

Review

# Implementation of Renewable Energy from Solar Photovoltaic (PV) Facilities in Peru: A Promising Sustainable Future

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**Abstract:** In the last two decades, Peru has experienced a process of transformation in the sources of its energy matrix, increasing the participation of clean energy such as solar photovoltaic (PV), on-shore wind, biomass, and small hydro. However, hydropower and natural gas remain the main sources of electricity, whereas off-shore wind, biogas, waves, tidal, and geothermal sources are currently underdeveloped. This article presents the enormous potential of Peru for the generation of electrical energy from a solar source equivalent to 25 GW, as it has in one of the areas of the world with the highest solar radiation throughout the year. In addition, this article presents the main advantages, benefits, and considerations of the implementation of solar photovoltaic technology, with emphasis on (i) the potential of solar energy, showing the available potential and an installed capacity by the year 2024 equivalent to 398 MW, (ii) current solar energy sources, characterizing existing industrial solar photovoltaic (PV) energy plants, and (iii) future solar energy facilities projections, stating the portfolio of solar renewable energy plant projects to be implemented in the future considering an installed capacity of 7.2 GW by 2028. Additionally, lessons learned, challenges, and directions for the future development of solar energy in the country are presented. Finally, the article concludes that if Peru takes advantage of solar potential by considering a sustainable future perspective and implementing strategic land-use planning, the southern region will be transformed into a world-class territory for renewable energy development considering the hybridization of concentrated solar power (CSP) systems with solar photovoltaic (PV) systems and solar energy storage systems.

**Keywords:** renewable energy; solar energy; solar photovoltaic (PV); concentrated solar power (CSP); sustainability



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## 1. Introduction

### 1.1. Implementation of Renewable Energies in Peru

Peru is one of the most diverse countries on the planet, considering its geography, climate, ecosystems, and ancestral culture [1]. It is a country whose economy is characterized by having the following activities: (i) mining, being the second-highest world producer of copper; (ii) agriculture, being one of the world leaders in the export of organic fruits and vegetables without the use of genetically modified crops; (iii) fishing, being one of the world leaders in fishmeal exports; (iv) tourism, being known worldwide for its countless destinations, such as the city of Lima, Colca Valley, Titicaca Lake, Inca Sacred Valley, and the Inca city of Machu Picchu, among others; and (v) gastronomy, possessing some of the most diverse and tasty foods in the world. Its population is equivalent to approximately 33 million inhabitants, and it has a gross domestic product (GDP) of 222 \$USD billion, with an annual economic growth rate of 2%, a human development index (HDI) equivalent to 0.759, and a per capita income equivalent to 6491 \$USD. Peru is a place that offers adequate conditions to promote investment projects because social inclusion is respected, ecosystems

are protected, and companies are allowed to generate value and employment under a regulatory framework based on sustainable development and human well-being [2].

According to the Ministry of Energy and Mines of Peru (MINEM), energy consumption in the country is estimated to increase by 10% annually, related mainly to industrial development [3]. Concerning data from the Economic Operation Committee of the National Interconnected Electricity System of Peru (COES–SEIN), the total electricity generated in 2012 was 37,617.6 GWh, while in 2022 it was 56,084.2 GWh, equivalent to a growth of 49.1% in comparison to 2012. This projection has persisted in recent times, mirroring the rise in electricity demand in Peru that drives the country's robust economic, technological, and population expansion [4].

The increase in energy demand in Peru is monitored by the COES–SEIN, which projects the energy demand in the country for the short term (3 years) and long term (10 years) under different scenarios, predicts the amount of efficient energy required, and estimates the years when it would be needed and its location. Unfortunately, the COES is a private institution that provides guidance and possible solutions to the electricity system of the country, but it does not have a binding planning role [5].

According to the Supreme Decree N° 031-2007-EM, the General Directorate of Energy Efficiency of the Ministry of Energy and Mines is the regulatory technical body in charge of proposing and evaluating the policy for energy efficiency and renewable energies, as well as conducting energy planning. To date, the only measure for promoting the development of renewable energy technologies has been the promulgation of the Legislative Decree N° 1002 and its regulations approved by Supreme Decree N° 050-2008-EM and modified by Supreme Decree N° 012-2011-EM. This legal framework led to the execution of four auctions for renewable energy resources (RER) generation, assigning contracts to 64 solar, wind, biomass, and small hydroelectric power plant (less than 20 MW) projects for a total installed capacity of 1274 MW and one off-grid auction for the installation and maintenance of up to 500 thousand autonomous photovoltaic (PV) systems throughout the country [6].

By the end of 2023, Peru had a total installed capacity of 13,693.278 MW on its electricity matrix [5]. It generated 58,393.34 GWh/year from its three main natural gas reserves (42.7%), while 44% came from conventional renewable energy (hydropower), and only 9.9% came from non-conventional renewable energy resources (RER) like on-shore wind and solar photovoltaic (PV) [7].

On the other hand, in 2023, the maximum power demand in the country was 7605.51 MW in the National Interconnected Electrical System (SEIN), 86.2% of which was required in the central zone of Peru, where one-third of the population of the country lives mainly in urban zones (Lima, Huancayo, and Huaraz cities, among others). The north of Peru uses 7.31% of the energy, and the population lives mainly in urban zones (Piura, Chiclayo, and Trujillo cities, among others) and some rural zones (the Loreto, Tumbes, Piura, Lambayeque, San Martín, and Cajamarca regions, among others), and the south of Peru uses 6.48%, and the population lives mainly in urban zones (Arequipa, Puno, Tacna, and Cuzco cities, among others) and some rural zones (the Madre de Dios, Arequipa, Apurímac, Moquegua, and Tacna regions, among others) [5].

There is a key difference between the useful clean-energy potential and its realization, and the 2023 data shown below in Table 1 demonstrate that Peru can do a lot more to harness renewable energy sources.

Table 1 shows that, in first place with respect to the potential use of renewable energy is the electrical energy generated by biomass, which is equivalent to 14.67% of its potential, then in second place, the hydroelectric source in Peru is the largest and has used 7.23% of its potential, followed by the on-shore wind source with 3.26%, then the solar source with 1.59% of its potential, and the geothermal, off-shore wind, waves, and tidal sources use none of their potential.

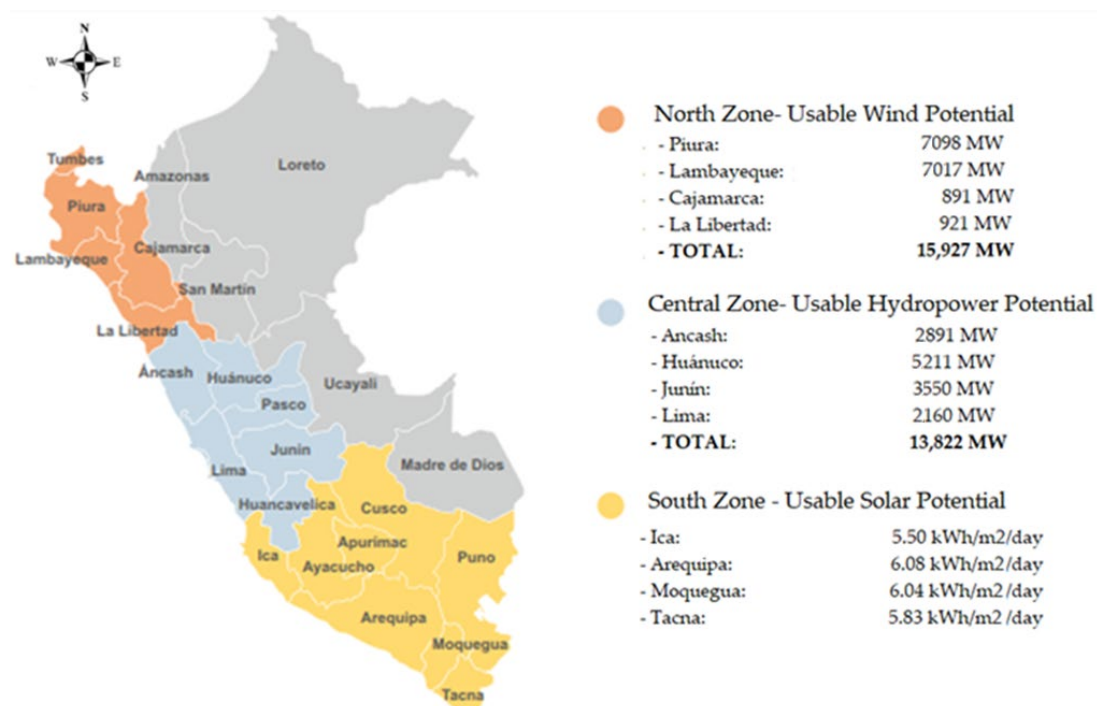
The SEIN of Peru has an efficient generation offer of 819 MW until 2025, related to investment projects with high implementation certainty. However, from 2026 it is expected that there will be a deficiency in efficient electricity production in the SEIN due to future

high consumption, which would be an additional 1600 MW by 2030 [4]. This means that if the required efficient generation is not met by 2026, thermal power plants run by diesel will come into operation, increasing the electricity costs and GHG emissions of the system.

**Table 1.** Status of implementation of renewable energy in Peru in 2023.

| Renewable Energy                         | Installed Capacity (MW) | Usable Potential (MW) | Percentage of Resources Used | References |
|------------------------------------------|-------------------------|-----------------------|------------------------------|------------|
| Hydroelectric (Conventional > 20 MW)     | 4748.37                 | 70,000                | 7.23%                        | [6]        |
| Hydroelectric (Non-Conventional < 20 MW) | 319.28                  |                       |                              |            |
| On-shore Wind                            | 668.00                  | 20,500                | 3.26%                        | [8]        |
| Solar                                    | 398.07                  | 25,000                | 1.59%                        | [4]        |
| Biomass                                  | 66.00                   | 450                   | 14.67%                       | [6]        |
| Geothermal                               | 0.00                    | 2860                  | 0.00%                        | [6]        |
| Off-shore Wind                           | 0.00                    | 347,000               | 0.00%                        | [8]        |
| Waves                                    | 0.00                    | 3500                  | 0.00%                        | [9]        |
| Tidal (Currents and Range)               | 0.00                    | Not determined        | 0.00%                        | [9]        |
| <b>Total</b>                             | <b>6199.72</b>          | <b>469,310</b>        | <b>1.32%</b>                 |            |

To address the surge in energy demand, Peru must promptly meet its electricity generation needs. International pressures urging an energy transition focused on a sustainable model direct us to leverage Peru's abundant renewable energy potential as a promising avenue to enhance energy supply through the utilization of non-conventional renewable resources like solar, wind, biomass, and geothermal energy. In this context, solar energy is playing a significant role in the energy landscape of the country, being one of the most attractive clean-energy options for energy companies. Figure 1 shows the potential for wind, hydroelectric, and solar energy in the northern, central, and southern territories of Peru.



**Figure 1.** Some examples of the available potential of renewable energies in some regions of Peru. Note: North Zone—wind potential, Central Zone—hydropower potential, South Zone—solar potential [6].

Figure 1 indicates that the northern zone of Peru has a high wind potential that has not yet been used. In addition, in the central zone of Peru in the Andes sector there is a high hydroelectric potential and, finally, in the southern zone of Peru, there is an extraordinary solar potential that has not yet been fully exploited.

Considering the use of more clean energy presents several key issues. First, it needs to be produced. This will mean increasing our availability to generate electricity from renewable resources with the least impact on ecosystems, particularly through solar, geothermal, and wind energy technologies. More renewable energy plants will be needed, and more electricity will also be generated locally, using, for example, photovoltaic rooftops, micro-hydroelectric plants, and micro wind turbines [10].

In this sense, massive investments will be needed to expand and modernize Peruvian electrical networks to account for the increase in loads and different energy sources. Electricity will need to be transmitted from solar photovoltaic facilities, concentrated solar facilities, offshore wind turbines, or remote geothermal plants to towns and cities while minimizing the impact of new transmission lines or underground cables [11].

Regarding technical aspects, two relevant issues will allow humanity to meet its energy demands using clean sources: (i) it is necessary to decrease electricity needs by improving energy efficiency and decreasing energy waste; and (ii) because electricity and heat are the mechanisms of energy most easily generated from renewable energy, the use of electricity and direct heat will have to be optimized, supported by improvements to electrical networks [12].

### *1.2. A Promising Future of Sustainability with the Use of Solar Renewable Energy*

Solar energy utilization has benefits not only for the environment, such as the reduction of the carbon footprint, as it is a clean technology, and it is possible to generate electricity using solar facilities in strategic places of the Peruvian territory. The solar energy industry is following the advances of the wind energy industry in Peru, where all stakeholders (communities, authorities, investors, and NGOs, among others) of the territory are accepting this clean energy as a road to reach sustainable development [8]. Thus, we can see that the main benefits of using solar technology for energy generation are as follows:

Firstly, the reduction of GHG emissions. Relevant information indicates that 97% of the electrical energy that was consumed during the first mandatory social isolation against COVID-19 was generated from renewable sources such as solar, avoiding the emission of more than 0.4 Mtons of carbon dioxide equivalent ( $\text{CO}_2\text{eq}$ ), from other energy sources [13,14].

Secondly, the use of energy sources from the sun avoids the use of highly polluting fossil fuels (e.g., oil, coal, pet coke, and natural gas, among others) [15]. According to the Intergovernmental Panel on Climate Change, including the whole life cycle of the different technologies, utility-scale solar energy plants emit 48  $\text{gCO}_2\text{eq/kWh}$  on average, with much lower emissions than coal power plants, which emit 820  $\text{gCO}_2\text{eq/kWh}$ , or combined-cycle natural gas power plants, which emit 490  $\text{gCO}_2\text{eq/kWh}$  [16].

Thirdly, the use of energy sources such as solar panels or solar facilities creates employment opportunities and increases the value of the properties surrounding the built infrastructure [6].

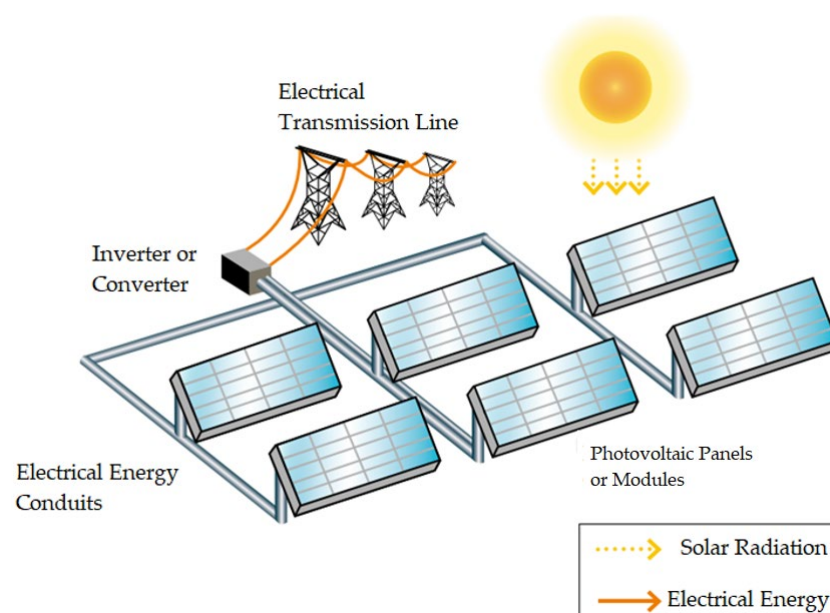
Fourthly, the generation of solar energy contributes to the supply of energy to communities that are far away, contributing to their development and visibility. Solar energy generation projects allow the facilities to be located where energy from other sources does not reach, such as energy plants that must be close to fossil fuel extraction points [17].

In Peru, over the years, solar energy generation projects and their importance, as indicated by international treaties and conferences, and of course the promulgation of general regulations for their development, have been mainly promoted by the MINEM. Thus, the start of new electrical generation using clean-energy resources such as solar has even been announced as a national priority and subject of public interest [18].

Without prejudice to the above and the effort imposed by the MINEM, with the support of environmental organizations such as the Ministry of the Environment (MINAM) and various NGOs, the measures implemented by the Peruvian government still do not cover the minimum electricity production through solar energy. Accordingly, a large percentage of electrical energy still comes from the burning of fossil fuels and hydroelectric plants [19].

Solar energy, along with wind energy, is the main target of the current energy transition. Although not often taken into account until a few decades ago, it is now experiencing rapid growth: global solar PV capacity increased from 40 GW in 2010 to 580 GW in 2019 [20]. The credit goes to technological innovation, mainly in the materials science sector, which made solar PV facilities competitive, even from an economic point of view compared with fossil sources. Considering the information published by IRENA, the costs of photovoltaic energy production have dropped by 82% in the last decade. The prospects are even more encouraging: with new generation technologies, it will be feasible to increase the efficiency of PV panels by 30% compared with nowadays, and energy generation by more than 20% [20].

Solar energy using photovoltaic cells, which transform sunlight directly into electricity, can be incorporated into industries, houses, or city infrastructures [21]. A photovoltaic solar system transforms the radiant energy emitted by the sun into electrical energy using photovoltaic panels. These cells are made of silicon, a semiconductor element that generates small amounts of electrical energy when it receives a significant amount of radiation. Photovoltaic cells are the basic units and elements that form so-called photovoltaic modules or panels and photovoltaic fields [22]. A photovoltaic module or panel is made up of the union and interconnection of a defined number of cells, whose electrical arrangement in series or parallel will lead to the generation of a certain voltage measured in volts and a current intensity measured in amperes. In general, a photovoltaic cell generates a voltage of approximately 0.5 volts; therefore, the interconnection of 36 cells in series will generate about 18 volts (12 working volts) [23]. Today, at a commercial level, there are modules with 36, 60, and 72 cells whose interconnection will determine the working voltage of the module. Figure 2 shows a typical schematical view of a functioning solar photovoltaic facility.



**Figure 2.** Schematical view of a functioning solar photovoltaic (PV) facility. Adapted from [24].

According to Figure 2, the sun emits solar radiation, which is captured by the photovoltaic panels where said solar radiation is transformed into electrical energy through the flow of electrons generated in the photovoltaic cells. Then, the flow of electrons from the photovoltaic cells is conducted by cables as a direct current to a system called an

inverter or converter. In this system, the direct electrical current is transformed into an alternating electrical current [25]. Finally, the alternating electrical current is conducted to urban, industrial, or commercial areas through high-, medium-, and low-voltage electrical transmission networks.

Now, it is important to keep in mind that international organizations promote the use of clean technologies for energy generation such as solar facilities, and they invite countries to replace fossil energy sources or the generation of energy based on the burning of polluting elements [26].

### 1.3. Aim of the Article

Solar energy stands as an attractive alternative to cope with the effects of climate change in Peru, aligning with the United Nations Sustainable Development Goals (SDGs) outlined in the 2030 Agenda. This review studies the solar PV energy generation potential in the country. Additionally, the production of electricity from solar energy in the future is presented by studying a relevant portfolio of solar PV facilities, where an equivalent installed capacity of 7218 MW is projected to be carried out in 2028 (Figure 3).



**Figure 3.** Rubi solar photovoltaic facility, located in a desert landscape in Peru.

Furthermore, this article outlines the key advantages, benefits, and limitations associated with introducing solar energy facilities in Peru, focusing on (i) assessing the potential of the solar resource at hand, (ii) describing the current solar photovoltaic facilities, (iii) describing the portfolio of solar photovoltaic (PV) projects up to 2028, and (iv) analyzing the hybridization with other solar energy technologies. Additionally, recent advances, challenges, and prospects in the implementation of the clean-energy industry from solar sources are discussed.

This review contribution highlights the application of solar energy technologies in Peru to improve human livelihood and well-being, considering the negative impacts of the climate change crisis faced by society. In this sense, this review is relevant for scientists, economists, politicians, professionals, and communities, among others, being a database for future research and an example of applying actions for the mitigation of climate change by (i) publishing data on solar resource potential and the use of solar energy in Peru, (ii) describing actions carried out by Peru to promote the implementation of renewable

solar energy, (iii) showing the compromise and efforts of Peru to cope with the climate change crisis, and (iv) sharing practical experience in technical, social and environmental issues regarding the implementation of solar energy technologies to make a sustainable society, among others.

## 2. Potential of Solar Energy Resources in Peru

In Peru, the orographic, climatic, and oceanographic conditions, among other factors, determine the existence of three large natural regions: the coast, the Andes Mountains, and the jungle. The coast is the region limited by the Pacific Ocean and the Andean slopes below 2000 masl. The Andes Mountains are characterized by the presence of peaks and mountains with heights of 6768 masl. The jungle is a region formed by two zones, the Amazonian tropical forest or low jungle and the slopes and valleys to the east of the Andes below 2000 masl known as the high jungle [1].

The distribution of the solar resource primarily drives the geographical variability of the solar energy yield. The key characteristics of the solar resource are defined mainly by latitude, the presence of clouds, topography, shade, atmospheric aerosol concentration, and air moisture content [27].

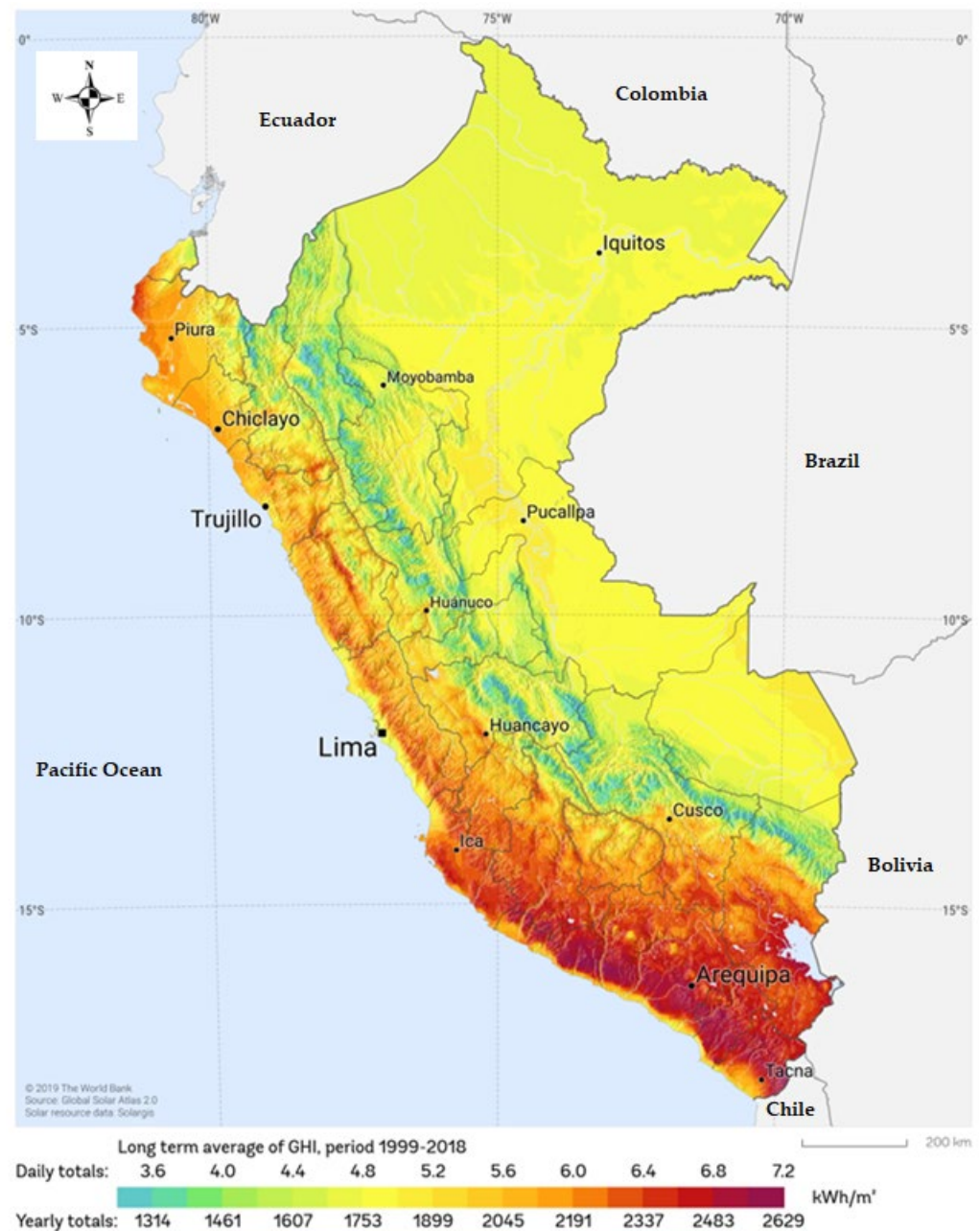
Considering annual variations, the area with the greatest solar energy potential in the Peruvian territory is mainly located on the southern coast ( $16^{\circ}$  to  $18^{\circ}$  S), where global horizontal irradiation (GHI) of 6.0 to 6.5 kWh/m<sup>2</sup>/day is available. Other areas in which high availability of daily solar energy is recorded, with global horizontal irradiation (GHI) of 5.5 to 6.0 kWh/m<sup>2</sup>/day, are the northern coast ( $3^{\circ}$  to  $8^{\circ}$  S) and a large part of the mountains above 2500 masl. In order of importance in terms of their surface area, these include the southern mountain range, the central mountain range, and the northern mountain range. The area with low solar energy values in the territory is the jungle, where values of global horizontal irradiation (GHI) of 4.5 to 5.0 kWh/m<sup>2</sup>/day are recorded, with an area of minimum values in the extreme north near the equator ( $0^{\circ}$  to  $2^{\circ}$  S) [28].

When explaining the distribution of solar energy in the Peruvian territory, we must take into account various factors that control the climate, such as the Andes mountain range, which shapes the orography of the Peruvian territory; the South Pacific Anticyclone, which produces great atmospheric stability owing to the presence of downward vertical movements in the middle troposphere; the South Atlantic Anticyclone, which provides humidity and feeds the south-east trade winds; the Peruvian cold current in the Pacific Ocean, which reinforces stability in the atmosphere; the Equatorial warm current (El Niño Southern Oscillation—ENSO), which destabilizes the atmosphere on the northern coast in the summer months; the Intertropical Convergence Zone, which generates very active cloud systems; and the Alta of Bolivia, which is associated with convective systems that tend to mainly affect the northern and central mountains and jungle of Peru [28].

In general terms, in the central and southern coast regions, high values of solar energy occur during the austral summer; however, it is necessary to detail some exceptions. In the coastal strip close to the coast, located below 600 masl, the behavior described above changes during late autumn, winter, and early spring, when this region shows markedly low levels of solar energy and constitutes an area of minima in the territory. At the end of spring, on the desert terraces of Arequipa, Moquegua, and Tacna ( $13.5^{\circ}$  to  $18^{\circ}$  S and  $70^{\circ}$  to  $76^{\circ}$  W) above 1000 masl, the highest annual values of solar energy of the Peruvian territory are reached. This is because they are located above the thermal inversion layer and have clear skies throughout the year. The northern coast, between  $3^{\circ}$  and  $6^{\circ}$  S and  $80^{\circ}$  to  $81^{\circ}$  W (the regions of Tumbes, Piura, and northern Lambayeque) also presents high values of solar energy during the austral summer; however, the maximum values of solar energy in October and November (spring) are also high in annual terms [28].

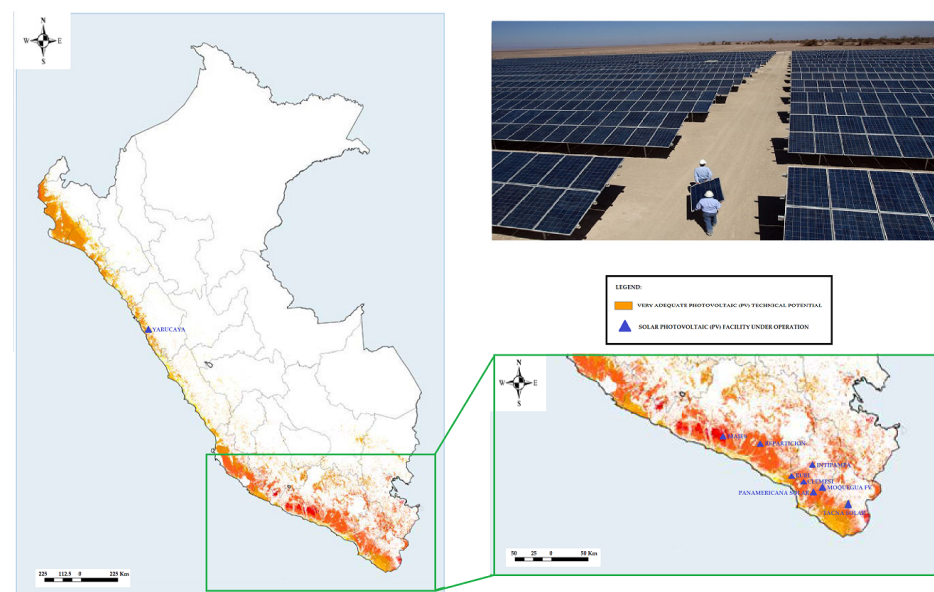
According to the map of solar energy presented in the Global Photovoltaic Power Potential by Country report generated by ESMAP [29], Peru has considerable and under-utilized solar potential. These conditions are mainly concentrated in the southern and northern parts of the country. Figure 4 shows the global horizontal irradiation (GHI) map

of Peru. The irradiance level is the most crucial parameter for calculating energy yield and evaluating the performance of flat-plate photovoltaic modules. It is also the most widely adopted technology in the field.



**Figure 4.** Solar resource map—Global Horizontal Irradiation (GHI) registered in Peru. Adapted from [29].

Currently, the country has nine solar photovoltaic facilities in operation (information correct as of March 2024). All these solar PV facilities are integrated into the SEIN. Eight are found in the southern regions of (i) Arequipa (Majes and Repartición), (ii) Moquegua (Moquegua FV, Intipampa, Rubi, Panamericana Solar, and Clemesi), and (iii) Tacna (Tacna Solar) [6] (Figure 5), and one is located close to the capital city of Peru, specifically in the Lima region (Yarucaya).

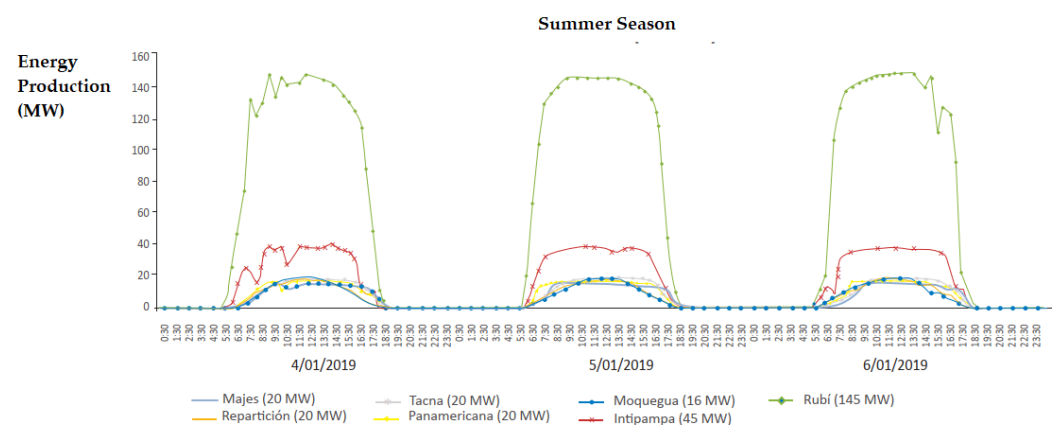


**Figure 5.** Maps of adequate solar photovoltaic (PV) technical potential in Peru. Adapted from [30].

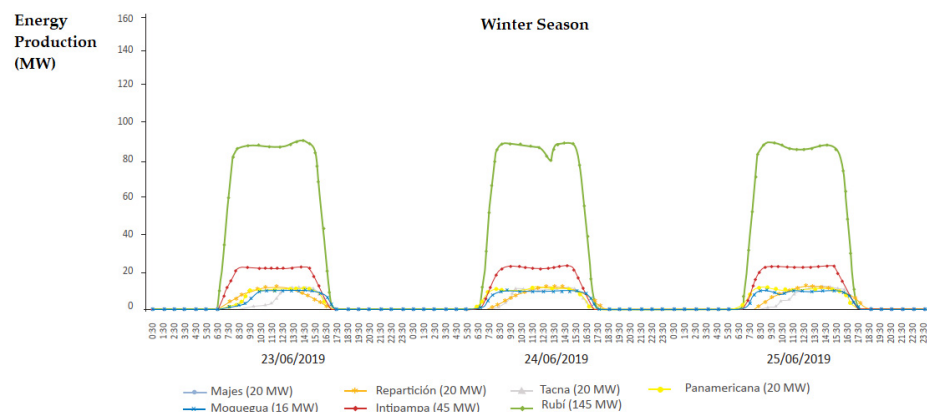
These geographical areas of Peru are characterized by an average daily solar irradiation of over 6.0 kWh/m<sup>2</sup>/day, as well as capacity factors between 22% and 35% [6]. This situation facilitates efficient energy transformation, which is particularly intensified during peak hours, thereby improving SEIN's economic commercial conditions.

The production of solar PV energy is conditioned to irradiation characteristics, which can fluctuate by season or be affected by the presence of clouds. However, solar PV facilities present a very similar hourly behavior, so the electricity generation increases accordingly [31]. Figures 6 and 7 show the average hourly solar PV energy generation pattern in Peru according to the annual seasonal period and some solar PV facilities under operation in the southern region of the country in 2019.

Figure 6 corresponding to the summer season shows the time of the day when the greatest amount of electrical energy is generated in solar photovoltaic facilities in Peru (between 5:30 a.m. and 6:30 p.m.). Also, Figure 7 corresponding to the winter season shows the hours of the day when the greatest amount of electrical energy is generated in solar photovoltaic facilities (between 6:30 a.m. and 5:30 p.m.).



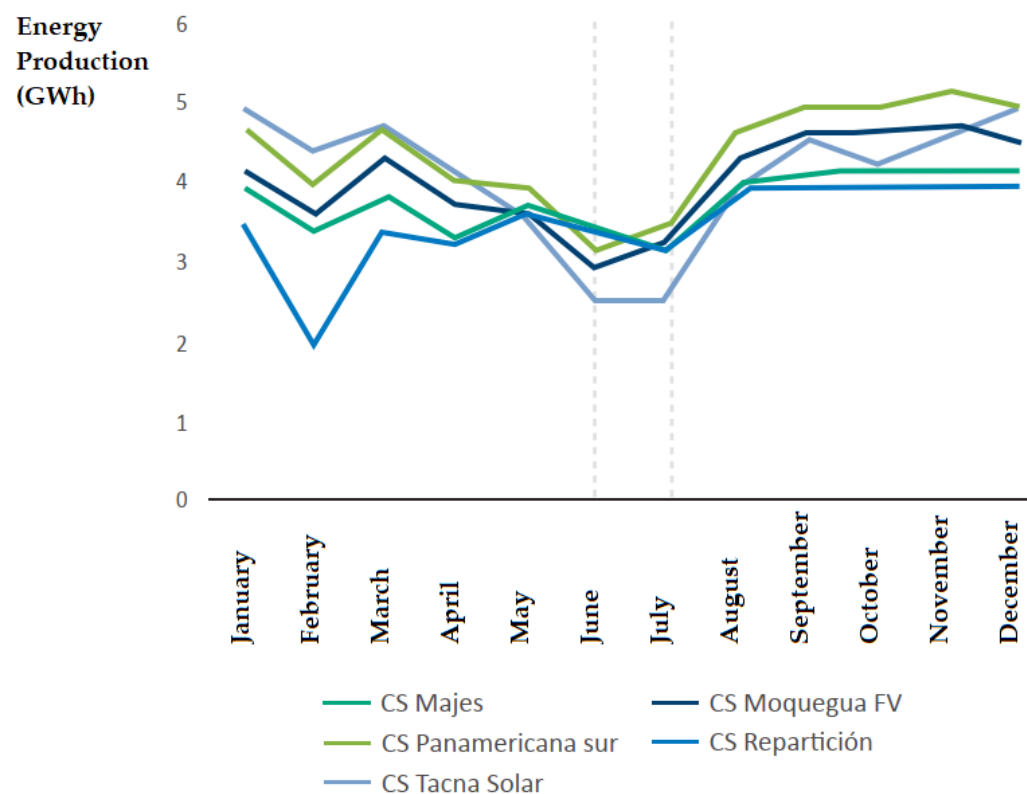
**Figure 6.** Average hourly solar energy generation registered during the summer season in Peru in 2019 [6].



**Figure 7.** Average hourly solar energy generation registered during the winter season in Peru in 2019 [6].

This behavior is a result of the reduced climatic instability in the southern region, which is attributed to the presence of aerosols and water vapor that create a dry climate with low cloud cover. Consequently, solar radiation remains stable for at least seven hours per day (in winter), facilitating consistent energy production between 8:30 a.m. and 01:30 p.m. Although electricity generation commences between 6:00 a.m. and 6:30 a.m., production continues until 06:00 p.m.

Moreover, seasonal variations can be observed based on the time of year. The winter season typically yields the lowest energy output, whereas the summer season has the highest energy generation. Specifically, the reduction in solar energy generation during the winter season can range from 30% to 50% compared with the summer months (See Figure 8).



**Figure 8.** Variation in energy production (GWh) during a year in some solar photovoltaic (PV) facilities in Peru [6].

All the solar PV facilities currently functioning are in the desert territory of Peru. In these locations, relevant amounts of solar irradiation are generated during much of the day (Figure 9). Overall, Peru's solar resources have been estimated at a useful potential of 25 GW, and only 2% of the potential has been used as of 2024.



**Figure 9.** Rubi solar photovoltaic facility located in a desert landscape in Peru.

The usable potential study considers the technical energy capacity and production of a specific technology given resource potential, device performance, terrain restrictions, ecosystem attributes, and land-use limitations. The information to be considered in the usable potential estimation includes [32]:

- Minimum resource constraints ( $4\text{--}5 \text{ kWh/m}^2/\text{day}$ ),
- Maximum allowable terrain slope ( $3\text{--}5\%$ ),
- Power density for a given technology ( $25\text{--}30 \text{ MW/km}^2$ ),
- Maximum distance to transmission lines (5 Km),
- Maximum distance to roads (5 Km), and
- Land exclusion types (agricultural, forest, urban, water bodies, wetlands, and environmentally protected areas).

The non-available land area in the southern region of Peru is likely restricted by steep topography and the distance to transmission lines and roads, while the land area in the Amazon region is likely restricted by land type (forest) and insolation values [33]. The useful solar energy technical potential for Peru is equivalent to 25,000 MW. Table 2 shows details of the geographical areas of the country with the greatest average solar energy, where values between  $4.00$  and  $7.00 \text{ kWh/m}^2/\text{day}$  are recorded.

**Table 2.** Geographical areas of Peru with the greatest average daily solar energy [6].

| Region   | Daily Solar Energy–Solar Irradiance ( $\text{kWh/m}^2/\text{day}$ ) |
|----------|---------------------------------------------------------------------|
| Arequipa | 5.2 min–7.0 max; Average 6.08                                       |
| Moquegua | 4.9 min–6.9 max; Average 6.04                                       |
| Tacna    | 5.2 min–7.0 max; Average 5.83                                       |
| Tumbes   | 4.0 min–6.1 max; Average 5.67                                       |
| Piura    | 4.8 min–6.4 max; Average 5.54                                       |
| Ica      | 5.3 min–6.7 max; Average 5.50                                       |

Table 2 shows that the geographical areas of the country with the greatest solar energy potential are Arequipa, Moquegua, Tacna, Tumbes, Piura, and Ica. They highlight the relevant potential of Arequipa, Moquegua, and Tacna, with an average solar radiation of  $250 \text{ W/m}^2$ . These regions are part of the Coast Desert of Peru, in which nine photovoltaic solar energy plants are in operation in 2024. Also noteworthy are the northern regions of the country (i.e., Tumbes and Piura and part of the Sechura desert), which, despite their attractive solar resources, have not been used to date. The Ica region also stands out for its

attributes of renewable wind and solar resources, with wind farms already in operation but no photovoltaic solar energy plants to date. Finally, the Lima region has one solar photovoltaic facility operating called Yarucaya, and it is expected that more solar energy projects will be constructed in this region.

### 3. Practical Experiences of Solar Photovoltaic Facilities Registered in Peru

Below, key data and practices of the development of solar photovoltaic facilities in Peru are presented in detail, including (i) facilities in the operational stage, (ii) facilities under construction, and (iii) projected solar PV facilities (under engineering phases and/or EIA studies).

#### 3.1. Solar PV Facilities in Operation

The following paragraphs present the solar PV facilities currently functioning in the country.

##### 3.1.1. Repartición Solar Photovoltaic Facility—Arequipa Region

The Repartición solar facility is a facility located in the district of La Joya in the province of Caylloma, Department of Arequipa, 555 km from the city of Lima at an elevation of 1187 masl. This solar complex began its construction phase in 2011 and came into operation in July 2012. The land area occupied by the solar facility is equivalent to 102 Ha. Figure 10 shows panoramic images of the solar facility, and Table 3 provides specifications of the infrastructure.



**Figure 10.** Landscape showing photovoltaic panels in the Repartición solar facility.

**Table 3.** Main characteristics of the Repartición solar photovoltaic facility [4].

| Specification            | Data                           | Units |
|--------------------------|--------------------------------|-------|
| Project Zone             | Arequipa Region                | -     |
| Energy Company           | GTS Repartición S.A.C. T-Solar | -     |
| Type of Solar Facility   | Photovoltaic                   | -     |
| Quantities of PV Modules | 58,000                         | -     |
| Module Type              | Polycrystalline silicon        | -     |
| Power of Modules         | 350                            | W     |
| Number of Inverters      | 32                             | -     |
| Type of Structure        | 1-axis horizontal tracker      | -     |
| Tracking Angle           | 45                             | °     |
| Installed Capacity       | 20                             | MW    |
| Capacity Factor          | 0.25                           | -     |

Figure 10 shows that the Repartición solar facility is in an area close to the coastal zone in a desert landscape where no contiguous communities are located.

As shown in Table 3, this solar facility has a total of 58,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 350 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 20 MW, considering a tracking angle for the photovoltaic panels equivalent to  $45^\circ$  with an estimated capacity factor of 0.25.

### 3.1.2. Majes Solar Photovoltaic Facility—Arequipa Region

This solar facility is in the department of Arequipa, province of Caylloma, in the district of Majes, 550 km from the city of Lima at 1680 masl. Construction began on this solar facility in 2011 and it came into operation in July 2012. The land area occupied by the solar facility is equivalent to 102 Ha. Figure 11 shows panoramic images of the solar facility, and Table 4 provides specifications of the infrastructure.



**Figure 11.** Landscape showing photovoltaic panels in the Majes solar facility.

**Table 4.** Main characteristics of the Majes solar photovoltaic facility [4].

| Specification            | Data                      | Units    |
|--------------------------|---------------------------|----------|
| Project Zone             | Arequipa Region           | -        |
| Energy Company           | GTS Majes S.A.C. T-Solar  | -        |
| Type of Solar Facility   | Photovoltaic              | -        |
| Quantities of PV Modules | 58,000                    | -        |
| Module Type              | Polycrystalline silicon   | -        |
| Power of Modules         | 350                       | W        |
| Number of Inverters      | 32                        | -        |
| Type of Structure        | 1-axis horizontal tracker | -        |
| Tracking Angle           | 45                        | $^\circ$ |
| Installed Capacity       | 20                        | MW       |
| Capacity Factor          | 0.26                      | -        |

Figure 11 shows that the Majes solar facility is in a desert area where there are no adjacent communities.

As shown in Table 4, this solar facility has a total of 58,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 350 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 20 MW, considering a tracking angle for the photovoltaic panels equivalent to  $45^\circ$  with an estimated capacity factor of 0.26.

### 3.1.3. Tacna Solar Photovoltaic Facility—Tacna Region

This solar facility is in the district of Tacna, province of Tacna, in the department of Tacna at 560 masl. Construction began on this solar facility in 2011 and it came into

operation in October 2012. The land area occupied by the solar facility is equivalent to 102 Ha. Figure 12 shows panoramic images of the solar facility, and Table 5 provides specifications of the infrastructure.



**Figure 12.** Landscape showing photovoltaic panels in the Tacna solar facility.

**Table 5.** Main characteristics of the Tacna solar photovoltaic facility [4].

| Specification            | Data                         | Units |
|--------------------------|------------------------------|-------|
| Project Zone             | Tacna Region                 | -     |
| Energy Company           | Tacna Solar S.A.C. Solarpack | -     |
| Type of Solar Facility   | Photovoltaic                 | -     |
| Quantities of PV Modules | 58,000                       | -     |
| Module Type              | Polycrystalline silicon      | -     |
| Power of Modules         | 350                          | W     |
| Number of Inverters      | 32                           | -     |
| Type of Structure        | 1-axis horizontal tracker    | -     |
| Tracking Angle           | 50                           | °     |
| Installed Capacity       | 20                           | MW    |
| Capacity Factor          | 0.30                         | -     |

Figure 12 shows that the Tacna Solar facility is in a desert area without adjacent communities.

As shown in Table 5, this solar facility has a total of 58,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 350 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 20 MW, considering a tracking angle for the photovoltaic panels equivalent to 50° with an estimated capacity factor of 0.30.

#### 3.1.4. Panamericana Solar Photovoltaic Facility—Moquegua Region

This solar facility is in the district of Moquegua, province of Mariscal Nieto, department of Moquegua at 1410 masl. The construction phase began in 2011 and the facility came into operation in December 2012. The land area occupied by the solar facility is equivalent to 123 Ha. Figure 13 shows panoramic images of the solar facility, and Table 6 provides specifications of the infrastructure.

Figure 13 shows that Panamericana solar facility is located in a desert area where there are no adjacent communities.

As shown in Table 6, this solar facility has a total of 58,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 350 W, which, considering all the photovoltaic modules, means that the solar facility has an installed

capacity equivalent to 20 MW, considering a tracking angle for the photovoltaic panels equivalent to  $55^\circ$  with an estimated capacity factor of 0.33.



**Figure 13.** Landscape showing photovoltaic panels in the Panamericana solar facility.

**Table 6.** Main characteristics of the Panamericana solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Panamericana Solar S.A.C. | -     |
| Type of Solar Facility   | Solarpack                 | -     |
| Quantities of PV Modules | Photovoltaic              | -     |
| Module Type              | 58,000                    | -     |
| Power of Modules         | Polycrystalline silicon   | -     |
| Number of Inverters      | 350                       | W     |
| Type of Structure        | 32                        | -     |
| Tracking Angle           | 1-axis horizontal tracker | -     |
| Installed Capacity       | 55                        | °     |
| Capacity Factor          | 20                        | MW    |
|                          | 0.33                      | -     |

### 3.1.5. Moquegua FV Solar Photovoltaic Facility—Moquegua Region

The Moquegua FV solar facility is in the district of Moquegua, province of Mariscal Nieto, department of Moquegua. Construction began on this solar facility in 2013 and it came into operation in December 2014. The land area occupied by the solar facility is equivalent to 134 Ha. Figure 14 shows panoramic images of the solar facility, and Table 7 provides specifications of the infrastructure.



**Figure 14.** Landscape showing photovoltaic panels in the Moquegua FV solar facility.

**Table 7.** Main characteristics of the Moquegua FV solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Moquegua FV S.A.C.        | -     |
| Type of Solar Facility   | Solarpack                 | -     |
| Quantities of PV Modules | Photovoltaic              | -     |
| Module Type              | 58,000                    | -     |
| Power of Modules         | Polycrystalline silicon   | -     |
| Number of Inverters      | 280                       | W     |
| Type of Structure        | 26                        | -     |
| Tracking Angle           | 1-axis horizontal tracker | -     |
| Installed Capacity       | 55                        | °     |
| Capacity Factor          | 16                        | MW    |
|                          | 0.34                      | -     |

Figure 14 shows that the Moquegua FV solar photovoltaic facility is in a desert area with no communities around it.

As shown in Table 7, this solar facility has a total of 58,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 280 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 16 MW, considering a tracking angle for the photovoltaic panels equivalent to 55° with an estimated capacity factor of 0.34.

### 3.1.6. Intipampa Solar Photovoltaic Facility—Moquegua Region

The Intipampa solar facility is in the district of Moquegua, province of Mariscal Nieto, department of Moquegua, approximately 700 km from the city of Lima near the Panamericana Sur highway at 1410 masl.

The Intipampa solar facility came into operation in March 2018, and Engie Energía Perú S.A. began construction in January 2017. The land area occupied by the solar facility is equivalent to 322 Ha. Figure 15 shows panoramic images of the solar photovoltaic facility, and Table 8 provides specifications of the infrastructure.

**Figure 15.** Landscape showing photovoltaic panels in the Intipampa solar facility.

Figure 15 shows that the Intipampa solar photovoltaic facility is in a desert area where there are no adjacent communities.

As shown in Table 8, this solar facility has a total of 125,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 325 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 40 MW, considering a tracking angle for the photovoltaic panels equivalent to 55° with an estimated capacity factor of 0.27.

**Table 8.** Main characteristics of the Intipampa solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Engie Energía Perú S.A.   | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 125,000                   | -     |
| Module Type              | Polycrystalline silicon   | -     |
| Power of Modules         | 325                       | W     |
| Number of Inverters      | 18                        | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 55                        | °     |
| Installed Capacity       | 40                        | MW    |
| Capacity Factor          | 0.27                      | -     |

### 3.1.7. Rubi Solar Photovoltaic Facility—Moquegua Region

The Rubi solar photovoltaic facility is in the district of Moquegua, province of Mariscal Nieto, department of Moquegua, at 1410 masl. Construction began on this solar facility in 2017 and it came into operation in 2018. The land area occupied by the solar facility is equivalent to 400 Ha. Figure 16 shows panoramic images of the solar facility, and Table 9 provides specifications of the infrastructure.

**Figure 16.** Landscape showing photovoltaic panels in the Rubi solar facility.**Table 9.** Main characteristics of the Rubi solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Enel Green Perú S.A.      | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 450,000                   | -     |
| Module Type              | Polycrystalline silicon   | -     |
| Power of Modules         | 320                       | W     |
| Number of Inverters      | 164                       | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 45                        | °     |
| Installed Capacity       | 144                       | MW    |
| Capacity Factor          | 0.35                      | -     |

Figure 16 shows that the Rubi solar photovoltaic facility is in a desert area where there are no contiguous communities.

As shown in Table 9, this solar facility has a total of 450,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 320 W, which,

considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 144 MW, considering a tracking angle for the photovoltaic panels equivalent to  $45^\circ$  with an estimated capacity factor of 0.35.

### 3.1.8. Clemesi Solar Photovoltaic Facility—Moquegua Region

The Clemesi solar photovoltaic facility is in the district of Moquegua, province of Mariscal Nieto, department of Moquegua, at 1503 masl. Construction began on this solar facility in 2021 and it came into operation in 2023. The land area occupied by the solar facility is equivalent to 300 Ha. Figure 17 shows panoramic images of the solar facility, and Table 10 provides specifications of the infrastructure.



**Figure 17.** Landscape showing photovoltaic panels in the Clemesi solar facility.

**Table 10.** Main characteristics of the Clemesi solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Enel Green Perú S.A.      | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 221,000                   | -     |
| Module Type              | Monocrystalline silicon   | -     |
| Power of Modules         | 525                       | W     |
| Number of Inverters      | 132                       | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 50                        | °     |
| Installed Capacity       | 116.45                    | MW    |
| Capacity Factor          | 0.35                      | -     |

Figure 17 shows that the Rubi solar photovoltaic facility is in a desert area where there are no contiguous communities.

As shown in Table 10, this solar facility has a total of 221,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 525 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 116.45 MW, considering a tracking angle for the photovoltaic panels equivalent to  $50^\circ$  with an estimated capacity factor of 0.35.

### 3.1.9. Yarucaya Solar Photovoltaic Facility—Lima Region

The Yarucaya solar photovoltaic facility is in the district of Sayan, province of Huaura, department of Lima, at 1031 masl. Construction began on this solar facility in 2020 and it came into operation in 2021. The land area occupied by the solar facility is equivalent to 3.3 Ha. Figure 18 shows panoramic images of the solar facility, and Table 11 provides specifications of the infrastructure.



**Figure 18.** Landscape showing photovoltaic panels in the Yarucaya solar facility.

**Table 11.** Main characteristics of the Yarucaya solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Lima Region               | -     |
| Energy Company           | Colca Solar S.A.C.        | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 3070                      | -     |
| Module Type              | Polycrystalline silicon   | -     |
| Power of Modules         | 530                       | W     |
| Number of Inverters      | 7                         | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 45                        | °     |
| Installed Capacity       | 1.62                      | MW    |
| Capacity Factor          | 0.22                      | -     |

Figure 18 shows that the Yarucaya solar photovoltaic facility is in a valley area where there are some communities.

As shown in Table 11, this solar facility has a total of 3070 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules is 350 W, which, considering all the photovoltaic modules, means that the solar facility has an installed capacity equivalent to 1.62 MW, considering a tracking angle for the photovoltaic panels equivalent to 45° with an estimated capacity factor of 0.22.

### 3.1.10. Summary of the Total Installed Capacity of Solar Photovoltaic Energy in 2024

Table 12 shows the key specifications of the solar PV facilities functioning in Peru, showing the capacity of the solar PV energy infrastructure, and Figure 19 shows the percentage of electrical energy generated by solar PV facilities in Peru.

**Table 12.** Solar photovoltaic facilities functioning in Peru as of March 2024.

| #                               | Name of Solar Photovoltaic Facility | Region   | Energy Company                      | Installed Capacity (MW) |
|---------------------------------|-------------------------------------|----------|-------------------------------------|-------------------------|
| 1                               | Central Solar Repartición           | Arequipa | GTS Repartición S.A.C. T-Solar      | 20                      |
| 2                               | Central Solar Majes                 | Arequipa | GTS Majes S.A.C. T-Solar            | 20                      |
| 3                               | Central Solar Tacna Solar           | Tacna    | Tacna Solar S.A.C. Solarpack        | 20                      |
| 4                               | Central Solar Panamericana Solar    | Moquegua | Panamericana Solar S.A.C. Solarpack | 20                      |
| 5                               | Central Solar Moquegua FV           | Moquegua | Moquegua FV S.A.C. Solarpack        | 16                      |
| 6                               | Central Solar Intipampa             | Moquegua | Engie Energía Perú S.A.             | 40                      |
| 7                               | Central Solar Rubi                  | Moquegua | Enel Green Power Perú S.A.          | 144                     |
| 8                               | Central Solar Clemesi               | Moquegua | Enel Green Power Perú S.A.          | 116.45                  |
| 9                               | Central Solar Yarucaya              | Lima     | Colca Solar S.A.C.                  | 1.62                    |
| <b>Total Installed Capacity</b> |                                     |          |                                     | <b>398.07</b>           |

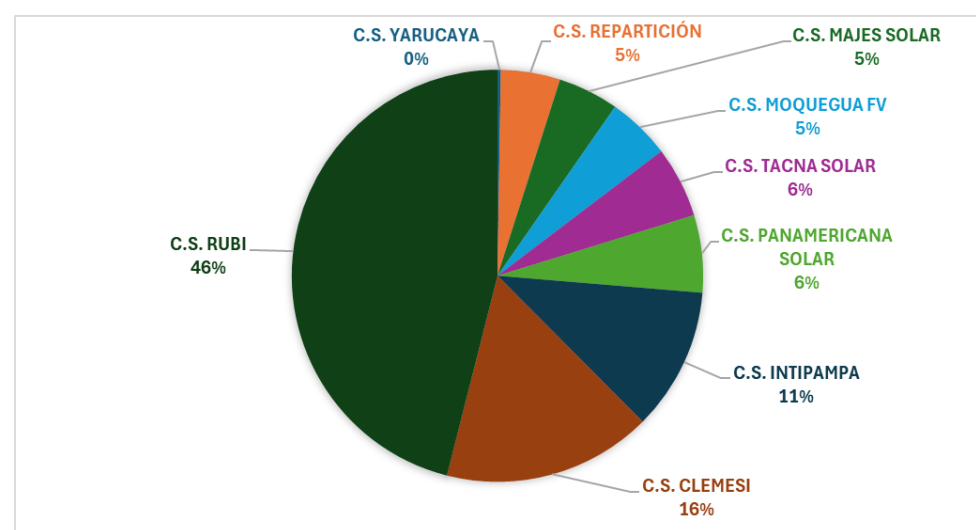
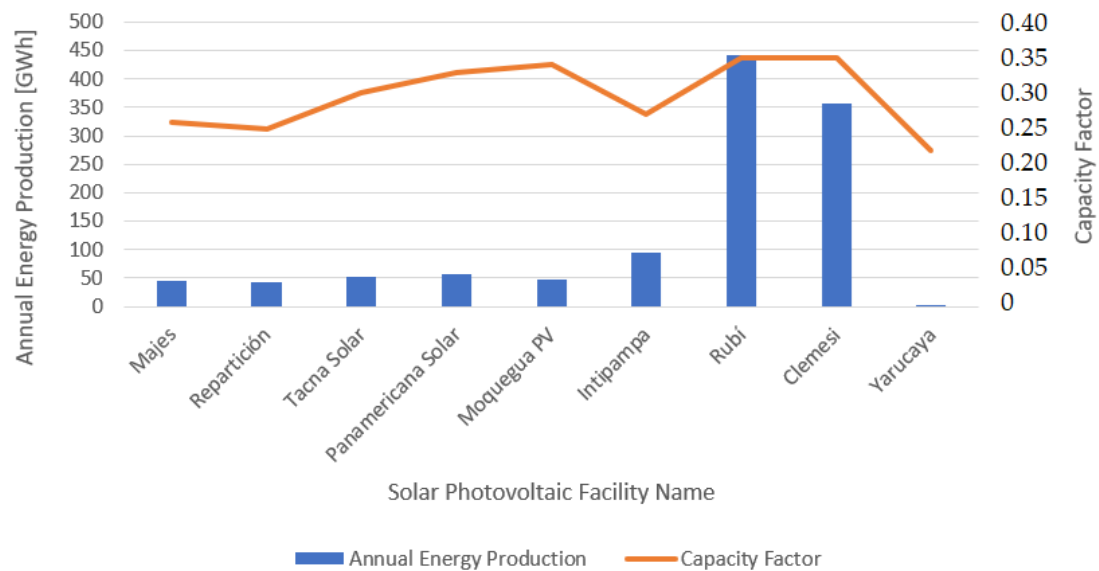
**Figure 19.** Percentage of electrical energy generated by solar photovoltaic facility sources in Peru.

Table 12 shows that, as of March 2024, there is a total of nine solar photovoltaic facilities in operation in Peru. In addition, it is possible to see that five solar photovoltaic facilities are in the southern part of Peru in the Moquegua region, while another two solar photovoltaic facilities are located in the Arequipa region, one solar photovoltaic facility is in the Tacna region, and one solar photovoltaic facility is in Lima region. It is observed that the solar photovoltaic facility with the lowest energy-generation capacity is Central Solar Yarucaya with 1.62 MW, while the Central Solar Rubi is the facility with the highest energy-generation capacity at 144 MW. Figure 19 shows the percentage of electrical energy generated by solar photovoltaic facility sources in Peru, with 46% of the total installed capacity corresponding to Central Solar Rubi. Finally, for the nine solar photovoltaic facilities in operation, the total installed capacity is 398.07 MW. The installed capacity as of 2024 is equivalent to 2% of the useful solar potential of 25 GW.

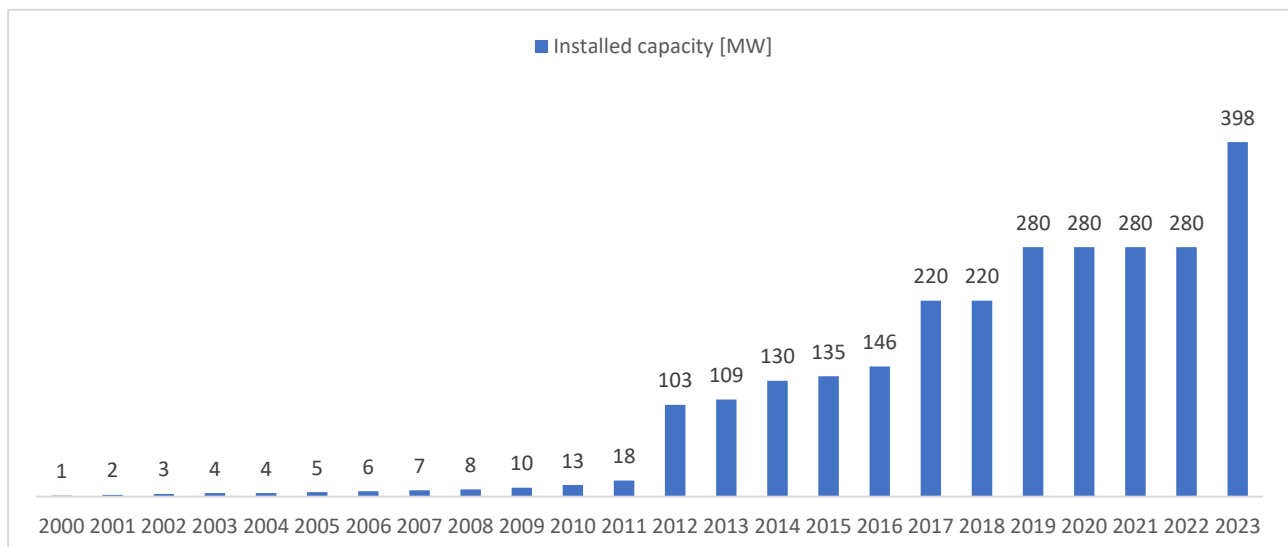
Figure 20 summarizes the quantity of annual energy produced in GWh and the capacity factor of each solar PV facility that is functioning in the country.

Figure 20 shows that the solar photovoltaic facility that produces the greatest amount of annual energy is Central Solar Rubi with approximately 441.5 GWh, while the Central Solar Yarucaya produces the least annual energy with 3.1 GWh. This is due to the power installed in each solar facility. Additionally, the capacity factors fluctuate in a range between 0.22 for Central Solar Yarucaya and 0.35 for Central Solar Clemesi and Central Solar Rubi.

Finally, Figure 21 shows the development over time of the installed capacity in MW of solar PV energy in Peru.



**Figure 20.** Annual energy production and capacity factor of solar photovoltaic facilities in Peru.



**Figure 21.** Evolution (years) of the solar photovoltaic installed capacity (MW) in Peru.

Figure 21 shows that the first stage of solar PV energy in the country began in 2012, with strong growth from 2012 to 2023.

### 3.2. Solar PV Facilities Approved and under Construction in 2024

The following paragraphs provide details on solar photovoltaic facilities with an approved EIA study that are under construction in 2024.

#### 3.2.1. San Martin Solar Photovoltaic Facility—Arequipa Region

The new San Martin solar photovoltaic facility is in the district of La Joya, province of Arequipa, department of Arequipa, at 1350 masl. Construction began on this solar facility in 2023 and it will come into operation in 2025. The land area occupied by the solar facility will be equivalent to 550 Ha. Figure 22 shows a typical image of the solar facility, and Table 13 provides specifications of this renewable energy facility.

Table 13 shows that this solar facility will have a total of 1,000,000 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules will be 300 W, which, taking into account all the photovoltaic modules, means that the solar facility

will have an installed capacity equivalent to 300 MW, considering a tracking angle for the photovoltaic panels equivalent to  $50^\circ$  with an estimated capacity factor of 0.40. This solar energy facility will generate 1000 GWh of electricity annually for the SEIN.



**Figure 22.** Landscape showing the San Martin solar photovoltaic facility under construction.

**Table 13.** Main characteristics of the San Martin solar photovoltaic facility [4].

| Specification            | Data                      | Units    |
|--------------------------|---------------------------|----------|
| Project Zone             | Moquegua Region           | -        |
| Energy Company           | Kallpa Generación S.A.C.  | -        |
| Type of Solar Facility   | Photovoltaic              | -        |
| Quantities of PV Modules | 1,000,000                 | -        |
| Module Type              | Polycrystalline silicon   | -        |
| Power of Modules         | 300                       | W        |
| Number of Inverters      | 150                       | -        |
| Type of Structure        | 1-axis horizontal tracker | -        |
| Tracking Angle           | 50                        | $^\circ$ |
| Installed Capacity       | 300                       | MW       |
| Capacity Factor          | 0.40                      | -        |

### 3.2.2. Lupi Solar Photovoltaic Facility—Moquegua Region

The new Lupi solar photovoltaic facility will be in the district of Carumas, province of Mariscal Nieto, department of Moquegua, at 4500 masl. This will be one of the highest-altitude photovoltaic solar energy projects in the world. Construction on this solar facility will begin in 2024 and it will come into operation in 2025. The land area occupied by the solar facility will be equivalent to 275 Ha. Figure 23 shows a typical image of the solar facility, and Table 14 provides specifications of the infrastructure.



**Figure 23.** Landscape showing the Lupi solar photovoltaic facility under construction.

**Table 14.** Main characteristics of the Lupi solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Moquegua Region           | -     |
| Energy Company           | Statkraft Perú S.A.C.     | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 470,000                   | -     |
| Module Type              | Crystalline silicon       | -     |
| Power of Modules         | 320                       | W     |
| Number of Inverters      | 68                        | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 45                        | °     |
| Installed Capacity       | 150                       | MW    |
| Capacity Factor          | 0.32                      | -     |

Table 14 shows that this solar facility will have a total of 470,000 photovoltaic modules of crystalline silicon. Furthermore, the power of the photovoltaic modules will be 320 W, which, considering all the photovoltaic modules, means that the solar facility will have an installed capacity equivalent to 150 MW, considering a tracking angle for the photovoltaic panels equivalent to 45° with an estimated capacity factor of 0.32. This solar energy facility is expected to generate 420 GWh of electricity annually for the SEIN.

### 3.2.3. Matarani Solar Photovoltaic Facility—Arequipa Region

The new Matarani solar photovoltaic facility will be in the district of Mollendo, province of Islay, department of Arequipa, at 500 masl. Construction began on this solar facility in 2023 and it will come into operation in 2024. The land area occupied by the solar facility will be equivalent to 130 Ha. Figure 24 shows a typical image of the solar facility, and Table 15 provides specifications of the infrastructure.

**Figure 24.** Landscape showing the Matarani solar photovoltaic facility under construction.

Table 15 shows that this solar facility will have a total of 123,500 photovoltaic modules of polycrystalline silicon. Furthermore, the power of the photovoltaic modules will be 650 W, which, considering all the photovoltaic modules, means that the solar facility will have an installed capacity equivalent to 80 MW, considering a tracking angle for the photovoltaic panels equivalent to 40° with an estimated capacity factor of 0.35. This solar energy facility will generate 245 GWh of electricity annually for the SEIN.

**Table 15.** Main characteristics of the Matarani solar photovoltaic facility [4].

| Specification            | Data                      | Units |
|--------------------------|---------------------------|-------|
| Project Zone             | Arequipa Region           | -     |
| Energy Company           | Yinson Renewables S.A.C.  | -     |
| Type of Solar Facility   | Photovoltaic              | -     |
| Quantities of PV Modules | 123,500                   | -     |
| Module Type              | Polycrystalline silicon   | -     |
| Power of Modules         | 650                       | W     |
| Number of Inverters      | 56                        | -     |
| Type of Structure        | 1-axis horizontal tracker | -     |
| Tracking Angle           | 40                        | °     |
| Installed Capacity       | 80                        | MW    |
| Capacity Factor          | 0.35                      | -     |

### 3.2.4. Summary of the Total Installed Capacity of Solar Photovoltaic Energy under Construction in 2024

Table 16 shows the key specifications of the solar PV facilities under construction in the country in 2024, indicating the installed capacity of each solar facility and the total installed capacity of solar PV energy.

**Table 16.** Solar photovoltaic facilities under construction in Peru as of March 2024 [34].

| # | Name of Solar Photovoltaic Facility | Region   | Energy Company                  | Installed Capacity (MW) |
|---|-------------------------------------|----------|---------------------------------|-------------------------|
| 1 | Central Solar San Martin            | Arequipa | Kallpa Generación S.A.C.        | 300                     |
| 2 | Central Solar Lupi                  | Moquegua | Statkraft Perú S.A.C.           | 150                     |
| 3 | Central Solar Matarani              | Arequipa | Yinson Renewables S.A.C.        | 80                      |
|   |                                     |          | <b>Total Projected Capacity</b> | <b>530</b>              |

Table 16 shows that by the end of 2024, there will be three solar photovoltaic facilities under construction in Peru. Furthermore, all facilities will be in the regions of Moquegua and Arequipa. It is observed that one of the new solar photovoltaic facilities is large, considering the existing facilities currently in operation, with an installed capacity of over 300 MW. Finally, considering the three new solar photovoltaic facilities in construction as of March 2024, the total projected installed capacity is equivalent to 530 MW.

### 3.3. Solar PV Facilities for the Future—Under Engineering Phase and EIA Study Processing

The COES has projected an income of 7218 MW from solar photovoltaic facilities by the year 2028 [4]. Table 17 shows the specifications of the solar PV facilities projected in Peru for the period 2024–2028 that are currently under engineering studies and processing of EIA studies.

**Table 17.** Solar photovoltaic facilities in Peru projected for the period 2024–2028 [4].

| # | Name of Solar Photovoltaic Facility | Region   | Energy Company                           | Installed Capacity (MW) |
|---|-------------------------------------|----------|------------------------------------------|-------------------------|
| 1 | Central Solar Continua Pichu Pichu  | Arequipa | CSF Continua Pichu Pichu S.A.C.          | 60                      |
| 2 | Central Solar Continua Chachani     | Arequipa | CSF Continua Chachani S.A.C.             | 100                     |
| 3 | Central Solar Continua Misti        | Arequipa | CSF Continua Misti S.A.C.                | 300                     |
| 4 | Central Solar Alto de Alianza I     | Tacna    | Atria Energía S.A.C.                     | 300                     |
| 5 | Central Solar Alto de Alianza II    | Moquegua | Atria Energía S.A.C.                     | 300                     |
| 6 | Central Solar Sunilo                | Moquegua | Enel Green Power Perú S.A.               | 120                     |
| 7 | Central Solar Yuramayo              | Arequipa | Empresa de Generación Eléctrica Yuramayo | 245                     |
| 8 | Central Solar Huarajone             | Puno     | Continua Energía Positivas S.A.C.        | 200                     |
| 9 | Central Solar Illa                  | Arequipa | Energía Renovable La Joya S.A.           | 385                     |

Table 17. Cont.

| #                               | Name of Solar Photovoltaic Facility | Region   | Energy Company             | Installed Capacity (MW) |
|---------------------------------|-------------------------------------|----------|----------------------------|-------------------------|
| 10                              | Central Solar Santa Isabel I        | Tacna    | Prodiel Perú S.A.          | 100                     |
| 11                              | Central Solar Santa Isabel II       | Tacna    | Prodiel Perú S.A.          | 100                     |
| 12                              | Central Solar Illari Norte          | Arequipa | Enel Green Power Perú S.A. | 112                     |
| 13                              | Central Solar Illari Sur            | Arequipa | Enel Green Power Perú S.A. | 312                     |
| 14                              | Central Solar Solimana              | Arequipa | Celepsa                    | 250                     |
| 15                              | Central Solar Sunny                 | Arequipa | Kallpa Generación          | 204                     |
| 16                              | Central Solar Sol de Verano I       | Arequipa | Majes Sol de Verano S.A.C. | 45                      |
| 17                              | Central Solar Sol de Verano II      | Puno     | Verano Capital Perú S.A.C. | 93                      |
| 18                              | Central Solar Sol de Verano III     | Arequipa | Verano Capital Perú S.A.C. | 600                     |
| 19                              | Central Solar Ruta del Sol          | Moquegua | Enel Green Power Perú S.A. | 308                     |
| 20                              | Central Solar Ruphay                | Arequipa | Engie Energía Perú S.A.    | 93                      |
| 21                              | Central Solar Hanaqpampa            | Moquegua | Engie Energía Perú S.A.    | 300                     |
| 22                              | Central Solar El Alto               | Moquegua | Blaud Energy Perú S.A.C.   | 76                      |
| 23                              | Central Solar La Bandera            | Tacna    | Blaud Energy Perú S.A.C.   | 120                     |
| 24                              | Central Solar Sol de Talara         | Piura    | Lader Energy Chile SPA     | 200                     |
| 25                              | Central Solar Windica               | Ica      | Fener Perú S.A.            | 25                      |
| 26                              | Central Solar Sol de Los Andes      | Arequipa | Lader Energy Chile SPA     | 250                     |
| 27                              | Central Solar Chalhuanca            | Arequipa | Tre Perú S.A.C.            | 106                     |
| 28                              | Central Solar Alba Solar            | Arequipa | Ignis Partners S.L.        | 200                     |
| 29                              | Central Solar Coral                 | Moquegua | Ignis Partners S.L.        | 403                     |
| 30                              | Central Solar Sumac Nina I          | Arequipa | Enel Green Power Perú S.A. | 447                     |
| 31                              | Central Solar Rubi V Fase I         | Moquegua | Enel Green Power Perú S.A. | 332                     |
| 32                              | Central Solar Rubi V Fase II        | Moquegua | Enel Green Power Perú S.A. | 332                     |
| 33                              | Central Solar Blanca Solar          | Arequipa | Ignis Partners S.L.        | 200                     |
| <b>Total Projected Capacity</b> |                                     |          |                            | <b>7218</b>             |

Table 17 shows that there is a total of 33 solar photovoltaic facility projects planned to be executed in Peru between 2024 and 2028. Furthermore, it is possible to see that the projects are in the northern zone (Piura) and southern zone (Ica, Tacna, Moquegua, Puno and Arequipa) of Peru. It is observed that the solar photovoltaic facility project with the lowest expected energy-generation capacity is the Central Solar Windica at 25 MW, while the Central Solar Sol de Verano III project is the solar photovoltaic facility with the highest expected energy-generation capacity at 600 MW. Finally, considering the 33 solar energy projects, the total projected installed capacity is equivalent to 7218 MW.

#### 4. Discussion

##### 4.1. Registered Progress

##### 4.1.1. Potentialities and Limitations of Solar Photovoltaic (PV) Energy in Peru

Solar PV energy advances on a large scale have already been carried out in Peru, as they are environmentally friendly and an attractive option to apply in different geographical locations with solar resource potentialities. In terms of the knowledge acquired about solar energy projects in Peru since 2012, the key potentialities and limitations are shown in Table 18.

The key potentialities shown in Table 18 indicate that the ecosystem damage to land from this clean-energy source is limited. It is also shown that its functioning is not complex to implement, and it also produces a large number of jobs, mainly during the construction process. Some limitations are observed, considering that it is a fluctuating energy technology, restricted to hours of daylight, and it cannot be applied in lands of heritage, protected environmental zones, and/or archaeological areas.

Table 18 above shows the main benefits offered by solar energy. However, its implementation also imposes challenges that must be faced. The main challenges are unavailability (or intermittency), its large-scale integration, and the impact it can have on the rates paid by users.

**Table 18.** Potentialities and limitations of solar photovoltaic facilities according to the knowledge acquired in Peru.

| Potentialities                                                                                                                                                                                                                                                                                                                                                                                                                                               | Limitations                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>Solar energy is an excellent clean-energy source because there is no air pollution when used.</li> <li>Peru has high solar radiation due to its geographical location, with close to 25 GW of usable power.</li> <li>The areas of greatest solar radiation coincide with areas with a main electrical network of 550 kV, 220 kV, and 138 kV, which allows the extraction of energy from the southern area.</li> </ul> | <ul style="list-style-type: none"> <li>Large industrial-scale solar PV projects can require large areas of land (hectares).</li> <li>The initial investment costs (CAPEX) for the installation of photovoltaic solar energy can be high compared with other alternatives.</li> <li>In some places, like the north of Peru, solar radiation does not have the intensity or is not sufficiently constant throughout the year, for example, due to the presence of clouds; therefore, a permanent flow of energy may not always be provided.</li> </ul> |
| <ul style="list-style-type: none"> <li>Solar energy is a practically unlimited renewable resource. The average daily solar window in Peru is between 9 and 11 h a day, which allows for steady electricity production from 6:00 a.m. to 5:00 p.m.</li> <li>It generates a large number of jobs, mainly in the construction process.</li> </ul>                                                                                                               | <ul style="list-style-type: none"> <li>The places where there is the greatest radiation are deserts and remote places, where it is difficult to harness the energy to develop agricultural or industrial activity.</li> <li>Solar photovoltaic (PV) energy can be stored, but it may be costly. Nowadays, there are several methods to store solar photovoltaic (PV) energy ranging from lithium batteries to pumped hydro.</li> </ul>                                                                                                               |
| <ul style="list-style-type: none"> <li>It has a low exploitation or OPEX. The only cost linked with the implementation of solar energy is the cost of manufacturing the components and installation. After the CAPEX there are no other costs linked with its use. The reduction of LCOE from 2010 (\$USD 212 MWh) to 2018 (\$USD 48 MWh) allowed rapid implementation in the SEIN.</li> </ul>                                                               | <ul style="list-style-type: none"> <li>Sometimes, owing the El Niño Southern Oscillation (ENSO), it is not possible to generate power during 9 or 11 h because of the microclimates and it is only feasible for 7 or 8 h of the day on average.</li> <li>The photovoltaic industry (manufacturing) requires certain processes that can have negative environmental impacts, such as the emission of greenhouse gases (GHG) and waste generation.</li> </ul>                                                                                          |
| <ul style="list-style-type: none"> <li>Photovoltaic power systems are designed to be flexible and expandable.</li> </ul>                                                                                                                                                                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>Dirty photovoltaic panels due to dust storms that occur in the desert landscape reduce energy production by up to 8%.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                              |
| <ul style="list-style-type: none"> <li>Photovoltaic solar energy can be implemented in remote places such as deserts.</li> <li>The operation of photovoltaic solar energy facilities does not generate noise.</li> <li>Photovoltaic solar energy can be easily hybridized with other technologies.</li> </ul>                                                                                                                                                | <ul style="list-style-type: none"> <li>Although solar photovoltaic (PV) systems can have storage systems, the BESS technology, due to its high cost, reduced or non-existent technical regulations for connection in the SEIN, and variations in marginal costs in the spot market, makes them unviable in Peru in the medium term.</li> </ul>                                                                                                                                                                                                       |

An obvious disadvantage of solar energy is that its supply is intermittent. Photovoltaic cells do not work during the night, although most electricity is demanded in daylight hours when sunlight is intense, and they are less effective when clouds are present.

Intermittency is defined as the unplanned unavailability or interruption of electricity generation from some renewable energy sources such as wind and solar, which, by definition, fluctuate. Solar energy's intermittency depends on the radiation level in a certain geographical area. It generally has a diurnal and seasonal pattern, that is, it reaches greater intensity during the day and in summer. Furthermore, seasonal intermittency is greater the further away you are from the equator. Diurnal and seasonal patterns provide some predictability in solar generation; however, radiation can be affected by other weather conditions that are difficult to predict, such as cloud cover and the composition of the atmosphere. Thus, a thick cloud layer can absorb available solar radiation, thereby decreasing energy production [35].

The operation of the current nine solar PV facilities conforms to the support of future solar energy investments to be implemented in Peru. The knowledge acquired to date has allowed construction companies to work in an environmentally friendly way during the implementation of solar energy projects. Experience has also been acquired in environmental impact assessment (EIA) studies and acquiring socio-environmental licenses for operation.

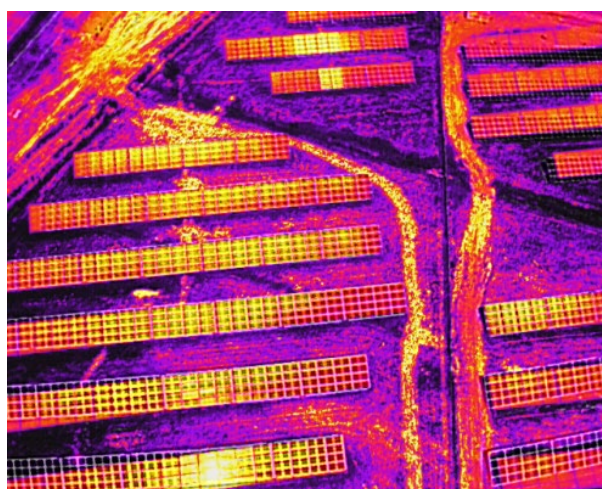
The advances in solar energy in Peru are helping the clean transformation of the energy matrix; however, its application is still in the early stages despite the enormous potential available [36].

#### 4.1.2. New Technologies Applied to Solar Photovoltaic (PV) Energy Projects in Peru

Solar facilities are optimizing their photovoltaic panel inspection processes with the help of drones, especially those located in places where high solar radiation makes manual field surveys even more difficult for personnel. The integration of drones allows solar energy facility operators to decrease surveys by 70% compared with conventional human techniques. Traditional surveys of photovoltaic solar facilities entail the review of panels one by one with the human use of a laser temperature device. After identifying faults in solar panel arrays, field workers register the positions of the panels for repair or replacement. Considering the large scale of these solar photovoltaic facilities, these conventional techniques are inefficient for operation and maintenance field operators.

The use of technological advances in the Industry 4.0 paradigm, such as the integration of drones, also known as unmanned aerial vehicles (UAVs), increases the efficiency and precision of inspections of photovoltaic panels in solar plants [37]. Drones equipped with thermal cameras can carry out surveys of vast zones of photovoltaic solar facilities, collecting high-resolution RGB and thermal map data. Thermal imaging facilitates fault detection based on abnormal temperature patterns between cells or panels (Figure 25). Using a combination of visual RGB information and thermal maps, it is possible to estimate whether these abnormal temperature patterns are the result of physical conditions such as delamination, cracking, or particulate matter, or if they are due to connectivity issues such as inverter failures or wiring faults [37].

Photogrammetry software reconstructs RGB orthomosaic and thermal maps and adjusts the location using ground control points. After location and rebuilding adjustments, maps are created and then linked to a GIS, where solar energy facility field operators can rapidly identify anomalies and detect solar panel failures [38].

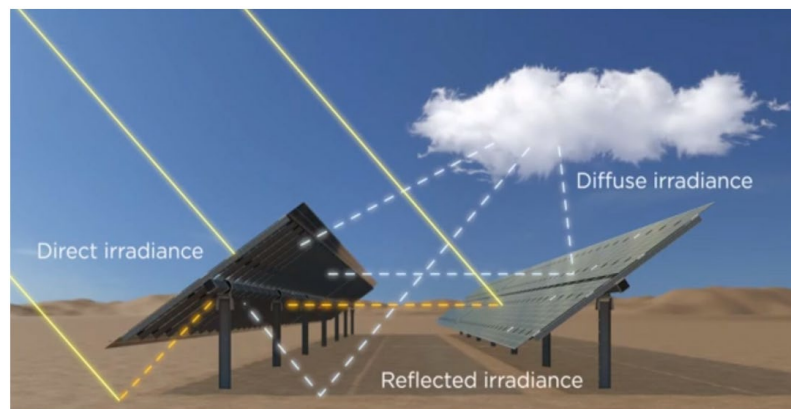


**Figure 25.** Example of high-resolution RGB and thermal images obtained by drone flight for conducting a PV panel inspection in a solar energy plant (layout view). Adapted from [39].

It is expected that in the coming years, the evolution of artificial intelligence (AI) and machine learning (ML) technologies as part of the Industry 4.0 paradigm will contribute to

the solar energy industry, for example, in global solar irradiation modeling/prediction and solar power production estimates, among other areas [40,41].

Finally, we can mention one of the most important technological advances applied in photovoltaic solar energy plants in Peru, the use of photovoltaic panels called bifacial solar panels. Bifacial solar panels can capture energy on both sides of the photovoltaic solar panel, whereas monofacial modules only receive energy on their front side [42]. Bifacial modules expose both the front and back of solar cells (See Figure 26).



**Figure 26.** Schematic view of the functioning of bifacial solar photovoltaic panels [43].

When bifacial modules are installed on a highly reflective surface, up to a 25% increase in power output can be obtained just from the additional power harvested from their rear [42]. Bifacial modules have different configurations, such as (i) framed or (ii) frameless. Other key characteristics of bifacial modules are with respect to their materials, such as: (i) some have double glass, or (ii) some use transparent back sheets. The vast majority use monocrystalline cells, but polycrystalline arrays also exist.

Bifacial technology is expected to strongly enter the market and account for one-third of global solar module production by 2025. Bifacial and half-cell solar panel technologies have gained momentum owing to their improvements in solar energy harvesting.

The intermittent nature of solar photovoltaic (PV) generation, which depends on the weather and amount of daylight, presents a particular issue. In this sense, accurate solar energy forecasting has emerged as a critical issue in maximizing energy production and seamlessly integrating solar power into the grid to overcome this obstacle. Some key aspects of carrying out a forecast model for further economic growth in the use of solar energy sources are (i) resource planning and investment decisions, (ii) optimizing energy production, (iii) grid stability and reliability, and (iv) economic efficiency.

In this context, the Energy and Mines Ministry of Peru considers conventional weather-based solar energy forecasting models and in recent years has incorporated the following cutting-edge technologies to improve solar irradiation prediction precision: (i) satellite data, (ii) artificial intelligence (AI), and (iii) machine learning (ML).

For decades in Peru, forecasts of solar energy have been based on conventional weather-based models. These models are based on historical meteorological information, which includes parameters such as solar irradiance, temperature, cloud cover, and humidity, among others. These models frequently have trouble when there is cloud cover or other unfavorable weather conditions rather than clear skies.

Satellites with cutting-edge remote sensors offer a variety of useful information for solar forecasting by incorporating satellite data into conventional solar forecasting models. They can take high-resolution pictures of the Earth's surface and atmosphere, which enables tracking of significant meteorological variables like cloud cover and water vapor concentration in real time.

Solar energy forecasting carried out by the Energy and Mines Ministry of Peru uses artificial intelligence (AI) and machine learning (ML) algorithms to process massive volumes

of weather data. Prediction accuracy is greatly increased by using historical information on solar energy output, weather patterns, satellite photography, and artificial intelligence (AI)/machine learning (ML) algorithms. Some examples of the tools used are (i) convolutional neural networks (CNNs) and (ii) recurrent neural networks (RNNs), which have demonstrated promise in the analysis of satellite pictures and the identification of cloud-cover patterns that impact solar irradiance. These models have been trained to recognize various cloud forms and calculate how they will affect solar energy output.

#### 4.2. Policy Gaps

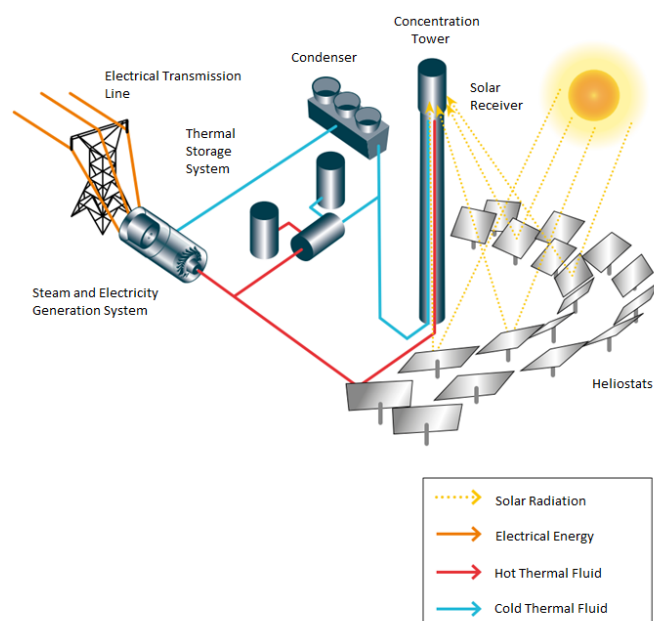
Even though Peru has legislation related to the promotion of investment for the generation of electricity with the use of renewable energy in Legislative Decree N° 1002 and its regulations approved by Supreme Decree N° 050-2008-EM and modified by Supreme Decree N° 012-2011-EM, renewable energy projects still face policy barriers for their appropriate implementation in the electricity market [6].

One of the main limitations of solar projects is that the current technical procedure for the calculation of firm power in Peru is based on the electricity system's peak hours (between 05:00 p.m. and 11:00 p.m.) when solar radiation is not present. Therefore, solar projects cannot state any amount of firm power and receive income for it. Moreover, there are no separate markets for energy and power that allow solar projects to commercialize energy through power purchase agreements.

Complementary regulation is needed to compensate solar projects for the energy and firm power that they offer, considering that the peak hours for electricity consumption in Peru are not necessarily between 05:00 p.m. and 11:00 p.m. Also, regulations to let solar projects participate in long-term tenders that are controlled by the electricity distributors are suggested, as well as the publication of the distributed generation regulation.

#### 4.3. Challenges and Opportunities Linked with Sustainability

Peru can become a development pole and place of technological innovation in the production of electricity using solar energy. For example, one of the technologies not applied in the country is a concentrated solar power (CSP) facility, where heliostats are used to locate the sun's rays in a specific area where the heat is concentrated [44]. Unlike conventional solar PV facilities, concentrated solar power (CSP) facilities use technological advances that allow the sun's heat to be stored to produce electricity for 24 h. Figure 27 shows an example of this technology.



**Figure 27.** Schematic view of a concentrated solar power (CSP) plant. Adapted from [24].

Figure 27 shows that one of the key elements of this type of project is the 250-m central tower where the heat receiver is placed and to which the thousands of heliostats will point. The heliostats are mirrors with a reflective surface of  $140\text{ m}^2$  and a weight of three tons each, and they follow the path of the sun with movement along two axes, reflecting and directing solar radiation toward the receiver. Molten salts circulate through this receiver at a temperature of  $560\text{ }^\circ\text{C}$ , transferring the heat to a circuit that drives a steam turbine to generate electrical energy [45].

For example, concentrating solar systems could store energy in the form of heat for up to 15 h per day. The aspect of fluctuation can also be addressed by integrating solar electricity with alternative clean-energy sources. In South America, the first project of this type was inaugurated in Chile, where the concentrated solar power (CSP) plant occupies an area of 1000 Ha and is located on Cerro Dominador, a location with one of the highest solar radiation levels on the planet, located close to the city of Calama in the Antofagasta region [46–48].

Solar irradiation levels are higher in the south of Peru due to the reduced presence of water vapor, which is why direct normal irradiance (DNI) levels in this area ranging from  $5.2$  to  $8.8\text{ kWh/m}^2/\text{day}$  can be reached [29]. For example, regarding solar irradiance, in the southern area of the Tacna region, an average of  $750\text{ W/m}^2$  is received at noon in the coastal zone, with up to  $990\text{ W/m}^2$  in higher-altitude areas. These values are suitable not only for solar PV technology but also for concentrated solar power (CSP) systems. These systems typically require a midday direct normal irradiance (DNI) ranging from  $800$  to  $950\text{ W/m}^2$  to be technically and economically feasible. In Peru, some basic studies have been conducted to validate their feasibility, leading to favorable results. Of these, special attention is deserved by the hybridization of solar energy infrastructure with other clean-energy technologies [49]. For example, the hybridization of solar photovoltaic (PV) with concentrated solar power (CSP) facilities ensures energy delivery within a window of up to 10 to 11 h per day, with solar energy storage systems taken as a reference. This is largely controlled by the excellent conditions of the sun source. Solar thermal technologies show great promise, particularly in regions with high direct normal irradiance (DNI) levels, such as northern Chile and southern Peru. Despite Peru's abundant solar resources that are ideal for the implementation of such technology, solar thermal technology has not yet been introduced in the country.

Considering Table 19, which shows the current technologies and technical conditions in Peru, the most viable options would likely be the utilization of parabolic trough collectors and solar power tower projects.

Table 19 shows that it is possible that these concentrated solar power (CSP) technologies would be particularly profitable if hybridized with other energy systems. In this case, the hybridization of solar photovoltaic (PV) with tower concentrated solar power (CSP) facilities would ensure energy delivery within a window of up to 10 to 15 h, with thermal storage systems taken as a reference. This is largely considering the excellent conditions of the sun source in the site-specific conditions of Peru. Also, the hybridization of solar photovoltaic (PV) energy with existing on-shore wind energy plants or future off-shore wind energy facilities appears to be promising, especially in areas where both resources converge, such as the coast of the Ica region. Similarly, hybridization with hydropower proves to be significant, with Yarucaya serving as a prime example of successful operation in regions abundant in hydro resources and suitable solar conditions. The solar photovoltaic (PV) plants collaborate with a hydroelectric facility under the ownership of the Huaura Power Group, and both belong to CFI Holding. Together, they form the initial renewable hybrid system integrated into the SEIN.

The stringent environmental assessment requirements often cause delays, and many of the prescribed procedures are better suited for the oil and gas industry rather than renewable energy projects.

While the potential for renewable energy development in the Amazon and Andes regions is substantial, these areas lack the necessary transmission infrastructure to distribute

electricity nationwide. Therefore, investing in large-scale renewable energy projects may require substantial upfront investment in transmission infrastructure.

**Table 19.** Characteristics of concentrated solar power (CSP) technologies considering the site-specific conditions of Peru [50].

| Characteristics                                               | Parabolic Trough Collector            | Linear Fresnel Reflector | Solar Power Tower                     | Parabolic Dish Systems         |
|---------------------------------------------------------------|---------------------------------------|--------------------------|---------------------------------------|--------------------------------|
| Area Requirement (m <sup>2</sup> /MWh)                        | 4–6                                   | 6–8                      | 8–12                                  | 30–40                          |
| Thermal Efficiency                                            | 30–40%                                | -                        | 30–40%                                | 30–40%                         |
| Plant Peak Efficiency                                         | 14–20%                                | 18%                      | 23–35%                                | 30%                            |
| Direct Normal Irradiance (DNI)                                | 1800–2000 kWh/m <sup>2</sup>          |                          |                                       |                                |
| Water Requirement (m <sup>3</sup> /MWh)                       | 5.40                                  | 3.20                     | 4.25                                  | 0.15                           |
| Operation Temperature of Solar Field (°C)                     | 290–550                               | 250–560                  | 250–650                               | 800                            |
| Grid Stability                                                | Medium to High                        | Medium                   | High                                  | Low                            |
| Storage Possibility                                           | Yes                                   | Yes                      | Yes                                   | Depends on plant configuration |
| Heat Transfer Fluid                                           | Synthetic Oil, Water/Steam            | Water/Steam              | Water/Steam, Molten Salt              | Air, H <sub>2</sub> , He       |
| Technology Development Risk                                   | Low                                   | Medium                   | Medium                                | Medium                         |
| Possibilities of Implementation in Peru                       | High                                  | Low                      | Medium                                | Low                            |
| Possibilities of Hybridization with other Energy Technologies | Photovoltaic, Geothermal, Natural Gas | Natural Gas              | Photovoltaic, Geothermal, Natural Gas | Natural Gas                    |

#### 4.4. Sustainable Grid Integration

Based on the above, it is evident that the solar technologies suitable for development in Peru include photovoltaic (PV) systems and concentrated solar power (CSP) facilities using both parabolic solar collectors and central tower configurations, as well as hybrid systems combining solar photovoltaic (PV) and concentrated solar power (CSP) with or without energy storage systems. To successfully implement these technologies, certain considerations need to be considered:

- **Grid Stability:** The variability of solar photovoltaic (PV) generation can impact grid stability, underscoring the need for energy storage systems to enhance grid stability. Solar thermal systems with storage offer increased reliability and resilience.
- **Regulation and Standards:** As these would be new systems in Peru, having well-defined regulations and current standards is crucial for the seamless integration of solar photovoltaic (PV) systems into the National Interconnected Electrical System (SEIN). This is particularly important in the southern region, which boasts significant solar potential.
- **Transmission Capacity:** The geographic location of solar photovoltaic (PV) and concentrated solar power (CSP) projects, along with their distance from grid connection points, may influence transmission capacity and necessitate upgrades to the transmission infrastructure. Strengthening transmission lines and enabling energy exchange with other countries can be beneficial.
- **Solar Irradiation Prediction Systems:** Implementing predictive models for solar radiation and generation behavior is essential to anticipate voltage fluctuations caused by factors like cloud cover or unexpected solar photovoltaic (PV) system failures. This predictive capability ensures the continuity and reliability of electrical supply.

By considering these conditions and factors, Peru can effectively harness solar energy resources for sustainable and reliable electricity generation, paving the way for a cleaner and more resilient sustainable energy future.

#### 4.5. Outlook and Future Directions

A promising large-scale advance of clean energy has been achieved in Peru through the under-functioning of solar PV facilities, but the implementation of solar energy on a smaller scale still needs to be promoted in remote communities in rural areas [21,51]. This would promote rural electrification and benefit many persons that still do not have electricity [52–56].

In the south of the country, the regions of Ica, Moquegua, Arequipa, and Tacna have some of the highest solar radiations in the world, with values of 6.5 kWh/m<sup>2</sup>/day equivalent to 2300 kWh/kW. This represents an opportunity for the mining sector to implement sustainability solutions and contribute to the road to carbon neutrality, as there are important mining operations in the country, such as Cerro Verde, Cuajone, Toquepala, Las Bambas, Antapaccay, San Rafael, Pucamarca, and Quellaveco, among others. Likewise the south of the country has a large portfolio of new phases of mining projects such as San Gabriel, Mina Justa, Corocohuayco, Inmaculada, Los Chancas, Corani, Pampa de Pongo, Tia María, Los Calatos, and Zafranal, among others [7]. For example, some studies have been carried out in Chile to implement solar energy technologies and hybridize with other clean-energy infrastructures in copper mining projects, providing a road to a green mining solution [57].

There are high expectations that the country's political authorities will foster public policies that seek the implementation of solar energy facilities, which will allow the production of clean energy and foster sustainable development and human well-being.

Some countries in South America have extraordinary attributes for implementing solar photovoltaic facilities to take advantage of renewable solar energy. Western South America is one of the most significant global horizontal irradiation (GHI) hotspots on the planet. Results of studies presented in the Global Solar Atlas place Chile as the South American country with the highest practical long-term solar energy production potential, with 5.00 kWh/m<sup>2</sup>/day on average, followed by Peru and Bolivia. However, South America has been unable to take full advantage of solar energy to date and has faced difficulties such as high initial investment costs, legal and economic barriers for investors, and a lack of policies from governments that promote the mass implementation of this technology, among others [58].

It is recommended that Peru considers as a guide the successful experience of solar energy advances in neighboring South American countries, such as Chile and Brazil, where there is an important number of solar photovoltaic (PV) facilities in operation. Chile is a reference country for Peru considering its technological development and aggressive policy of implementation of renewable energies, where, for example, alliances have been created between energy-generating companies and mining companies, where copper and lithium mining projects, photovoltaic solar (PV) plants, concentration solar power (CSP) plants, and solar energy storage systems are being implemented [59–63].

The solar photovoltaic (PV) facilities in Peru are in sites that, until now, presented adequate solar energy potential; however, given the diverse site-specific characteristics of Peru with respect to the complex conditions of geography, terrain, and climate, high CAPEX is required to build infrastructures such as electrical transmission networks and access roads. Regarding these aspects, the Sechura Desert and the Coast Desert of Peru represent the greatest solar energy hotspots, hence the growth expectations in coming decades will focus on these zones of the country.

Variations in solar radiation with respect to the ENSO climatic phenomenon and the impacts of global climate change must be monitored, and such variations play a key role in the generation of electricity from solar energy [64].

The current progress of solar energy in Peru is incipient, so analysis of the solar photovoltaic (PV) facilities that are in operation and improvements and increases in the number of photovoltaic modules and total installed capacity is in progress (Figure 28). Shortly, it is likely that solar energy companies will provide the opportunity for energy market growth and remote rural electrification, specifically for communities in the Amazon

zone. Its use is extremely simple and appropriate for rural electrification, but the main difficulty is its high cost.



**Figure 28.** Sunset over the Rubi solar PV facility, which has enormous solar potential waiting for sustainable use.

Clean-energy sources must be at the forefront of sustainable development policies and international cooperation programs. In this sense, more advances in research are needed concerning the storage of solar energy, such as hydrogen, batteries, and heat storage [65].

Finally, the future of the production of electricity from solar sources considering the portfolio of investments in Peru is promising, with an installed capacity of more than 7218 MW expected to be implemented in the coming years, thus meeting the commitment to carbon neutrality goals by 2050.

## 5. Conclusions

Peru's solar resources have been estimated, resulting in a useful potential of 25 GW; this is due to having territory in one of the areas of the world with the highest solar radiation throughout the year. The regions with the greatest solar potential are Arequipa, Moquegua, Tacna, Piura, and Tumbes, with a significant global horizontal irradiation of 5.00 kWh/m<sup>2</sup>/day on average. Considering the solar photovoltaic facilities currently in operation in Peru, there is a total installed capacity of 398 MW, which is equivalent to 2% of the usable solar energy potential of 25,000 MW (25 GW).

In the case of Peru, the impacts of solar radiation with respect to the ENSO climatic phenomenon and the effects of global climate change must be monitored by experts from academia as research develops.

Therefore, the integration of solar PV facilities into the SEIN has allowed constant technological advances, which have facilitated private investment, training of Peruvian professionals, and job opportunities.

For a country like Peru with topographic barriers and complex geographical conditions, solar energy can generate electricity in rural areas, in the mountains, and in remote places like the Amazon that are not connected to the electrical grid. Despite the development of rural electrification projects using renewable energies, 100% coverage has not yet been achieved. This is mainly due to the low population density in remote areas, which hinders its progress. Here, innovative mechanisms for private investment in the execution of projects with mini-grids and isolated systems must be prioritized, and the approval of the regulations for distributed generation by the Ministry of Energy and Mines is required.

Solar energy for significant power generation will continue to grow gradually, mainly in the north and south of the country, which is why it is estimated that 7.2 GW of installed capacity of PV energy portfolio projects will be implemented in the coming years. However,

regulatory modifications are necessary to ensure that solar generating companies can build contracts with free users and distributors of both power and energy, thereby modifying the methodology for calculating firm power for solar plants or opening new markets for the sale of energy by hourly blocks.

Regarding direct normal irradiance (DNI), the values reached in the southern coastal zone are significant, which initially ensures technical feasibility for the development of concentrated solar power (CSP) systems with storage. However, economic conditions hinder their development, and there is also a lack of specific energy regulations and policies for this type of technology. Concentrated solar power (CSP) technology will need more advances in research to guarantee its implementation, including information about the experience of operating the Cerro Dominador concentrating solar facility located in Chile.

Concerning strategic political terms, the government of Peru should implement policies to promote investment in solar energy generation industries, eliminate legal and economic barriers to investors, and incentivize research into new technologies related to solar energy and energy efficiency.

In this scenario, it is possible to conclude that if Peru takes advantage of solar potential by considering a sustainable future perspective and implementing strategic land-use planning, the southern region will be transformed into a world-class territory for renewable energy development considering the hybridization of concentrated solar power (CSP) systems with solar photovoltaic (PV) systems and solar energy storage systems. Also, the hybridization of solar photovoltaic energy with on-shore wind energy appears to be promising, especially in areas where both resources converge, such as the coast of the Ica region.

Finally, Peru contributes to mitigating global climate change, decreasing greenhouse gas (GHG) emissions from the energy generation matrix by considering the implementation of renewable energy with solar photovoltaic facilities. Also, Peru compromises by implementing sustainable development goals (SDGs) and generating a decarbonization economy to guarantee an environmentally friendly planet for future human generations. The enormous solar energy potential of the country, if used adequately and taken advantage of, promises a sustainable future for the development of the local economy, the well-being of communities, and the care of the environment.

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## Abbreviations

|                    |                               |
|--------------------|-------------------------------|
| SDGs               | Sustainable Development Goals |
| UN                 | United Nations                |
| PV                 | Photovoltaic                  |
| CSP                | Concentrated Solar Power      |
| GHG                | Greenhouse Gas                |
| CO <sub>2</sub> eq | Carbon Dioxide Equivalent     |
| GDP                | Gross Domestic Product        |

|                    |                                                                            |
|--------------------|----------------------------------------------------------------------------|
| HDI                | Human Development Index                                                    |
| DHI                | Diffuse Horizontal Irradiance                                              |
| DNI                | Direct Normal Irradiance                                                   |
| GHI                | Global Horizontal Irradiance                                               |
| SEIN               | National Interconnected Electricity System of Peru                         |
| ESMAP              | Energy Sector Management Assistance Program                                |
| IRENA              | International Renewable Energy Agency                                      |
| WHO                | World Health Organization                                                  |
| NGOs               | Non-Government Organizations                                               |
| CF                 | Capacity Factor                                                            |
| EIA                | Environmental Impact Assessment                                            |
| MINAM              | Environmental Ministry of Peru                                             |
| SENAMHI            | Meteorological and Hydrological National Service of Peru                   |
| COES               | Economic Operation Committee of the National Interconnected System of Peru |
| OSINERGMIN         | Energy Investment Supervisory Agency of Peru                               |
| CAPEX              | Capital Costs                                                              |
| OPEX               | Operational Costs                                                          |
| AI                 | Artificial Intelligence                                                    |
| ML                 | Machine Learning                                                           |
| CNNs               | Convolutional Neural Networks                                              |
| RNNs               | Recurrent Neural Networks                                                  |
| UAVs               | Unmanned Aerial Vehicles                                                   |
| RGB                | Red Green Blue Colors                                                      |
| GIS                | Geographical Information System                                            |
| RER                | Renewable Energy Resources                                                 |
| ENSO               | El Niño Southern Oscillation                                               |
| LCOE               | Levelized Cost of Electricity                                              |
| BESS               | Battery Energy Storage System                                              |
| MW                 | Megawatts                                                                  |
| GW                 | Gigawatts                                                                  |
| MWh                | Megawatts-Hour                                                             |
| GWh                | Gigawatts-Hour                                                             |
| kWh/m <sup>2</sup> | Kilowatt-hour per square meter                                             |
| kWh/kW             | Kilowatt-hour per Kilowatt                                                 |
| \$USD              | United States Dollar                                                       |
| Mtons              | Millions of tons                                                           |
| Ha                 | Hectare                                                                    |
| masl               | Meters above sea level                                                     |

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