Challenges and Opportunities of Agri-PV systems in a Clean Energy Transition for Rural Areas

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***Abstract*—A powerful conceptual element in a clean energy transition vision to achieve climate neutrality by 2050 is represented by the development of Agri-PV systems, which have the potential to provide a deep transformation of the agricultural sector, while providing also electrical energy for local needs. The paper presents an analysis of some of the most important challenges of Agri-PV systems, to make the agricultural sector more resilient and to support delivery of sustainable energy and food all over the world.**

Keywords—energy transition, renewable energy sources, photovoltaic system, Agri-PV, emerging technologies, combined use of land, agriculture.

I. INTRODUCTION

Today the net-zero global goal remains unsolved: greenhouse gas emissions continue unbated and the extreme conditions of climate change are increasingly visible all over the world. A clean energy transition needs to be accelerated most likely in an exponential progress in order to help stabilising the earth's climate.

Reaching the ambitious goal in maintaining a global temperature increase below two degrees Celsius requires a crucial shift in the agricultural and energy sectors. New clean energy technologies such as Agri-PV systems will contribute simultaneously to promote sustainable agriculture in the rural areas and the clean energy transition. By combining Agri-PV solutions with solar potential can drive the modernisation of rural communities to be more competitive and sustainable.

This concept of Agri-PV, implying land use for agriculture and solar energy generation, has enormous potential to contribute to the sustainable development of rural areas. Farmers have the opportunity to obtain new sources of income without losing the productivity of their land. Other used terms for describing Agri-PV are Agrivoltaics (widely used but with less accurate content, as the "photo" term is missing, even if it is essentially bound to "voltaics") or Agri-Photovoltaics (this being the correct description behind "Agri-PV" denomination), the latest being an extended version of the compact term which is used in this paper.

According to IEA Net Zero Emissions by 2050 Scenario (NZE) [1] wind and solar account for around 70% of total generation, and total installed capacity reaches around 23 TW, almost triple total global installed power capacity from all sources today. As it is seen in the figure 1 – the main key driver of electricity sector transitions by 2050 represents solar PV in terms of global installed capacities, while Agri-PV can give an important contribution to this trend, as agricultural capabilities are naturally linked to solar abundance (high level of kWh/m^2/year), which is also a guarantee for PV production.

The scope of the paper is to present meaningful aspects, to analyse challenges and to highlight advantages of the Agi-PV emerging paradigm, to support accelerated efforts of human activity decarbonation with solutions compatible with the agricultural activity.

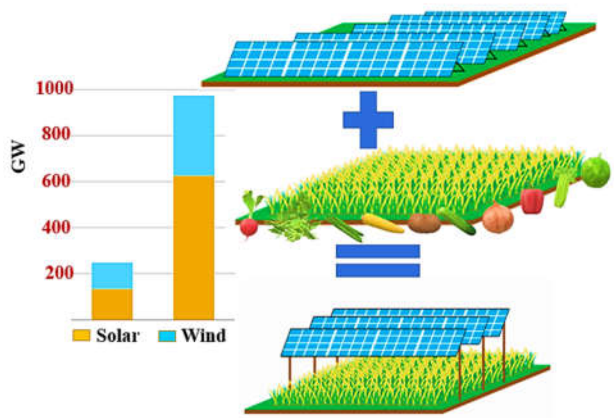

Fig. 1. Capacity additions of Net Zero Emissions by 2050 Scenario (IEA) and development Agri-PV systems, to address both food and energy

The paper is organised as follows: a first section makes a review of representative today experience on the Agri-PV approach; the next section shows aspects of "competition" of the combination of agriculture with PV systems: competition of sunlight and competition of land use; a third section addresses design solutions and challenges, and a final section shows multiple advantages and synergies when using Agri-PV systems.

II. A REVIEW OF TODAY AGRI-PV EXPERIENCE

In the last 10 years, Agri-PV systems have been the subject of numerous studies and research due to their potential in the land-use and "co-existence" with agricultural farming activities [2] in the producing sustainable PV energy.

Extreme weather events put in danger the resilience of agricultural sector, especially rural areas which are particularly vulnerable to climate change. Agri-PV can help to contribute to climate change mitigation and achieve more sustainable agricultural practices. Within this framework, Agri-PV systems offers an opportunity to simultaneously realise the European Green Deal, meet the EU's decarbonisation targets, and achieve the objectives of the Common Agricultural Policy [3].

An extensive literature developed in [4] presents a review concerning PV systems, a technology which introduces dual land use through agricultural and solar energy production developed over the last 10 years. The research is focused on factors which govern Agri-PV production, as well as issues in its implementation and the benefits of the approach. It has been estimated that deploying Agri-PV on only 1% of global cropland could help meet total global energy demand [5].

In this context, it should be noted that the exponential growth of photovoltaics creates potential conflict between food production and electricity generation in the use of land in rural areas [6,7]. However, photovoltaics requires relatively large areas to be installed. Identifying suitable land areas is one of the biggest problems faced in rural areas. A main solution would be the integration of photovoltaic panels in different areas of the environment for example on the agricultural areas, which would be used with a dual purpose. Rather than competing for land use, these two areas can complement each other very well.

Agri-PV systems offer to the farmers additional opportunities to diversify their incomes and protect their crops. In particular, the metal constructions and photovoltaic panels can be designed to better protect agricultural crops against hail, frost and drought.

Multi-land use efficiency through Agri-PV can help deliver sustainable energy and food (Figure 2). It has the potential to be a win-win solution for renewable energy sources, agricultural sector, energy sector and other sustainability dimensions for future resilient communities.

Fig. 2. Applications for integration Agri-PV systems.

Agri-PV should be seen as a long-term project of clean energy transition guarantee the efficiency, sustainability, and viability between solar and agriculture to a new state of the energy competitive rural communities. The implementation of Agri-PV currently is in development around the world, and it is not an isolated concept. However, Agri-PV systems differs from country to country in terms of the opportunities and aims, drivers and governance, related challenges, and motivation.

The start-up of Agri-PV “new deal” requires the establishment of a special program with the support from the government of each country that would pursue a strategy with medium and long-term objectives. The launch of Agri-PV requires broad public acceptance in the interests of a better future to increase the resilience to climate change, while also asking for debunking the misconception that the two domains are only able to compete each-other.

The main policy recommendations for developing and strengthening the Agri-PV sector at the national level are as follows:

- Integration of Agri-PV systems within climate change adaptation strategies of the global and European level.
- Development of Agri-PV systems regulatory frameworks and promote investments into solar within Common Agricultural Policy Strategic Plans.
- Support Agri-PV research through international, European projects frameworks such as in Horizon Europe.
- Encouragement the use of Agri-PV systems in EU islands’ decarbonisation strategies.
- Ensuring accessibility for all inhabitants to clean Agri-PV systems.
- Mainstream Agri-PV systems within the implementation of the development an overall farm strategy such as Farm to Fork Strategy.

In this sense, public policies should boost the deployment of established Agri-PV systems for a clean energy transition, while simultaneously supporting innovative Agri-PV solutions.

III. Agri-PV Systems – Aspects of Competition

There are several aspects which need be considered in order to see synergies, thus win-win situations between agriculture and PV systems. The paper is approaching three such aspects.

a) Competion of using the sunlight

One reason for reducing land competition through the dual use of the land between Agri-PV technologies and rural farmland areas is the increasing climate protection measures avoiding traditional energy based on fossil fuels to a new state of the energy sector, characterized by renewable energy sources.

The shading of the land-use of agricultural areas creates under the photovoltaic panels a specific microclimate through the following aspects:

- The soil temperature drops especially on hot and dry days, the air temperature drops less and so the humidity is also better preserved.
- Regulation of plant insolation regarding negative effects of radiation on plants (reducing the effects).
- The orientation and design of the Agri-PV system has also an impact on local aeration (air breeze), as the wind speed is reduced or increased. The effects of the wind tunnel on the plants growth should be taken into consideration when a Agri-PV system is planning.
- The evaporation of water from the soil is less when it is installed an Agri-PV system.

In this context, most types of plants (crops) are suitable to be grown under the Agri-PV systems, but the effects of shading on each plant must also be analyzed carefully and to adapt the solution with each specific crop.

The technical approaches for the integration of Agri-PV systems in agricultural sector are varied according to a rough classification as “cropland”, “grassland”, and “greenhouses” is possible [8].

It is very important to take into consideration the concept of light saturation point to increase the rate of photosynthesis that differs with the type of plant. As it is observed in a schematic mode in Figure 3 – The dependence of photosynthesis rate according to the light intensity for sun and shade plants [9].

It is essential for Agri-PV systems to adjust correctly the size and placement of solar modules to generate electricity while maintaining a sufficient amount of sunlight for growing plants. With careful design, generating electricity is safe without having an impact on the plants [10].

Usually, there are specific plants, such as leafy vegetables, which are very shade tolerant (for example, green salad), fodder plants (clover grass), various types of stone fruits and berries, as well as other plants specific (e.g., asparagus or hops). Specific for Republic of Moldova as grapevine plants being a traditional culture, the vine plant is very vulnerable to light. The heat can affect the amount of sugar in the fruits (grapes), thus can affect the alcohol content of wines reducing their quality on a national and international level.

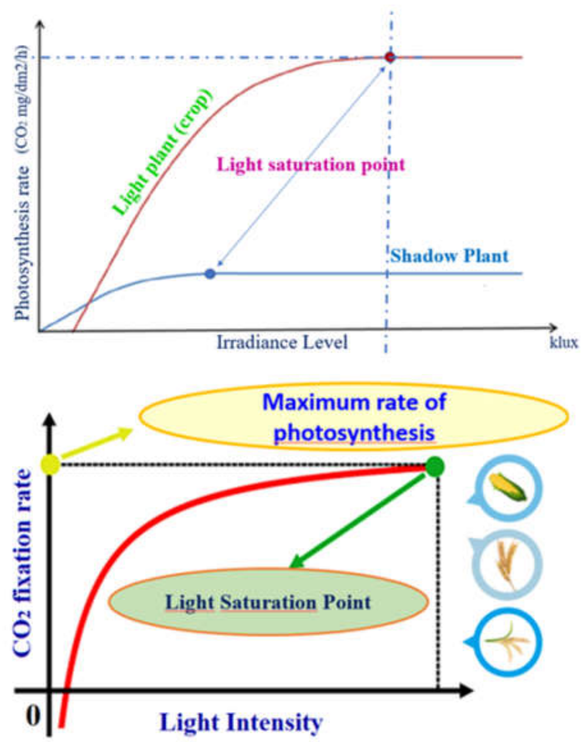

Fig. 3. Schematic presentation of corelation between photosynthesis rate with the light intensity for sun and shade plants

Most of the studies and research justify the use of photovoltaic panels alongside agricultural production [11]. Technological development of Agri-PV systems with respect to transparency and energy efficiency could make their coexistence with greenhouse crops more economically viable. In this context, it is primordial to be searched the percentage of shading that makes the shading compatible for each type of crop in agricultural sector.

Agri-PV systems represent a combination of agricultural crop production and photovoltaics (PV panels) on the same land [12]. According to the actual increasing interest regarding this upcoming technology, there are still many challenges at design, policy and economic level.

The potential of Agri-PV systems concerning the opportunities and land-use possibilities are the following:

- to reduce the irrigation needs by up to 20%.
- to promote rainwater collection possibilities for irrigation.
- to reduce wind erosion.
- to use the photovoltaic substructure for attaching the protective net.
- to optimize the light for agricultural crops.
- to increase the PV module efficiency through better convection.

According to [13], one of the essential elements for increasing the flexibility in electrical power systems is the short-term daily storage associated to the PV systems. The work proposed a new approach of a sustainable development, by combining in harmony the agriculture with photovoltaic plants at national level. Such a concept is extremely adequate for a country like republic of Moldova (RM), having important agricultural activities, which can see new valences through the potential of supporting a society which can keep in a sustainable and durable manner traditional activities. Another aspect considered in the assessment of such approach is the necessary land-use for implementing the PV production, which has been calculated for Republic of Moldova.

a) Competion of using the agricol land

The high penetration of PV powerplants is frequently questioned as being a threat against food production with the same land, which may not cover the food population needs. In this respect, PV powerplants are seen as a danger and as a competition against the traditional agricultural activity. Consequently, the assessment on land use impact was essential in [13].

According to [14], the area needed for 1 kW of PV panels depends on various factors:

a) the efficiency of PV panels; current market products have efficiency of more than 19%, with a trend to 21%. A conservative value may be $\eta = 19.5\%$.

b) the chosen density of PV panels, usually correlated also with the tilt angle. In [15] it is made an analysis of tilt angle versus area used and density of energy obtained on square meter. In agricultural areas the land is considered to be cheap enough such that tilt angle can be nearby the optimal value over a year - which is around 34º in Republic of Moldova.

For such cases it is needed to have an area of around 20 m^2 for 1 kW of installed PV modules. In restricted areas, where areas are limited, such as rooftops, tilt angles can be 10º to 15º, as it is more attractive to obtain more yearly energy on the existing rooftop, bringing the needed area down to $10\, m^2/1kWp$. We consider in our assessment the conservative value of $A_{1kW} = 20\, m^2/1kWp$, for having PV panels maximum efficiency over a whole year.

The needed land is therefore calculated with the formula:

$$A_{Needed} = P_{PV} A_{1kW} \quad (1)$$

By applying the formula for two scenarios developed in [14] – meaning 30% and 50% of RM yearly consumption covered by PV production - asking for 1722 and 2878 MW of PV power investment, it has been obtained:

$$A_{Needed\_30\%} = P_{PV30\%}A_{1kW} = 1722 * 1000 * 20 = 34.4\ km^2 \quad (2)$$

$$A_{Needed\_50\%} = P_{PV50\%}A_{1kW} = 2869 * 1000 * 20 = 54.4\ km^2 \quad (3)$$

which means an equivalent of a square having the side length $L = \sqrt{A_{Needed}}$ as follows: $L_{30\%}$=5.9 km, $L_{50\%}$ =7.4 km

It was demonstrated that for 30% and 50% PV penetration, it is only 0.23% respectively 0.37% of the agricultural use area of RM as being around 14800 km^2 [16], which is practically not affecting the agriculture, while a clever distribution of the energy production areas may also have lower impact on electrical grid. To be noted that percentage of land use reported to RM area (33846 km) will give even lower values.

There are appropriate conditions for PV installations everywhere across RM, from North to South (Fig. 4). For a 100% coverage of electricity in RM will be then necessary less than the 1% of agricultural area, as has been shown in the same study. The fact that converting just 1% of land to solar farms would be enough to provide the EU's electricity needs is already reported in other studies [17], while 2% of Germany's surface is enough for covering its consumption with 100% renewables [18]. which shows consistency and similar range with the results obtained for Republic of Moldova.

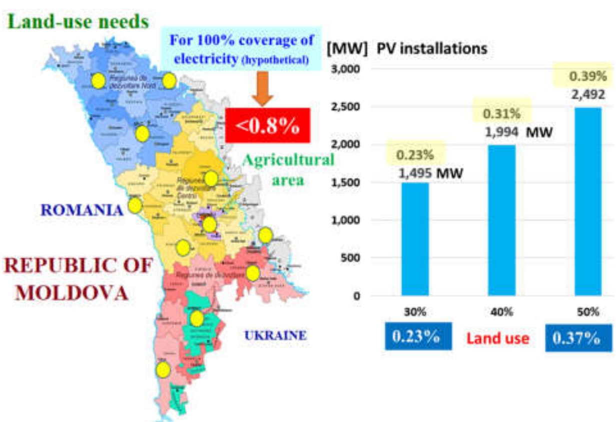

Fig. 4. The agricultural use area of RM covering its consumption with 100% renewables

In this context for Republic of Moldova, the initial analysis made for 30% respectively 50% coverage of consumption on a yearly basis, has been extended to cover 100% from this consumption. It has been shown that if hypothetically it is chosen to cover 100% of national consumption, the installed power is as much as 5.74 GW (by using coverage factors), which represent only 0.8% of the agricultural area of RM.

The PV density and overall potential is also treated in other works such as in [19], showing the areas of the Republic of Moldova with solar potential, and dealing with their integration into the national energy system of the Republic of Moldova.

b) Possible disadvantages

The two classes of "competition" presented above show that there are no real bottlenecks in approaching Agri-PV.

Some disadvantages can be still pointed:

- The crops to be raised in an Agri-PV paradigm need to be carefully selected, such that they cope acceptably with the competition of the sunlight
- Agricultural works need to be adapted to cope with coexistence of panels structures. This may ask for more manual works or for more automation of the mechanical tools (e.g., self-driven electric tractors), which may bring initially over-costs.
- Depending on design, PV structures may have higher costs for both investment and operation
- Higher level and multidisciplinary skills may be needed for a part of the personnel involved in the hybrid use of land.

The today lack of experience, the people resistance to changing mentality are currently still high; however, more, and successively bigger demonstrators may change this view.

IV. A Glimpse on Design Solutions and Challenges

A wide spectrum of intensity and type of agricultural land-use is covered by Agri-PV systems. The performance of an Agri-PV system depends on several factors as follows:

- photovoltaic technology.
- height and orientation of PV system.
- orientation of the structure and foundation.

To be mentioned that all these constructive elements of Agri-PV systems must be adapted to the management of agricultural machines and to the characteristics of the existing crops.

Moreover, the light and water management are very important to ensure high performance. Through the physical gaps between the PV panels, light penetrates toward the agricultural crops. Different types of agricultural use corresponding to PV systems are shown in Fig. 5.

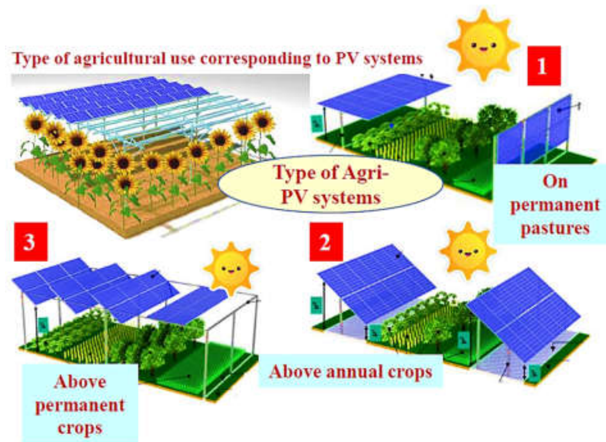

Fig. 5. Type of agricultural use corresponding to PV systems: 1 – on permanent pastures; 2 – above annual crops; 3 – above permanent crops

There are several forms of installation of Agri-PV systems, from linear panels separated by a few meters to setting the panels in corridors through which agricultural machinery passes and the soil is processed. According to the scientifical studies literature, two types of installations are used:

- Fixed support - It consists of supports on the ground that allow the panels to be placed at a certain height, for example about five meters, so that agricultural machines have access to the crops located below.
- Solar greenhouses - Greenhouse roofs are converted into solar energy generation systems by installing photovoltaic panels.

Greenhouses are ideal for installing solar panels because it has the potential for a higher power production. It maintains a microclimate inside that involves energy expenditure considerable, expenses that with the placement of solar panels are significantly and immediately reduced.

The results of several studies show that all types of solar modules [20] can be used in Agri-PV systems. In principle, silicon solar cells account for approximately 95% of the global PV market. According to IEA (Figure 6) the calculations of solar PV material demand under the Net Zero Scenario for selected materials, 2022-2050 [21] take into account the historical evolution of material intensity in the different generations of solar PV modules put on the market since 1990 and assume further material intensity improvements of 10% over 2020-2050 for glass, 30% for silicon and 75% for silver. For the sake of simplicity, calculations assume a recovery rate of 85% for all materials. However, recovery rates above 90% for silver and up to 95% for silver and copper are considered achievable [22].

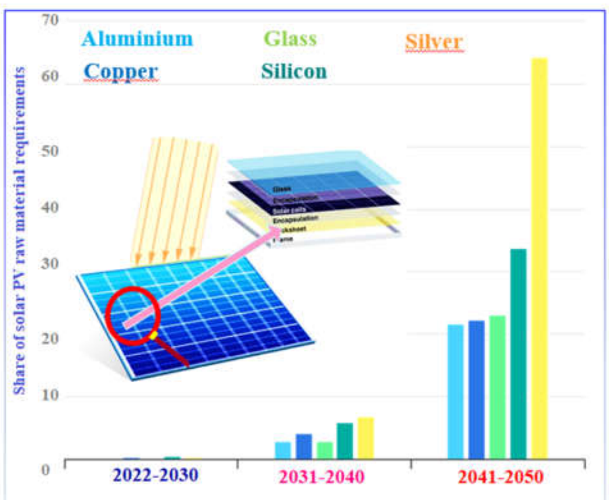

Fig. 6. Potential contribution of module recycling to solar PV material demand under the Net Zero Scenario for selected materials, 2022-2050 (source IEA)

V. Advantages and Synergies of Using Agri-PV Systems

As pointed above, the main advantage of Agri-PV is the synergy between agricultural corps and PV panels production.

However, the approach is opening the door for even more opportunities, for instance to the electrification of agricultural mechanisation. With today point of no return foreseen for the light vehicles towards an increase of electromobility, there are already signs of electrification of heavier vehicles and tractors are also seen as having an impact on the agricultural activity. It may be easily then foreseen that electrical tractors (ET) can take advantage of locally produced energy from the PVs of the Agri-PV system such that they can eventually have charging stations in the field – meaning where they perform their work.

Another opportunity of having electricity produced "in the agricultural field" is the possibility to sustain in a better way the irrigation activity, especially as climate change often show lack of sufficient natural water from rains which ask for alternatives. It is another challenge which can be addressed with Agri-PV. In this case, pumping water from the depth waters (e.g., 10 to 50 meters depth, depending on the region) and using it with temporary water reservoirs to allow day pumping and night irrigation, may be another win-win solution enabled by Agri-PV systems.

In both ET charging and irrigation based on electrical pumping of the water, an essential aspect is the fact that the electrical energy needed for these activities is obtained in the same place where it is needed the consumption and that these activities are requested in the same season when crops need them. This means that a smaller battery energy storage system may be needed to accommodate the connection to the main grid, as part of the energy can be consumed on purpose locally.

While a complete list of Agri-PV systems benefits has to be kept open, some of the most relevant are the following:

- using the same land for agricultural purposes and valorisation of renewable energy sources.
- the construction of Agri-PV systems on 1% of the existing agricultural land worldwide would cover the energy needs of the entire planet, so there is no land issue.
- has potential to contribute to the substantial reduction of greenhouse gases in the agricultural sector;
- reducing pressure on ecosystems and biodiversity by concentrating areas of cultivation and electricity production;
- increasing the efficiency and yield of the land-use in the rural areas by reducing the evaporation of water from the soil (which can reduce the need for water) and minimizing the impact of radiation on the crop;
- favourable landscape impact.
- has potential to combine photovoltaic energy with agriculture and animal husbandry.
- different possibilities of supplying irrigation pumps with electricity.
- reducing the impact of solar radiation on plants.
- reduction of soil temperature during scorching heat.
- job creation both during the construction period and during the subsequent maintenance.
- more efficient transport of electricity to remote areas.
- reducing the negative impact of climate change on land-use and crops.
- protecting crops from hail and frost.
- providing local energy for irrigation.
- providing charging to emerging electrical tractors, as an extension to the already ongoing paradigm shift in electromobility.

Agri-PV systems is far more than the transformation of the agricultural and energy sector; it will change the way all the citizens produce and use energy and food, how to transport people and goods. It is foreseen that new business models will emerge, which will change the coexistence in the society to be in harmony with the nature. The main objective of the Agri-PV systems is to decarbonise the economy, stabilize the climate on the Earth and boost the clean energy transition in competitive and sustainable rural communities.

VI. CONCLUSIONS

The paper presents essential aspects of Agri-PV systems to serve resilient rural energy communities. It is time for a coordinated effort to boost the clean energy transition through development of Agri-PV systems across all over the world, especially in agricultural countries.

Efforts to replace fossil fuels come with growing interest in renewable energy sources due to the 'Green New Deal' policy. Agri-PV systems allow farming and production of electricity at the same time, which is growing the attention as one of the leading solutions to tackling climate change.

The paper makes a review of representative today experience on the Agri-PV approach; shows aspects of "competition" of the combination of agriculture with PV systems, presents some design solutions and challenges, and shows multiple advantages and synergies when using Agri-PV systems.

Furthermore, Agri-PV system can help to efficiently utilize the land in rural communities, increase farm income, and reduce carbon emissions since it makes use of the existing agricultural land-use, where electricity is seen as an additional "crop" of the land. Supporting Agri-PV would further put the EU at the forefront of a key innovative solution to the challenges of the clean energy and sustainable agriculture transitions.

The results of the research provide arguments and suggest that Agri-PV systems, as part of the effort for a clean energy transition, will undoubtedly have an impact on world's energy economy and security, especially for the countries with significant rural areas.

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