapshot of the regulatory framework, which is changing continuously.

2.2 On-grid photovoltaic systems

The fundamental components of a photovoltaic system are:

- photovoltaic panels;
- subsystem of energy conditioning (inverter);
- batteries (some systems).

Photovoltaic panels are semiconductor devices exposed to solar radiation (photons), moving the electrons or gaps from one layer to another of a semiconductor due to the photoelectric effect [10, 11].

Due to reduced production costs, the most used are panels from silicon (amorphous or crystalline), though there are some other applications with arsenic, indium, gallium, tellurium, and cadmium. Every type has advantages and disadvantages concerning price, yield, and lifetime.

A photovoltaic system based on PEROVSKITE crystals (calcium oxide and titanium) with a higher yield (30%) compared with the one based on silicon (20%) at a lower price, at the moment the most significant inconvenience being lifetime.

These panels produce DC with a specific voltage and intensity, so they act like a generator (photovoltaic generator). Depending on each panel's electric features, it can produce the maximum power for specific solar radiation around a maximum voltage named maximum power peak – Umpp [10, 11].

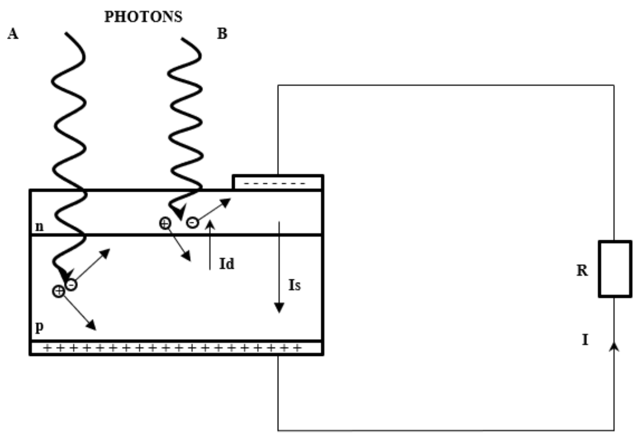

Figure 1. On-grid system [11]

Inverters can be for DC, single phase, or tri-phase, with one or more trackers to supervise maximum power peak. The inverter injects energy into the network, and the inverter is responsible for ionizing the produced electricity with the one in National Energetic System – this is the situation when they are called on-grid. The produced energy cannot be used as it is produced; it is converted to standard values: 12 V DC, 24 V DC, 48 V DC, and 230 V, 400 V, and 50 Hz AC, so the role of this system is, from one standpoint, to keep the panels in the area of maximum power and to offer an exit at an expected value. A drawing of this sort of system is displayed in Figure 2 [12].

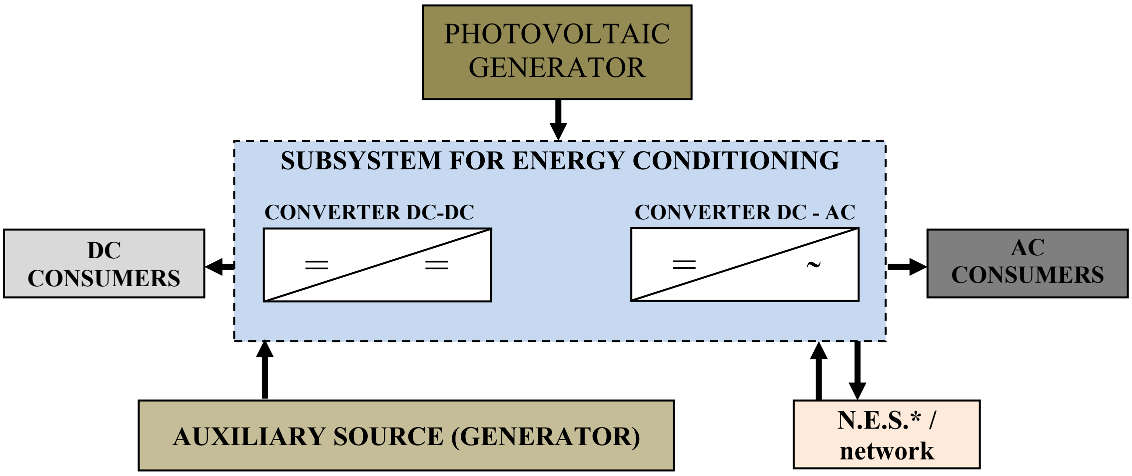

Figure 2. On-grid system diagram [2, 12]

In Figure 2, the N.E.S. stands for Romanian National Energetic System and consists of all equipment, plants, infrastructures, and societies involved in electricity production, transport, and distribution [2].

During certification and acceptance, the on-grid inverters do not inject energy during the power supply interruption to avoid affecting maintenance personnel. The superiority of this solution is that when the panels produce energy, the user will pay just for the difference between the integral and consumed portion, and by selling the surplus, they can get some money. Another advantage is that these panels do not pollute the environment during the operation and do not require fuel. The main shortfall of this system is that most types of on-grid inverters do not operate in island mode, isolated from the network, so when power is not available in the network though the panels are working, the inverter needs to produce the necessary energy. Some inverters can work disconnected from the network till the fault is restored.

2.3 Off-grid photovoltaic systems

For the situations when the system is not connected to the National Energetic System, it is called off-grid and has an array like in Figure 3.

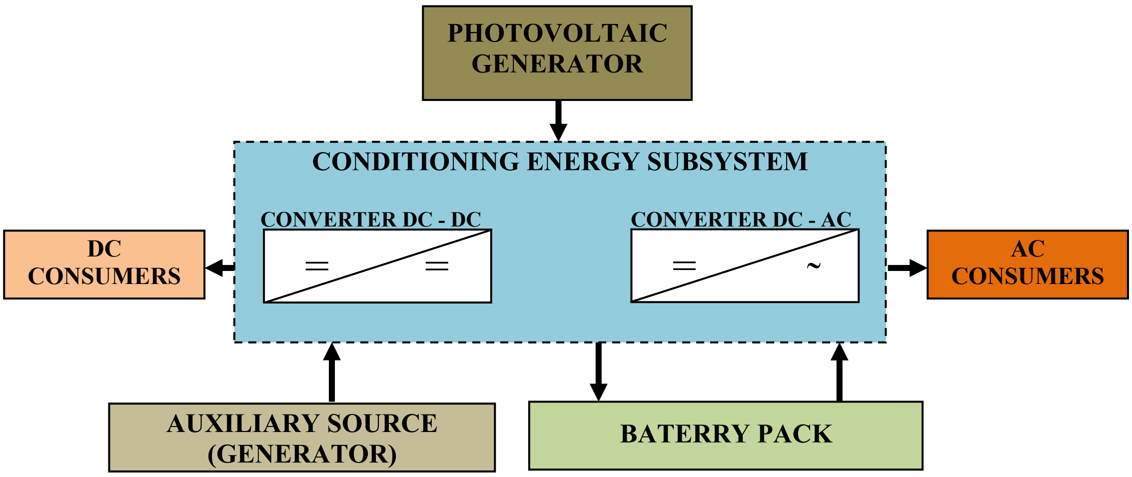

Figure 3. Off-grid system diagram [13]

Figures 1 to 3 represent the author's contribution after [11] – 1, [2, 12] – 2, and [13] – 3.

Figure 4. The Planet Solar ship [16]

Besides the consumers from the nearshore area for the off-grid systems, the energy can power a ship.

The excess energy cannot be delivered into the network; this is stored in batteries. There are some ships with electric propulsion which have already installed photovoltaic systems. Planet Solar, the ship is depicted in the figure 4, is one of them, having a length of 31 m, a breadth of 15 m, and 500 square meters of solar panels installed at a nominal power of more than 90 kW. For the storage of energy, it uses lithium–ion batteries. The ship traveled worldwide at a medium speed of 8 knots [14 - 16].

Besides the two systems presented, we can have a hybrid system that can work connected to the network (on-grid), but they can also charge electrochemical batteries. Other types of used batteries refer to lead–sulfuric acid. However, they have some shortfalls and are rarely used in the solid state, redox flow batteries, supercapacitors, and sodium batteries, some of them being in an inception stage.

The most frequently used batteries with photovoltaic systems are LiFePO4 due to their reduced auto discharge, good stability to the environmental temperature, reasonable charging-discharging rate, many cycles, and reduced possibility of ignition.

3. Results and discussion

We have compared the Romanian on-grid and off-grid systems from the technic and economic points of view. For our analyses, we have used the prices available at the local or European scale, and we have used, too, the energy prices of known providers of electricity available at [17] for the county of Constanta, low voltage.

We chose two known providers: CEZ and SPEEH and found that for 1000 kWh, a domestic consumer will pay:

-SPEEH 796 RON/month (9,564 RON/year) from which electric energy is 282 RON / month without VAT;

-CEZ 1,239 RON/month (14,868 RON/year) from which electric energy 649 RON / month without VAT; and a non-domestic consumer:

-SPEEH 1,299 RON/month (15,588 RON/year) from which electric energy 703 RON / month without VAT;

-CEZ 1,230 RON/month (14,760 RON/year) from which electric energy 644 RON / month without VAT, rounded values at the beginning of April 2023.

There are also options from smaller providers with 8 to 10 RON / kWh without VAT leading to bills of around 12,000 RON/month.

Following the" Photovoltaic Geographical Information System" [18] for a 9 kW system optimal oriented, in the Black Sea coastal area, we can get 11,833 kWh (close to 12,000 kWh required annually). By coincidence, this is the capping for the maximum power approved for a domestic consumer. By using bifacial panels or installing an additional panel, we can quickly get the approved 12,000 kWh. Installing 9.5 kWh panels from a 9 KW inverter is called clipping.

Unfortunately, not all the energy is produced, mostly during summer time and less in the winter; so, we considered that 50% is used and a surplus of 50% is injected into the network. The cost of an on-grid 9 kW system is around 45,000 RON.

In the case of consumers using half for their consumption and injecting half into the network, the consumer benefits of bills are reduced by 50% and from the reimbursement of the injected energy into the National Energetic System at a price without taxes and VAT.

Further, we calculated the investment amortization period.

As a partial conclusion, the 45,000 RON investment in the photovoltaic system will get amortized in 4 – 7 years—the amortization period increases along with the decrease in energy cost. A solution to reduce the amortization period is to increase the own consumption by programming activities with a high demand for energy during the maximum productivity period of the system. This task is simple for non-domestic consumers as they work mainly during daylight—domestic consumers must install electrochemical batteries to store energy.

In the next section, we analyze the off-grid system, as in the case of an isolated building or even a ship. The off-grid system is more suitable for floating hotel ships (barges) than cargo vessels.

Table 1. The monthly production 9 kW photovoltaic panels system [18]

Month	**E_m [kWh]**	**H(i)_m [kWh/m^2]**	**SD_m [kWh]**
January	564.9	72.4	122.2
February	629.6	81.9	152.9
March	970.2	130.6	133.5
April	1,179.2	165.1	156.8
May	1,291.9	186.7	85.2
June	1,311.2	193.3	83.6
July	1,401.5	208.6	90.8
August	1,431.7	211.3	63.2
September	1,147.4	163.9	106.4
October	865.3	118.7	144.7
November	572.2	76.5	105.6
December	518.4	67.2	139.9

E_m –average monthly electricity production from the defined system

H(i)_m – Average monthly sum of global irradiation per square meter received by the modules of the given system

SD_m – standard deviation of the monthly electricity produced

Table 2. Determination of the amortization period – author work after [17, 18]

Consumer type	Provider	Annual consumption [kWh]	Annual costs [RON]	Cost of 50% consume from N.E.S. [RON]	Energy injected in N.E.S. [kWh]	Energy unit price [RON/kWh]	Equivalent injected energy [RON]	Invoice difference [RON]	Installation cost on-grid system [RON]	Investment amortization period [Years]
		1	2	3	4	5	6	7	8	9
Domestic	SPEEH	12,000	9,564	4,782	6,000	0.282	1,692	6,474	45,000	6.95
	CEZ	12,000	14,868	7,434	6,000	0.649	3,894	11,328	45,000	3.97
Non-domestic	SPEEH	12,000	15,588	7,794	6,000	0.703	4,218	12,012	45,000	3.75
	CEZ	12,000	14,670	7,335	6,000	0.644	3,864	11,199	45,000	4.02

We have determined the invoice difference (column 7) as a sum of the cost of half of N.E.S. consumption (column 3) and the price of equivalent injected energy in column 6. In the same way, we determined the period of investment amortization (column 9) by dividing the cost of on-grid system installation (column 8) by the value of invoice difference (column 7).

Table 3. The monthly production for 9 kWp panels optimal orientation (South /inclination 35°) – author work after [18]

Parameter / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly consumption [kWh]	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Monthly production [kWh]	565	630	970	1,179	1,292	1,311	1,402	1,432	1,147	865	572	518
Difference [kWh]	-435	-370	-30	179	292	311	402	432	147	-135	-428	-482

It is observed that during winter, the production needs to be improved; the mere installation of a battery will not solve the issue; the solution implies an oversizing of the system along with the change in panel orientation or the use of an additional source like a generator.

Assessing simulations from [18], we found that covering the consumption from every month required increasing the dimensions of the system to 16 kWp panels oriented south tilt to 600. This value of inclination, though, decreases the annual production; it is required to increase the production during winter time with an additional advantage that, at this angle, the panel will get less covered by snow.

Table 4. The monthly production for 16 kWp panels optimal orientation (South /inclination 60°) – author work after [18]

Parameter / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly consumption [kWh]	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Monthly production [kWh]	1,126	1,171	1,685	1,888	1,925	1,879	2,040	2,233	1,948	1,590	1,114	1,053

Even in this case, it is required to install a spare generator because during the winter, the periods with reduced solar radiation are more extended, and the energy stored in the battery will get consumed.

A more efficient solution consists of using a hybrid system connected to the network and having the option of battery storage. This array will allow the maximum use of solar energy, the cashing of the equivalent of the energy injected into NES during the summer, and the reduction of expenditure proportionally with the battery capacity without additional expenditure with the backup source.

Further, we have determined the total cost of battery operation by choosing batteries for photovoltaic energy storage lithium based:

- battery HUAWEI LUNA 2000-10-S0 10kWh based on LiFePO4 price 29,500 RON including VAT;
- battery Orient Power OP48V230 11,7kWh 16,500 RON including VAT.

Table 5. Batteries features – author work after [19, 20]

Battery brand	Price including VAT [RON]	Used power [kWh]	Numbers of cycles 80% DOD [cycles]	Stored energy 5=(3x4)x0.8 [kWh]	Unit price energy storage 6=2/5 [RON/kWh]
1	2	3	4	5	6
Huawei LUNA 2000-10-S0	29,500	10	6,000	48,000	0.615
Orient Power OP48V230	16,500	11.7	7,000	65,500	0.252

In the table 6 we have determined if the battery storage unit price is higher than distribution cost.

Table 6. The difference storage vs. distribution – author work after [17 - 20]

Consumer type	Provider	Total unit cost [RON/kW]	Unit cost of energy [RON/kWh]	Distribution 5=3-4 [RON]	Storage 2000-10-S0 [RON/kWh]	Storage OP48V230 [RON/kWh]	Difference storage distribution 8=5-7 [RON/kWh]
1	2	3	4	5	6	7	8
Domestic	SPEEH	0.796	0.282	0.514	**0.615**	0.252	0.262
	CEZ	1.239	0.649	0.590	**0.615**	0.252	0.338
Non-domestic	SPEEH	1.299	0.703	0.596	**0.615**	0.252	0.344
	CEZ	1.230	0.644	0.586	**0.615**	0.252	0.334

We observed that for the Huawei LUNA 2000-10-S0 battery, the price /kWh is more significant than the distribution rate, so this battery will not get amortized. However, its installation is still justified as a replacement for auxiliary sources in places where the damages from the electrical equipment downtime are more significant than the battery's cost. For the other battery, the price is lower than the distribution rate from NES.

Table 7. Amortization period of the battery Orient Power OP48V230 – author work after [17-20]

Consumer type	Provider	Storage price [RON]	Difference distribution - storage [RON]	Equipment price [RON]	Available stored energy [kWh]	Gain storage/ cycle 7=4x6 [RON/cycle]	Amortization period 8=5/7 [days]	Amortization period 9=8/365 [years]
1	2	3	4	5	6	7	8	9
Domestic	SPEEH	0.252	0.262	16,500	9.36	2.45	6,728.32	18.43
	CEZ	0.252	0.338	16,500	9.36	3.16	5,215.45	14.29
Non domestic	SPEEH	0.252	0.344	16,500	9.36	3.22	5,124.48	14.04
	CEZ	0.252	0.334	16,500	9.36	3.13	5,277.91	14.46

We found that the amortization period of the battery is 14 to 18 years in the scenario that daily occurs a cycle of charging (100%) and discharging (20%). In precise operation, it is difficult to establish such a cyclicity, and even the most optimistic assessment for the battery life is below 14 years. To be feasible, the price of a hybrid system connected to the network should decrease by 25%.

Conclusions

Based on the previous calculations, we found that in the actual market conditions and with the existing regulatory framework for prosumers, the storage of electrochemical batteries is not justified from an economic point of view if the possibility of connection with the National Energetic System exists.

To be competitive, it should have a distribution rate three times bigger or the batteries to have a price of 25-30% of the actual price (from 280 EUR/kWh to reach 100 EUR/kWh) or the number of cycles charging-discharging 80% to be three times bigger (more than 20000 cycles).

A way ahead in the aftermath research could be the efficiency study of storing energy in heat where necessary. In the same direction, the batteries connected to a heat pump could have a COP of a minimum of 3.

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