THE USE OF THE AGROPHOTOVOLTAIC SYSTEMS – A METHOD FOR THE SUPPORTING SUSTAINABILITY

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Abstract

The crisis in the energy sector that the European Union has faced in recent years, as a result of the armed conflict between Ukraine and Russia, has forced national and European authorities to turn to alternative sources of energy. In this context, the objective of the authors in this article is to identify the extent to which the introduction of agrophotovoltaic systems in Romania contributes to the diversification of the energy mix, simultaneously realizing a reterritorialization of the land, by using the space around the photovoltaic panels for agricultural crops or other complementary destinations, a concept known as agrophotovoltaics. The agrophotovoltaic model involves the integration of photovoltaic panels with agricultural activities on the same land, optimizing both uses. By using the agro-photovoltaic model, a link can be made between renewable energy production and agriculture, participating in a greener and more resilient economy. The research methodology consisted in the use of time series, based on the data published by the Romanian National Institute of Statistics and Eurostat. Both structurally and dynamically, indicators such as share of energy from renewable sources in the European Union or solar energy produced in photovoltaic installations were studied. For a better understanding of the data, they were represented in tabular and graphical form. Following the study, it can be found that the system that combines the production of green energy with agricultural activities contributes to the efficient use of land and the improvement of sustainability. At the same time, the upward evolution of green energy sources, especially solar energy and wind energy, is evident.

Keywords: *Photovoltaic panels, solar energy, wind energy, agricultural crops, sustainability,*

Clasificare JEL : *O13, Q42*

1. Introduction and context of the study

The energy use is widely recognized as a fundamental factor in increasing economic efficiency, fostering financial stability and promoting sustainable development. Most modern countries rely on energy because it drives economic growth, capital and labor. It is also a critical constituent in the creation of almost all goods and services. However, the issue of energy security has emerged as a significant phenomenon highlighted in the sustainable development goals. These goals emphasize the need for green energy, innovation and finance to promote sustainable development. Achieving sustainable development and productivity requires a substantial and especially greener energy source.

The balancing economic ambitions with the environmental objectives requires some innovative financial mechanisms and strategic planning. Fixing this methodological gap becomes imperative for the European Union to successfully navigate the transition to a sustainable and secure energy future. Moreover, in the last decade, debates and measures in the sphere of renewable and low-carbon energy have been amplified. The energy transition to clean sources requires capital investment in solar and wind farms, as well as carbon capture technologies. At the same time, investments in clean energy can reduce the impact of climate change on the risk of energy security. Investments in workforce development and reskilling programs ensure that the workforce is equipped with the skills necessary to thrive in the burgeoning clean energy industry.

The transformation of energy production from fossil fuels to renewable energy sources plays a significant role in reducing greenhouse gas emissions, which is essential in combating climate change. The decarbonisation of electricity grids stands out as one of the most effective climate change mitigation techniques.

2. Literature review

Angelsen (2010) presented, in his work, a series of elements related to agricultural production, and Anghel, Anghelache and Panait (2017) analyzed the results obtained by agriculture in the European Union, both as a whole and for each member state. Anghelache, Samson and Stoica (2020) highlighted the main elements of the European Union's strategy regarding the agricultural branch. In their work, Anghelache, Strijek and Dumitru (2024) conducted a study on vegetable production in Romania. Anghelache et al (2024) highlighted the need for the fair use of lands displaced from the agricultural circuit and the creation of synergy between the two branches in the context of sustainable and sustainable development.

Bezemer and Headey (2008) addressed aspects regarding the measures that can be implemented for the development of agriculture. Cheikh and Rault (2024) conducted a study that aimed to identify whether the promotion of financial inclusion influences carbon dioxide emissions, for which purpose they used a sample of 70 countries. Dawkins et (2023) investigated the demand-side aspects of the low-carbon transition with a focus on the transport and food sectors. Economidou et al (2024) analyzed the role of regional and local authorities in the implementation of relevant energy efficiency programs in stimulating energy upgrades in residential, commercial and public buildings in Europe.

Jouttijarvi et al (2024) carried out an analysis of different photovoltaic systems suitable for individual houses in high latitude locations and the quantification of key economic indicators affecting their competitiveness. Ma et al (2024) studied how policy measures influence corporate green investment. Quamrul and Michalopoulos (2015) researched the implications of climate fluctuations on agricultural activities. Saqib et al (2023) investigated how technological innovation, financial inclusion, economic growth and renewable energy affected the ecological footprint of emerging economies over the period 1990-2019, applying panel estimation methods for empirical analysis. Swintona, Lupi, Robertson, Hamilton (2007) analyzed the role of agricultural ecosystems for diverse benefits. Strijek (2024) presented the importance of energy in industrial production.

Wang et al (2022) showed that the renewable energy industry without the constraint of energy that is imported is detrimental to economic and climate goals. Zadeh and Romagnoli (2024) offered an alternative for financing energy transitions, namely the development of a national energy token (energy tokens), using blockchain technology. The authors consider that, in a digital economy environment, a new energy token can be a safe financing mechanism to reduce energy prices.

3. Data, results and discussion

The access to green, reliable and sustainable energy is essential for human well-being, education, economic growth and air quality. In the next 50 years, a rapid transition to renewable energy is imperative to prevent the worst consequences of climate change. National initiatives aimed at mitigating greenhouse gas emissions and aligning with the United Nations Sustainable Development Goals emphasize mechanisms for increasing the share of energy from renewable sources.Collaboration across sectors, including agriculture, transport and urban planning, is vital to create integrated policies that support clean energy initiatives and ensure comprehensive sustainability goals are met. The continuation of the sustainable development policy represents an opportunity to build a modern pro-ecological society that develops economically based on modern and innovative solutions and technologies. In figure no. 1 graphically highlights the evolution of the share of energy from renewable sources in the European Union, in the period 2013-2022.

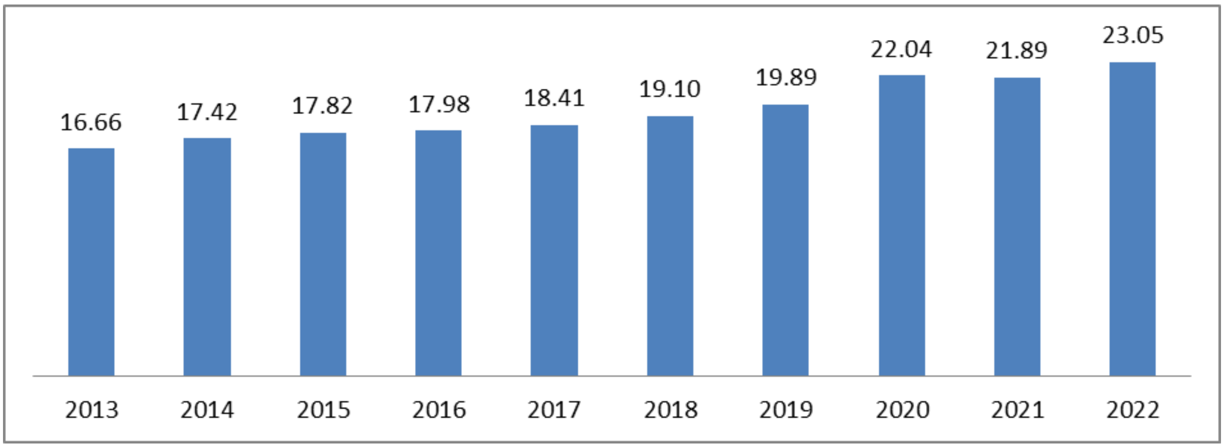

Figure no. 1. The evolution of the share of energy from renewable sources in the European Union, in the period 2013-2022 (%)

Source: authors' representation, based on Eurostat data, accessed on November 10, 2024.

As can be seen from the analysis of the previous graph, at the level of the European Union, during the period 2013-2022, the share of energy from renewable sources has increased every year. In 2022, the EU reached the share of 23.0% of gross final energy consumption from renewable sources, which means 1.1 percentage points (pp) more than in 2021.

In the analyzed interval, the increase in electricity generated from renewable sources highlights a development of wind energy and solar energy. In 2022, renewable energy sources represented 41.2% of gross electricity consumption in the EU, almost 4 percentage points more than in 2021 when it was 37.5%.

We mention the fact that wind energy and hydropower constituted more than two thirds of the total electricity generated from renewable sources, namely 37.5% and 29.9%, respectively. 18.2% of the electricity generated came from solar energy, 6.9% from solid biofuels, and 7.5% from other renewable sources. The fastest growing source is solar energy, which has increased from just 7.4 TWh in 2008 to 210.3 TWh in 2022.

The economic value of photovoltaic electricity correlates strongly with self-consumed electricity. Overall, maximizing the amount of self-consumed solar energy was the most profitable strategy. When photovoltaic electricity is consumed on site, the electricity purchase price, which also includes transport charges, is avoided.

Although both residential and commercial solar installations contribute to the overall benefit of the grid, their characteristics and impacts are distinct. Commercial solar systems have larger and more efficient panels, but are not as widely adopted as residential solar systems.

The agrophotovoltaic systems assume a balance between the optimal capture of solar energy and the provision of the necessary conditions for growing plants. The link between energy and agriculture can contribute to a more efficient use of land, thus ensuring a more sustainable agriculture.

Reterritorialization is a concept materialized as part of the ideology of sustainable development and sustainability that is expanding more and more. Regarding the reterritorialization of agricultural lands, this is transposed in the case of energy parks, either within photovoltaic parks forming the agrophotovoltaic concept, or within wind energy projects.

Following the energy policies of the European Union to protect the environment, the green energy projects that materialize in the production of electricity with the help of solar energy and also the projects of the production of wind energy displace from traditional agriculture significant areas of land necessary for the establishment of these energy parks, but the necessary technical specifications lead to the use of only a part of the total area displaced for the establishment of the energy park. This is how it happens that together with the positive effects for the environment resulting from the decarbonization of the energy-producing industry, a material damage is created to agriculture, by reducing the cultivated areas, areas that are increasingly important in the light of climate changes and in the light of global population growth, growth of the population that requires an increased need for food.

The concept of reterritorialization through the symbiosis of renewable energy and agriculture represents a sustainable and effective solution for optimizing land use. Implementation requires detailed analysis of local conditions and careful planning, but the economic and environmental benefits are significant, making this model ideal for the transition to a green economy.

The reterritorialization is an effective solution for sustainable land use, but successful implementation requires the identification of well-calibrated statistical-econometric models. These models can help assess the impact on the economy, environment and agri-food markets, ensuring a land use strategy that is efficient and profitable in the long term.

The concept of reterritorialization is, as a result, one of great importance for humanity, both from an economic and environmental point of view, and not least in terms of social impact.

To establish a photovoltaic park with an installed power between 1-10 MW/hectare, a spacing between panels of 5-8 meters must be taken into account to allow agriculture, but if a more oriented agro-photovoltaic park is designed to agriculture, the distances between the rows can reach up to 12 meters. Installation costs are between 800,000 - 1,200,000 €/MW.

For wind farms, the installed power of a turbine is in the range of 2-5 MW/unit, and the height of the turbines is between 80-120 m. The area required for operation is between 0.5-1 ha/turbine with minimal impact on the agricultural soil, but even here, depending on the plan to integrate agriculture within the energy park, the distance between the production units can be increased to a suitable value the development plan. Installation costs for each unit are between 1.2 - 1.5 million €/MW.

Just as for the establishment of an energy park, the general environmental, climate and social conditions must be taken into account, so also for the establishment of symbiotic agricultural crops to the energy parks, some essential aspects must be taken into account such as the pedoclimatic conditions, i.e. the type of soil, the rainfall related to the area and its specific temperatures. Market demand would be another condition, in the sense of the choice of crops with high economic value and the conditions for capitalization, including storage, transport or regional demand, which would produce an additional infusion into the local economy. Another condition would be the impact on energy production, i.e. evaluating the shade generated by panels or turbines on crops.

If in the case of wind farms the technical challenges in designing a symbiosis with the agricultural industry are reduced in principle to the optimal distance between the production units to give a maximum yield, in the case of photovoltaic parks that are to integrate agricultural activities there are several elements that must be analyzed at creating the symbiosis of the agrophotovoltaic park.

If the decision to introduce the agrophotovoltaic concept is made in the case of an existing photovoltaic park, then the possibilities of implementation are reduced to the level of available technical permissibility, often being extremely limited.

If, instead, this option is taken into account from the project stage, then the design can be done taking into account all the necessary elements to be able to optimize and maximize the economic result of the project, the mounting of the panels in the agrophotovoltaic system is done taking into account several elements. The mounting height of the panels is important, because in this case, the photovoltaic panels are mounted at a higher height than in conventional systems, they are placed at a height of 2-3 meters above the ground to allow agricultural activities to be carried out below them. This height can vary depending on the type of crops and the agricultural machinery that will be used. The angle of inclination is another element, since the main objective remains the generation of energy, in this sense, the panels must be mounted at an optimal angle to efficiently capture sunlight, taking into account the latitude of the location. Mounting angles usually vary between 20° and 35°, but this angle can also be adjusted to minimize shading on the crops and allow the light needed by the plants to pass through.

At the same time, the distance between the rows of panels varies depending on the size of the panels and their height. In the case of agrophotovoltaic systems, the distances between them can be 6-12 meters, leaving enough space for crops and for the access of agricultural machinery. Photovoltaic panels can also be fixed or tracker type, i.e. mounted on structures with a sun tracking system, which automatically adjusts the position of the panels to maximize the capture of sunlight. Tracker panels are more efficient, but can affect the space available for crops due to their movement. The degree of shading on crops is one of the challenges in agrophotovoltaics. The panels must be placed in such a way as to leave enough light for the plants. Some plants can tolerate partial shade and others require more sun exposure. Therefore, distances and angles must be adjusted according to the type of crop, but in practice, the agro element is always secondary to the main object, in conclusion the choice of crop is secondary to energy production.

Last but not least, the technical and operational elements will be taken into consideration. The space between the panels must allow periodic interventions for their maintenance. The photovoltaic systems require minimal maintenance such as cleaning them and checking electrical connections, but this should not interfere with agricultural activities. Crops should also be easily accessible for care. And water management is an important element. Agro-photovoltaic projects may require specially adapted irrigation systems, especially if the panels reduce water evaporation. In some cases, even the water used to clean the panels can be reclaimed for irrigation. The panels can also change the local microclimate, with their placement reducing soil temperatures and increasing humidity. This can be beneficial for certain crops, but must be analyzed according to the specifics of the region and the types of plants grown. In conclusion, the design of an agrophotovoltaic system involves a balance between the optimal capture of solar energy and ensuring the necessary conditions for growing plants. This synergy between energy and agriculture optimizes land use and contributes to more sustainable agriculture.

The symbiosis between photovoltaic parks and agriculture certainly brings benefits such as increasing farmers' incomes because energy production and agriculture can coexist, generating additional income. The panels can also provide shade and reduce water evaporation, being the ideal protection for crops sensitive to high temperatures. And reducing the ecological impact is an element worthy of consideration, the dual use of land limiting the need for deforestation or changing the destination of land, this being one of the main elements of sustainability that generated the concept of reterritorialization.

In the case of wind farms, however, agricultural land can be used almost entirely, in parallel with the production of wind energy. They can co-exist very well with agriculture or grazing due to the small footprint that the turbines leave on the ground. In this case, there is a minimal impact on the agricultural land, because the turbines occupy, depending on the type of project, less than 5% of the agricultural area displaced from the agricultural circuit. The turbines do not affect the soil structure, and access roads created for maintenance can be used for agricultural activities. Additional income from symbiotic use can be substantial, with farmers even receiving compensation for land use.

For implementation, however, there are a number of different technical criteria that must be met to create the symbiosis of the two activities, just as in the case of photovoltaic parks, small compromises will be made. The location of the turbines must be planned so as not to interfere with agricultural work, that is, it will be done respecting a minimum distance between the turbines of approximately 5-10 diameters of the rotor. The height of the turbines will be changed, reaching heights between 80-120 m to reduce ground turbulence and not affect crops. As well as suitable crop types, here the palette of options is wider, practically all crops can coexist, including cereals, fodder plants and technical crops such as sunflower, canola and maize.

In order to have a clearer picture of how energy park land areas are used within each of the two types of energy parks, we have created a graph based on data obtained from various information sources and databases. The graph shows the degree of surface use compared between photovoltaic parks and wind farms and the remaining areas available for agriculture within them.

According to the graph below, agriculture practiced within photovoltaic parks can have 70% of the land area, only 30% of the area being occupied by panels and related structures. Regarding wind farms, only 5% of the area is used by turbines, access roads and infrastructure, while 95% of the land remains available for agriculture.

This comparison highlights the higher spatial efficiency of wind farms for dual land use.

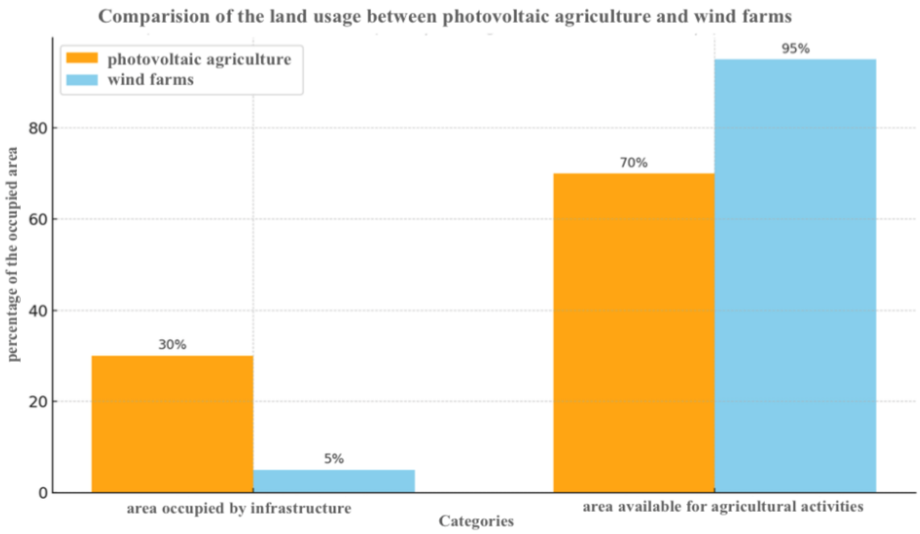

Figure no. 2. The comparison between the use of the surface in photovoltaic agriculture and wind farms

Source: authors' representation.

Based on the graph above, we can make a projection of the probable yield using indicative figures that emerge from various databases and commercial reports of economic operators in the relevant industries:

- The yield of photovoltaic panels (30% of the area)
  Simple photovoltaic park yield = €7,000/ha/year
  Traditional farming yield (estimated, without panels): €1,000/ha/year
  The yield for 70% of the land (70% of the surface of one ha of the photovoltaic park) €700/ha/year
  Total combined yield: 7,000 +700=7,700 €/ha/year
- The yield of wind farm (5% of area)
  Simple wind farm yield = €4,000/ha/year
  Traditional farming yield (estimated, without panels): €1,000/ha/year
  Yield for 95% of the land (95% of the surface of one ha of the photovoltaic park) €950/ha/year
  Total combined yield: 4,000 +950=4,950 €/ha/year

We can identify from the figures above that an agrophotovoltaic park brings an income 10% higher than a simple photovoltaic park, and a wind farm where agriculture is included brings income 23.75% higher than a simple wind farm.

It certainly seems much more efficient to operate a simple energy park than an energy park where agricultural activity is included, looking exclusively at the yield on the land area. At the same time, the amount of labor involved in agricultural activities can be much higher compared to the amount of work required for the maintenance of the energy park, but overall the net advantages of the symbiosis of these activities must be emphasized.

Starting from the concept of reterritorialization, a first advantage is the re-introduction of significant areas of land into the agricultural circuit, which would otherwise have been permanently excluded from the agricultural circuit.

Another advantage is the support of the local economy, of small farmers, farmers or animal breeders thanks to the activities carried out around these energy parks. Whether they are agricultural activities or livestock activities, they directly benefit local communities.

Hiring the local workforce and capitalizing on the products obtained as a result of the symbiosis of the two activities brings added value to the energy park investment region.

Although there are theories that claim that a combined activity can reduce the economic efficiency of energy parks by dissipating the attention given to the primary purpose of the energy park, i.e. that of energy production, these can be easily dismantled based on the concepts of sustainability and sustainable development, integration of force of local labor and the social element. The integration process of agricultural activities is relatively easy, especially if they are foreseen from the design stage.

What is true, however, is that the economic yield of agricultural activity is much lower than the yield obtained from the production of energy from renewable sources. This yield obtained on the difference of unused land must be quantified as a net advantage, this being done in comparison with a zero value existing from the non-use of the available space. This comparison can only be properly made if agriculture is introduced into an existing and operational energy park.

If the energy park is in the development stage and the option of agricultural activity will affect the density of energy-producing cells or wind turbines, and the installation costs will be affected by the elements necessary to establish the specific agricultural crops, including the amount of energy expected to be obtained will be reduced due to these changes, then calculations must be made taking these elements into account. On the other hand, the indirect costs and social implications that I mentioned before must also be taken into account.

For an in-depth analysis of all elements, it is preferable to use econometric elements to analyze the factors that influence the activity and the results obtained through reterritorialization.

The identification of statistical-econometric models that can be applied for the reterritorialization of agri-food strategies and markets involves several consecutive stages, starting from the collection and preparation of data to the selection and calibration of the most suitable econometric models. The purpose of identifying these patterns is to analyze and predict the impact of changes on markets and land use, providing decision-makers with information to optimize agri-food strategies.

In order to evaluate and optimize reterritorialization strategies, it is necessary to develop adequate statistical-econometric models that can analyze and project their efficiency. The essential steps to identify such models start from the collection of relevant data on agricultural production, in this case the yield of different crops according to the microclimatic conditions created by the photovoltaic panels, the water requirement, the yields by soil types. Energy production data on the efficiency of solar energy capture in the context of mixed-use land is essential, as are the installation and maintenance costs of PV panels and integrated agricultural infrastructure and the revenues generated by both activities. Based on the principle of sustainable development, the impact on the environment must be considered through the lens of data collected on changes in biodiversity, soil quality, water consumption and carbon emissions.

The use of specific econometric models such as multiple regressions that can be used to identify the relationships between different factors, such as agricultural productivity, energy efficiency and environmental conditions such as panel height, light intensity, or humidity.

Efficiency analysis models can be applied to assess the technical and economic efficiency of reterritorialized land compared to conventional uses. Usable models are those such as Data Envelopment Analysis (DEA) or Stochastic Frontier Analysis (SFA).

Monte Carlo simulation models can be used for simulations and forecasting, or time series can be useful to predict long-term revenue trends based on different climate and economic scenarios.

Economic and social impact assessment is another element that needs to be included in the analysis. Input-output models and Computable General Equilibrium (CGE) models can be used to estimate long-term effects on the local and regional economy, including effects on agri-food markets and supply chains. Models for assessing externalities must include the impact of positive externalities such as emission reduction or soil regeneration and negative externalities such as possible competition between land uses or upfront costs.

Market and demand analysis for agricultural products can be done using econometric models that assess demand for various crops based on changes in local or regional markets. Also, price elasticity will be introduced into the econometric calculations using price elasticity estimation models for renewable energy and agricultural products in the context of the national or international market.

The necessary tools and methodology include, but are not limited to the use of econometric software, namely applications such as STATA, R, Python, or EViews can be used to run complex econometric analyses. GIS (Geographic Information Systems) can be used to analyze the spatial characteristics of land and visualize the impact of photovoltaic panels and agricultural crops, and pilot projects in certain regions can provide empirical data needed for model calibrations and adjustments.

Alongside policy initiatives targeting clean energy investment and adoption, it is critical to encourage community engagement and public education programs. These efforts play a crucial role in securing public acceptance and promoting a societal shift towards the adoption of cleaner energy sources. Emphasizing the benefits of clean energy, educating about its affordability, and involving communities in decision-making processes regarding energy transitions are fundamental. Encouraging international cooperation to honor climate agreements and supporting developing nations in their clean energy transitions is a global imperative.

4. Conclusions

The development of wind and solar energy requires significant investment to reduce technology costs. At the same time, it is an advantage that the wind energy, clean energy and solar energy sectors are considered to be the most attractive renewable energies for investors. Countries around the world have introduced significant financial incentives to promote sustainable technologies such as residential solar PV panels. Clean and affordable energy is among the UN's 17 Sustainable Development Goals.

The solar energy storage (SES) is gaining ground, so SES analysis offers the possibility to understand the socio-technical transition within the energy system. At the same time, it is necessary to analyze the factors, mechanisms and regulations that will facilitate the adoption of SES, in order to move towards energy independence. Low costs and excellent scalability have made the solar photovoltaic energy production an affordable solution. As the share of solar energy in electricity generation increases across the globe, its diurnal and weather-dependent nature poses some challenges. The financial inclusion is fundamental to the growth of a nation's performance, and the green economy has emerged as one of the dominant drivers of environmental sustainability.

Exploring the socio-economic impact and behavioral changes associated with the adoption of clean energy would provide valuable insights into society's acceptance and adaptation to these transitions. Addressing these limitations and delving into these unexplored areas would significantly contribute to a more comprehensive understanding of the link between climate change, energy security and clean energy investments.

At the European level, the EU has registered a significant increase in the installation of renewable, photovoltaic energy. However, the concept of reterritorialization is quite new, the proportion of agrophotovoltaics is difficult to measure at the level of the entire European Union, because the initiatives are also quite recent and vary a lot between the member states. Countries like Germany and France are much more advanced in this practice, while Romania is still developing new projects of this type, and sustainability concepts are still overshadowed by the targets of maximum profitability with minimum investment or work.

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