ASSESSING RISKS AND THE STRATEGIC ROLE OF PHOTOVOLTAIC PARKS IN ROMANIA AS CRITICAL ENERGY INFRASTRUCTURE

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Abstract. Renewable energy (solar, wind, hydro, biomass, geothermal) plays a key role in ensuring national energy security by diversifying energy sources, reducing dependence on imports and reducing environmental impact. Here are some of the most important strengths: reducing dependence on imports, diversifying the energy mix, reducing the vulnerability of energy infrastructure, long-term sustainability, reducing environmental impact, creating jobs and boosting the economy and increased energy independence. Countries that invest in renewable energy can ensure greater energy autonomy without being influenced by the global policy of energy resources. As technologies advance, renewable energy becomes more affordable and efficient, thereby strengthening energy security and sustainable development. Photovoltaic fields play a key role in ensuring energy security by diversifying energy sources, reducing dependence on fossil fuels and increasing the resilience of the energy system. Here are some key aspects of their importance: reducing dependence on imports, renewable and inexhaustible energy sources, energy stability and diversification, reducing long-term costs, reducing environmental impact, local energy independence and resilience to crises. In the current geopolitical context, investment in renewable energy reduces the vulnerability to supply crises and the instability of international energy markets. Thus, the development of photovoltaic fields is a crucial strategy for ensuring a safe, sustainable and economically advantageous energy system in the long run. However, these infrastructures are exposed to significant risks of instability and insecurity, which may affect their efficiency and reliability. The purpose of the study is focused on two very important areas: risk analysis by SWOT technique (identifying strengths, weaknesses, opportunities, threats) and designating photovoltaic fields as critical energy infrastructures. Following the intrinsic analysis of photovoltaic fields in Romania, security, safety and protection measures will be developed, which have the role of ensuring energy security, economic security and national security.

Keywords: risk analysis, photovoltaic fields, critical infrastructures

1. INTRODUCTION

Renewable energy plays a key role in the global energy transition, and photovoltaic (PV) infrastructures are essential for ensuring and stability of a state's energy security. PV infrastructure plays a key role in Romania's energy transition, contributing to the development of an efficient sustainable energy system and the reduction of dependence on fossil fuels.

Among the major benefits of these are: [1]

- *Green energy production:* solar energy is an inexhaustible, non-polluting source that contributes to reducing greenhouse gas emissions and combating climate change;

- *Energy dependency reduction:* Romania can reduce its energy imports by using its own resources, increasing its energy security;
- *Economic development:* investments in PV fields generate jobs, stimulate local industry and attract European funds for energy infrastructure development;
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- *Low long-term costs:* after installation, the operating and maintenance costs of PV fields are relatively low, which can lead to more affordable energy for consumers;
- *Conformity with European objectives:* Romania has obligations to increase the share of renewable energy in line with the EU's strategy for a sustainable future.

However, these infrastructures are exposed to significant risks of instability and insecurity, which may affect their efficiency and reliability. The safety and security of PV infrastructures in Romania are essential to ensure an efficient and sustainable energy transition, and the adoption of integrated and proactive solutions can help reduce vulnerabilities and increase the resilience of the National Power System (according with fig. 1).

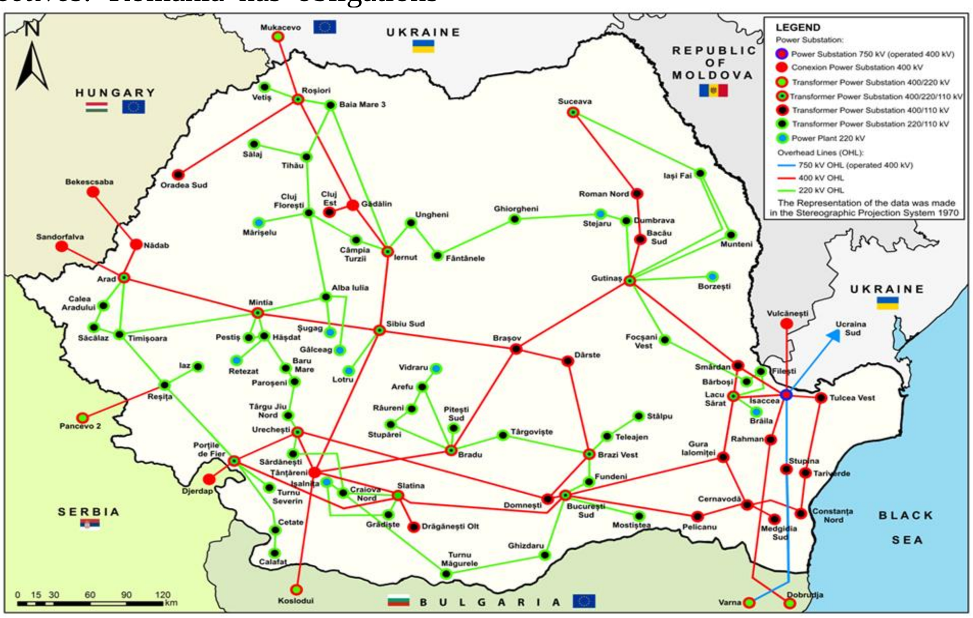

Figure. 1: National Power System

2. ROLE OF PV FIELDS IN ELECTRICITY SUPPLY AND NATIONAL SECURITY

PV fields play an essential role in ensuring the energy and national security of Romania, having multiple economic, ecological and strategic benefits. Here are the main aspects of their contribution: [2]

a) Diversification of energy sources:

- Romania is reducing its dependence on fossil fuels and energy imports, in particular gas and coal;
- solar power complements hydro and wind production, reducing vulnerability to seasonal fluctuations.

b) Energy independence and economic stability:

- the development of PV capacities helps Romania to become more energy autonomous;
- repending on renewable energy attracts European and private funding, supporting the national economy.

c) Reducing environmental impact:

- solar energy does not produce CO_2 emissions, contributing to pollution reduction targets;
- diminishing the use of coal and natural gas reduces Romania's carbon footprint.

d) National security and energy resilience:

- decentralised PV fields reduce the risk of disruption caused by cyberattacks, geopolitical conflicts or network failures;
- Local energy production eliminates the risks associated with imports of gas or oil from politically unstable states.

e) Compliance with EU objectives:

- Romania must meet the renewable energy targets set by the European Green Pact and the National Integrated Energy and Climate Change Plan;
- Particulars contribute to the reduction of dependence on fossil fuels and the transition to a sustainable economy.

f) Job creation and technological development:

- The renewable energy industry generates jobs in the construction, operation and maintenance of PV fields;
- Stimulating innovation and digitalization in the energy field.

PV fields are not only an ecological solution, but also a strategic factor for the energy and economic security of Romania. Their expansion contributes to energy independence, pollution reduction and long-term economic stability.

This is why PV fields are becoming more and more critical infrastructures in the context of energy transition and national security.

There are several reasons for this change: [3]

a) *Increased dependence on renewable energy:* countries reduce their dependence on fossil fuels and adopt renewable sources, making photovoltaic fields essential for energy security;
b) *Cyber and physical security risks:* as part of national energy networks (transport and distribution), these fields can become targets for cyberattacks or sabotage, requiring additional protection measures;
c) *Strategic role in the stability of the electricity transmission and distribution network:* PV fields help to balance energy demand and supply, being critical for the stable operation of the power system;
d) *Integration with other critical infrastructures:* many PV fields are connected with smart grids, electricity storage systems and essential infrastructure (hospitals, data centres, defence), which increases their importance.

Many states are beginning to classify them as critical infrastructures and impose stricter regulations on their security and operation. In Romania, for example, there are discussions about their inclusion in the legislation on the protection of critical infrastructures.

3. STATE OF ART

PV energy will continue to play a key role in the global energy transition, with the potential to become the main renewable energy source in the future.

The growth of global PV technology has been impressive over the last decade, thanks to lower costs, improved solar panel efficiency and government support through subsidies and green energy policies.

Some key aspects of this growth include: [4]

- *Expansion of installed capacity:* overall installed PV power capacity has increased exponentially. According to the International Energy Agency (IEA), solar photovoltaic power has become one of the fastest renewable energy sources, reaching hundreds of gigawatts (GW) installed annually;
- *Decrease in costs:* the cost of solar panels has fallen by more than 80% in the last 10-15 years, thanks to technological advances and economies of scale. This makes solar energy more affordable than traditional sources such as coal or gas;
- *Emerging technologies:*
    - Solar cells with perovskite: promise higher efficiency and lower costs;
    - Bifacial panels: capable of capturing light from both sides, increasing energy production;
    - Photovoltaic integration in buildings: solar panels integrated into windows or facades.
- *Large scale adoption:* countries with the highest installed photovoltaic capacity include:
    - China: global leader with the highest installed capacity and strong production industry;
    - USA: massive investments in solar energy, supported by federal and state policies;
    - Europe (Germany, Spain, Italy): pioneers in the energy transition, with policies favorable to renewable energies.
- *Challenges and perspectives:*
    - Electricity storage: batteries are essential for storing solar energy and using it at night or in periods without sun;
    - Smart grids: integrating solar energy into power grids requires efficient energy flow management solutions;
    - Recycling of panels: with the increase of installations, the management of solar waste becomes a concern.

Romania has made significant progress in the adoption of renewable energy, especially PV energy. By the end of 2017, the installed solar power capacity reached 1.374 MW, a notable increase from the 0.30 MW in 2007. This growth was supported by favorable government policies and the country's high solar potential, estimated at about 210 sunny days per year and an annual solar energy flow between 1.000 and 1.300 kWh/m². In 2023, 20 solar projects were operational or planned, the largest being Ucea de Sus Solar Park in Brasov County, with a capacity of 82 MW. Other notable projects include Sebis Solar Park in Arad County (65 MW) and Livada Solar Park in Satu Mare County (56 MW). To support solar energy production, the Romanian state offers six green certificates for each MWh produced and delivered to the network. These certificates can be traded on the regulated market, with prices ranging from EUR 27 to EUR 55 per certificate, indexed to the euro area inflation rate. At European level, the REPowerEU Plan aims to double the PV capacity to 320 GW by 2025 and reach 600 GW by 2030. This plan includes legal obligations to install solar panels on new buildings and strategies to accelerate the implementation of heat pumps. In recent decades, Romania has experienced significant growth in the development of PV fields, due to its favorable geographical position and increased interest in renewable energy sources. [5]

Evolution of installed capacity: [6]

- until 2011: the installed capacity was modest, with only a few small projects;
- 2012: a notable increase, reaching 51 MW installed capacity;
- 2013: peak year, with growth of over 1.100 MW, reaching a total capacity of about 1.151 MW;
- 2014-2017: growth continued at a slower pace, reaching 1.374 MW at the end of 2017;
- 2021: according to the available data, the total installed capacity in Romania's accredited PV power plants was 1.357 MW.

Notable projects: [7-8]

- *Livada (Ciuperceni) PV field, Satu Mare County:* with a capacity of 56 MW, built on an area of 135 hectares, includes 230.000 PV panels and was completed in November 2013;
- *Izvoarele PV field, Giurgiu County:* it has a capacity of 42.5 MW and is built on an area of 125 hectares, with 215.000 panels installed;
- *Planned project in Arad County:* in 2025, it was announced the completion of the procedures for the construction of the largest PV fields in Europe, with a capacity of 1.044 MW, on an area of 1.064 hectares, following an investment of 800 million euros.

Favourite factors: the geographical position of Romania offers a considerable solar potential, with an annual solar energy flow between 1.000 and 1.300 kWh/m²/year, the most favorable regions being Dobrogea and Oltenia.

Legislative support: the Romanian state supported the production of solar energy by granting green certificates for each MWh produced and delivered on the network, with prices ranging from 27 to 55 euros per certificate.

Romania has demonstrated significant progress in the development of PV fields, with ambitious projects and growing installed capacity, thus contributing to the transition to renewable energy sources. Romania continues to advance in the adoption of PV energy, benefiting from support policies and considerable solar potential.

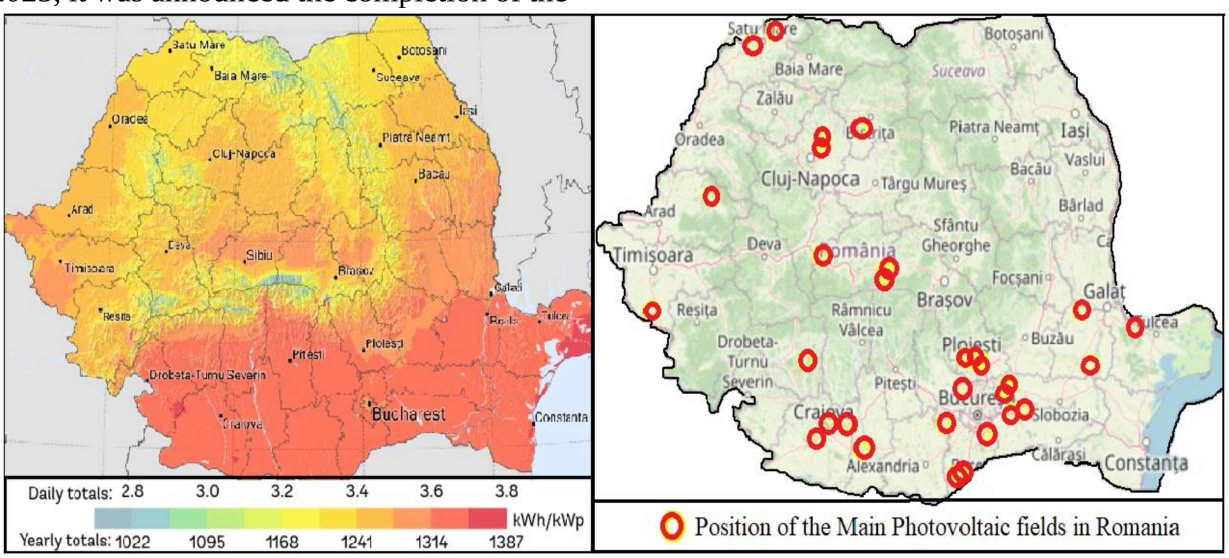

Figure 2: (a) Long term average of PVOUT in Romania and (b) The main PV fields

4. RISK ANALYSIS BY SWOT TECHNIQUE

Strengths:

a) Sustainability and low environmental impact:

- produce clean energy, without CO_2 emissions;
- do not generate noise pollution or hazardous waste;
- have a minimal impact on biodiversity, especially if they are harmoniously integrated into the landscape.

b) Energy efficiency and independence:

- reduce dependence on fossil fuels and their price fluctuations;
- can contribute to the energy independence of a country or region;
- are scalable, and can be expanded according to needs.

c) Low long-term costs:

- after the initial investment, operating and maintenance costs are relatively low;
- PV panels have a lifespan of 25-30 years, offering long-term returns;
- Government subsidies and support schemes can make the investment even more profitable.

d) Easy installation and maintenance:

- installing a PV system is faster compared to other types of power plants;
- requires little maintenance, as the panels have no moving parts that wear out quickly.

e) Flexibility and diversification of land use:

- can be installed on unproductive or unused land;
- coexist with other activities, such as agriculture (agrivoltaics);
- can be integrated into smart-grid networks to optimize consumption.

Weaknesses:

a) Dependence on weather conditions: the efficiency of the panels decreases on cloudy or rainy days, and the electricity production is zero at night;
b) The need for large land areas: to produce a significant amount of energy, PV fields require large areas of land, which can lead to deforestation or the reduction of agricultural land;
c) Relatively low efficiency: the conversion of solar energy into electricity is not 100% efficient, with most panels having efficiencies of 15-22%;
d) High initial costs: although the prices of solar panels have decreased in recent years, the initial investment for a PV fields remains significant;
e) Environmental impact: although solar energy is considered clean, the production and disposal of PV panels can generate toxic waste and CO_2 emissions;
f) Dependence on batteries for storage: to ensure continuous electricity, storage systems (batteries) are needed, which are expensive and have their own environmental impact;
g) Issues related to grid integration: production fluctuations can create difficulties in the stability of the electricity grid and require solutions to balance supply and demand;
h) Limited lifespan: PV panels have a lifespan of approximately 25-30 years, after which their efficiency decreases, requiring replacement and recycling;
i) Possible maintenance issues: although they are relatively easy to maintain, the panels must be cleaned periodically and monitored for defects or loss of efficiency;
j) Impact on biodiversity: in certain cases, the construction of PV fields

can affect local flora and fauna, especially in protected natural areas.

Opportunities:

a) Economic opportunities:

- Energy cost reduction: own solar energy production can lead to lower costs for consumers and businesses;
- Profitable investments: the financial returns of PV fields are attractive due to the decrease in the prices of solar panels and their increase in efficiency;
- Job creation: the installation and maintenance of solar panels generates jobs in the renewable energy sector;
- Subsidies and financing: governments and international organizations offer various financial support schemes for the development of renewable energy.

b) Environmental opportunities:

- CO_2 emission reduction: solar energy is clean and contributes to reducing dependence on fossil fuels;
- Long-term sustainability: the sun is an inexhaustible resource, and its use does not negatively affect the environment;
- Reuse of degraded land: PV fields can be located on unproductive or abandoned land, giving it a new utility.

c) Technological Opportunities:

- Innovations in electricity storage: modern batteries allow the storage of solar energy for use at night or on cloudy days;
- Integration into smart grids: PV fields can be connected to smart grids, optimizing energy distribution;
- Increased automation and efficiency: new technologies, such as artificial intelligence and cleaning robots, improve the performance and maintenance of PV fields.

d) Security Opportunities:

- Critical Energy Infrastructure: the possibility that PV fields can become critical energy infrastructure, with a role in ensuring energy and national security

Threats, Risks, Vulnerabilities and Hazards:

a) Threats:

- Natural factors: storms, hail, wildfires, earthquakes or floods can damage solar panels and fields infrastructure;
- Vandalism and theft: solar panels, inverters and cables are attractive to thieves, and vandalism can affect energy production;
- Cyber-attacks: control and monitoring systems can be targets for cyber attacks, affecting the operation of the park;
- Regulations and policies: changes in legislation, new taxes or land restrictions can threaten the economic viability of the project.

b) Risks:

- Decreased efficiency: dust, dirt or degradation of panels over time can reduce electricity production;
- Technical problems: failures in inverters, connections or electricity storage system can affect the continuity of production;
- Dependence on weather conditions: the performance of a PV fields depends directly on the intensity of sunlight, with the risk of lower production on cloudy days;
- Impact on the environment and biodiversity: deforestation for the installation of the field or changes to the ecosystem can affect local fauna and flora;
- Unforeseen costs: increased maintenance costs, repairs or price

changes to equipment can affect profitability.

c) Vulnerabilities:

- Physical security: a poorly protected field is vulnerable to vandalism and theft;
- Dependence on supply chains: problems with suppliers of panels, inverters or batteries can delay projects and increase costs;
- Lack of infrastructure: connecting the field to the electricity grid can be difficult if the local infrastructure is not ready for such integration;
- Long payback period: the amortization of the initial costs can take years, and fluctuations in the price of electricity can affect profitability.

d) Hazards:

1. Environmental Impact:

- Deforestation and habitat loss: PV fields are sometimes built on agricultural land or forests, affecting biodiversity;
- Impact on wildlife: animals may be disturbed by changes in habitat or by the reflection of solar panels;
- Impact on soil and water: changes to the land for the installation of panels can lead to erosion or changes in water runoff.

2. Economic and social issues:

- Agricultural land use: if installed on fertile land, they can reduce the agricultural area available for food production;
- Visual impact: PV fields can alter the landscape and may be considered unsightly by local communities;
- Noise and nuisance: although the panels themselves do not produce noise, auxiliary equipment such as inverters and cooling systems can generate some level of noise pollution.

3. Recycling and waste management issues:

- Difficulty in recycling panels: solar panel components (glass, silicon, heavy metals) are difficult to recycle, which may lead to environmental problems in the future;
- Use of rare materials: panels contain metals such as cadmium or tellurium, the extraction of which may have a negative impact on the environment.

4. Technical, safety and security aspects:

- Fire risk: solar panels and electrical equipment can present hazards in case of overload or technical defects;
- Material degradation: solar panels have a limited lifespan (around 25-30 years), and managing the resulting waste can be problematic;
- Electromagnetism: some studies suggest that equipment used in PV fields could generate electromagnetic fields, but the effects on health are still debated;
- Blackout risk: some inverters can be remotely controlled by certain manufacturing companies, which makes the risk of disconnection of PV fields very likely and with a very serious gravity and impact on energy and national security.

5. SECURITY, SAFETY AND PROTECTION MEASURES

Security, safety and protection measures is next: [9-15]

- Physical protection and security;
- Electrical safety and equipments protection;
- Protection against natural factors and disaster.

Physical protection and security:

- Fencing and access control: installation of security fences and

controlled access gates to prevent intrusion;
- Video surveillance systems: use of surveillance cameras with motion detection and 24/7 monitoring;
- Detection sensors: implementation of sensors to detect movement, vibration or opening of panels;
- Security patrols: presence of security personnel or drones for regular inspections;
- Anti-theft and anti-vandalism systems: GPS tracking devices for panels, alarms and invisible markings for components.

Electrical safety and equipment protection:
- Grounding system: prevention of electric shock and protection of equipment against atmospheric discharges;
- Lightning protection: installation of lightning rods and surge arresters;
- Circuit breakers and overload protection: installing safety equipment to prevent short circuits and fires;
- Adequate ventilation and cooling: preventing equipment from overheating through efficient cooling systems;
- Periodic maintenance and inspection: checking connections, wiring and panels to prevent failures.

Protection against natural factors and disasters:
- Wind and weather protection: installation resistant to strong gusts, hail and floods;
- Fire prevention: using fire-retardant materials and a rapid-fire response plan;
- Weather monitoring: alert systems for extreme conditions that can affect production and park safety.

6. CONCLUSIONS

Following the intrinsic analysis of PV fields in Romania, as well as their role in ensuring energy security, the authors propose their transformation (designation) into critical energy infrastructures, because they have a strategic role in the stability and resilience of the National Power System and ensuring national security and well-being.

Arguments: *compliance with EU objectives; creation of jobs and technological development; diversification of energy sources; increased dependence on renewable energy; energy independence and economic stability; reduction of environmental impact; strategic role in the stability of electricity transmission and distribution networks within the National Power System; strategic role in ensuring the resilience of the National Power System; integration with other critical systems and infrastructures; strategic role in ensuring economic security; strategic role in ensuring national security and well-being.*

Following the SWOT analysis of PV fields, 5 strengths, 10 weaknesses, 4 opportunities, 4 threats, 5 risks, 4 vulnerabilities, 4 hazards, 5 measures on physical protection and security, 5 measures on electrical safety and equipment protection and 3 measures on protection against natural factors and disasters were identified.

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