SPOT-BY-SPOT DIVERSITY IN THE GLOBAL POTENTIAL OF SOLAR ENERGY

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Abstract**—** Because solar energy's potential differs widely by geographical area, this is an important consideration in designing and promoting sustainable energy strategies. This article examines the variety of solar resources in different places and why a regionally focused approach is needed. Latitude, climate, and topography all affect the intensity of light. Closer to the equator and with higher solar irradiance, conditions for generating solar energy are most favorable. These geographical contrasts provide both dangers and opportunities, as this paper observes. In addition, regions with rich sunshine are appropriate places for building solar power projects. However, such factors as cloud cover limit generating capacity, as do things like air and ground relief. Understanding the local climate and utilizing adaptable technologies can help to resolve these differences. In addition, the summary points out that solar energy policies and investments must adapt to local circumstances. It implies a comprehensive view towards taking advantage of renewable power potential anywhere. By recognizing and taking account of geographical differences, nations and stakeholders can correct solar errors to create a sustainable tomorrow**.**

Keywords**—** *Global Solar Energy Variations, Policy, Investments, Sustainable Tomorrow, Equator.*

I. INTRODUCTION

A. Background on the importance of solar energy as a renewable resource

Solar energy is one of the fastest-growing forms of renewable energy globally. For humans, it is a clean source of pollution-free, noiseless energy. Recently, given the thinning of ozone layers, global warming, and rising prices for fossil fuels, solar energy is gaining favor as a new form of green power. The electricity generated by solar energy needs to be explored. Some parts of Nigeria, where most agricultural and economic activity occurs without electricity or water supply, have found solar energy to be a low-cost and novel way out(Njok et al., 2020). Also, the increasing need for a sustainable, environmentally friendly, and cost-effective power supply has created a pressing need to harness clean power from nature. (Ogunjo et al., 2021).

B. Significance of understanding geographical variations in solar energy potential

Variations in temperature, humidity, wind speed, and direction determine the quantity of energy that can be obtained from the sun. These changes occur naturally as a result of human activities(Agbo et al., 2021). Geographic information data and maps add value to information obtained from solar energy. A region's unique geographical characteristics create technical and environmental constraints for developing a solar power plant(Agbo et al., 2021).

C. Research objectives and questions

The study examines geographical differences in solar energy potential. The research objective is to explore the differences in solar energy potential by latitude, climate, and topography. Based on this, we propose strategies for better utilizing local resources.

II. LITERATURE REVIEW

The evolution of new technologies ameliorates the efficiency of solar cells and reduces the cost of solar cell production (Das, 2019).

A. Overview of solar energy technology and its applications

There are three major forms of sun-conversion technology--solar photovoltaic conversion, thermal conversion and concentrated solar power. Sunlight can be turned into electricity without heat engines, as in photovoltaic conversion(Parida et al., 2011). PV devices are sturdy and have a simple structure; they require little maintenance and can deliver output power from microwatts to megawatts. This is why such crystals are used as power sources for water pumps and remote houses; they cause solar homes to keep food cold and communications systems like satellites to go into space. Even in reverse osmosis, plants producing megawatt-scale electric generation use them.
According to (Thirugnanasambandam et al., 2010), it was indicated that a thorough survey of literature on solar thermal technologies, including solar water heaters, solar cookers and driers, solar ponds, and architecture, conditioning, chimneys, power plants and stills, was also undertaken (Thirugnanasambandam et al., 2010). The review summarizes the evolution of technology in each area, as mentioned earlier, to improve the existing system's performance or to develop a new technology that gives better results than the present ones. Thus, the paper points out scopes of future research in solar thermal technology.
Reference (Sonawane et al., 2018) discusses the different types of concentrating solar energy (CSE) technology: flat plate collector, stationary compound parabolic collector (CPC), parabolic trough collector, total suspended particles, linear Fresnel

collector and sterling dish collector. A synopsis of concentrating solar energy technologies covers the state of current solar energy projects worldwide. CSE applications reduce emissions and stimulate the economy (Sonawane et al., 2018).

B. Historical context of solar energy utilisation

Solar energy has been used for heating and lighting since prehistoric times, with ancient Greeks using passive solar energy in the 5th century BC. Later, humans developed explicit materials on windows to prevent heat dissipation (Jones, 2012).

Following World War 2, photovoltaic cells transformed solar energy technology, leading to a more resource-intensive industry. The modern solar PV industry comprises three sectors: wafer production, cell installation, and polysilicon production. Polysilicon, a key raw material for PV cells, was sourced from by-products of electronics manufacturing until the 21st century (Jones, 2012).

C. Factors influencing geographical variations in solar energy potential

Many environmental factors have a positive or negative effect on the performance of a solar cell. The solar cell becomes less efficient when the temperature rises, reducing power yield. High humidity reduces energy production through the shortened life of the solar cell and reduced power generation. Apart from this, dampness will corrode the solar cell module and shorten the life of a solar panel. However, wind helps solar panels work better by making the temperature of the surface of the panel module cooler. Solar panel efficiency hinges on light intensity--the higher the light intensity, the greater the number of protons striking the surface of a solar cell. As a result, more electricity is produced by the solar cell, and its parent module becomes even more efficient. Higher height means that more sunlight reaches the surface of the solar panel, raising its overall performance and efficiency(Das, 2019).

III. SOLAR ENERGY POTENTIAL FACTORS

By introducing novel techniques and technologies, solar cell efficiency has been enhanced in recent years, accompanied by reduced manufacturing costs(Das, 2019). Despite these advancements, solar energy potential is determined by these factors:

A. Solar Insolation and Irradiance Levels

Change in irradiance directly affects the maximum power point of solar modules. Cloud cover can damage parts of a PV system, such as inverters and fuses. Such damage will likely emerge when the high-energy visible light generated by forward Mie scattering and multiple reflections meets favorable temperature conditions. As a result, in designing an overall PV system, engineers must be conscious of diurnal, monthly or seasonal fluctuations in solar radiation and the peak irradiance values possible from a PV module (Ramgolam & Soyjaudah, 2015).

B. Latitude and its Impact on Solar Energy Availability

No matter how solar cells are made, the electric current they produce at any given instant relates to the amounts of sunlight, span times of daily light, lengths and depths of monthly and annual lighting periods, and cloud cover rates. These factors change with latitude and longitude. Solar times and solar radiation values are also affected (Sarkin & Ndar, 2017).

C. Climate and Weather Patterns Affecting Sunlight Hours

Temperature, humidity, wind speed, light intensity, altitude, and air pressure are all external conditions that affect the performance of solar cells. The documentation shows these factors can improve or reduce power efficiency (Das, 2019).

Temperature: Temperature and solar cell performance are inversely correlated, meaning higher temperatures result in lower performance.

Humidity: Humidity, measured as the amount of water vapor in the air, affects solar cell module performance in two ways. Firstly, water droplets deposited on the module's surface reflect sunlight, impacting total output. Secondly, humidity contributes to the rusting of metals in the solar panel module, reducing the panel's lifespan.

Wind Velocity: Wind velocity positively influences solar cell performance by enhancing efficiency by passing across the surface of the solar cell module; it lowers the panel's temperature and enhances performance overall, helping to lessen the effects of temperature.

Light Intensity: Reduced light intensity causes a drop in voltage and current, directly impacting the solar cell's efficiency. Maintaining the best possible output from solar cells requires the right amount of light.

Altitude: Changes in altitude affect power generation. Moving closer to the light source increases intensity and improves solar cell performance.

Air pressure: There is a direct relationship between air pressure and light intensity: light intensity directly relates to air pressure and air pressure directly relates to solar panel power production. The solar cell's performance improves with increasing light intensity.

D. Topography and Terrain Features Influencing Solar Access

The amount of solar radiation the surface receives on Earth is ruled mainly by topographical differences. Some factors combine to engender local differences in sun radiation, such as changes in elevation, slope configurations, slope direction and shading. These gradients impact biophysical processes, including primary production, energy and water balances, and heating of the air and soil directly and indirectly(Taylor et al., 2007).

IV. REGIONAL DISPARITIES IN SOLAR ENERGY POTENTIAL

A. *Analysis of solar energy potential variations by region or geography*

Regions possess untapped renewable energy potentials distributed across multiple nations(Alkholidi & Hamam, 2019). Changes influence these variations in specific renewable energy categories relevant to regional development driven by socio-economic factors, as shown in Table 1(Alkholidi & Hamam, 2019). This awareness prompts communities and the sector to recognize trends and the necessity of adopting best practices to achieve energy access and security. Disseminating information about these profiles and potentials serves as a platform to highlight the current understanding of renewable energy potentials and their significance in shaping public policy(Lucas et al., 2021).

B. *Case studies of regions with high and low solar potential*

Table 1: Top 5 European Solar Markets 2017 (Alkholidi & Hamam, 2019)

Country Name	Turkey	Germany	UK	France	Netherland
Solar Market	21%	20%	11%	10%	10%

C. *Identification of regions with untapped solar energy resources*

Solar energy stands out as a significantly underused and neglected renewable resource, according to reference (Kashif et al., 2020). Photovoltaic (PV) technologies remain the predominant means of harnessing solar power. Off-grid solar systems have much-unrealized potential, mainly because organizations and legislation enabling them are still slowly emerging. Notably, Africa boasts some of the sunniest locations globally (Kashif et al., 2020).

Theoretically, Africa has roughly 470 and 660 -petawatt hours (PWh) of unrealized PV and concentrated solar power (CSP) potential. Alternatively, non-African regions such as the Middle East, North and Southern Africa, Central and South America, the Southwest of the United States, and the desert plains of Australia, Pakistan, and India have a limited potential collectively, producing only 125 gigawatt hours (GWh) from a 1 km square land area. An instance is the enormous unused land, which spans approximately 6300 km2 in the northern and western parts of China and has powerful solar radiation. An estimated 1300 GW of power might be produced in this region. In contrast, the National Renewable Energy Laboratory (NREL) in the United States estimates that solar energy may produce 400 zettawatt-hours (ZWh) per year, which is more than the 22,813 terawatt-hours (TWh) of electricity that is currently produced. Morocco has proactively embraced solar energy. Morocco is a country in North Africa that receives about 3000 hours of sunshine annually. Intending to produce 2000 megawatts (MW) by 2020, the country has started one of the biggest solar energy projects in the world, using both PV and CSP technology. This strategic approach is considered excellent because of Morocco's advantageous atmospheric conditions—including high heights, little fugitive dust, great transparency, and low humidity(Kashif et al., 2020).

V. TECHNOLOGICAL SOLUTIONS

A. *Solar panel efficiency improvements*

Solar energy is focused onto solar cells using concentrated photovoltaic technology (CPV), which uses optical components like mirrors and lenses, generating electricity more efficiently. CPV offers advantages over non-concentrated photovoltaic systems, requiring fewer solar cells for equivalent power output. The sun's warmth, sunlight duration, and intensity levels also greatly affect PV module performance. As temperature rises, output power under high sun radiation declines by 50 % when temperature jumps from 46°C to 84 °C. Therefore, an effective cooling system is required to ensure the highest solar cell efficiency and avoid degradation and damage. Solar panels can be cooled actively or passively. The latter needs an external power source, while the former feeds off residual energy(Arshad et al., 2014).

B. *Tracking Systems and Sun-Following Technology*

Any of the three specified modes of operation for the sun tracker is available: In clock mode, the sun position is calculated using the real-time clock (RTC), pointing mistakes are saved for future study, and the sun position is reset to the morning position when it sets. When the solar monitor signal falls below a certain threshold, the tracker immediately switches to clock mode and actively modifies pointing. The INTRA unit operates in clock mode at night, which is advised for best pointing outcomes, particularly following initial installation. With no special night operations required, the remote mode allows the setting of primary and secondary values using commands provided through the serial port. A monitor mode is offered for non-operational settings, and these quantities are measured in the astronomical system, which differs slightly from the tracker system(Georgiev et al., 2004).

C. *Energy storage solutions to address intermittency*

Improving the overall flexibility of the electrical grid is one strategy that might be used to mitigate the uncertainty resulting from the variable features of renewable energy sources (VREs). Increasing the energy system's storage capacity allows more flexibility in controlling peak demands and bridging energy gaps. Currently, several storage technologies and approaches—such as chemical, thermal, electrical, mechanical, and electrochemical energy storage—are available to lessen the intermittent nature of VRE sources (refer to Fig. 1). Flow batteries, molten salt thermal storage, pumped hydro storage (PHS), and compressed air storage are notable examples of large-scale energy storage technologies (see Fig. 2)(Zsiborács et al., 2019).

VI. POLICY AND INCENTIVES

A. Government policies and incentives for promoting solar energy adoption

Government policies have encouraged the production and use of renewable energy, and technological developments have resulted in cost reductions. These factors have recently contributed to the spectacular rise of solar energy. Various policy instruments have been implemented to encourage the use of solar photovoltaic (PV) systems. These instrumental measures include Feed-in tariffs, investment tax credits, subsidies, finance facilitation, mandatory access and purchase, renewable energy portfolio criteria, and public investment.

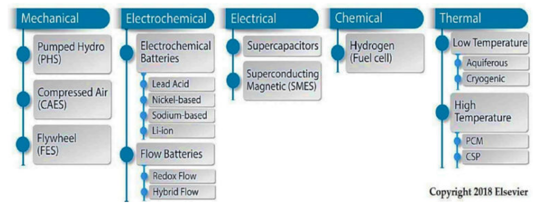

Fig. 1: Classification of energy storage technologies by the form of stored energy (Zsiborács et al., 2019).

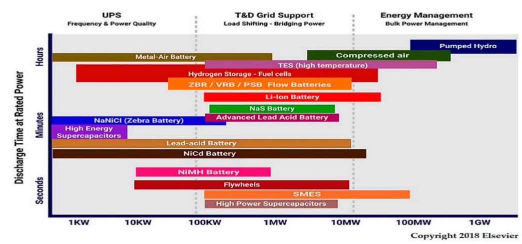

Fig. 2: Energy storage technologies by discharge time and power capacity (Zsiborács et al., 2019).

B. Feed-in tariff, tax credit, and subsidies

A feed-in tariff (FIT) involves providing an additional payment or tariff to emerging renewable energy technologies that may be relatively costly or less competitive than conventional methods for electricity generation. The cost of producing power and a fair profit margin for the generator are considered while determining this tariff. FIT aims to alert potential investors and urge them to participate in the solar energy industry.

The ultimate goal of lowering the costs of these technologies depends mainly on long-term investments in innovative and cutting-edge technology. The main instrument utilized worldwide to promote solar energy development is subsidies. These subsidies take many forms, including interest-subsidized soft loans, output—or production-based payments, capacity payments, investment grants, and soft loans. Regarding investment tax credits, several varieties have been implemented in numerous jurisdictions globally to support the advancement of solar energy.

For instance, support for fuel cells and solar energy is provided via the federal corporate energy investment tax credit in the United States. More specifically, the credit is for 30% of the costs of solar-powered equipment that generates electricity, heats or cools buildings, and lights with hybrid solar power(Timilsina et al., 2012).

C. Regulatory frameworks for grid integration and net metering

Despite the numerous technical solutions for enhancing the hosting capacity of distribution grids for photovoltaic (PV) systems, their practical application may encounter obstacles due to existing regulations. It is imperative to reassess current regulatory frameworks to establish the mechanisms that facilitate interaction between distribution system operators (DSOs) and PV units and prosumers. Competent national regulatory bodies should establish appropriate guidelines controlling DSO access to PV inverters' sophisticated features.

Specifically, the balance between the capabilities mandated by grid codes and the services offered voluntarily, potentially in exchange for specified compensation, needs to be addressed. This trade-off should be duly acknowledged and analyzed. Furthermore, mechanisms for coordinating actions between DSOs and transmission system operators (TSOs) must be established to prevent conflicts between TSOs and energy providers(Mateo et al., 2017).

VII. GRID INTEGRATION STRATEGIES

A. Smart grid technologies for efficient solar energy distribution

Smart grid technologies are autonomous systems that identify and resolve issues within existing systems, reducing workforce dependency and delivering sustainable, reliable, safe, and high-quality electricity. They address various aspects of the grid, including data analysis, loss tracking, troubleshooting, charge density assessment, billing procedures, and power line analysis(Bayindir et al., 2016).

B. Energy storage and grid balancing to optimise solar use.

The real-time equilibrium between electricity generation and demand is crucial for ensuring the stability of the power grid. To facilitate this balance, grid-scale energy storage systems are becoming more prevalent, offering grid operators the flexibility to manage generation and demand effectively. Additionally, integrating energy storage contributes to the resilience and robustness of the overall grid infrastructure(Chalamala & Gyuk, 2017).

C. Regional energy sharing and interconnection

Promoting energy access, guaranteeing energy security, and carrying out multilateral actions require improved international cooperation, which can be achieved by sharing best practices. Establishing competitive global energy markets is supported by this cooperative strategy(Indeo, 2019).

VIII. COMMUNITY AND RESIDENTIAL SOLUTIONS

A. Residential solar panel installations and incentives

Offering monetary incentives is essential to the growth of the solar markets. Within communities and among residents, we are facilitating a closer alignment with solar parity. The strategic use of adequate financial incentives is instrumental in fostering significant growth in solar installations, resulting in substantial reductions in greenhouse gas emissions(Kornfeld, 2016).

B. Community solar project and shared solar initiatives.

It is possible for solar energy systems to significantly improve a country's energy portfolio if they show increasing economic feasibility in terms of design, delivery, and operating costs. Of the different types of solar power, "shared solar," a community-based system with an array size that falls between a large field and a single residential system, has certain benefits that utility-scale projects might not have. An evaluation of the potential for community solar projects to aid in the shift to a more resilient and sustainable energy future considers several factors, including geography, perceived individual advantages, the reliability of information sources, and project funding(Peters et al., 2018).

C. Off-grid and remote area solutions

Ensuring dependable and economical services is a significant global challenge in the 21st century. While extending the central electricity grid remains the favored approach for rural electrification, extending the grid to geographically remote and thinly populated rural areas may prove financially unfeasible or practically impractical. In such scenarios, off-grid alternatives become a valuable and practical solution(Sen & Bhattacharyya, 2014).

IX. ENVIRONMENTAL CONSIDERATIONS

A. Impact of increased solar adoption on the environment

Sustainable development of human activities is facilitated by solar energy technologies, such as photovoltaics, solar thermal, and solar power, which provide notable environmental benefits compared to conventional energy sources. They might, however, have unfavorable environmental implications if they are widely implemented. Environmentally, these problems include things like visual and acoustic disturbance, greenhouse gas emissions, soil and water pollution, energy use, workplace accidents, damage to sensitive ecosystems or archaeological sites, and positive and negative socio-economic effects during the building, installation, and removal stages (especially for central solar technologies).

B. Sustainability and land use considerations for extensive solar projects

Large-scale solar projects' impact on natural ecosystems and land use sustainability depends on factors like landscape topography, PV system area, land nature, and biodiversity. Construction-related operations may cause landscape modifications and social dissatisfaction due to the emotional connection between cultivators and their land.

C. Habitat conservation and biodiversity protection

Solar energy's planning, building, and operation stages profoundly impact vegetation, soil, and habitats. Central concentrator power systems, which employ high-temperature heat from concentrating solar collectors for power generation in a conventional cycle without burning fuel, may threaten birds (Pitz, 2017). However, practical experience indicates that birds tend to avoid potential danger zones, possibly due to their sensitivity to air turbulence. Flying insects near the reflector's area may face combustion, but the impact on the overall insect population is considered negligible (Tsoutsos et al., 2005).

X. ECONOMIC VIABILITY

A. Economic benefits of solar energy development in regions with high potential

One reliable power source that can provide widespread energy independence and security is solar energy. Individuals' potential and value greatly impact the socio-economic well-being of businesses, society, states, and countries. Compared to other renewable sources, solar energy is one of the most advantageous ways to satisfy future energy demands when considering several characteristics like availability, cost-effectiveness, accessibility, capacity, and efficiency (Kabir et al., 2018).

B. Job creation and local economic impacts

Compared to plants that use traditional energy sources, renewable energy for electricity generation offers a greater potential to create jobs. Renewable energy sources are predicted to create between 1.7 and 14.7 times more jobs per installed megawatt (MW) than natural gas power facilities and up to four times more jobs per plant supplied by coal. In terms of employment creation per dollar invested, the employment impact of renewable energy sources is about 1.4 times higher than that of a coal-fired thermal power plant during the same time (Bribia et al., 2010).

C. Cost-benefit analysis of solar energy projects

The costs and advantages of a project to society are assessed through social cost-benefit analysis. Since solar energy is still in its infancy, examining how it will affect civilization is critical. Solar energy has many benefits, including reduced greenhouse gas emissions, jobs, employment opportunities, rural electrification, carbon credits, renewable energy certifications, and general development. The high cost of solar power generation is a major disadvantage. To ensure solar power's economic sustainability, crucial actions must be taken to lower its cost(Natarajan, 2016).

XI. CHALLENGES AND BARRIERS

A. Technical and economic challenges in regions with lower solar potential

Although solar energy has enormous potential—tens or hundreds of Terawatts (TWs) are feasible—it is inconsistent (Fthenakis et al., 2009)Despite their unlimited abundance, the sun and wind do not always provide an endless supply, and electrical grids cannot function unless they can balance supply and demand. However, to address this problem, large batteries must be created that can compensate for the times when a renewable resource is unavailable.

B. Political and regulatory barriers to solar energy development

Several issues have made it difficult for renewable energy to expand significantly, including the lack of national policies, administrative and bureaucratic roadblocks, inadequate incentives, irrational government targets, and a lack of standards (Moorthy et al., 2019).

C. Public awareness and cultural factors affecting adoption

Accurate information is crucial for empowering consumers and building a sustainable energy system. However, public media often propagates misconceptions about renewable energy sources, and gaps exist in addressing public concerns about renewable energy space(Lucas et al., 2021).

XII. CONCLUSION

Geographical variation in solar energy potential is due to climate, topography, and solar irradiance. Solar energy is untapped despite its abundance due to a lack of governmental policies and incentives. Feed-in tariffs, tax credits, and subsidies can help increase solar energy efficiency in untapped regions. Technological solutions like optics and cooling can also enhance solar systems' effectiveness.

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