Integrating Solar PV into the Main Grid for Sustainable Power Supply

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ABSTRACT

As a sustainable option to meet the rising global demand for energy, integrating solar photovoltaic (PV) technology is essential to achieving sustainable energy goals. This study comprehensively reviews the technological, economic, regulatory, and environmental aspects of solar grid integration, emphasizing practical examples and detailed findings. It identifies critical challenges such as grid stability problems, the intermittency of solar power, and high upfront infrastructure costs and significant advantages, such as lowering GHG emission levels, increased energy access and reduced operating costs. The research approach includes a thorough literature review of more than 204 peer-reviewed articles covering recent advances in solar technology, grid integration issues, economic impacts, and policy frameworks. To facilitate solar PV deployment and maximize its environmental and economic benefits, addressing technical and regulatory barriers, investing in grid modernization and implementing supportive policies are critical. These findings highlight significant opportunities for solar PV to address climate change and energy access, in line with global sustainable development goals. The study concludes that, despite the challenges involved, integrating solar PV into the main grid promises to deliver a safer, more secure and more efficient energy system.

Keywords: Solar photovoltaic, Energy, Electricity grid, Integration, Grid connections, Sustainability, Supply chain

Abbreviation

BSS	Battery Storage System	IEEE	Institute of Electrical and Electronics Engineers
CO2eq	Carbon Dioxide Equivalent	IEC	International Electrotechnical Commission
ESS	Energy Storage System	IRENA	International Renewable Energy Agency
FITs	Feed-in Tariffs	NREL	National Renewable Energy Laboratory
GHG	Greenhouse Gas	RPS	Renewable Portfolio Standards
PV	Photovoltaic	SDG	Sustainable Development Goals

INTRODUCTION

To ensure that the electrification demands of households for energy, water and food to meet, a substantial portion of energy is needed for the electricity requirements to directly support the three sustainable development goals: SDG2, SDG7, SDG13, and indirectly other SDGs [1]. Unfortunately, world energy demand is rising to the detriment of the environment around us. Fossil fuels are being misused in response to energy sector growth. This considerable usage has an impact on climate change and is anticipated to affect the physical, economic, cultural, and political equilibrium of our planet [2], [3]. Ensuring both energy sustainability and the economic and social advancement of the population, it is imperative to adopt renewables, as a key consideration regarding the ongoing shift to green energy [4]-[6]. In light of the present shortfall in basic needs, the increasing requirements of a dramatically increasing population as well as the concerns about climate change, it is necessary to find alternative energy options that can help achieve a sustainable energy transition, as many hundred millions of people are left without electricity access [7], [8].

Worldwide demand of energy is projected to grow by 43% by 2035 [9]. As the global population grows and its development advances, the level of needed energy is skyrocketing. Meanwhile, the production of energy from fossil fuel sources is finite. Therefore, to solve this problem seems to be to create sustainable and unlimited energy by using renewable sources for power generation. Non-toxic, harmless, limitless, and with no CO2 emissions to convert are only a couple of the features that make it such a captivating subject [10]-[12]. Some nations have already begun to substitute conventional fossil fuel generation with renewables to ensure the achievement of SDGs and the reduction of GHG emissions levels [13]. In addition, renewables play a crucial part of the global energy economy and security [14], [15]. Over the years, the renewable energy sector has grown dramatically and is anticipated to keep growing in the years ahead [16], [17].

According to the report of the renewable energy policy network, it shows that worldwide production capacity from major renewable energy sources has risen by nearly 95 times by 2020 as compared to 2007 [18]. IRENA said the global nations installed a historical 260 GW of renewable generating capacity in 2020, up by 50% on the previous year as they lowered their dependence on traditional sources of energy [19]. Wind power and sun energy are regarded as among the important renewables for generating power and have been developing at a rapid speed in the past three decades [20].

At present, clean energy technologies are advancing and proven effective. PV energy is considered to be the most attractive energy option as it is non-polluting and widely available around the world. Solar energy is particularly advantageous in remote locations such as deserts or rural areas, where the difficulty of transporting fuel and the unavailability of power grids make the use of fossil fuels difficult or impractical [21].

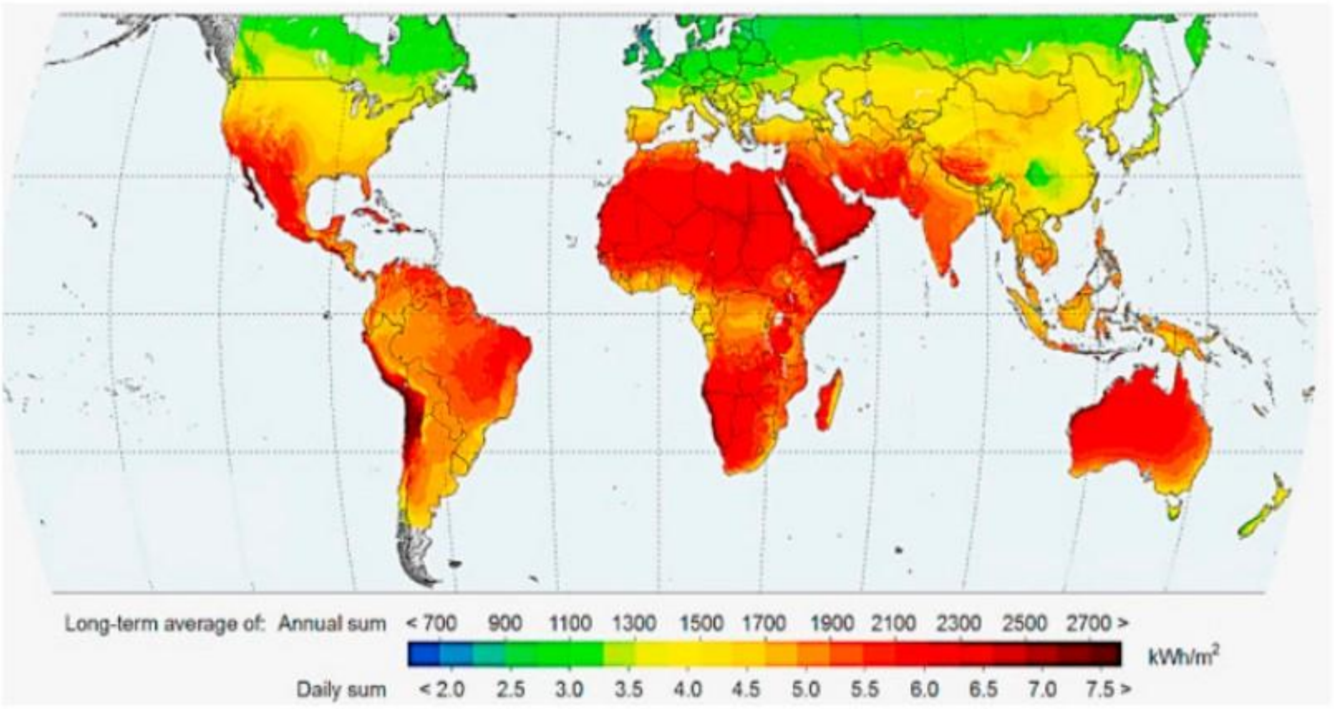

Fig. 1: World solar energy map [23]

By way of comparison, 6.5×10^{20}J of solar energy reaches the earth in 1.5 hours, which is greater than the cumulative primary energy consumption of humanity on the planet in 1 year (~5.4×10^{20}J in 2013) [22]. Fig. 1 illustrates the global region of solar energy potential [23].

In the near future, large amounts of solar energy are expected to be integrated with existing grid systems in most countries. Nevertheless, exploiting solar energy for uninterrupted power supply is still a challenge as it involves the integration of conversion systems with effective storages to compensate for the intrinsic intermittent nature and non-uniform geographic distributions of solar insolation [24]. It is projected that by 2040, PV technologies will be the largest contributor to power generation out of all other renewable energy candidates [25]. In developing nations, there is strong market interest for PV systems in the form of rooftop installations connected to the national grid, which will significantly expand the adoption of decentralized renewable energy [26]. Customer preference for small-scale PV is driven by a combination of steadily rising grid electricity prices and various government incentives making PV attractive and affordable, as well as driving down the prices of PV technology [27].

In recent times, the need to improve solar photovoltaic (PV) generation plants' power conversion efficiency, power quality, and grid integration into the main grid has become necessary. The feed-in tariff relay scheme, which works well for the promotion of solar PV with eligible technologies, could be a challenge for grid system security, power system stability, voltage quality, and other power quality disturbances associated with unpredictable solar power supplies. As countries strive to shift to green energy, the use of solar PV technologies faces technical, economic, and policy-related hurdles. These challenges can hinder the successful adoption of solar energy, impacting network stability, electricity prices, and overall market dynamics. Identifying these obstacles is critical to devising approaches to most appropriately integrate PV into existing grid infrastructures.

The incorporation of PV into the electricity network is important for the achievement of a clean energy supply as it enables renewables to ensure a substantial share in the global energy mix and reduces the dependence on fossil fuel, limiting GHG emissions and promotes greener, more resilient energy generation [28]. Advanced technologies like energy storage and smart grids make it possible for solar power to be more consistent and reliable. In addition, grid integration supports the accessibility and cost-effectiveness of energy and promotes a sustainable economic model for the production and use of energy that is ultimately in line with global sustainability goals. However, large-scale grid-tied PV systems can induce backward power flows that can affect the stability, reliability, and financial viability of the power system, leading to harmful outcomes such as voltage transients and higher power losses. Proper optimization, allocation and use of energy storage system (ESS) can successfully mitigate these drawbacks [29].

This review aims to comprehensively analyse these challenges while assessing the implications of solar PV integration on different aspects of the electricity market. It will assess existing policy and regulatory frameworks, such as net metering schemes and feed-in tariffs, to identify incentives and barriers to solar PV deployment. The study will also explore the environmental, economic and social benefits associated with solar PV integration, highlighting its potential to contribute to climate change mitigation and promote universal access to clean energy. By exploring the synergies between solar PV and sustainable development goals, the study aims to provide policymakers, industry stakeholders and researchers with valuable insights for transitioning to a sustainable energy future.

METHODOLOGY

This study is purely a literature review and hence, does not contain any original results drawn from personal experimentation, surveys, or practical field experience. The data used are mainly quantitative. A total of 204 peer-reviewed articles were used in the review. This review is structured into five major parts. The first part contains an introductory section on solar energy. The second part discusses the overview of PV technology along with related work. The third part of the paper examines grid integration challenges and strategies to mitigate the challenges. The fourth part discusses the benefits of PV integration to the main grid. The paper then concludes in the fifth part with a series of future work and recommendations regarding solar PV integration to the main grid for sustainable power.

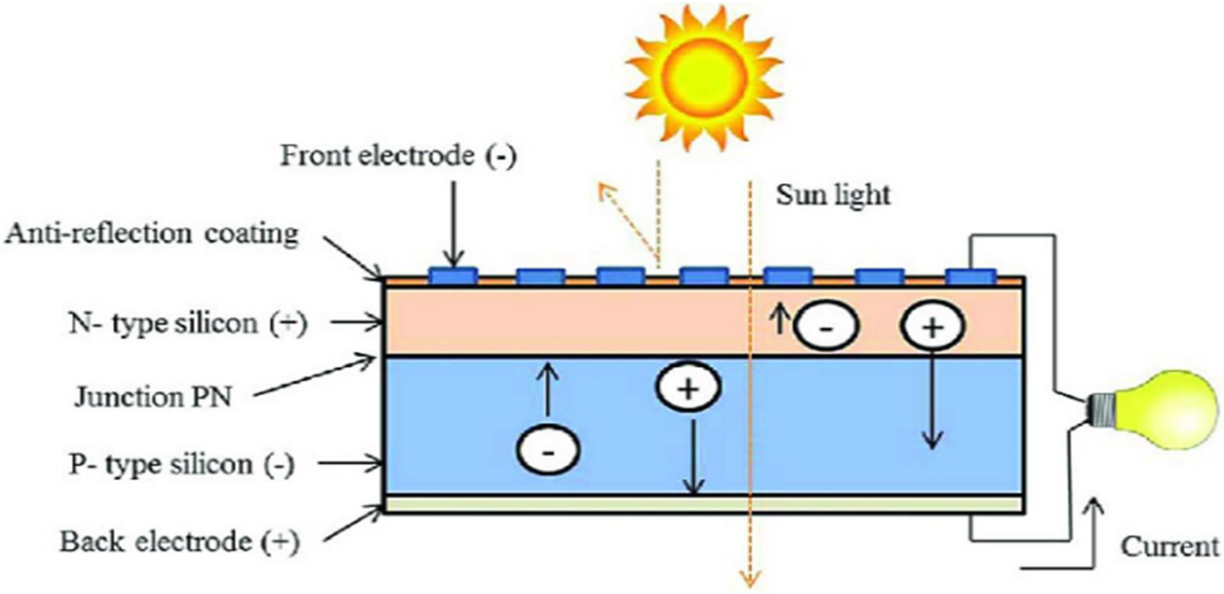

Fig. 2: Semiconductor P-N Junction under Load

LITERATURE REVIEW

A. Overview of Solar Technology

The development of photovoltaic cell technology began in 1839, when Alexandre Edmond Becquerel first documented the photovoltaic effect [30]. A major milestone occurred in 1946, when Russell Ohi produced the first modern silicon photovoltaic cell. Current PV systems predominantly use thin silicon wafers for the conversion of sunlight into electrical energy. As shown in Fig. 2, this progressive technology works based on electron-hole pairing [31].

The key concept behind advanced solar cells is light trapping, which involves designing the cell's surface to capture incoming light within a semiconductor, enhancing light absorption through multiple reflections. Silicon-based PV cells have a layer structure which allows radiation to bounce back and forth between the silicon layer and the surfaces of the cell. Each solar cell consists of two different semiconductor layers that create a p-n junction. When a photon with adequate energy hits this junction, it releases an electron. This electron gains energy from the photon and shifts to another layer, creating a vacancy (hole), that contributes to electricity generation [32], [33].

1) Importance of PV energy: Solar energy is currently the most prevalent among distributed renewable resources. The primary reason for its popularity is that it is renewable and accessible on a large scale almost everywhere in the world [34]. A little computation reveals that the quantity of energy that the earth receives from the sun in one hour is equal to the energy consumed by the world in one year [35]. Unlike nuclear energy, there are no security or military risks associated with solar energy. In contrast with fossil fuels, sunlight is available and abundant in most parts of the world. Like fossil fuels, solar energy is clean and produces very little environmental impact [34]. Achieving SDG 7 and related synergies will face significant challenges in improving energy access in remote, off-grid areas where, despite progress in urban areas, electricity access and security are low or nonexistent [36].

2) Global Status of PV Deployment: Despite national and regional variability, accessibility to cheap, safe and clean energy is increasing: By the end of 2021, 91% of the global population had access to energy, up from 87% in 2015, when the SDGs were initiated, thanks to the rapid adoption of cost-effective on-grid and Off-grid electrification schemes [36]. There are inequalities within and between countries, leaving 745 million people lacking electrification, with vast majority living in remote areas, where the electrification rate is around 80 %, compared to 97 % in urban areas [36], [37].

The installed global PV capacity increased by a record 407 GW in 2023, bringing the cumulative worldwide PV capacity to 1,589 GW by the year-end 2023 [38], [39]. This continued the record-setting trend of PV installations from 2007 to 2023 set a record for new installations as demonstrated in Fig. 3 [38].

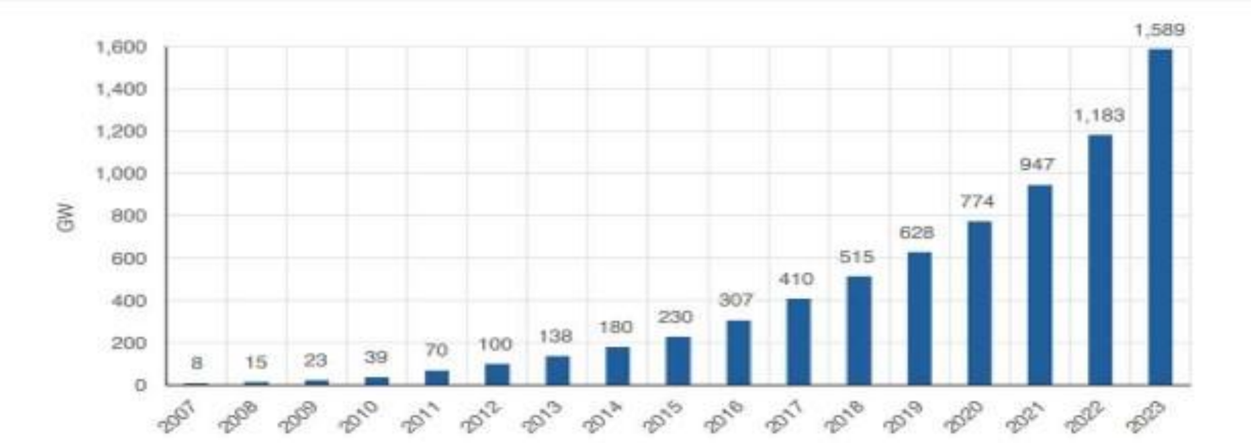

Fig. 3: Illustration of PV Installations from 2007 to 2023 [38]

B. Types of Solar PV Systems

PV system is in three form which include grid tie, off-grid and hybrid systems.

1) Grid tie solar system: Grid connected PV systems are those that use solar photovoltaic panels for the generation of electricity and its supply to the grid [40]. Grid-connected systems consist of solar panels, an inverter, a meter, and a grid. Solar panels produce direct current, which the inverter converts to alternating current that can be used by appliances. Excess power is sold back to the grid and paid for by the grid operator. Electricity from the grid can be used at night or in bad weather when there is not enough solar power [41]. On-grid solar has the disadvantage of not being able to store electricity in certain weather conditions or during a power outage [42].

The drawback of the grid-supplied systems is the fact that they can only be operated in the daytime. It cannot store power for future use, such as during a power outage. Although it is possible to address this disadvantage by incorporating a battery pack to stores the electricity being generated throughout the day, this new feature will ultimately contribute to the overall costs of the system [43]. Fig. 4 shows a schematic residential grid-connected PV system [43].

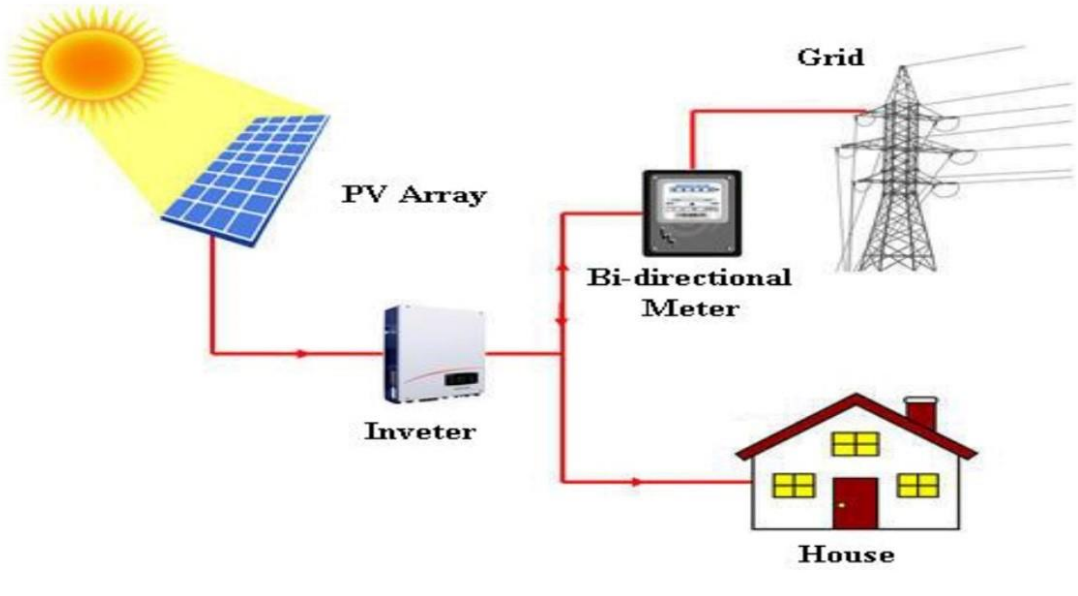

Fig. 4: Schematic residential grid-connected PV system [43]

2) Off-grid solar system: Off-grid solar energy system, also called a "stand-alone" system, has battery storage [41]. Off-grid solar power converts solar radiation into electricity, which is converted by an inverter into an alternating current. Excess electricity is stored in batteries to provide backup power when solar power is not available [44]. However, when the electricity demand is high and there's insufficient solar power or battery power, it becomes impossible to meet the demands. A straightforward scheme for a PV standalone system is shown in Figure 5 [45]. Thus, off-grid solar systems are more beneficial for people residing in isolated locations without access to the main grid.

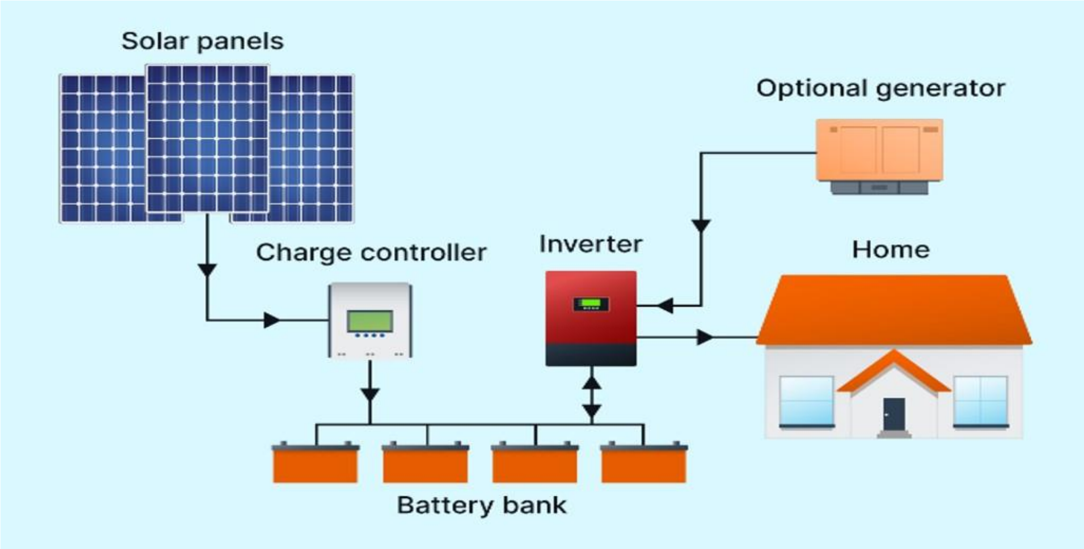

Fig. 5: Off grid pv system [45].

3) Hybrid PV system: A hybrid system is a combined on-grid or off-grid PV system. By storing energy in batteries for use at any time without drawing from the grid, this system is convenient to use and reduces electricity costs. How the hybrid photovoltaic system works: Throughout the day, sunlight is converted into electricity. In a similar way to an off-grid system, any excess power is stored in the batteries. If there is an excess of stored electricity, it is fed back into the grid [46], [47]. The batteries can provide power in the absence of solar or grid support. Similarly, if there is insufficient battery backup and no solar power, uninterrupted power can be drawn from the grid and the battery can be charged [48], [49]. To eliminate the drawbacks of on-grid and off-grid PV systems, a hybrid PV solution can be used rather than these two energy generation approaches [50], [51]. Fig 6 show a possible hybrid power system schematic [52].

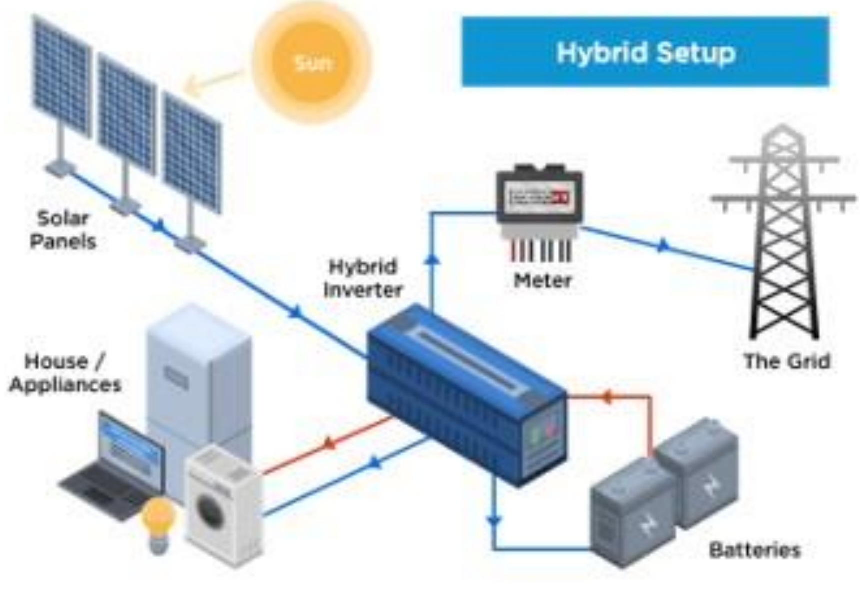

Fig.6: Possible Hybrid Power System Schematic

C. General information on the incorporation of PV into the grid

An electricity grid, also known as the power grid or electrical grid, is a complex network of inter-connected components that generates, transmits, and distributes electricity to consumers. The main components of a typical electricity grid consist of Power generation, transmission system, transformer substation, distribution system, and loads [53].

Due to the difficulty of storing electrical energy, it is consumed at the same time as it is produced, so we are constantly faced with a balance between production and consumption [54]. An electrical network must also ensure the dynamic management of all production - transport - consumption, implementing settings aimed at ensuring the stability of shared electrical quantities such as voltage and frequency which must be maintained within acceptable margins according to a standard [55].

1) Grid synchronization: There is an increasing research focus on PV systems connected to the smart grid, where a better comprehension, detailed analysis, and critical assessment of both regular and irregular grid operation is required. Appropriate grid synchronization requires compliance with four critical factors: phase-sequence, phase, voltage, and frequency [56], [57]. Fig. 7 shows a traditional grid connected PV system that uses a series of advanced power electronic inverters to effectively capture the greatest amount of energy possible out of the PV resource and deliver it to the grid.

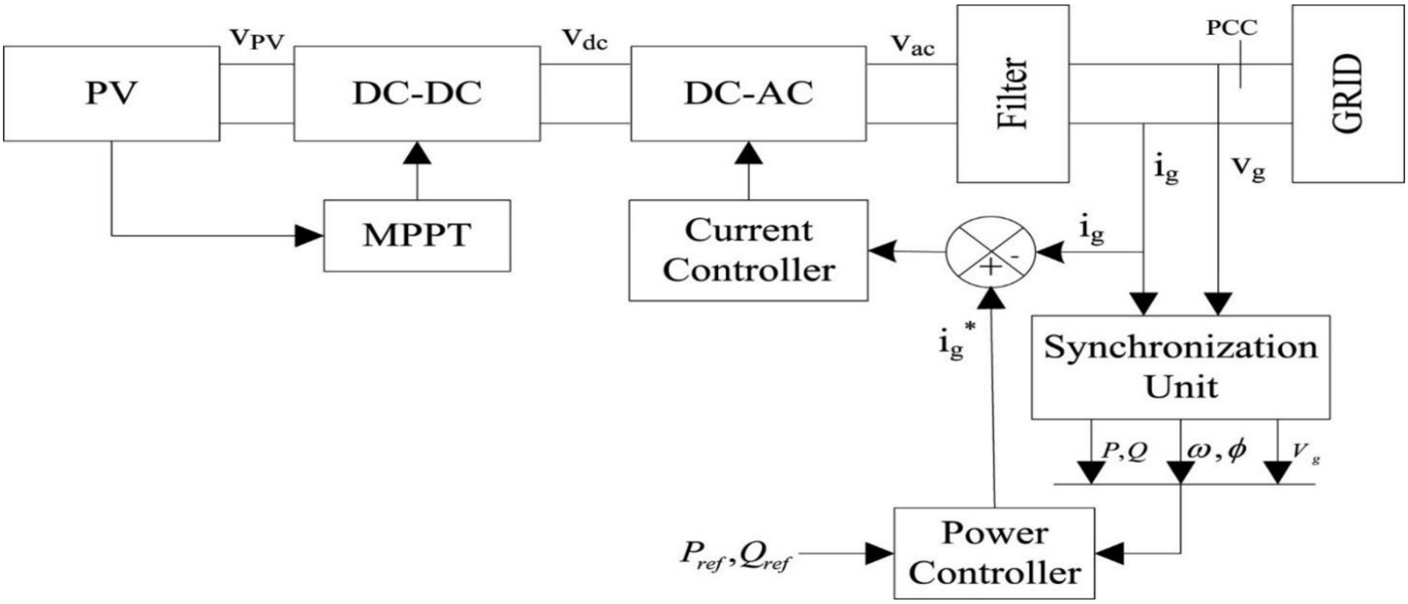

Fig. 7: PV Based Grid Tied System

Solar PV outputs (vpv) are low DC and need to be raised for multiple application using a DC-DC converter. The DC-DC converter are mostly used to track the MPP on the I-V curve. The DC to AC inverter converts DC to AC for grid-connected power appliances. Switching frequency harmonic generated by grid-connected inverter [58]. The intermediate filter is used to manage the inverter current and prevent harmonics from the switching frequency from reaching the grid. Since the injection of current into the grid is critical to the efficiency and integrity of the system, this ensures efficient grid integration.

Grid-connected inverters need to be synchronized with the grid so that the inverter can deliver the correct quantity of power even when the grid is fluctuating [59]. In a PV grid interconnection, the utility is responsible for controlling the voltage output of the inverter, with the inverter using a current controller. For grid synchronization and grid supervision, accurate measuring of phase, amplitude, and frequency is essential [60]. The synchronization control algorithm is critical for controlling the inverter and synchronizing it with the grid. It is responsible for assuring that even if the grid voltage phase, frequency, and amplitude vary, the inverter will be able to deliver maximum power to the grid. It has to monitor grid voltage signals, react to changes and suppress harmonics [61], [62]. The inverter output voltage must be synchronized with the grid voltage to avoid distortion and transient phenomena that can impact stability, safety and continuity.

2) Benefits of incorporating PV into the main grid: Grid-tied solar PV systems generate electricity on the consumer's side, so that the electricity is delivered to the appliance most efficiently, and in many situations, the generating behavior of the solar PV system matches the usage behavior [53]. Both utilities and end-users are attracted to distributed generation systems because of the benefits of grid-connected PV but from different perspectives. Utilities are motivated by grid-connected PV because it allows them to harvest power from their existing grid and sell it to their customers. Large-scale PV on the grid is perceived by many utility companies as a means of offsetting traditional grid expansion [63]. The advantage of grid-connected PV from the point of view of electricity consumers is that they can take advantage of standby or backup generation.

D. Review of Related Works

Interest in research and developments in PV systems is stimulated by the increasing potential of solar energy around the world owing to plentiful sunlight and the drive to reduce CO2 emissions from power generation systems. This huge potential has led to significant investments in PV research and integration into existing grids, as well as an enormous growth in energy demand and usage, which is expected to reach 41% by 2035. Firstly, sun shines differently in different parts of the world due to latitudinal differences. Also, the amounts of insolation that reach the earth's surface are reduced by natural seasons and cloud cover. Suri et al. [64] found out that cloudy weather greatly affects the output of larger PV farms, and that fluctuations in the cloud cover lead to variations in the output power generated by the PV plant.

Paulescu et al. [65] discuss how to model the installations to enable better operation under varying atmospheric conditions. Consequently, when examining the effects of incorporating solar into a main power grid, it is very essential to account for the fluctuating cloud cover as an influential factor in power generation. In other words, it is a challenging aspect for utilities as well as transmission and distribution system operators as the integration of PV power is rising all over the world. At both transmission and distribution levels, the effects of the integration are not completely understood. Also, Shaha et al. [66] report the technological problems related to integrating PV on a large scale into electricity networks, such as stability issues, power quality, harmonics, dynamic modelling, and grid codes. Depending on the grid structure and the distance from the main power source, integrating PV may increase the voltage level and profile. It further summarizes the results of research on technical solutions to address such challenges, especially in a comprehensive manner for transmission and substation or medium-voltage distribution networks. Al-Sabounchi et al. [67] investigated the potential impact of integrating PV into UAE's main grid by studying two utility-scale pilot plants with capacities of 9 kW and 36 kW. The study emphasized the importance of carefully selecting the installations site and size of the PV based on the electricity requirements of customers and the generation patterns of the PV output. It was noted that the nature of the grid, its layout, and the costs associated with transmitting and distributing the generated electricity can differ from one region to another. This suggests that the considerations for integrating solar power into the grid should take into account the specific characteristics and needs of the local area.

According to studies conducted by Widen et al. [68] stated that the increasing utilization of PV systems presents unique difficulties in system modelling and simulation. With the rising implementation of distributed photovoltaic generation in residential areas, it becomes crucial to comprehensively analyze its impact on distribution grids. The study presents a stochastic method that employs intricate generation and demand models to replicate the effects of PV generation on low-voltage networks. The study utilized a methodology that involved power flow analyses using MATLAB in three low-voltage networks in Sweden. Its purpose was to assess load adjustment, voltage levels, and network losses under various PV penetration rates. The findings indicated that the integration of PV led to enhanced on-site demand response, alleviated voltage drops, and decreased losses on the network. Similarly, Chowdhury and Khan [69] presented the modelling and assessment of the performance of a PV system connected to an integrated IEEE 14 bus network using the software MATLAB/SIMULINK. For various irradiances, load magnitudes, and load types, evaluate the efficiency of the planned electrical grid. Simulation is performed about voltage swing and harmonic distortion at the point of common coupling to investigate the impact of PV integration on major grid quality characteristics.

Celvakumaran et al. [70] analyzed various scenarios to assess the impact on power quality. The results suggested that careful consideration is needed when designing net metering policies to avoid potential power quality issues in the distribution network. The study recommended the implementation of proper grid codes, technical standards, and guidelines for the seamless integration of PV into the grid. Additionally, they proposed the use of advanced inverters with grid-supportive features to mitigate the adverse effects on power quality caused by high penetrations of solar PV. This study highlights the importance of proactive measures to maintain power quality and grid stability in the context of increasing solar PV integration through net metering schemes. Also, Shafiullah [71] explored the harmonics associated with integrating renewables into the distribution network. This study assessed the harmonic effects of renewables integration at penetration levels of 0%, 50%, and 100% for solar PV, as well as hybrid combinations with wind energy at 50% and 100%. The results revealed that higher levels of renewables penetration led to increased harmonic distortion. Specifically, at 100% PV integration, the current harmonic distortion exceeded standard limits, while voltage harmonic distortion remained within acceptable thresholds.

Eni et al. [72] examined the opportunities, perspectives, and challenges associated with generating electricity from PV at scale, demonstrating how decreases in the release of greenhouse gases of 1975.70 and 3590.03 lb/day can be accomplished with solar energy integration rates of 10 and 20%. The findings of the investigation revealed that the shift to clean and sustainable power generation via utility-scale PV can mitigate the impact of GHG emissions and the diversification of power sources. A study by Widén et al. [73] analyzes the incorporation of PV into the grid. The study aims to demonstrate the impact of the voltage level on integrating PV into Sweden's grid. Three networks were the subject of the studies and had an impact on the voltage increase at the bus. Two of the three networks had voltage spikes but no variation, and one had an over voltage on a couple of buses. In addition, the study by Walla et al. [74] To quantify the capacity to accommodate solar photovoltaic (PV) generation in the Swedish electricity distribution networks. Three grids, which belong to the Swedish distribution network operator “Fortum”, are modelled and simulated in a Matlab environment. The results show that Swedish grids can accommodate high PV penetration. For the rural and suburban grids, an acceptance capacity of 60% of the PV electricity generation as a fraction of the annual load has been determined. The study also demonstrated that the voltage profile is not the most important factor in determining the maximum intrusion level. In addition to voltage level and profile, other six parameters, such as the loading and losses of the lines, need to be considered when establishing the capacity of the networks. Lelis et al. [75] evaluated the overvoltage concerns associated with the increasing PV incorporation into the grid. The study employed an iterative power flow solution algorithm in the distribution networks. The results indicated that the overvoltage situation could be mitigated by the reactive power control mechanism. Also, You et al. [76] examined a variety of strategies to achieve improved frequency response without restricting PV generation on the “US Eastern Interconnection network and the Texas grid”. In addition to exploiting available grid resources, the authors investigated energy storage devices to improve the frequency response of photovoltaic systems even in the presence of large amounts of solar energy. The implications and management measures for improving frequency stability will be critical as the proportion of intermittent renewables increases in years to come, resulting in a reduction in system inertia. Therefore, further research is needed to properly mitigate its effects in this area.

Murdan and Jeetun [77] described the layout and implementation of a PV connected to the grid. It is modelled on a client participating in a 'net metering' program so that the output of the system can be benchmarked against that of a typical client. Simulations show that PV excess production can be fed to other clients connected on the same phase, leading to significant savings. The benefits of net metering are emphasized, as is the possibility of supplying any surplus generation to a second subscriber in the same phase. The study suggests that if the scheme is extended over a macroscopic scale, it could lead to a greener future for the planet.

Adams et al. [78] stated that the judgments of governments and policymakers are crucial in shaping energy growth outcomes. Using a Westerlund panel-based error-correction test for thirty countries in sub-Saharan Africa, they found that countries with more stable governments had a higher percentage of renewables in their energy mix. This is likely to be because stability provides for improved policies that favour the development of the power sector. In a similar view, da Silva et al. [79] argued that providing green certificates, quotas, and direct investments would be useful to promote renewable energy development, especially in rural areas, where income and wealth levels are low.

To guide decision-makers, researchers, and novices in the field of grid integration of solar energy, a large number of reviews have been published in reputable journals. Most papers merely discussed and reviewed the technical challenges and solutions associated with the grid integration of solar energy. Others have tackled more targeted challenges like power forecasting, fault resilience, protections, and grid code standards. The goal of this study is to fill important technical gaps in the utility grid integration of PV. It examines advanced technology solutions, such as demand response plans, that maintain grid stability in the face of solar intermittency. The study will also examine the development of energy storage technologies to alleviate PV intermittency and enhance grid efficiency. The need for standardized grid integration protocols will be explored to ensure that distributed PV systems are compatible with existing infrastructure. The study also explores the use of smart grid technology, including advanced metering and data analytics, to optimize PV integration.

PV GRID INTEGRATION CHALLENGES

The challenges of PV grid integration can be divided into technical, economic and regulatory challenges that need to be addressed to realise the full potential of PV energy [80]. Technical difficulties include voltage variations, frequency variations, grid instability, flicker, harmonics, and control issues [81]. The implications of these technical issues largely result from size, as small-scale PV installations are usually suitable for distribution grids, whereas their large-scale equivalents are often designed for the transmission network. For example, for small-scale PV systems on the distribution grid, voltage regulation issues are often considered to be the most crucial technical issues. Several prominent research works that have addressed some of these concerns, and the application of mitigation strategies were highlighted.

A. Technical Challenges

1) Voltage Regulation: Given the intermittency of PV generation, injecting huge amounts of PV into the electricity grid distribution network will result in variations and imbalances in the voltage profile. Given the frequent changes in weather conditions, the voltage variation on the distribution network is susceptible to sudden swings, which can lead to malfunctioning of the voltage regulating units [82], [83]. In addition, due to climate change, the PV system may cause a variation in irradiance for either a long or short duration, affecting the PV system's voltage output at the point of common coupling. The distribution system voltage problem caused by connecting large numbers of PV systems could be categorized as voltage imbalance, and flickering in the network [84], [85].

2) Power Quality Challenges: Power quality is a major worry for utility companies, particularly harmonic distortion in distribution networks. By integrating PV into the electric grid, there is a large amount of power electronics equipment which is a source of harmonic injection into the grid. Harmonic distortion is a significant challenge to power quality. It can arise from using converters to convert DC to AC [19], [86]. Power quality indices are measures of the distortions of the voltage and current waveforms about an idealized pure sinusoidal waveform. Typically, harmonics are the consequence of the switching lag of the converter, which is considerable if the output power of the PV varies [87]. In capacitor banks, this may cause parallel and series resonances, overheating, and malfunction of protective equipment. Harmonic current generation is a common problem in PV systems and can increase total harmonic distortion at common interconnection points [88], [89]. The experience of operating a large PV installation shows that although the distortion of the output harmonics is minimal for a single inverter connected to the PV grid, in the event of several shunt converters, the harmonics can be significantly higher than the normal standards [90], [91].

3) Frequency response: Synchronous generators in traditional power systems provide natural inertia, allowing them to respond instantly to changes in power flow, stabilizing frequency fluctuations [92]. However, solar PV systems lack this inertia, making the grid more susceptible to frequency instability, especially during disturbances or demand spikes. Without adequate inertia, the grid faces an increased risk of frequency deviations, leading to system faults or outages [93].

Also, the imbalance between the generation and the demand may cause the frequency of the networks to fluctuate, resulting in a temporary or permanent failure to supply electricity [94]. As more intermittent photovoltaic systems become more prevalent in the coming years, improving frequency response will be key to reducing system inertia [95], [96].

4) Reactive Power Support: Reactive power availability is tightly correlated with voltage levels and monitoring the voltage stabilization of the electrical network [97]. Unlike traditional power sources like coal or natural gas plants, PV power does not have any inherent reactive power. Reactive power is needed to balance voltage levels on the grid, absorb variations, and ensure smooth power flow. Without reactive power, the grid faces voltage instability, which can cause power quality problems, inefficiency and potential blackouts. This need must be addressed to guarantee the successful and efficient integration of PV-generated electricity into the grid [89], [98].

5) Islanding (Protection challenges: A condition known as islanding is one of the most critical concerns for the safety of customer-sited small PV systems. Islanding happens if a part of the supply system, containing both the loads and the generating unit, is disconnected from the main supply system but still energized. When this occurs with PV, it is termed PV-assisted islanding [99]. The security worry is that an island created by a PV system is beyond a utility's control, although it can be assured that its generation sources are disconnected or shut down from areas in need of work [100]. An unintended consequence of islanding is that a utility operator may be exposed to an unexpectedly energized line. Therefore, inverters with built-in anti-islanding capabilities are essential [100], [101]. Grid-connected inverter systems are capable of monitoring the grid and shutting down as rapidly as possible in the instance of an anomaly in the grid. An islanding event is the last intervention to recover a grid before it collapses. Fig. 8 illustrates the layout for islanding detection, where the coupling point is the interface between the PV inverter and the grid [102]. Integrating a PV into the utility grid requires a substantial re-evaluation and possible modernization of the overall protection scheme. This is due to the intrinsic shortcomings of traditional protective apparatus, which is simply not suited to the detection of PV system faults [103]. The fluctuating generation and voltage/current characteristics cause significant changes in fault current. This change creates a significant challenge for traditional protection devices, requiring improvements to efficiently handle the unique nature of PV system faults [91], [104]. The incorporation of PV energy into the electrical grid tends to improve overall performance and stability. At the same time, it poses a possible constraint in the way of an enhanced short-term current contribution in the instance of a grid fault [105]. Although electrical networks usually employ safeguards to protect against such faults, integrating PV changes the behaviour of the system, potentially compromising the effectiveness of these safeguards. Despite the existence of rapid-response safety features in grid-connected converters, it is essential not to overlook the inherent risk [42].

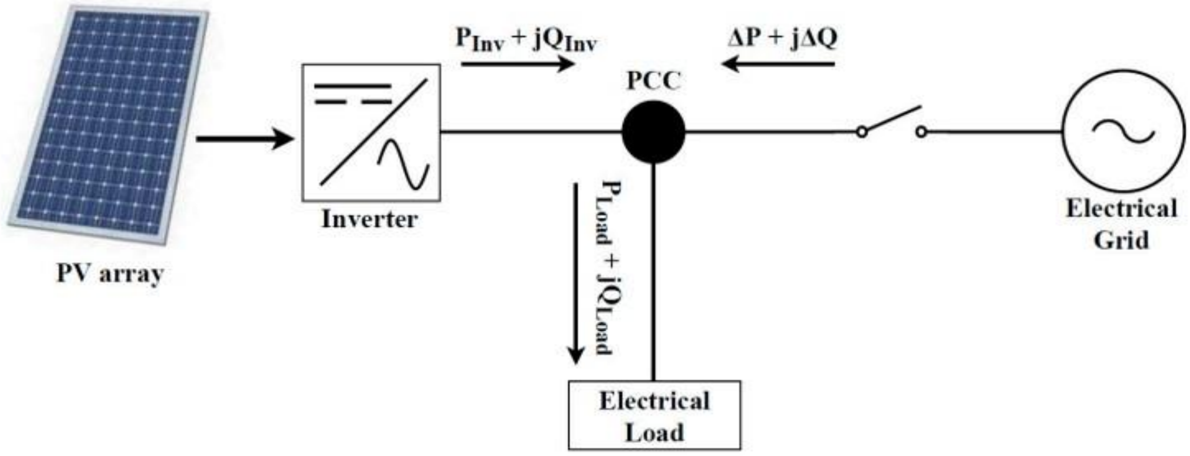

Fig.8: Illustrates a Common System Layout for Islanding Detection

6) Line loading and Losses Challenges: Very critical characteristics of a power system are losses and line load. Both parameters can change with the injection of PV into a grid. Distribution lines and feeders have a maximum load. Furthermore, these losses can expand or decrease the cost of operating a grid [106]. According to Widén et al [73], grid losses tend to decrease at lower PV penetration and show increasing grid losses with increasing penetration. Nevertheless, the likelihood of reverse power flow in a radial grid is associated with the increase in grid losses with rising penetration. The reason for this is that reverse power flow leads to an increase in the load on the feeder lines and hence losses. It could also affect the functioning of the protective equipment in the network [107].

7) Impact of Large-Scale Penetration: To address the increasing energy needs of the world and to ensure ecologically sustainable growth in electricity generation, solar energy is essential. However, the dependability, security, and stability of the entire electric network can be jeopardized if solar energy is widely generated and fed into the electricity grid without appropriate control measures [108]-[110]. PV-based generation has now emerged as an essential part of the grid, just like any other traditional power plant, and further small plants of several hundred megawatts or more are being built, as penetration into the grid increases all the time [111]. There is still no dedicated grid support control, however, and the units are frequently turned off during grid disturbances that are likely to affect the grid.

B. Technical Solutions to solar Integration to the main grid

1) Codes and Standards: Grid codes are a series of requirements that all grid-connected facilities must meet to ensure stable and economic grid operation. Enabling the transmission and reliable distribution of power over the grid network, Setting standards for technical, operation and efficiency by network operators and regulators [112]. The first step in overcoming the challenges of grid integration is to ensure that the requirements set out in the grid code are strictly adhered to [113], [114]. The main standards and safety organizations dealing with PV are International Electrotechnical Commission, Institute of Electrical and Electronics Engineers, Underwriters Laboratories, and National Renewable Energy Laboratory. In formulating interconnection guidelines and rules, most utilities around the world have accepted IEEE Standard 1547-2003 titled “IEEE Standard for the Interconnection of distributed-resource systems with Electric Power Network, 2003” [115], [116].

2) Advanced Energy Storage Solutions: Recognising the intermittencies of PV generation, an effective strategy to ensure a more consistent flow of energy is the deployment of storage systems such as battery storage, hydro pumped storage or thermal storage. These systems not only contribute to mitigating the intermittency of the PV system, but also provide valuable support to the grid in terms of voltage stability and frequency control. The deployment of energy storage technologies is emerging as an important strategic approach to improving the resilience and performance of PV Integrated into the main grid [117], [118]. In addition, grid operators can better anticipate periods of high solar generation and more effectively manage grid stability through advanced forecasting and predictive analytics. This strategy improves the integration of solar energy, enables its efficient use, improves grid reliability and reduces overall electricity costs.

3) Smart Grid Technologies: The use of smart grids offers an increasingly efficient and effective approach to the challenges posed by integrating solar PV into the main grid. Critical to the integration of PV systems are smart grid technologies that improve the flexibility, stability and responsiveness of the grid to the variable nature of solar power [119]. This technology uses digital communications and automation to monitor and manage power flows on an instantaneous basis so that power generation can be adjusted quickly to meet weather and diurnal variations. Advanced metering infrastructure provides real-time data on the generation and consumption of energy, enabling operators to identify and resolve problems quickly. This allows utilities to match demand to solar output and reduce the need for backup generation by adjusting power usage during periods of high solar output or grid congestion [120]. Smart inverters designed specifically for PV systems provide reactive power support and voltage regulation. This helps maintain power quality and mitigate instability.

4) Forecasting and Prediction Techniques: Forecasting and prediction techniques help integrate PV systems into the power grid and improve solar power generation prediction. Since PV generation is variable and dependent on weather conditions, accurate forecasting helps to better balance supply and demand [121]. Forecasting technology based on statistics, machine learning or satellite imagery is useful for real-time network management. Advanced machine learning models, such as neural networks and ensemble learning techniques, can handle complex weather patterns and improve forecast accuracy [122]. Long-term forecasting, from weeks to months, supports the planning and scheduling of network maintenance and the management of renewable energy. This helps optimise resources and reduce costs. Hybrid approaches, combining numerical weather prediction models with real-time data from PV systems and sensors, improve accuracy and reliability, allowing grid operators to predict the variability of solar output. By reducing power imbalances and blackouts, these technologies will allow for better load balancing and greater stability of the grid.

5) Deploying small solar farms: Small solar farms distributed across a wider geographic area can help reduce the strain on the main grid by generating electricity closer to where it is needed [123]. This can help alleviate congestion on transmission lines and reduce the need for costly grid upgrades. Additionally, small solar farms can be strategically located in areas with high solar potential, which can help optimize energy production and reduce the variability of solar energy output. This can help to smooth out the intermittency of PV generation and make it easier to integrate into the main grid. Deploying small solar farms can also provide benefits such as voltage support, reactive power injection, and frequency regulation, which can help improve the overall stability and reliability of the grid [111]. Overall, the deployment of small solar farms can help to address the technical challenges of integrating solar into the main grid by reducing transmission constraints, optimizing energy production, and providing valuable grid services [124].

C. Economic Challenges of Integrating Solar into the Main Grid

1) Grid Integration Costs: One of the primary economic challenges is the cost of integrating solar PV into the existing grid infrastructure. This can include the costs of upgrading transmission and distribution lines, installing advanced inverters and control systems, and expanding grid-scale energy storage capabilities [125]. A study by the NREL estimated that the grid integration costs for solar PV could range from $0.15 to $7.30 per watt, depending on the level of solar PV penetration and the specific grid characteristics [126]. These integration expenses can pose a formidable barrier to the adoption of solar PV technology by individuals, businesses and governments.

2) Capacity Utilization and Overcapacity: The high capital costs of solar PV systems, combined with their relatively low capacity factors (typically around 15-25% for utility-scale solar), can lead to concerns about overcapacity and underutilization of the grid infrastructure [127], [128]. This can result in higher per-unit electricity generation and distribution costs, which can be passed on to consumers. Addressing this challenge may require innovative approaches to grid planning, asset utilization, and market design.

3) Intermittency and Variability: The intermittent and variable nature of solar power generation presents a significant economic challenge for grid integration [129]. Solar PV output can fluctuate rapidly due to changes in cloud cover, weather patterns, and time of day, which can create supply-demand imbalances and increase the need for ancillary services, such as quick-ramping conventional power plants or grid-scale energy storage [130]. These variability-related costs can be difficult to quantify and can differ greatly based on the utility's network and market constraints.

D. Strategies to mitigate the economic challenges

1) To address the grid integration cost, through investment in grid modernization and development of ESSEM, smart meters, and grid management software that can efficiently handle the fluctuations in solar energy production [131]. Utilities can improve the integration of solar energy into the grid, thereby reducing the need for costly grid upgrades and improving overall grid stability and performance, by investing in modern grid infrastructure [132]. In addition, policies and regulations can compensate for some of the integration costs and promote the deployment of a greener and more resilient energy system by incentivizing or mandating the integration of renewable energy sources into the grid.

2) Addressing capacity utilisation and overcapacity through the implementation of dynamic pricing structures, to incentivize solar owners to match their generation to peak periods of power demand on the grid and reduce the risk of overcapacity [133]. This includes the implementation of ESS options such as batteries. ESS can help compensate for the intermittency of PV power generation by storing surplus energy during peak production periods and delivering it when demand is higher [134]. This can ultimately improve the integration of PV into the main grid by optimizing the use of PV energy and reducing the risk of overcapacity [135].

Additionally, energy storage can provide grid stability and support in times of high demand or unexpected fluctuations in solar energy output.

E. Regulatory and Policy Framework

The move towards sustainable energy sources is accelerating, with renewable technologies playing a critical step in this transition [136]. Integrating solar PV into the main grid presents immense opportunities for sustainable power generation. However, this integration requires a robust regulatory and policy framework to ensure PV's successful and efficient grid inclusion.

1) National and International Standards for Solar PV Integration: National standards serve a critical purpose in enabling the quality, safety, and performance of solar PV systems. Several countries have established specific national standards that outline the technical specifications for connecting PV energy to the grid [137], [138]. These standards cover aspects such as electrical safety, grid compatibility, and performance standards. IEEE-1547 sets technical standards for connecting distributed energy resources like PV to the grid [138]. The standards address concerns such as voltage control, islanding protection, and power quality to ensure that distributed generation can be integrated without compromising grid stability [139]. Adhering to national standards is vital to ensure the secured integration of PV into the grid.

International standards provide a common framework for PV connection to the grid. In addition to national standards, organizations such as the International Electro-technical Commission (IEC) have developed standards that unify the requirements for integrating PV into the main grid worldwide. IEC 61724 provides guidelines on the monitoring and performance analysis of grid-connected PV installations [140]. Additionally, IEC-62109 addresses the safety of inverters for use in PV systems. It sets out requirements for the design, construction and testing of PV inverters to reduce the risk of electrical and fire hazards [141]. IEC-62446 provides guidelines for installing, inspecting and maintaining PV grid integration. It covers aspects such as how to design the system, how to commission the system, and how to document the system [142]. Adhering to international standards ensures interoperability, reliability, and smooth grid integration of solar PV systems across different regions, contributing to the global harmonization of solar PV integration practices.

2) Grid Code Requirements and Compliance: Grid codes define the requirements for connecting power generation facilities, including PV, to the main grid [143]. They include aspects such as voltage regulation, frequency control, fault ride-through capabilities, and reactive power support [144]. Grid code compliance is essential for solar PV systems to contribute effectively to the main grid without causing disruptions or compromising grid stability [144].

Compliance with grid code requirements is a critical aspect of integrating solar PV into the main grid. Solar PV systems must demonstrate compliance with grid code requirements during the design, installation, and operation phases [145]. This entails ensuring that the technical characteristics of PV systems are in line with the grid code specifications. Compliance testing and verification processes are necessary to confirm that the solar PV systems can operate following the grid code requirements [145]. Adhering to grid code compliance measures is essential to ensure the proper incorporation of PV into the main grid while ensuring the stability and security of the grid.

3) Policy Recommendations for Promoting Solar PV in the Main Grid: Renewable energy policies are a vital component of any country's commitment to shift towards a clean energy system. With the increasing focus on integrating solar power into the main grid, governments need to implement effective policies that support the growth of solar energy while also ensuring the stability and reliability of the grid. Supportive policies, such as feed-in tariffs, investment tax credits, renewable portfolio standards, net energy metering, green certificates, capital subsidies, and national renewable energy targets, facilitate mass deployment and grid integration [146], [147].

Net Metering Policies: Net metering is a payment scheme that rewards consumers for energy generated and injected into the grid. During the billing period, the bills of the prosumers are usually credited in kWh of energy. If their systems generate more than they consume, their electric meters run backwards, causing them to purchase less electricity from the utility [148]. Net metering schemes can include simple net metering, buy-pack, rolling credit, or rolling credit and buy-back. Simple net metering does not provide credits or payments for excess energy, while buy-pack pays for excess energy at a rate below or above the market rate. Rolling credit and buy-back schemes provide monetary credit for surplus energy [149][143]. The net metering schemes can have several different remuneration approaches to take account of the value of the energy produced by the prosumers' facilities.

Renewable Portfolio Standards (RPS): RPS are regulations that mandate a certain share of electricity in a given jurisdiction to come from renewables. RPSs are put in place to encourage the evolution and usage of renewables, such as solar, and to help limit GHG emissions [150]. Renewable portfolio standards have been implemented in several countries and states, with varying levels of success. Some studies have shown that RPS can lead to a decrease in overall electricity costs and an increase in renewable energy generation. However, there have also been challenges in implementing RPS, including concerns about the cost of compliance and the impact on electricity prices for consumers. One specific area where RPS has been particularly impactful is the integration of PV into the main grid [151], [152]. Solar PV is an increasingly popular renewable energy source, but its intermittence can pose difficulties for utility operators in managing fluctuations in electricity generation. Renewable portfolio standards help deploy renewable energy and speed up the transition to green energy [153].

Feed-in Tariffs (FITs): FITs are fixed prices, based on the actual cost of generating electricity from each technology, for purchasing a unit of green energy. These tariffs are often granted for 15-20 years and compel the grid operator to procure all energy from renewables, irrespective of the overall energy demand. FITs are financed through a minor increase in retail electricity prices, with the extra cost shared amongst all ratepayers through national cost-sharing schemes [153]. The effectiveness of FITs hinges on a high level of investment certainty, as it lowers the volume/ price risk for investors and eliminates the balancing risk for renewable electricity producers [151]. FITs offer a technology-specific approach, allowing policymakers to promote costly but high-potential technologies like solar PV and wind energy. However, FITs have some disadvantages, such as not conforming to competition and hindering technological learning [143]. Tariff degressions and periodic reviews of the tariff level can help to address these issues. Network compensation problems and increased network operating costs can also result from a purchase obligation.

Tax and Investment Incentives: On the question of government policy, Destek [154] regarded economic incentives, such as tax breaks and subsidies, as an important way to attract investors and increase investment in renewables deployment. In the 1980's and 1990's, investment subsidies, tax breaks, tax credits, and low-interest loans were the primary support systems for renewables [155]. These schemes have been used mainly for demonstration projects and have been complemented by tax and other incentives for investment in the earlier stages of the emergent market. Investment incentives tend to be capacity and investment-based, with government subsidies depending on the capacity of the generation plant [156]. In many cases, capital subsidies help to cover the total cost of investment and renewable energy producers may be exempted from certain taxes, such as carbon taxes and import taxes on renewable energy technology in the emerging world. The justification for tax exemptions is unfair competitiveness with traditional energy sources and the absence of internalization of negative external costs [157], [143]. While these incentives have worked well as complementary and supportive tools for promoting renewable energy, they have shortcomings. Incentives are designed to stimulate investment in a technological option and do not provide incentives to improve the long-term operational management of solar power plants [158]. Tax incentives like quick depreciation and tax credits tend to favour larger power plants and more affluent consumers, limiting the ability of individuals with smaller businesses to participate in the renewable energy market.

4) Evaluation of Existing Policies: Policies like feed-in tariffs, net metering, RPS, and tax incentives have driven the adoption of solar PV. The FIT has provided predictable returns, accelerating solar PV deployment in many countries [146]. Overcapacity and financial burdens on utilities and consumers highlight the need for periodic adjustments. Net metering has empowered prosumers, but high penetration can strain the grid and reduce utility revenues. RPSs have driven long-term demand for renewable energy, but uneven regional enforcement has limited their impact. Tax incentives and subsidies lower barriers to entry, but often benefit wealthy customers [147].

Grid integration standards increase PV technological viability and safety, yet rigid requirements may slow innovation and increase compliance costs. However, the regulatory policies have created a solid foundation for PV deployment, but they need to be refined to address new challenges such as grid congestion, intermittency, and equitable access. To be effective, they need to be dynamically updated and better integrated with emerging technologies such as smart grid technologies, advanced energy storage systems, AI and machine learning in grid management, etc.

SYSTEM SUSTAINABILITY OF PV INTEGRATION INTO THE MAIN GRID

The integration of solar energy into the electricity grid has many advantages in terms of social, economic, and environmental benefits [159]. The energy sector has become a major source of GHG emitted, with energy-related emissions predicted to rise by 16% in 2040 [160], [161]. The energy sector should therefore be an essential part of any attempt to limit the impacts of climate change. Therefore, integrating PV into the grid is an important contribution to the transition to a greener energy supply [162].

A. Environmental Benefits of Solar PV Integration

Solar PV technology is revolutionizing the way energy is produced and consumed, with numerous environmental benefits. Grid integration of solar PV is critical as the world transitions to sustainable, renewable energy sources [163]. Solar PV systems reduce GHG emissions, and reliance on conventional fuel, making grid integration an essential step towards a sustainable energy supply.

1) Reduction in Greenhouse Gas Emissions: The generation of electricity from conventional power plants is a large emitter of GHGs [164]. According to the IEA, the lifecycle GHG emissions of PV-grid systems range from 18 to 60 g CO_2-eq/kWh, whereas emissions from coal-fired generating plants range between 898 to 1129 gCO_2-eq/kWh [165], [166]. The significant reduction in GHG emissions from solar PV systems plays a substantial role in climate change mitigation initiatives, as the power sector is a huge emitter of global GHGs. By replacing fossil fuel-based electricity generation with solar PV, the overall carbon footprint of the energy system can be significantly reduced, contributing to a low-carbon economy [167], [168].

2) Reduction in Water Usage: Significant volumes of water are needed to cool and for other operations in conventional thermoelectric power plants. The use of this water is detrimental to local and regional water resources, particularly in regions where water availability is limited [169]. In contrast, PV systems do not require water to generate electricity, except for small amounts for occasional cleaning of the panels. Reducing water use can help conserve scarce water supplies and reduce water conflicts between the energy sector and water-dependent activities such as agriculture, which is particularly important in water-stressed regions [170].

3) Other Ecological Impacts: PV systems are more eco-friendly than large hydroelectric or fossil fuel power plants due to their relatively smaller land footprint in comparison to the energy output [171]. Producing and installing PV is less polluting than extracting, transporting and refining fossil fuel, further minimizing the environmental impact, the distributed nature of solar PV systems eliminates the need for extensive transmission and distribution networks [172].

4) Reduction in Energy Resource Depletion: Reducing the depletion of energy resources is another environmental benefit of integrating solar PV into the grid. Fossil fuels are finite resources that are rapidly depleted as they are extracted and consumed [173]. Relying on conventional fuels for electricity generation is unsustainable and threatens global energy stability. PV is a sustainable, reliable source, providing unlimited energy supply. It diversifies the energy mix, reduces vulnerability to supply disruptions, and offers flexibility and resilience, making it suitable for various scales, from residential installations to utility-scale farms [174]. This can have a positive impact on the stability and security of electricity supply, particularly in regions that are heavily dependent on fossil fuel imports.

B. Technical Benefits of Integrating PV into Main Grid

1) System Loss Reduction: By generating power close to the load in radial distribution networks, solar systems can effectively reduce system losses [175]. This proximity reduces transmission and distribution line losses by permitting solar power to substitute for some of the transmission power. thereby promoting a more "sustainable" energy environment, as owners of PV systems and their communities enjoy lower overall energy costs [176]. This reduction in system loss is an important point to emphasize when marketing solar systems to potential customers, highlighting the economic and environmental benefits of investing in PV energy.

2) Enhances Power Quality: A solar installation with an inverter interface can enhance power quality on the AC grid by controlling both real and reactive power components. This allows the distributed generator to regulate the voltage, the overall power factor of the plant, and the voltage flicker [177], [178]. The inverter can also do voltage sag correction, but this may be a function of the size of the inverter. If properly sized and executed, this connection will be able to cancel out grid distortions, regulate the voltage, and minimize harmonics.

3) Network Upgrade Extension: Electricity grid upgrade deferment is the opportunity to defer the investment required to strengthen feeders and transformers due to solar integration. As solar installations are connected close to the demand side, the low and medium levels of distributed energy resources tend to diminish the power flow that comes from the national grid. This generation can help offset peak loads and load spikes [179], [180]. The need for network upgrades (mainly transmission lines) is limited due to the demand reduction.

4) Short Construction Time: Solar power units can be installed in a short time and have a lower investment risk thanks to their modular nature, which makes them easy to install in any location. Each module is autonomous, can start generating electricity as soon as it is installed and is not compromised by failures in other modules [181].

C. Economic Benefits of Integrating PV into Main Grid

1) Reduction of Operative Cost: The potential for cost savings is one of the major economic benefits of integrating PV into the main electricity grid. Solar energy is a cost-effective and abundant resource, and once the initial cost of installation has been covered, the cost of operating and maintaining a solar PV system is comparatively lower [182], leading to substantial long-term savings for both utility companies and consumers. Additionally, solar PV systems can help reduce the need for expensive infrastructure upgrades and expansions, as they can help offset peak load and reduce the burden on the power grid [183].

2) Job Creation: Furthermore, the integration of PV into the grid can also create job opportunities and stimulate economic development. A study by the IREA found that the renewable energy sector, including solar PV, holds the prospect of creating millions of new jobs worldwide as the industry continues to grow [184]. The potential to attract skilled labour and support local economic growth through the installation, maintenance, and manufacture of solar PV systems [185].

3) Potential Revenue Streams: Integrating solar PV into the main grid can create potential revenue streams for both utilities and individuals. For utilities, the incorporation of solar PV systems can provide the ability to sell surplus electricity back to the grid under net metering or feed-in tariffs, creating an incremental revenue stream [186]. For home or business owners with PV installations, the ability to generate power could save money on your utility bill and allow the owner to earn money by feeding surplus energy onto the grid [183].

D. Impact of solar PV on electricity prices and market dynamics

Integrating solar PV into electricity grids can have both positive and negative implications for electricity pricing, market dynamism, and overall electricity system costs. A substantial benefit of the integration of PV into the electric grid is the ability to lower the price of electricity by offering a low-cost source of renewable energy. PV has no associated fuel costs and can be used to generate electricity as a result of solar irradiation, which can help lower the overall price of electricity during periods of peak demand [187]. This can lead to decreased reliance on more expensive fossil fuel-based generation, resulting in lower electricity bills for consumers. In a study by [188] carried out in the United States, each additional gigawatt of solar PV capacity led to a $0.13/MWh reduction in wholesale electricity prices [189].

However, the intermittent nature of PV can also have negative impacts on electricity prices and market dynamics [190]. The rise of distributed solar PV systems can disrupt traditional centralized power generation models, leading to a more decentralized and dynamic electricity system. This can change the balance of power between different market participants, such as utilities, independent power producers, and prosumers (consumers who also produce electricity). There is therefore the need for flexible resources, such as energy storage and demand response, which may increase to balance the intermittency of PV generation and maintain grid stability. PV generation is dependent on solar radiation, which varies all over the day and seasonally. This can cause fluctuations in power generation, resulting in price volatility in the electricity market. Additionally, when solar PV systems produce excess electricity during sunny periods, it can lead to negative wholesale electricity prices, as generators may have to pay to offload their surplus power onto the grid [191]. PV integration can significantly reduce electricity system costs by meeting growing electricity demand and reducing the need for expensive new power plants and infrastructure upgrades. However, the integration may require investment in ESS, grid upgrades and other infrastructure to accommodate the intermittency of PV generation. This added cost can offset some of the savings from the use of solar PV, potentially increasing the overall cost of the electricity system.

E. Synergies between Solar PV Integration and Sustainable Development Goals.

The global community has set forth an ambitious agenda for achieving sustainability, as set out in the 17 SDGs. Several of these 17 goals relate to integrating solar PV into global electricity grids. PV technology holds tremendous potential to advance progress towards SDG2, SDG7, and SDG13 [36], [192].

The synergies between solar PV integration and these three key SDGs highlight how integrating PV into the man grid can catalyze sustainable development in these critical areas.

1) SDG2-Zero Hunger: SDG 2 aims to end hunger, achieve food security, and promote sustainable agriculture. Solar PV integration into the main grid can play a key role in achieving this goal by ensuring reliable and affordable energy to power agricultural activities such as irrigation, processing, and storage [192]. By enabling farmers to access clean and reliable energy, solar PV integration can improve the productivity of agriculture, minimize post-harvest loses, and increase food security. Additionally, solar energy can also be used to power food processing and preservation facilities, ensuring that more produce reaches the market and is available for consumption [36].

Moreover, it can help address the energy needs of rural communities, where access to electricity is often limited. By providing clean and affordable energy, solar PV integration can enable the development of agro-processing industries in remote communities, which creates employment and fosters economic expansion [192], [193]. This, in turn, can help reduce poverty and improve the livelihoods of smallholder farmers, contributing to the overall goal of achieving zero hunger.

2) SDG-13-Climate Change Action: SDG-13 requires immediate measures to address climate change and its impacts. Integrating solar power into the main grid is a strong tool for tackling climate change by limiting GHG emissions, facilitating renewable energy, and minimizing the impacts of climate change [194]. Solar PV is a sustainable option to conventional fuels, as it is a green, sustainable source of energy that emits no GHGs. Greenhouse gases during operation. Countries can reduce their carbon footprint, reduce their reliance on coal and other fossil fuels, and shift to a carbon-free energy system by integrating solar PV into the main grid [36][195]. PV integration can also help strengthen vulnerability to the effects of global warming, such as more intense precipitation, water scarcity, and food insecurity. By expanding the reach of cleaner, eco-friendly solutions, PV integration can support climate change mitigation efforts and contribute to the overall goal of combating climate change. By aligning with SDG 13, solar PV integration into the main grid can contribute to the worldwide commitment to mitigating the challenges posed by climate change.

3) SDG-7 Cheap and clean energy: SDG7 is at the heart of the synergies between solar PV integration and sustainable development. Promoting the deployment of PV energy can contribute to the achievement of this goal in several ways:

Increased access to electricity: PV can provide cheap and clean electricity to underserved or off-grid communities, improving their access to basic services and enhancing their quality of life [36].

Energy mix diversification: Integrating PV into the grid diversifies the energy mix, reduces dependence on fossil fuels, and promotes sustainable energy [196].

Distributed generation and grid resilience: The decentralized nature of PV systems can enhance the resilience of the electricity network, reducing the vulnerability to centralized system failures and improving energy security [197].

By addressing the challenges of energy access, affordability, and reliable energy transition, the integration of PV can make significant contributions towards achieving SDG 7.

FUTURE PROSPECTS AND INNOVATIONS

A. Emerging Technologies in Solar PV

Solar PV technologies are becoming more efficient, more reliable, and more versatile, making solar power generation more adaptable to a variety of environments and grid requirements. Major advances include “bifacial solar cells, perovskite solar cells”, floating solar farms, and building integrated photovoltaics. The bifacial PV panel captures sunlight on both faces and can enhance energy generation by up to 30% [198]. Perovskite solar cells, with efficiencies greater than 25%, offer higher efficiencies and reduce costs of manufacturing compared to conventional silicon cells [199]. Floating solar farms reduce evaporation and take advantage of water cooling. They are ideal for space-constrained locations, especially in densely populated areas. Building-integrated photovoltaics embeds solar cells into building materials. This makes them suitable for urban areas. These advanced solar technologies, especially when combined with intelligent grid technologies and the ESS, increase the likelihood of high levels of PV integration into the grid.

B. Research and Development Trends

Research and development in the area of PV integration is focused on the optimization of grid compatibility, the improvement of energy storage, and the advancement of grid-tie inverters. Large-scale battery systems are essential for storing surplus energy production during periods of peak solar irradiation [200]. AI and machine learning are becoming more and more prominent in PV energy research, including the forecasting of solar power and the management of the grid. Accurate forecasting can help grid operators predict the generation of solar power, adjust load balancing, and mitigate the risks associated with intermittent power generation. AI-powered predictive models like artificial neural networks can improve solar integration by identifying weather data, solar performance, and demand patterns, allowing the grid to dynamically adapt to changing conditions [201], facilitating greater adoption of solar power penetration while supporting its stability. These research and development trends are critical to improving the resiliency of the grid and preparing the infrastructure for greater solar deployment.

C. Potential for Hybrid Renewable Systems

The combination of PV with other renewables such as wind, biomass, or battery storage, can help to mitigate the intermittency challenges associated with single-source renewables by providing a more balanced energy supply [202]. Solar and wind complement each other: Sunlight is typically available during the day, while wind speeds tend to increase at night. Hybrid systems can provide more consistent energy output, better matching grid demand and limiting the reliance on fossil fuel backup [203]. Hybrid systems can provide flexibility in urban and rural environments by operating independently as a mini-grid or connecting to the main grid. They also facilitate the creation of virtual power plants, which bring together several distributed energy resources to provide a coordinated supply of power to the grid. This model provides the resiliency and flexibility to support a renewable energy future.

D. Vision for a Decentralized Power Grid

Distributed power grids are networks of distributed energy resources that generate store, and manage electricity at multiple locations, reducing transmission losses and increasing energy security. This shift empowers consumers to become prosumers. Prosumers foster a more participatory energy ecosystem by generating electricity for personal use and selling surplus energy to the utility grid [204]. Distributed networks also benefit microgrids, which can be operated autonomously or in combination with the main network, providing resiliency during extreme weather or grid instabilities.

E. Future Outlook

i. Future research will explore the evolution of policy frameworks across regions to identify best practices for solar PV integration. In-depth case studies will be conducted to understand key factors contributing to successful regulatory environments. The study will also analyze the evolution of policy frameworks, considering technological advancements, market dynamics, government priorities, innovative business models and financing mechanisms. Key lessons learned will be applied to develop effective policies for solar PV integration in other regions. The research will also examine stakeholder engagement and regulatory approaches, contributing to an in-depth knowledge of the policy landscape and future recommendations for global solar PV integration.

F. Advanced Energy Storage Systems (ESS)

Advanced energy storage systems such as battery and thermal storage, alleviate the intermittency inherent in solar PV by storing surplus energy during periods of peak generation and releasing it during periods of low generation [134]. ESS helps to maintain grid stability by smoothing out voltage and frequency fluctuations, allowing for smoother incorporation of solar PV into the grid. Storage can also provide backup power and support demand response, reducing fossil fuel dependency and increasing grid efficiency [203].

Another further research work is to develop innovative grid management and control strategies to accommodate high levels of PV penetration. As the integration of PV in the grid increases, there is a need for the development of more advanced grid management and control strategies that can effectively integrate and utilize this renewable energy source. Further investigation may examine the use of advanced control and optimization techniques to manage the variability and uncertainty of solar PV generation. There is a need to develop new grid management protocols and standards that are tailored for high levels of solar PV integration.

RECOMMENDATIONS

To facilitate the successful integration of PV into the grid, several recommendations should be considered:

A. Investment in Grid Infrastructure

For a sustainable energy future, upgrading the current grid infrastructure to accommodate intermittent renewables is essential. Using "smart grid" technology will enable better integration of renewables, like solar, allowing the grid to efficiently manage changes in energy supply and demand. This upgrade will improve overall flexibility and reliability, leading to a stronger and more effective energy system. A key step in building a cleaner and stable energy ecosystem is the modernization of the grid infrastructure.

B. Implement Regulatory Reforms

Implementing regulatory reforms is crucial to creating a stable and predictable environment for solar PV investments. This can be achieved by reforming policy frameworks and establishing clear guidelines for net metering, FITs, and renewable energy certificates that incentivize solar energy production. Doing so provides investors with the confidence to make long-term commitments and enables a favourable environment to grow the photovoltaic industry. Additionally, these reforms can attract more investments, spur economic growth, and support the shift to an eco-friendly and greener energy mix. Overall, implementing regulatory reforms is essential to ensure that the appropriate policy and support framework is in place for solar PV investment to flourish.

C. Foster Public-Private Partnerships

One way to boost solar integration is to foster public-private partnerships, which can facilitate joint efforts between the private and public sectors to leverage resources, share risks, and develop innovative solutions. By working together, these partnerships can facilitate investment in infrastructure and technology, making it more cost-effective to implement solar PV systems. This collaboration can also lead to the emergence of innovative solutions to facilitate broader acceptance of PV technology and make it more affordable to a variety of consumers. By promoting these partnerships, policymakers and industry leaders can work together to overcome the difficulties and opportunities faced in integrating PV into grid infrastructure, thus resulting in a robust and sustainable energy system.

D. Community Solar Programs

Access to renewable energy can be made more affordable by developing a supportive mechanism for community solar initiatives. Such schemes would enable individuals or groups, including tenants and low-income homes, to co-invest in shared PV projects. By extending the reach of PV beyond residential homeowners with suitable rooftops, community solar also addresses equity by offering concerns about the shared benefits of lower energy bills and the ownership of clean energy. The integration of these initiatives with localized energy storage solutions can further improve the resiliency of the grid and increase adoption rates.

CONCLUSION

Integrating PV into the grid is a revolutionary step toward becoming more sustainable. It promises to support a cleaner and more resilient energy system, to reduce greenhouse gas emissions, and to reduce our dependence on fossil fuels. However, this transition comes with several technological, financial and regulatory barriers. For its full potential to be realized, these issues need to be addressed. The management of PV power fluctuations, the maintenance of grid stability, and the creation of supportive policies to encourage innovation and investment in solar technology are some of the key barriers. The modernization of the grid infrastructure to accommodate renewable energy sources is also essential for the efficiency and reliability of the grid. Addressing these challenges requires widespread adoption of advanced technologies such as energy storage, smart grid and distributed generation. These innovations can provide a more consistent supply of electricity and improve grid resilience by mitigating the inherent intermittency of solar PV. Furthermore, supportive regulatory frameworks and incentives are needed to create an enabling environment for solar PV investment, allowing these technologies to scale up at national and global levels. The long-term benefits of solar power, including security, sustainability and alignment with global climate objectives, make this technology an important part of the future energy strategy, although grid integration will involve significant technical and financial expenditure. PV can contribute significantly to developing stable energy systems and achieving global renewables and SDGs by addressing existing challenges through strategic investments, regulatory reforms, and technological advances.

Credit Authorship Contribution Statement

Charity M. Nkinyam: Writing – original draft, Investigation, Conceptualization, Visualization. Abdoul Aziz: Writing – review & editing, Tagne Takote B. Clausel: Validation, Formal analysis.

Declarations of Interests

The authors declare no competing interests

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

1. F. Y. Almulla, C. Ramirez, B. Joyce, A. Huber-Lee, “Fuso-Nerini, From participatory process to robust decision-making: an Agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco, Energy for Sustainable Development 70,” pp. 314–338., 2022.
2. S. Olaleru, J. Kirui, F. Elegbeleye, and T. Aniyikaiye, “Green Technology Solution to Global Climate Change Mitigation,” Energy, Environ. Storage, vol. 1, no. 1, 2021, doi: 10.52924/dnrm8834.
3. J. O. Adetokun, B. B., Muriithi, C. M. & Ojo, “Voltage stability assessment and enhancement of power grid with increasing wind energy penetration.,” Int. J. Electr. Power Energy Syst., 2020.
4. X. L. J. Qian, K. Li, H. Wu, J. Yang, “Synergetic control of grid-connected photovoltaic systems,” Int J Photoenergy 2017, pp. 1–11, 2017.
5. J. Mnisi, S. P. D. Chowdhury, and L. Ngoma, “Grid integration of solar PV for green energy,” 6th IEEE Int. Energy Conf. ENERGYCon 2020, no. September, pp. 782–786, 2020, doi: 10.1109/ENERGYCon48941.2020.9236485.
6. C. M. Nkinyam, C. O. Ujah, K. C. Nnakwo, O. Ezeudu, D. V. V Kallon, and I. I. C. Ezema, “Design and implementation of a waterless solar panel cleaning system,” Unconv. Resour., vol. 5, no. August 2024, p. 100131, 2025, doi: 10.1016/j.uncres.2024.100131.
7. K. Nyarko, J. Whale, and T. Urmee, “Drivers and challenges of off-grid renewable energy-based projects in West Africa: A review,” Heliyon, vol. 9, no. 6, p. e16710, 2023, doi: 10.1016/j.heliyon.2023.e16710.
8. C. M. Nkinyam, C. Oliver, K. C. Nnakwo, and D. V. V Kallon, “Insight into organic photovoltaic cell: Prospect and challenges,” Unconv. Resour., vol. 5, no. April 2024, p. 100121, 2025, doi: 10.1016/j.uncres.2024.100121.
9. “International Energy Outlook 2013 by US. Energy Information Administration. access on 27 June 2024”.
10. P.M. Kumar, R. Saminathan, A. Sumayli, M. Mittal, A.S. Abishek, A.A. Kumaar, “Experimental analysis of a heat sink for electronic chipset cooling using a nano improved PCM (NIPCM), Mater Today:,” Proc 56, pp. 1527–1531, 2022.
11. S. C. Bhattacharyya, “Mini-grids for the base of the pyramid market: A critical review,” Energies, vol. 11, no. 4, 2018, doi: 10.3390/en11040813.
12. and F. M. O. M. Ian, E. Gençer, “‘A general model for estimating emissions from integrated power generation and energy storage. Case study: integration of solar photovoltaic power and wind power with batteries,’ Processes,” vol. 6, no. 12, p. 267, 2018.
13. M. Agoundedemba, C. K. Kim, and H. G. Kim, “Energy Status in Africa: Challenges, Progress and Sustainable Pathways,” Energies, vol. 16, no. 23, 2023, doi: 10.3390/en16237708.
14. F. Gökgöz and M. T. Güvercin, “““Energy security and renewable energy efficiency in EU,””” Renew. Sustain. Energy Rev., vol. 96, pp. 226–239, 2018, doi: doi: 10.1016/J.RSER.2018.07.046.
15. M. Shafiullah, M. A. Abido, and A. H. Al-Mohammed, “Smart grid fault diagnosis under load and renewable energy uncertainty,” Power Syst. Fault Diagnosis, pp. 293–346, 2022, doi: 10.1016/b978-0-323-88429-7.00006-0.
16. A. Gulagi, M. Alcanzare, D. Bogdanov, E. Esparcia, J. Ocon and C. Breyer, “““Transition pathway towards 100% renewable energy across the sectors of power, heat, transport, and desalination for the Philippines,””” Renew. Sustain. Energy Rev., vol. 144, 2021, doi: doi: 10.1016/j.rser.2021.110934.
17. M. Ram, A. Aghahosseini, and C. Breyer, “Job creation during the global energy transition towards 100% renewable power system by 2050,” Technol. Forecast. Soc. Change, vol. 151, 2020, doi: 10.1016/j.techfore.2019.06.007.
18. REN21 Secretariat., “Renewables 2021 Global Status Report. Paris, France. Accessed: June. 25, 2024.

[Online].," Available: https://www.ren21.net/gsr, 2021.
19. K. N. Nwaigwe, P. Mutabilwa, and E. Dintwa, "An overview of solar power (PV systems) integration into electricity grids," Mater. Sci. Energy Technol., vol. 2, no. 3, pp. 629–633, 2019, doi: 10.1016/j.mset.2019.07.002.
20. T. Mahbub, M. F. Ahammad, S. Y. Tarba, and S. M. Y. Mallick, "Factors encouraging foreign direct investment (FDI) in the wind and solar energy sector in an emerging country," Energy Strateg. Rev., vol. 41, no. March, p. 100865, 2022, doi: 10.1016/j.esr.2022.100865.
21. E. Mbaka, "Evaluation of optimal photovoltaic hybrid systems for remote villages in Far North Cameroon," Renew. Energy, vol. 51, pp. 482–488, 2013, doi: 10.1016/j.renene.2012.09.035.
22. "U. S. Energy Information Administration (EIA)," World Energy Outlook2020–Summary, Rep., p. p1, 2020.
23. N. Kannan, and D. Vakeesan "Solar energy for future world: -," A Rev. Renew. Sustain. Energy Rev., no. 62, pp. 1092–1105, 2016.
24. D. E-theses, "Feasibility of Solar Energy and its Ability to Support Libyan Grid in Facing its Energy Crisis Feasibility of Solar Energy and its Ability to Support Libyan Grid in Facing its Energy Crisis," 2024.
25. G. Zhang, H.L.; Baeyens, J.; Degrève, J.; Cacères, "Concentrated solar power plants: Review and design methodology.," Renew. Sustain. Energy Rev, vol. 22, pp. 466–481., 2013.
26. H. Chowdhury, T. Chowdhury, N. Hossain, P. Chowdhury, J. dos Santos Mascarenhas, and M. M. K. Bhuiya, "Energy, emission, profitability, and sustainability analyses of a grid-connected solar power plant proposed in airport sites of Bangladesh: a case study," Environ. Sci. Pollut. Res., vol. 28, no. 43, pp. 61369–61379, 2021, doi: 10.1007/s11356-021-14973-5.
27. J. M. A. Branker, K.; Pathak, M.J.M.; Pearce, "review of solar photovoltaic levelized cost of electricity.," Renew. Sustain. Energy Rev. , no. 15, pp. 4470–4482., 2011.
28. W. K. Ntuli, M. Kabeya, and K. Moloi, "Review of Low Voltage Ride-Through Capabilities in Wind," 2024.
29. S. Wang, H.; Wang, J.; Piao, Z.; Meng, X.; Sun, C.; Yuan, G.; Zhu, "The Optimal Allocation and Operation of an Energy Storage System with High Penetration Grid-Connected Photovoltaic Systems. Sustainability," no. 12, 2020.
30. R. A. Marques Lameirinhas, J. P. N. Torres, and J. P. de Melo Cunha, "A Photovoltaic Technology Review: History, Fundamentals and Applications," Energies, vol. 15, no. 5, pp. 1–44, 2022.
31. K. S. Barada, P. Dash, Swaraj Kumar Beriha, Brundabana Naik, "Organic materials based solar cells," vol. 67, pp. 1057–1063, 2022.
32. Y. Srinivas, B. Balaji, S., Nagendra Babu, "Review on Present and Advance Materials for Solar cells.," Int. J. Eng. Res. Online, vol. 3, pp. 178-182., 2015.
33. S. K. Gupta, K. Dharmalingam, L. S. Pali, S. Rastogi, A. Singh, and A. Garg, "Degradation of organic photovoltaic devices: A review," Nanomater. Energy, vol. 2, no. 1, pp. 42–58, 2013, doi: 10.1680/nme.12.00027.
34. A. Zahedi, "Maximizing solar PV energy penetration using energy storage technology," Renew. Sustain. Energy Rev., vol. 15, no. 1, pp. 866–870, 2011, doi: 10.1016/j.rser.2010.09.011.
35. D. Qerimi, C. Dimitrieska, S. Vasilevska, and A. Rrecaj, "Modeling of the solar thermal energy use in urban areas," Civ. Eng. J., vol. 6, no. 7, pp. 1349–1367, 2020, doi: 10.28991/cej-2020-03091553.
36. J. K. Angela Mae Minas, Samira García-Freites, Christopher Walsh, Velma Mukoro, Jhud Mikhail Aberilla, Amanda April, A. G.-S. Carlos Gaete-Morales, and S. Mander, "Advancing Sustainable Development Goals through energy access: Lessons from the Global South," Renew. Sustain. Energy Rev., vol. Volume 199, 2024.
37. G. T. Tucho and D. M. Kumsa, "Challenges of Achieving Sustainable Development Goal 7 From the Perspectives of Access to Modern Cooking Energy in Developing Countries," Front. Energy Res., vol. 8, no. November, pp. 1–11, 2020, doi: 10.3389/fenrg.2020.564104.
38. A. Elshurafa, "Trends in Global Solar Photovoltaic Installation in 2023," pp. 2–5, 2024.
39. H. H. Pourasl, R. Vatankhah, and V. M. Khojastehnezhad, "Solar energy status in the world : A comprehensive review," Energy Reports, vol. 10, no. July 2022, pp. 3474–3493, 2023, doi: 10.1016/j.egyr.2023.10.022.
40. R. B. M. Obi, "Trends and challenges of grid-connected photovoltaic systems - A review, Renewable

and Sustainable Energy Reviews," pp. 1082–1094., 2016.
41. N. Wagner, M. Rieger, A. S. Bedi, J. Vermeulen, and B. A. Demena, "The impact of off-grid solar home systems in Kenya on energy consumption and expenditures," Energy Econ., vol. 99, p. 105314, 2021, doi: 10.1016/j.eneco.2021.105314.
42. A. O. Cyril, C. O. Ujah, B. N. Ekwueme, and C. O. Asadu, "Photovoltaic mini-grid incorporation: The panacea for electricity crisis in sub-Saharan Africa," Unconv. Resour., vol. 4, no. March, p. 100079, 2024, doi: 10.1016/j.uncres.2024.100079.
43. Solarpowerworldonline, "What are some common types of solar PV and storage installations.," 2015.
44. R. Trotter, P.A.; McManus, M.C. and Maconachie, "'Electricity Planning and Implementation in Sub-Saharan Africa: A Systematic Review'," Renew. Sustain. Energy Rev., no. 74:, pp. 1189–1209, 2017.
45. Zeeshan Hyder, "Solar system types compared: Grid-tied, off-grid, and hybrid".
46. N. L. T. Giuseppe, M. Lelia, A.D. Paola, H. Rita, C. Isaac, M. Madalena, P. Antonio, L. Luigi, "Energy and environmental performances of hybrid photo voltaic irrigation systems in Mediterranean intensive and super-intensive olive orchards," Sci. Total Environ. 651, pp. 2514–2523., 2019.
47. O. Babayomi, B. Olubayo, I. Denwigwe, "A review of renewable off-grid mini-grids in Sub-Saharan Africa," Front. Energy Res., vol. 10, no. January, pp. 1–30, 2023, doi: 10.3389/fenrg.2022.1089025.
48. T. Chow, "A review on photovoltaic/thermal hybrid solar technology," Appl. Energy, vol. 87, no. 2, pp. 365–379, 2010, doi: 10.1016/j.apenergy.2009.06.037.
49. O. M. Hamdoon, O. R. Alomar, and B. M. Salim, "Performance analysis of hybrid photovoltaic thermal solar system in Iraq climate condition," Therm. Sci. Eng. Prog., vol. 17, 2020, doi: 10.1016/j.tsep.2019.100359.
50. W. López-Castrillón, H. H. Sepúlveda, and C. Mattar, "Off-grid hybrid electrical generation systems in remote communities: Trends and characteristics in sustainability solutions," Sustain., vol. 13, no. 11, 2021, doi: 10.3390/su13115856.
51. A. De Almeida and P. Moura, "Energy-efficient off-grid systems — review," 2019.
52. N. I. Hansen UE, Pedersen MB, "Review of solar PV policies, interventions and diffusion in East Africa. Renew Sustain Energy Rev.," no. 46:, pp. 236-248., doi: doi:10.1016/j.rser.2015.02.046.
53. J. Kok, M. Scheepers, I. Kamphuis, "Intelligence in Electricity Networks for Embedding Renewables and Distributed Generation," in Intelligent Infrastructures, no. February 2016, 2010. doi: 10.1007/978-90-481-3598-1.
54. S. Zhang, P. Ocłoń, J. J. Klemeš, P. Michorczyk, K. Pielichowska, and K. Pielichowski, "Renewable energy systems for building heating, cooling and electricity production with thermal energy storage," Renew. Sustain. Energy Rev., vol. 165, no. January, 2022, doi: 10.1016/j.rser.2022.112560.
55. A. Gómez-Expósito, A. J. Conejo, and C. Cañizares, Electric energy systems: Analysis and operation. 2016. doi: 10.1201/9781420007275.
56. M. Hafeez, M. Hariri, M. Khairunaz, M. Desa, and S. Masri, "Grid-connected PV generation.," Energies, vol. 13, no. 17, p. 4279, 2020.
57. G. Spagnuolo, L. Franquelo, T. Suntio, and W. Xiao, "Grid Connected Photovoltaic Generation Plants .," pp. 1–29.
58. N. Jaalam, N. A. Rahim, A. H. A. Bakar, C. K. Tan, and A. M. A. Haidar, "A comprehensive review of synchronization methods for grid-connected converters of renewable energy source," Renew. Sustain. Energy Rev., vol. 59, pp. 1471–1481, 2016, doi: 10.1016/j.rser.2016.01.066.
59. S. P. Panda, A., Pathak, M.K., Srivastava, "A single phase photovoltaic inverter control for grid connected system.," vol. 1, no. 41, pp. 15–30., 2016.
60. P. Chandrakar, S. Saha, P. Das, A. Singh, and S. Debbarma, "Grid Integration of PV System Using Synchronverter," 7th IEEE Int. Conf. Comput. Power, Energy, Inf. Commun. ICCPEIC 2018, no. March, pp. 237–242, 2018, doi: 10.1109/ICCPEIC.2018.8525194.
61. N. F. Guerrero-Rodríguez, A. B. Rey-Boué, L. C. Herrero-de Lucas, and F. Martinez-Rodrigo, "Control and synchronization algorithms for a grid-connected photovoltaic system under harmonic distortions, frequency variations and unbalances," Renew. Energy, vol. 80, pp. 380–395, 2015, doi: 10.1016/j.renene.2015.02.027.
62. M. R. Kathiresan, A.C., PandiaRajan, J., Sivaprakash, A., Babu, T.S., Islam, "An adaptive feed-forward phase locked loop for grid synchronization of renewable energy systems under wide frequency deviations. Sustainability (Switzerland)," vol. 12, no. 17, pp. 1–15., 2020.

63. S. Oliva, I. MacGill, and R. Passey, "Estimating the Financial Costs and Benefits of Distributed Grid-Connected Photovoltaics for Different Electricity Industry Participants," no. 2, 2013.
64. M. Suri, T. Cebecauer, A. Skoczek, R. Marais, U. Mushwana, "'Cloud Cover Impact on Photovoltaic Power Production in South Africa', Stellenbosch University," 2014.
65. B. M. Paulescu, E. Paulescu, "'Weather Modeling and Forcasting of PV Systems Operation,' .," London: Springer-Verlag, 2013.
66. R. Shah, N. Mithulananthan, R. C. Bansal, and V. K. Ramachandaramurthy, "A review of key power system stability challenges for large-scale PV integration," Renew. Sustain. Energy Rev., vol. 41, pp. 1423–1436, 2015, doi: 10.1016/j.rser.2014.09.027.
67. H. Al-Sabounchi, A., Al-Hammadi, E., Yalyali, S., Al-Thani, "Photovoltaic-grid connection in the UAE: Technical perspective. Renewable Energy," vol. 49, pp. 39-43., 2013.
68. J. Widén, E. Wäckelgård, J. Paatero, and P. Lund, "Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids," Electr. Power Syst. Res., vol. 80, no. 12, pp. 1562–1571, 2010, doi: 10.1016/j.epsr.2010.07.007.
69. M. Z. R. Chowdhury, S. A., & Khan, "The Net Metering Guideline of Bangladesh-Potential and Way Forward.," 2020 11th Int. Conf. Electr. Comput. Eng. (ICECE)., 2020.
70. J. Celvakumaran, P., Ramachandaramurthy, V. K., Padmanaban, S., Padmanathan, K., Pouryekta, A., & Pasupuleti, "Technical Constraints of Integrating Net Energy Metering from the Malaysian Perspective.," in 2018 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)., 2018.
71. G. M. Shafiullah and A. M. T. Oo, "Analysis of harmonics with renewable energy integration into the distribution network," in 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2015, pp. 1–6. doi: 10.1109/ISGT-Asia.2015.7387191.
72. J. K. Eni, R. O. & Akinbami, "Flexibility evaluation of integrating solar power into the Nigerian electricity grid.," IET Renew. Power Gener., vol. 2, no. 11, pp. 239–247, 2017.
73. J. Widén, E. Wäckelgård, J. Paatero, and P. Lund, "Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids," Electr. Power Syst. Res., vol. 80, no. 12, pp. 1562–1571, 2010, doi: 10.1016/j.epsr.2010.07.007.
74. J. T. Walla, J. Widen, J. Johansson, and C. Bergerland, "'Determining and Increasing the PV Hosting Capacity for Photovoltaics in the Swedish Distribution Grids,' in European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, .," 2012.
75. E. Pompodakis, I. A. Drougakis, I. S. Lelis, and M. C. Alexiadis, "Photovoltaic systems in low-voltage networks and overvoltage correction with reactive power control," IET Renew. Power Gener., vol. 10, no. 3, pp. 410–417, 2016, doi: 10.1049/iet-rpg.2014.0282.
76. A. S. You, Y. Liu, J. Tan, M. T. Gonzalez, X. Zhang, Y. Zhang and Y. Liu, """Comparative assessment of tactics to improve primary frequency response without curtailing solar output in high photovoltaic interconnec_tion grids,""" IEEE Trans. Sustain. Energy, vol. 10, no. 2, pp. 718–728, 2019, doi: doi: 10.1109/TSTE.2018.2846233.
77. A. K. Murdan, A. P., & Jeetun, "Simulation of a Single Phase Grid-tied PV System under Net-Metering Scheme.," in 2021 IEEE Power and Energy Conference at Illinois (PECI)., 2021.
78. A. Adams, S., Klobodu, E. K. M., & Apio, "Renewable and non-renewable energy, regime type and economic growth. Renewable Energy," no. 125, pp. 755–767., 2018.
79. W. da Silva, P. P., Cerqueira, P. A., & Ogbe, "Determinants of renewable energy growth in Sub-Saharan Africa: Evidence from panel ARDL. Energy," no. 156, pp. 45–54., 2018.
80. E. Martinot, "Grid Integration of Renewable Energy: Flexibility, Innovation, and Experience," Annu. Rev. Environ. Resour., vol. 41, pp. 223–251, 2016, doi: 10.1146/annurev-environ-110615-085725.
81. C. Medina, C. R. M. Ana, and G. González, "Transmission Grids to Foster High Penetration of Large-Scale Variable Renewable Energy Sources -A Review of Challenges, Problems, and Solutions," Int. J. Renew. Energy Res., vol. 12, no. 1, pp. 146–169, 2022, doi: 10.20508/ijrer.v12i1.12738.g8400.
82. R. J. Broderick, B. Palmintier, B. Mather, M. Coddington, and K. Baker, "On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System.," Natl. Renew. Energy Lab., no. May, p. 55, 2016, [Online]. Available: http://www.osti.gov/scitech/biblio/1253983%0Ahttp://www.osti.gov/servlets/purl/1561033/.
83. N. Paliwal, P.; Patidar, "R.K. Planning of grid integrated generators: A review of technology,

84. objectives and planning.," Renew. Sustain. Energy Rev., no. 40, pp. 4557–4570., 2014.
85. M. S. Rawat and S. Vadhera, "A comprehensive review on impact of wind and solar photovoltaic energy sources on voltage stability of power grid," J. Eng. Res., vol. 7, no. 4, pp. 178–202, 2019.
86. L. Wang, R. Yan, and T. K. Saha, "Voltage regulation challenges with unbalanced PV integration in low voltage distribution systems and the corresponding solution," Appl. Energy, vol. 256, pp. 1–8, 2019, doi: 10.1016/j.apenergy.2019.113927.
87. H. Farhoodnea, M., Mohamed, A., Shareef, H., Zayandehroodi, "An enhanced method for contribution assessment of utility and customer harmonic distortions in radial and weakly meshed distribution systems.," Int. J. Electr. Power Energy Syst., vol. 43, no. 1, pp. 222–229, 2012.
88. C. Shiva, R. Bhavani, and N. R. Prabha, "Power quality improvement in a grid integrated solar PV system," Proc. 2017 IEEE Int. Conf. Intell. Tech. Control. Optim. Signal Process. INCOS 2017, vol. 2018-Febru, pp. 1–6, 2017, doi: 10.1109/ITCOSP.2017.8303144.
89. M. M. ElNozahy, and M.S. Salama, "Technical impacts of grid-connected photovoltaic systems on electrical networks—a review.," J. Renew. Sustain. Energy, vol. 5, no. 3, 2013.
90. A.Velayutham, "Expert talk on Power Quality (PQ) Issues in smart Grid and Renewable Energy Soures," Ex Member, MERC, SGRES, CPRI, Bangalore., 2015.
91. R. Al Badwawi, M. Abusara, and T. Mallick, "A Review of Hybrid Solar PV and Wind Energy System," Smart Sci., vol. 3, no. 3, pp. 127–138, 2015, doi: 10.1080/23080477.2015.11665647.
92. A. F. A. Kadir, T. Khatib, and W. Elmenreich, "Integrating photovoltaic systems in power system: Power quality impacts and optimal planning challenges," Int. J. Photoenergy, vol. 2014, 2014, doi: 10.1155/2014/321826.
93. F. Blaabjerg, Y. Yang, K. Ma, and X. Wang, "Power electronics-the key technology for renewable energy system integration," 2015 Int. Conf. Renew. Energy Res. Appl. ICRERA 2015, pp. 1618–1626, 2015, doi: 10.1109/ICRERA.2015.7418680.
94. H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy sources and frequency regulation: Survey and new perspectives," IET Renew. Power Gener., vol. 4, no. 5, pp. 438–457, 2010, doi: 10.1049/iet-rpg.2009.0049.
95. F. Peprah, S. Gyamfi, M. Amo-Boateng, and E. Effah-Donyina, "Impact assessment of grid tied rooftop PV systems on LV distribution network," Sci. African, vol. 16, 2022, doi: 10.1016/j.sciaf.2022.e01172.
96. R. A. J. Y. P. Agalgaonkar, B. C. Pal, "'Distribution voltage control considering the impact of pv generation on tap changers and autonomous regulators,'" IEEE Trans. Power Syst., vol. 29, no. 1, pp. 182–192, 2014.
97. M. A. Abdoulaye, G. J. P. Tevi, D. Diouf, and A. S. Maiga, "Impact of the Intermittency of Photovoltaic Power Plants on the Frequency Management: Case of the Senegalese Electricity Grid," J. Power Energy Eng., vol. 08, no. 07, pp. 55–70, 2020, doi: 10.4236/jpee.2020.87005.
98. R. Günther, "Reactive Power and its Impact on the Grid," CLOU Glob., 2023.
99. M. A. Eltawil and Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems-A review," Renew. Sustain. Energy Rev., vol. 14, no. 1, pp. 112–129, 2010, doi: 10.1016/j.rser.2009.07.015.
100. H. K. Khyani and J. Vajpai, "Integration of Solar PV Systems to the Grid: Issues and Challenges," Int. J. Eng. Res. Technol., pp. 393–397, 2018.
101. S. Gonzalez, A. Ellis, M. E. Ropp, C. A. Mouw, D. D. Schutz, and S. J. Perlenfein, "Unintentional Islanding Detection Performance with Mixed DER Types.," no. July, 2018.
102. C. Greacen, R. Engel, T. Quetchenbach, and L. Berkeley, "A Guidebook on Grid Interconnection and Islanded Operation of Mini - ¬ - Grid Power Systems Up to 200 kW," no. April, pp. 1–80, 2013.
103. Z. Tang, Y. Yang, and F. Blaabjerg, "Power electronics: The enabling technology for renewable energy integration," CSEE J. Power Energy Syst., vol. 8, no. 1, pp. 39–52, 2022, doi: 10.17775/CSEEJPES.2021.02850.
104. D. S. Pillai, J. P. Ram, N. Rajasekar, A. Mahmud, Y. Yang, and F. Blaabjerg, "Extended analysis on Line-Line and Line-Ground faults in PV arrays and a compatibility study on latest NEC protection standards," Energy Convers. Manag., vol. 196, pp. 988–1001, 2019, doi: 10.1016/j.enconman.2019.06.042.
105. J. C. H. Shah, "Protection challenges on integration of distributed sources to power system network: a

106. review," J. Appl. Res. Technol., pp. 212–226, 2023.
107. G. Missrani, N. Nabila, F. H. Jufri, D. R. Aryani, and A. R. Utomo, "Study on short circuit current contribution after photovoltaic solar plant integration in lombok's distribution network," 2nd IEEE Int. Conf. Innov. Res. Dev. ICIRD 2019, 2019, doi: 10.1109/ICIRD47319.2019.9074685.
108. J. C. S. and A. E. J. Schoene, V. Zheglov, D. Houseman, "'Photovoltaics in Distribution Systems-Integration Issues and Simulation Challenges,' in Power and Energy Society General Meeting (PES)," IEEE, 2013.
109. C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, "Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits," Energies, vol. 14, no. 17, 2021, doi: 10.3390/en14175375.
110. A. P. Kenneth and K. Folly, "Voltage rise issue with high penetration of grid connected PV," IFAC Proc. Vol., vol. 19, pp. 4959–4966, 2014, doi: 10.3182/20140824-6-za-1003.01989.
111. R. Shah, N. Mithulananthan, A. Sode-Yome, and K. Y. Lee, "Impact of large-scale PV penetration on power system oscillatory stability," IEEE PES Gen. Meet. PES 2010, pp. 1–7, 2010, doi: 10.1109/PES.2010.5589660.
112. Q. Alsafasfeh, O. A. Saraereh, I. Khan, and S. Kim, "Solar PV grid power flow analysis," Sustain., vol. 11, no. 6, pp. 1–25, 2019, doi: 10.3390/su11061744.
113. M. S. Hossain, N. Abboodi Madlool, A. W. Al-Fatlawi, and M. El Haj Assad, "High Penetration of Solar Photovoltaic Structure on the Grid System Disruption: An Overview of Technology Advancement," Sustain., vol. 15, no. 2, 2023, doi: 10.3390/su15021174.
114. S. Ghosh and S. Rahman, "Global deployment of solar photovoltaics: Its opportunities and challenges," IEEE PES Innov. Smart Grid Technol. Conf. Eur., pp. 1–6, 2016, doi: 10.1109/ISGTEurope.2016.7856217.
115. E. B. I. E. Davidson, "Overview of Fault Ride-Through Requirements for Photovoltaic Grid Integration, Design and Grid Code Compliance," Int. Conf. Renew. Energy Res. Appl. (ICRERA)., 2020.
116. Y. Yang, S. Member, P. Enjeti, and F. Blaabjerg, "Suggested Grid Code Modifications to Ensure Wide-Scale Adoption of Photovoltaic Energy in Distributed Power Generation Systems," 2015.
117. S. W. Ali M. Sadiq, Y. Terriche, and N. Yacine, "State space stability analysis Least square extended Prony analysis State of space analysis Hꝏ Equal area criterion Approx. dynamic programming Approx. dynamic programming," IEEE Access, vol. 9, pp. 102811–102827, 2021.
118. R. Hudson and G. Heilscher, "PV grid integration - System management issues and utility concerns," Energy Procedia, vol. 25, pp. 82–92, 2012, doi: 10.1016/j.egypro.2012.07.012.
119. M. Shafiul Alam, F. S. Al-Ismail, A. Salem, and M. A. Abido, "High-level penetration of renewable energy sources into grid utility: Challenges and solutions," IEEE Access, vol. 8, pp. 190277–190299, 2020, doi: 10.1109/ACCESS.2020.3031481.
120. A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, "Challenges in integrating distributed energy storage systems into future smart grid," IEEE Int. Symp. Ind. Electron., no. May 2015, pp. 1627–1632, 2008, doi: 10.1109/ISIE.2008.4676896.
121. T. Kataray et al., "Integration of smart grid with renewable energy sources: Opportunities and challenges – A comprehensive review," Sustain. Energy Technol. Assessments, vol. 58, 2023, doi: 10.1016/j.seta.2023.103363.
122. S. Supriya, M. Magheshwari, S. Sree Udhyalakshmi, R. Subhashini, and Musthafa, "Smart grid technologies: Communication technologies and standards," Int. J. Appl. Eng. Res., vol. 10, no. 20, pp. 16932–16941, 2015.
123. J. R. M.S. Eslahi, S. Vaez-Zadeh, "Resiliency enhancement and power quality optimization of converter-based renewable energy microgrids Trans. Power Electron. 38," IEEE, vol. 38, no. 6, pp. 7785–7795, 2023.
124. E. Hossain, I. Khan, F. Un-Noor, S. S. Sikander, and M. S. H. Sunny, "Application of Big Data and Machine Learning in Smart Grid, and Associated Security Concerns: A Review," IEEE Access, vol. 7, pp. 13960–13988, 2019, doi: 10.1109/ACCESS.2019.2894819.
125. V. Fthenakis, J. E. Mason, and K. Zweibel, The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US, vol. 37, no. 2. 2009. doi: 10.1016/j.enpol.2008.08.011.

126. M. Khalid, “Smart grids and renewable energy systems: Perspectives and grid integration challenges,” Energy Strateg. Rev., vol. 51, no. June 2023, p. 101299, 2024, doi: 10.1016/j.esr.2024.101299.
127. M.S. Hossain, N.A. Madlool, N.A. Rahim, J. Selvaraj and A. F. Khan, “Role of smart grid in renewable energy: An overview,” Renew. Sustain. Energy Rev., vol. Volume 60, p. Pages 1168-1184, 2016.
128. L. Bird, M. Milligan, D. Lew, L. Bird, M. Milligan, and D. Lew, “Integrating Variable Renewable Energy: Challenges and Solutions Integrating Variable Renewable Energy: Challenges and Solutions,” no. September, 2013.
129. L. Ahmad, N. Khordehgah, J. Malinauskaite, and H. Jouhara, “Recent advances and applications of solar photovoltaics and thermal technologies,” vol. 207, 2020.
130. M. Weimar, M. Mylrea, T. Levin, A. Botterud, E. O’Shaughnessy, and L. Bird, “Integrating Renewable Generation into Grid Operations,” p. 116, 2016.
131. Y. F. Xing Yao, Bowen Yi, Yang Yu and L. Zhu, “Economic analysis of grid integration of variable solar and wind power with conventional power system,” Appl. Energy, vol. Volume 264, 2020.
132. P. Denholm and R. Margolis, “Energy Storage Requirements for Achieving 50 % Solar Photovoltaic Energy Penetration in California,” Natl. Renew. Energy Lab., no. August, p. 37, 2016.
133. M. Emmanuel and R. Rayudu, “Evolution of dispatchable photovoltaic system integration with the electric power network for smart grid applications: A review,” Renew. Sustain. Energy Rev., vol. 67, pp. 207–224, 2017, doi: 10.1016/j.rser.2016.09.010.
134. C. Marino, A. Nucara, M. F. Panzera, M. Pietrafesa, and A. Pudano, “Economic comparison between a stand-alone and a grid connected PV system vs. Grid distance,” Energies, vol. 13, no. 15, 2020, doi: 10.3390/en13153846.
135. E. Koliou, Implementation of Smart Grids Elta Koliou Demand Response Policies Demand for the Implementation implementation of smart grids Smart Grids.
136. P. Zarębski and D. Katarzyński, “Small Modular Reactors (SMRs) as a Solution for Renewable Energy Gaps: Spatial Analysis for Polish Strategy,” Energies, vol. 16, no. 18, 2023, doi: 10.3390/en16186491.
137. S. Yu, T. Lu, X. Hu, L. Liu, and Y. M. Wei, “Determinants of overcapacity in China’s renewable energy industry: Evidence from wind, photovoltaic, and biomass energy enterprises,” Energy Econ., vol. 97, p. 105056, 2021, doi: 10.1016/j.eneco.2020.105056.
138. Q. Hassan, P. Viktor, T. J. Al-Musawi, and T. M. Ali, “The renewable energy role in the global energy Transformations,” Renew. Energy Focus, vol. 48, no. December 2023, p. 100545, 2024, doi: 10.1016/j.ref.2024.100545.
139. A. Arash and S. Arif, “Overview of Technical Specifications for 2 Grid-connected photovoltaic systems,” Energy Convers. Manag., 2017.
140. IEEE Standard Association, “Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std. 1547-2018.,” IEEE Std 1547-2018 (Revision IEEE Std 1547-2003), no. February, pp. 1–138, 2018.
141. R. Jain, Y. N. Velaga, K. Prabakar, M. Baggu, and K. Schneider, “Modern trends in power system protection for distribution grid with high DER penetration,” e-Prime - Adv. Electr. Eng. Electron. Energy, vol. 2, no. September, p. 100080, 2022, doi: 10.1016/j.prime.2022.100080.
142. A. Livera, M. Theristis, G. Makrides, and G. E. Georghiou, “Recent advances in failure diagnosis techniques based on performance data analysis for grid-connected photovoltaic systems,” Renew. Energy, vol. 133, pp. 126–143, 2019, doi: 10.1016/j.renene.2018.09.101.
143. J. Caron and J. R. Markusen, “Gap Analysis towards A Design Qualification Standard Development for Grid-Connected Photovoltaic Inverters by,” no. August, pp. 1–23, 2016.
144. J. V. Muñoz, G. Nofuentes, J. Aguilera, M. Fuentes, and P. G. Vidal, “Procedure to carry out quality checks in photovoltaic grid-connected systems: Six cases of study,” Appl. Energy, vol. 88, no. 8, pp. 2863–2870, 2011, doi: 10.1016/j.apenergy.2011.02.015.
145. N. Mukisa, R. Zamora, and T. T. Lie, “Energy Business Initiatives for Grid-Connected Solar Photovoltaic Systems: An Overview,” Sustain., vol. 14, no. 22, 2022, doi: 10.3390/su142215060.
146. A. Murdan, I. Jahmeerbacus, and S. Z. Sayed Hassen, “Challenges of existing grid codes and the call for enhanced standards,” Clean Technol. Recycl., vol. 3, no. 4, pp. 241–256, 2023, doi: 10.3934/ctr.2023015.
147. A. Q. Al-Shetwi, M. A. Hannan, K. P. Jern, A. A. Alkahtani, and A. E. P. G. Abas, “Power quality assessment of grid-connected PV system in compliance with the recent integration requirements,”

Electron., vol. 9, no. 2, pp. 1–22, 2020, doi: 10.3390/electronics9020366.
148. M. Castaneda, S. Zapata, and A. Aristizabal, "Assessing the effect of incentive policies on residential PV investments in Colombia," Energies, vol. 11, no. 10, 2018, doi: 10.3390/en11102614.
149. A. P. Pereira da Silva, G. Dantas, G. I. Pereira, L. Câmara and N. J. De Castro, """Photovoltaic distributed generation—An international review on diffusion, support policies, and electricity sector regulatory adaptation,""" Renew. Sustain. Energy Rev., vol. 103, pp. 30–39, 2019, doi: doi: 10.1016/j.rser.2018.12.028.
150. E. ugustine, P.; McGavisk, "The next big thing in renewable energy:," Shar. solar. Electr. J., no. 29, pp. 36–42.
151. B. N. Alajmi, N. A. Ahmed, I. Abdelsalam, and M. I. Marei, "An Assessment of Net Metering and Feed-in Tariffs for Grid-Connected PV Systems in the Kuwaiti Market," Arab. J. Sci. Eng., vol. 47, no. 3, pp. 3055–3067, 2022, doi: 10.1007/s13369-021-06052-1.
152. G. Barbose et al., "A retrospective analysis of benefits and impacts of U.S. renewable portfolio standards," Energy Policy, vol. 96, pp. 645–660, 2016, doi: 10.1016/j.enpol.2016.06.035.
153. N. Vo, "Assessing the impact of feed-in tariffs and renewable portfolio standards on the development of solar photovoltaic in Vietnam–opportunities and challenges," 2024.
154. B. Uzum, A. Onen, H. M. Hasanien, and S. M. Muyeen, "Rooftop solar pv penetration impacts on distribution network and further growth factors—a comprehensive review," Electron., vol. 10, no. 1, pp. 1–31, 2021, doi: 10.3390/electronics10010055.
155. V. Döme, "A global-scale study on decision making in renewable energy policy: Internal and external factors driving the adoption of Feed-in Tariffs and Renewable Portfolio Standards," Environ. Policy Gov., vol. 34, no. 3, pp. 321–335, 2024, doi: 10.1002/eet.2085.
156. M. A. Destek, "Renewable energy consumption and economic growth in newly industrialized countries: Evidence from asymmetric causality test. Renewable Energy," no. 95, pp. 478–484, 2016.
157. S. Zeng, Y. Liu, C. Liu, and X. Nan, "A review of renewable energy investment in the BRICS countries: History, models, problems and solutions," Renew. Sustain. Energy Rev., vol. 74, no. March 2016, pp. 860–872, 2017, doi: 10.1016/j.rser.2017.03.016.
158. D. Jacobs, "Framework Conditions and International Best Practices for Renewable Energy Support Mechanisms," pp. 1–22, 2009.
159. U. Kılıç and B. Kekezoğlu, "A review of solar photovoltaic incentives and Policy: Selected countries and Turkey," Ain Shams Eng. J., vol. 13, no. 5, 2022, doi: 10.1016/j.asej.2021.101669.
160. P. E. Anastasia Roth, Marianne Boix, Vincent Gerbaud, Ludovic Montastruc, Impact of taxes and investment incentive on the development of renewable energy self-consumption: French households' case study. 2020.
161. A. Jain, S.; Kalambe, S.; Agnihotri, G.; and Mishra, "Distributed generation deployment: state – of – the – art of the distribution system planning in sustainable era.," Renew. Sustain. Energy Rev., no. 77, pp. 363 – 385, 2017.
162. Bella G et al, "The relationship among CO2 emissions, electricity power consumption and GDP in OECD countries.," J Policy Model., vol. 6, no. 36, pp. 970–985., 2014.
163. Z. A. Elum and A. S. Momodu, "Climate change mitigation and renewable energy for sustainable development in Nigeria: A discourse approach," Renew. Sustain. Energy Rev., vol. 76, no. February, pp. 72–80, 2017, doi: 10.1016/j.rser.2017.03.040.
164. D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, "Full energy sector transition towards 100 % renewable energy supply: Integrating power, heat, transport and industry sectors including desalination," Appl. Energy, vol. 283, p. 116273, 2021, doi: 10.1016/j.apenergy.2020.116273.
165. D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," Energy Strateg. Rev., vol. 24, no. January, pp. 38–50, 2019, doi: 10.1016/j.esr.2019.01.006.
166. I. Gui, E.M.; Diesendorf, M.; MacGill, "Distributed Energy Infrastructure Paradigm: Community Microgrids in a New Institutional Economics Context.," Renew. Sustain. Energy Rev., no. 72, pp. 1355–1365., 2017.
167. L. Krebs, Environmental Life Cycle Assessment of Residential PV and Battery Storage Systems. 2020.
168. S. Malode, J. C. Mohanta, and R. Prakash, "A review on life cycle assessment approach on thermal power generation," Mater. Today Proc., vol. 56, no. February, pp. 791–798, 2022, doi:

10.1016/j.matpr.2022.02.258.
169. M. J. B. Kabeyi and O. A. Olanrewaju, “Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply,” Front. Energy Res., vol. 9, no. March, pp. 1–45, 2022, doi: 10.3389/fenrg.2021.743114.
170. T. Warbroek, B.; Hoppe, “Modes of Governing and Policy of Local and Regional Governments Supporting Local Low-Carbon Energy Initiatives, Exploring the Cases of the Dutch Regions of Overijssel and Fryslân,” Sustainability, vol. 9, no. 75, 2017.
171. C. Zhang, J. Yang, J. Urpelainen, P. Chitkara, J. Zhang, and J. Wang, “Thermoelectric Power Generation and Water Stress in India: A Spatial and Temporal Analysis,” Environ. Sci. Technol., vol. 55, no. 8, pp. 4314–4323, 2021, doi: 10.1021/acs.est.0c08724.
172. D. S. Nairizi, “Irrigated Agriculture Development under Drought and Water Scarcity,” Int. Comm. Irrig. Drain., pp. 1–168, 2017.
173. Abidur Rahman, Omar Farrok and H. M. Mejbaul, “Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic,” Renew. Sustain. Energy Rev., vol. Volume 161, 2022.
174. S. Dubey, N. Y. Jadhav, and B. Zakirova, “Socio-economic and environmental impacts of silicon based photovoltaic (PV) technologies,” Energy Procedia, vol. 33, pp. 322–334, 2013, doi: 10.1016/j.egypro.2013.05.073.
175. I. Capellán-Pérez, M. Mediavilla, C. de Castro, Ó. Carpintero, and L. J. Miguel, “Fossil fuel depletion and socio-economic scenarios: An integrated approach,” Energy, vol. 77, no. October, pp. 641–666, 2014, doi: 10.1016/j.energy.2014.09.063.
176. J. P. Gouveia, L. Dias, I. Martins, and J. Seixas, “Effects of renewables penetration on the security of Portuguese electricity supply,” Appl. Energy, vol. 123, pp. 438–447, 2014, doi: 10.1016/j.apenergy.2014.01.038.
177. V. Sharma, S. M. Aziz, M. H. Haque, and T. Kauschke, “Effects of high solar photovoltaic penetration on distribution feeders and the economic impact,” Renew. Sustain. Energy Rev., vol. 131, no. December 2019, p. 110021, 2020, doi: 10.1016/j.rser.2020.110021.
178. C. A. P. Pérez, L. G. Espinosa, and A. S. Fuentefria, “Reduction of energy losses through the integration of photovoltaic power plants in distribution networks,” IET Gener. Transm. Distrib., vol. 17, no. 16, pp. 3739–3750, 2023, doi: 10.1049/gtd2.12930.
179. M. Bajaj and A. K. Singh, “Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques,” Int. J. Energy Res., vol. 44, no. 1, pp. 26–69, 2020, doi: 10.1002/er.4847.
180. D. Razmi, T. Lu, B. Papari, E. Akbari, G. Fathi, and M. Ghadamyari, “An Overview on Power Quality Issues and Control Strategies for Distribution Networks With the Presence of Distributed Generation Resources,” IEEE Access, vol. 11, no. December 2022, pp. 10308–10325, 2023, doi: 10.1109/ACCESS.2023.3238685.
181. J. O. Petinrin and M. Shaabanb, “Impact of renewable generation on voltage control in distribution systems,” Renew. Sustain. Energy Rev., vol. 65, pp. 770–783, 2016, doi: 10.1016/j.rser.2016.06.073.
182. M. Bollen and F. Hassan, “Integration of Distributed Generation in the Power System,” Integr. Distrib. Gener. Power Syst., 2011, doi: 10.1002/9781118029039.
183. M. A. Hossain, H. R. Pota, M. J. Hossain, and F. Blaabjerg, “Evolution of microgrids with converter-interfaced generations: Challenges and opportunities,” Int. J. Electr. Power Energy Syst., vol. 109, no. February, pp. 160–186, 2019, doi: 10.1016/j.ijepes.2019.01.038.
184. Z. Dobrotkova, K. Surana, and P. Audinet, “The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries,” Energy Policy, vol. 118, no. June 2017, pp. 133–148, 2018, doi: 10.1016/j.enpol.2018.03.036.
185. T. P. Sopitsuda Tongsopit, Sunee Moungchareon, Apinya Aksornkij, “Business Models and Financing Options for a Rapid Scale-up of Rooftop Solar Power Systems in Thailand,” 2016, pp. 79–136.
186. (IRENA), “International Renewable Energy Agency ‘Renewable Energy and Jobs – Annual Review 2020.,’” Retrieved from.
187. B. Roose et al., “Local manufacturing of perovskite solar cells, a game-changer for low- and lower-middle income countries?,” Energy Environ. Sci., vol. 15, no. 9, pp. 3571–3582, 2022, doi: 10.1039/d2ee01343f.

188. C. W. Scott T. Bryanta, Karla Straker, “The Typologies of Power: Energy Utility Business Models in an Increasingly Renewable Sector,” vol. 19, no. 5, pp. 1–23, 2016.
189. M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, and C. Breyer, “A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030,” J. Clean. Prod., vol. 242, 2020, doi: 10.1016/j.jclepro.2019.118530.
190. T. L. Andrew D. Mills, R. Wiser, J. Seel, and A. Botterud, “Impacts of Variable Renewable Energy on Wholesale Markets and Generating Assets in the United States: A Review of Expectations and Evidence,” 2019.
191. R. W. oachim Seel, Andrew D. Mills, Cody Warner, Bentham Paulos and Ernest, “Impacts of High Variable Renewable Energy Futures on Electric Sector Decision-Making: Demand-Side Effects Implications,” Impacts High Var. Renew. Energy Futur. Electr. Sect. Decis., 2020.
192. The Energy Collective, “The Effect of Intermittent Renewables on Electricity Prices in Germany,” pp. 1–21, 2014.
193. G. Viljoen and F. Dube, “Realising the Right to Electricity Through Off-Grid Power Solutions in South Africa,” Potchefstroom Electron. Law J., vol. 26, no. 26, 2023, doi: 10.17159/1727-3781/2023/v26i0a15637.
194. S. N. Panda et al., “Solar Energy’s Role in Achieving Sustainable Development Goals in Agriculture,” Int. J. Environ. Clim. Chang., vol. 14, no. 5, pp. 10–31, 2024, doi: 10.9734/ijecc/2024/v14i54167.
195. K. Ulsrud, T. Winther, D. Palit, and H. Rohracher, “Village-level solar power in Africa: Accelerating access to electricity services through a socio-technical design in Kenya,” Energy Res. Soc. Sci., vol. 5, no. January, pp. 34–44, 2015, doi: 10.1016/j.erss.2014.12.009.
196. K. Obaideen et al., “Solar Energy: Applications, Trends Analysis, Bibliometric Analysis and Research Contribution to Sustainable Development Goals (SDGs),” Sustain., vol. 15, no. 2, 2023, doi: 10.3390/su15021418.
197. V. Venkatramanan, S. Shah, and R. Prasad, Sustainable Bioeconomy: Pathways to Sustainable Development Goals, no. July. 2020. doi: 10.1007/978-981-15-7321-7.
198. L. S. Paraschiv and S. Paraschiv, “Contribution of renewable energy (hydro, wind, solar and biomass) to decarbonization and transformation of the electricity generation sector for sustainable development,” Energy Reports, vol. 9, no. February, pp. 535–544, 2023, doi: 10.1016/j.egyr.2023.07.024.
199. G. Muthukumaran, M. V. Passos, J. Gong, M. Xylia, and K. Barquet, “Decentralized solutions for island states: Enhancing energy resilience through renewable technologies,” Energy Strateg. Rev., vol. 54, no. June, p. 101439, 2024, doi: 10.1016/j.esr.2024.101439.
200. W. Gu, S. Li, X. Liu, Z. Chen, X. Zhang, and T. Ma, “Experimental investigation of the bifacial photovoltaic module under real conditions,” Renew. Energy, vol. 173, pp. 1111–1122, 2021, doi: 10.1016/j.renene.2020.12.024.
201. Z. R. Lan, Y. Wang, J. Shao, and J. Jang, “Surface Passivation with Diaminopropane Dihydroiodide for p-i-n Perovskite Solar Cells with Over 25% Efficiency,” Adv. Funct. Mater., vol. 34, no. 12, 2024, doi: 10.1002/adfm.202312426.
202. S. B. Wali, M. Hannan, P. Ker, and P. Rahman, et al., “Grid-connected lithium-ion battery energy storage system towards sustainable energy: A patent landscape analysis and technology updates,” J. Energy Storage, vol. 77, 2024, doi: 10.1016/j.est.2023.109986.
203. S. B. Kurukuru, A. Haque, M. A. Khan, S. Sahoo, A. Malik, and F. Blaabjerg, “A review on artificial intelligence applications for grid-connected solar photovoltaic systems,” Energies, vol. 14, no. 15, 2021, doi: 10.3390/en14154690.
204. L. Olatomiwa, S. Mekhilef, M. S. Ismail, and M. Moghavvemi, “Energy management strategies in hybrid renewable energy systems: A review,” Renew. Sustain. Energy Rev., vol. 62, pp. 821–835, 2016, doi: 10.1016/j.rser.2016.05.040.
205. J. Jurasz, F. A. Canales, A. Kies, M. Guezgouz, and A. Beluco, “A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions,” Sol. Energy, vol. 195, pp. 703–724, 2020, doi: 10.1016/j.solener.2019.11.087.
206. Y. Parag and B. K. Sovacool, “Electricity market design for the prosumer era,” Nat. Energy, vol. 1, no. 4, 2016, doi: 10.1038/NENERGY.2016.32.