# A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation

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## Abstract

Solar energy is the powerhouse where all potential and classified renewable energies lug their sources. The energy transformation from the Sun to electricity requires an adequate control scheme to maximise the generated power and enhance the system efficiency. Besides, more than half of solar irradiation on conventional Photovoltaic (PV) panels is lost. The PV thermal (PV/T) modules have been introduced to convert the lost irradiation to heat. Thus, a systematic review of system components, development, and strategies for grid-connected solar PVs plants is presented. Two solar PVs, traditional PV and PV/T, are evaluated. Each grid-tied PV component is considered a subsystem to analyse the potential improvement of grid-connected PVs. This is from solar resources to grid-tied PV inverter techniques. An intensive assessment of the system improvements is presented to evaluate PV plants' benefits, challenges, and potential solutions. The improvement trends for the novel generation of grid-connected PV systems consist of applying innovative approaches. It is also found that intelligent strategies optimally ensure the overall efficiency of grid-tied PVs using real-time control and measurement under innovative applications and technologies. These methods effectively assist in enhancing grid-tied diverse solar power approaches. Therefore, this paper would offer a significant foundation for advanced research into the subject of grid-tied PV and PV/T and their innovation and/or technology development.

**Keywords**: Distribution system, energy storage system, renewable energy system, smart grids, solar power, solar thermal system

## Introduction

The new generation of power systems focuses on abundant, economically feasible and environmentally friendly resources[1]. Renewable energy resources (RERs) have become alternative power sources to replace conventional energy resources[2–4]. The advent of RERs has transformed the traditional configuration of the power grid. The decarbonisation of the power sector can be effectively achieved by the integration of renewable energy. This is considered a key technology achievement[5,6]. All RERs, biomass, fossil fuel, hydro, solar and wind, originate from sunlight. The generated power from the Sun, solar energy, that falls on the Earth is rated between 120 Petawatts (PW)[7] and 175 PW[8], with 1 PW = $10^{15}$W. The Sun can supply energy demand for the whole world for more than 20 years in one day[7].

The solar system influences humanity and its development in several ways. First, without this opportunity of the Earth orbiting the Sun at its current position, society would probably not be described as it is currently defined. Second, the energy produced from the Sun based on solar radiation gives life to the Earth in different aspects, from fauna and flora, water to food, power to transportation, day and night, etc. Third, the Sun is the primary source of different RERs classified to generate power. Therefore, the future of renewable energy systems (RES) is solar power. Finally, it is essential to note that solar radiation produces various RERs, such as solar itself, the atmospheric motion of wind speed, ocean waves, and ocean currents[8].

The development of PV systems started with PV installation in a small distributed system. In 2009, a considerable interest in the PV system connected at distribution levels rose among the power system stakeholders. The growing interest in connecting the PV solar panel to transmission and sub-transmission levels has improved the electrical system[9]. The PV solar panel has a different operation configuration. The most popular ones are the operation structures, which are islanded and grid-connected modes[10,11]. Various designs are used to utilise the energy from the PV systems under the microgrid scheme, connected or islanded to the main grid, such as solar farms and rooftop solar (building solar, etc.)[12].

Climate change leads to an increase in demand for electricity and heat globally[13–15]. In the last decade, various research works designed optimal approaches that can be utilised to meet the demand growth. The photovoltaic thermal (PV/T) system is an effective research area to maximise the PV module's generated power and provide an opportunity to supply the heat lost by the traditional PV system[16]. The combination of the PV and thermal system, also known as a hybrid PVT, enhances the efficiency of the PV cell and produces low-grade heat[17,18]. The optimisation coordination of the PVT system is one of the most critical research perspectives that is still in several laboratories because the actual commercial market does not have various types of high efficient PVT systems[19].

A solar PV system implementation has three or four principal components regardless of the load demand. These are PV panels, maximum power point tracking (MPPT), power converter and/or inverter. PV system implementation depends on the type of configuration used to supply the energy on the demand side, which can be connected to the grid or islanded from the main grid. The current generated from the solar panel needs to pass through a filter and/or transformer before connecting to the grid[20]. A systematic review to assess the grid-tied solar panels is presented. Some relevant published works are reviewed and evaluated based on the contributions of grid-connecting PV and PV/T systems, outlining their benefits, challenges, and mitigation[2,21,22,20,23–26]. Table 1 summarises some published review papers on grid-connecting PV and PV/T systems in function, their benefits, challenges, and mitigation regardless of a systematic aspect of their contributions. Some gaps have been observed in the current investigation research on evaluating all components and/or systems of solar power generation based-PV and PV/T in grid-connected modes. The assessments explore the entire system from RER-based solar power, PV modules, supporting equipment (MPPT, filter, etc.), synchronisation with the utility, and optimal operation for grid-tied PV panels. It is observed that an excellent enlightening of these particular subsystems of grid-connected PV and PV/T systems will put forward deep investigations regarding benefits, challenges and mitigation of the entire system. Therefore, this research deals with the overall scheme of grid-tied PV panels and provides a fundamental perspective on intelligent grid technologies about trends and applications for optimal system operation. The main contributions of this systematic review paper can be summarised as follows:

**Table 1.** Summary of relevant review papers about grid-connected PV and PV/T systems.

| Author(s) and Reference | PV | PV/T | Benefits | Challenges | Mitigation | Year |
|---|---|---|---|---|---|---|
| Malik et al.[27] | ✓ | ✗ | ✗ | ✗ | ✓ | 2022 |
| Gagliano et al.[28] | ✓ | ✗ | ✗ | ✓ | ✓ | 2021 |
| Hariri et al.[2] | ✓ | ✗ | ✗ | ✓ | ✗ | 2020 |
| Chatterjee et al.[26] | ✓ | ✗ | ✓ | ✗ | ✓ | 2018 |
| Balamurugan et al.[29] | ✓ | ✗ | ✗ | ✗ | ✓ | 2017 |
| Jaalam et al.[22] | ✓ | ✗ | ✗ | ✗ | ✓ | 2016 |
| Yang and Blaabjerg[20] | ✓ | ✗ | ✗ | ✓ | ✗ | 2015 |
| Latran and Teke[30] | ✓ | ✗ | ✗ | ✗ | ✓ | 2015 |
| Hassaine et al.[31] | ✓ | ✗ | ✗ | ✗ | ✓ | 2014 |
| This work | ✓ | ✓ | ✓ | ✓ | ✓ | Published Year |

- Assessment of various opportunities for RERs in solar irradiation demonstrates how solar energy is the future energy source that can effectively sustain life on earth.
- Analysis of different components (subsystems) of grid-connected PV and PV/T systems that aim to reinforce sustainable development goals and secure energy in the ever-increasing energy demand in a resource-constrained world and lend credence to efficiency measurement.
- Provide systematic discussions based on benefits, challenges and mitigation of grid-tied PV systems used in smart grid applications. This describes the trends and implementation strategies for the current and future perspectives of grid-connected PV modules.
- Address a future key recommendation of grid-connected PV and PV/T systems in the smart grid environment to support business development, enabling technologies, market design and efficient operation.

## Distributed energy resources

Energy plays a central role in human activity; it fuels and feeds human civilisation[8]. From climate change challenges in the Earth system to the green environment, energy supports sustainable development goals to limit atmospheric pollution in this growing world[32]. Energy is the development capital across generations. The economic and industrial progress of humanity has been sustained by the energy revolution that systematically transforms or produces a given type of energy from available sources. Digitisation provides an opportunity to address energy production, transpiration and consumption challenges effectively. The demand for clean and secure energy increasingly accentuates the traditional strategy of producing and distributing energy.

### *Variable renewable energy*

The most popular RERs possess a variable source; therefore, the concept of variable renewable energy (VRE), which is also known as intermittent energy sources (IRES), is introduced to diverge various renewable energy sources[33]. The most prominent VREs classified in the energy system are wind and solar powers[34]. The VRE contains a non-dispatchable source. Therefore, the novel electric power system looks to operate high levels of VRE to achieve about 100% of the grid-tied VRE. Several countries can achieve this goal; for example, Iceland supplies its total electricity with a 100% combination of geothermal or hydropower. Furthermore, some countries increased the renewable energy capacity based on hydropower, such as Brazil 76%, Canada 62%, Costa Rica 93%, and Norway 97%[35].

There are several options for addressing various challenging questions on integrating VRE[36]. Figure 1 presents the landscape of innovations that can facilitate the integration of VRE. The long-term energy planning and scenarios address the flexibility of the power network. This identifies a complementary between VRE and the electrification of end-use sectors. Therefore, several innovative strategies have been implemented to deal with the high penetration of VRE. The most famous innovation approaches are classified into four categories, as shown in Fig. 1. The fourth industry plays an essential role in improving the integration of VRE. This introduces novel approaches, such as artificial intelligence (AI), efficient use of the internet of things (IoT), integration of electric vehicles (EV), etc. The objective of these innovative strategies is to create better coordination between distributed energy resources (DERs) with distributed system operators (DSOs)[37], which can effectively cooperate with transmission system operators (TSOs)[38]. In addition, voltage regulation (VR) can also be ensured[39].

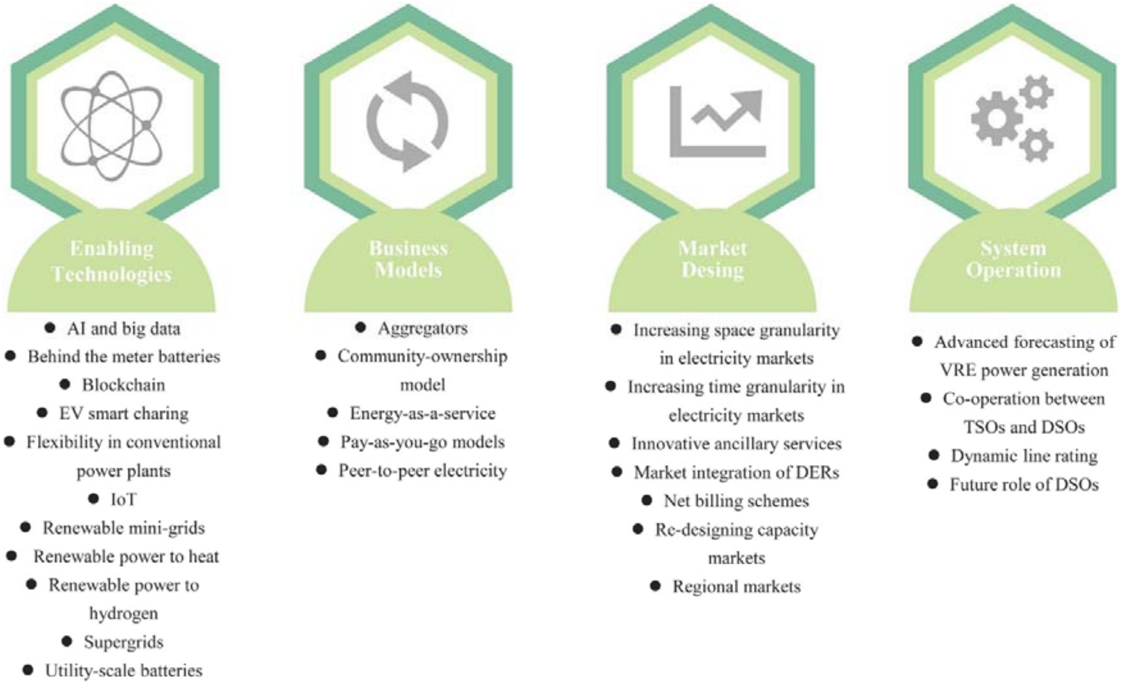


**Figure 1.** Innovations landscape to integrate variable renewable energy[39].

The market design of the electricity network is the interaction and coordination of different stakeholders. Therefore, integrating DERs in the electrical network benefits the market design policies that introduce various innovative services and applications to the power grid[40]. The demand response (DR) programs several programs to develop the market design of the electricity system. The advantage of the DR is its ability to facilitate various innovative ancillary services. Improving the electricity market for VRE is effective when it is optimally coordinated with different system operations. Therefore, the advanced forecasting of VRE power generation can be coordinated with the present and future demand to guarantee the stability of the power flow optimally[41]. The TSO and DSO have notable advantages when the integration of VRE operates under a stable, sustainable and innovative environment that improves the performance of the power system[39]. Environmental security threats are also shunned with large-scale power produced from VREs[42]. Therefore, the creation of a green and smart city can be guaranteed[43].

The planetary energy sources that the Earth system benefits from as VREs have three primary sources: the planetary source of solar radiation, gravitation (interactions of the Earth with the Moon and the Sun), and geothermal heat flux from the Earth's interior supplies. These three energy sources estimate the total rate of renewable energy for humanity, about 175053 TW. Table 2 describes the most relevant renewable energy sources ascertained on Earth. The top three power generation rates based on magnitude are classified as solar power in the first position, wind power holds the second position and biomass. All the powers generated that depend on the planetary solar radiation source are derived from the Sun, with a solar power of 175000 TW. As shown in Table 2, solar power estimation is the primal renewable energy resource. It also possesses a great potential to be effectively used in isolation. Therefore, solar power is the future of sustainable energy development[8,44].

**Table 2.** Generation rates estimation of renewable energy on the Earth system[8,45].

| Source of Energy | Type of power generated | Estimated power rate (TW) | Conversion activity | Location |
|---|---|---|---|---|
| Planetary source of solar radiation | Solar power | 175000 | Solar radiation | Land and Ocean |
| | Wind power | 1000 | Atmospheric motion | Land and Ocean |
| | Biofuels, Biomass | 152 | Biotic productivity | Land |
| | Hydro power | 12 | Continental discharge | Land |
| | Ocean thermal energy conversion | 28 | Desalination | Ocean |
| | Current power | 5 | Ocean current | Ocean |
| | Wave power | 60 | Ocean wave | Ocean |
| Gravitation | Tidal power | 3–5 | Tides | Ocean |
| Geothermal heat flux | Osmotic power | <47 | Geothermal | Land |

### *Energy storage system*

The energy storage applications in DERs store and dispatch the energy generated by VREs (wind and solar). The energy storage system (ESS) also improves the grid flexibility and minimises the power fluctuations from IRESs[46–49]. Several types of energy storage are based on technologies used to charge and discharge electricity, categorised by battery storage, flow battery storage, and no battery storage. Table 3 details various ESS technologies based on their category. The discharging time at rate power is one of the crucial factors for energy storage.

The application of the ESS depends on functionality purposes in the utility grid, which is a function of their power rating. These can be defined as low power rating, about 100 kW (uninterruptible power supply (UPS)/power quality, medium power rating of about 10 MW (TSO, DSO and load shifting), large power rating of about 1 G (bulk power storage)[50].

**Table 3**. Type of energy storage: technologies and important characteristics[56,50,53,51].\

| Energy storage | | Technologies | Efficiency (%) | Power rating | Time scale |
|---|---|---|---|---|---|
| Battery | Electrochemical: | Lead-acid ( Flooded) | 75–85 | <100 MW | few hours |
| | Batteries Storage | Lead-acid (Valve-regulated) | 75–85 | <100 MW | few hours |
| | | Lithium-ion | 90–95 | <100 MW | few hours |
| | | Nickel-cadmium | 60–85 | <100 MW | minutes |
| | | Nickel-hydrogen | | | |
| | | Nickel-metal hydride | | | |
| | | Nickel-zinc | | | |
| | | Sodium-nickel chloride | 86–89 | <10 MW | minutes |
| | | Sodium-sulfur | | | |
| | | Zebra | 70–90 | | |
| Flow batteries | Electrochemical: | Polysulphide bromide | 75 | <10 MW | hours |
| | Flow batteries storage | Vanadium redox | 70–80 | | |
| | | Zinc bromine | 75–80 | | |
| No battery | Electrical | Supercapacitor | 90–98 | <1 MW | Seconds |
| | Electromagnetic | Superconducting magnetic | 90–99 | | |
| | Hydrogen | Hydrogen | 65–75 | <1000 MW | days |
| | Mechanical | Compressed air | 64–75 | <1 GW | days |
| | | Flywheel | 80–90 | <1 MW | days |
| | | Pumped hydro | 70–85 | <1 GW | days |
| | Thermal | Thermal | 80–90 | | |
| No in the market | Mechanical | Fireless locomotive | | | |

| | | | | | |
|---|---|---|---|---|---|
| | | Gravitational potential energy (device) | | | |
| | | Hydraulic accumulator | | | |
| | | Liquid nitrogen | | | |

In[51], typical application scenarios of energy storage in high renewable integration into the power grid are described. The energy storage applied in large renewable energy differs from the various components of the traditional power grid, namely generation, transmission, distribution and consumption components[52]. On the generation side, energy storage is applied to assist in integrating renewable energy, improve the low voltage ride-through capability for wind turbines, minimise the demand for power generation capacity, and stabilise the system fluctuation from IRES. There are several challenges that TSO can improve. First, the high renewable energy integration assists the TSO in alleviating network congestion, maximising system stability, and regulating system frequency. Power quality is one of the major concerns on the distribution side. The DSO enhances the power quality, guarantees the peak loads and provides an opportunity for a backup power source when the ESS is applied with large-scale renewable energy penetration. Finally, integrating ESS with a high renewable energy system (RES) on the consumer side is considered an opportunity to design a novel strategy that optimally handles system performance. The most common applications that guarantee energy consumption efficiency during this scenario are demand response and/or demand-side management[51].

## Solar photovoltaic system

There are various technologies and challenges in converting solar radiation into VRE. The RERs, as described in Table 2, face multiple challenges before their deployment as electricity to supply the end-users. The most important ones are due to conversion implementation. In[53], seven implementation steps to convert RERs are pinpointed, as depicted in Fig. 2. The resource of RERs plays a significant role before any implementation strategy and possesses three out of the seven steps. The resource tile frames mainly deal with the seasonal classification of RER magnitude to optimally manage the system.

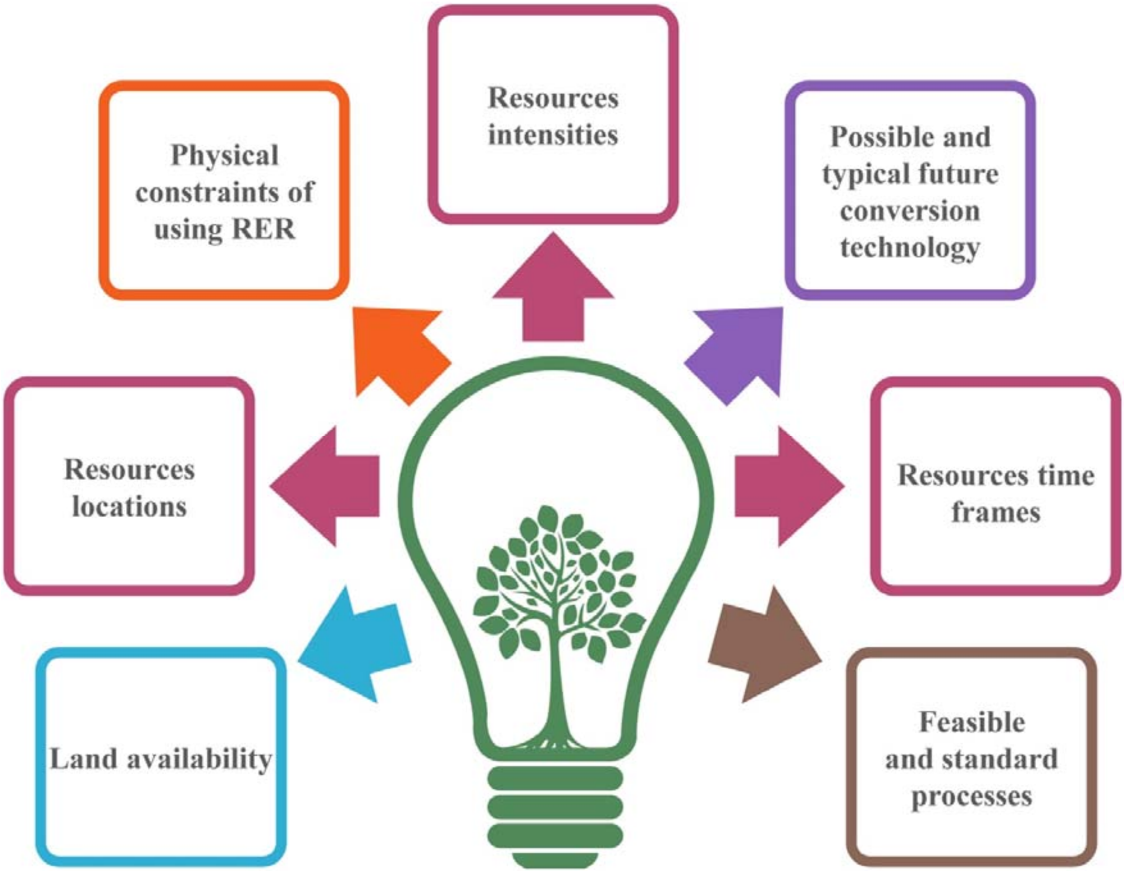


**Figure 2**. Steps towards RERs implementation.

Solar energy, or solar power, the primary purpose of this research study, goes through a conversion process. Table 4 encapsulates three processes of solar energy conversion. Regardless of the solar energy conversion process, conventional solar PV possesses various novel emplacement technologies of the panels, such as the panel being placed on water[54], on building facades[55], etc. In addition, it should be noted that solar panels' installation plays an essential role in maximising solar irradiation for efficient electrical power generation. Therefore, any configuration requires an optimal emplacement to capture maximum energy from the Sun.

**Table 4**. Energy conversion in the function of the Sun.

| Process | Focus | Reference |
|---|---|---|
| Heliochemical | A chemical process that is mainly based on the photosynthesis process | 53,57 |
| Helioelectrical | An electrical process that serves to exploit solar cells or PV to generate electricity | 53,58,59 |
| Heliothermal | A thermal process that aims to convert sunlight to heat. Usually operate inside concentrating solar power plants | 53,57,58 |

The emergent technology of solar energy requires increasingly new materials. Several possibilities exist that allow the conversion of solar radiation or solar energy into renewable energy. Two principal technologies have been detailed in[60]. These are direct concentrated solar

(DCS) and PV. DCS is also called concentrated solar power (CSP). In[53], three principal technologies are detailed. These are based on solar PV, solar thermal electric for thermal electricity or heat and solar thermal heating. Solar technologies depend on three principal aspects: available techniques for commercialisation, converting energy, and collecting irradiation. Five techniques classify solar technologies, including PV solar panel, CSP, Solar thermoelectricity (STE) system, Concentrated PV system and Dye-sensitised solar cell (DSSC), giving a rundown of solar power technologies. The non-concentrated PV and CSP are the most mature technologies due to their rapid growth in the market. Other available techniques are considered emerging technologies and are still under intensive investigation and research[7]. Based on Table 4 and their classified technologies, the solar energy technologies can be summarised as follows: PV, CSP, solar heating and cooling.

### *Solar photovoltaic cell*

The advantages of PV compared to other RERs are cleanliness, low maintenance, most essential RES and no noise. Figure 3 depicts the equivalent circuit of the PV. This structure is based on a single diode model to characterise the PV cell, constituting four main components. These are a photocurrent defined by $I_{SC'}$, a diode parallel to sources, a shunt resistor illustrated by $R_{sh,}$, and a series resistor named $R_{s-}$. From these specified components, the relationship between the current and voltage of the solar PV can be described in Eq. 1[26].

$$I = I_{sc} - I_s \left[ e^{\left( \frac{q(V_{cell} + R_s I)}{BkT} \right)} - 1 \right] - \frac{V_{cell} + R_s I}{R_{sh}} \tag{1}$$

where is the PV cell output current $I_{sh}$, is the reverse saturation current of the diode, $I_{sc}$ is the light current, $V_{cell}$ is the output voltage of the PV; $B$, $k$ and $T$ are the ideality factor of the PV junction, Boltzmann constant and temperature in Kelvin respectively.

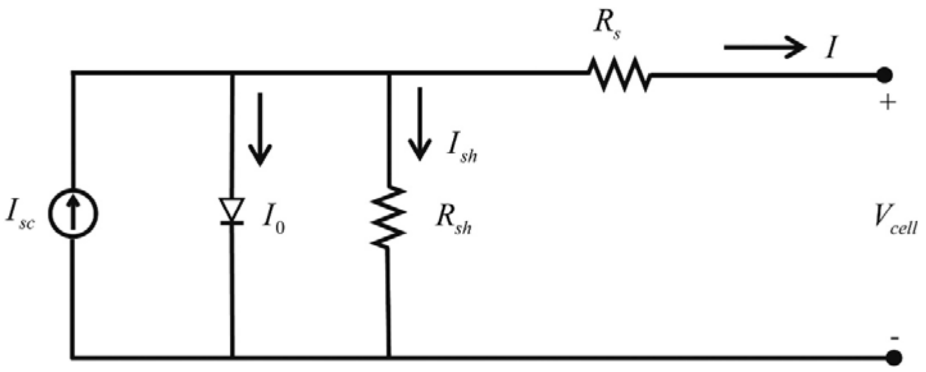


**Figure 3.** Electrical circuit equivalent of PV cell.

It can be observed that due to the low current that can be generated in solar PV, as detailed in Figure 3, the effectiveness of the PV operation requires a series and parallel combination of several cells. The interconnection increases the current and/or the voltage of the PV to achieve the system requirement of a given electrical system. Thus, the notion of a PV module is introduced. Apart from the current and voltage which are the main characteristic of solar PV, it is essential to specify that different factors, such as cell temperature and solar irradiation, on which the solar PV depends, are imperative to consider for the PV performance. There are various types of PV modules[24]. The technologies detailed in solar panels are necessary to identify PV modules regardless of their classification.

### *Solar Photovoltaic Thermal*

PV panels are one of the best devices to use in the extreme condition of solar irradiation, where they can effectively work under the diffuse radiation from the Sun. Therefore, their implementation is increasing worldwide. However, the efficiency of Solar PV panels is a concern in the energy market. This is due to climate change's controversial green planet perspective and its ability to transform only about 15-20% of solar irradiation to electricity. The PV module efficiency can drop about half of its regular operation during only one degree of the increment of module temperature[61]. As detailed in Eq. 1, the temperature of the PV module is one of the important factors and should not be neglected, as it can reach up to 80 in some hot arid regions of the globe. Thus, cooling PV cells is required to maintain the system stability[62]. Therefore, the PV/T concept is initiated to optimally use the extreme temperate from the PV module to generate electricity and heat at the same device[61–63].

The solar PV/T is a combined hybrid PV and thermal collector system, as depicted in Figure 4[62]. This establishes a comparison between PV, PV/T and solar thermal systems. Several categories of PVT systems can assist in identifying the type of device used to produce heat and electricity. PV/T systems supply the end-users with three necessary consumable energies based on the combination of electricity plus water heater, process heat, and space heating[64]. A concentrated photovoltaic thermal (CPV/T) is also a valuable approach to maximising solar energy. There are two types of CPV/T based on their thermal aspect: thermally coupled and thermally decoupled (spectrum/beam splitting, high transmittance and high thermal conductivity and direct absorption collector)[65]. Some essential aspects of the CPV/T system describe three types of CPV/T collector: single-cell, linear geometry, and densely packed module concentrators[62]. Table 5 classifies the PV/T system and provides its application within the different infrastructures of the network[62,19]. These are the most popular PV/T that are commercialised in the market.

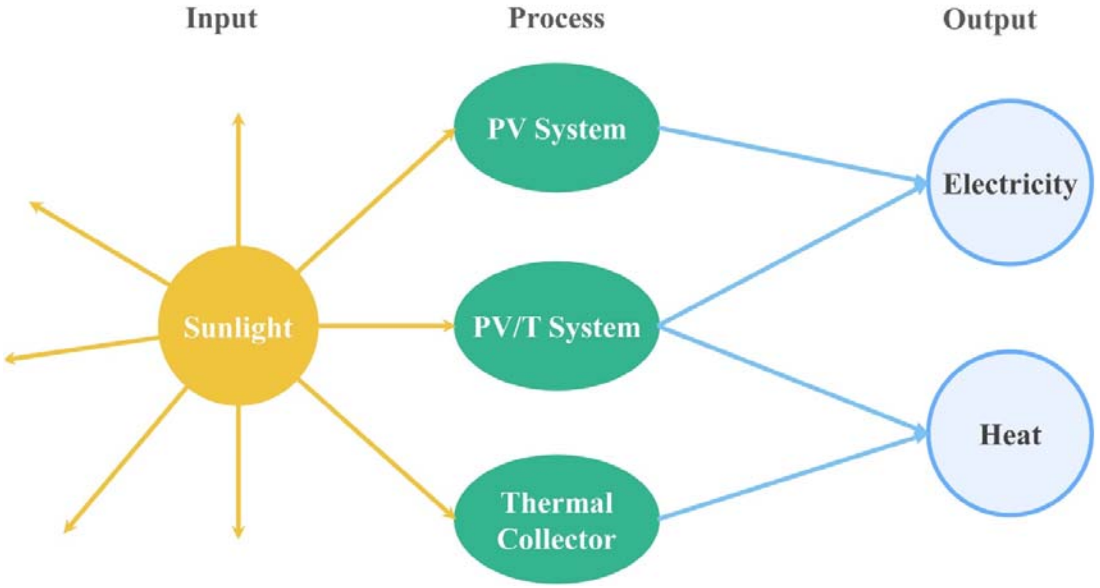
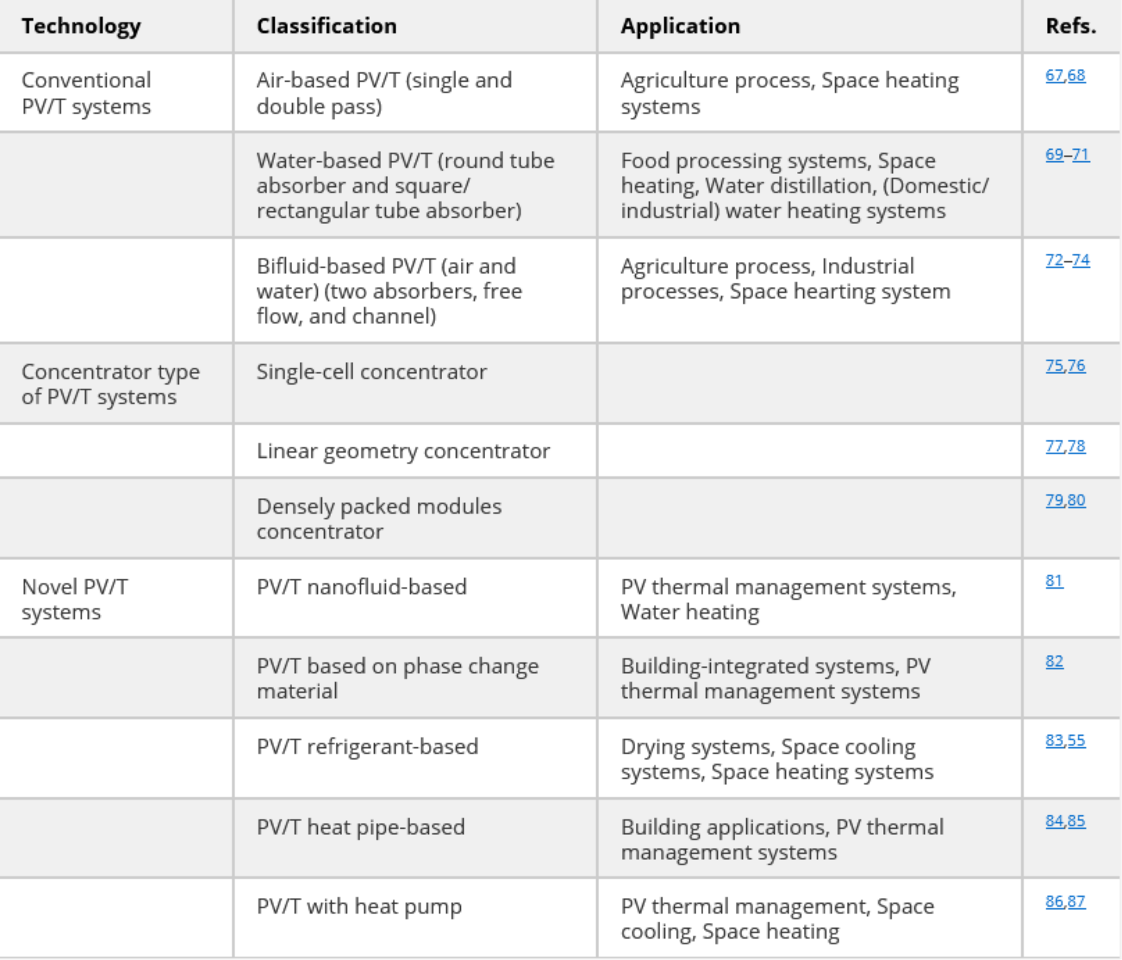


**Figure 4**. Electricity and Heat generation assessed between PV, PV/T and solar thermal systems.

**Table 5**. Photovoltaic thermal systems classifications and their infrastructure.



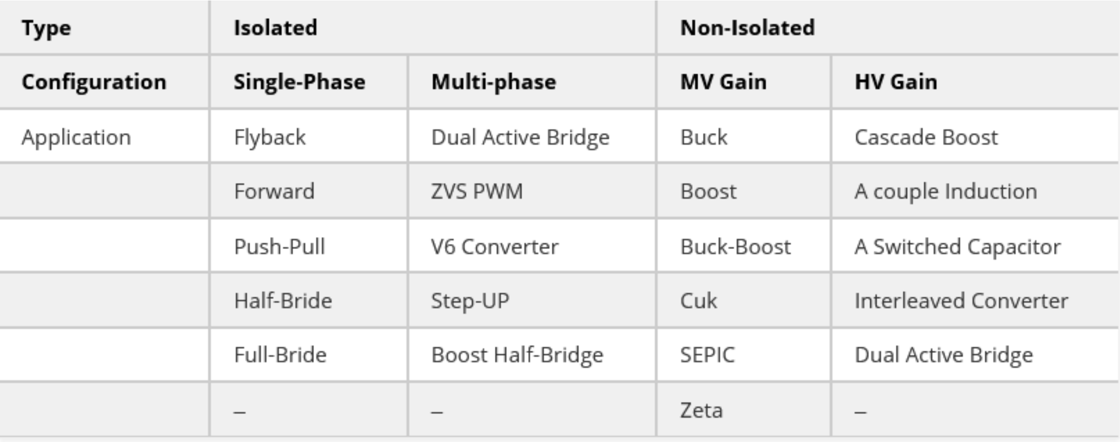
| Technology | Classification | Application | Refs. |
|---|---|---|---|
| Conventional PV/T systems | Air-based PV/T (single and double pass) | Agriculture process, Space heating systems | 67,68 |
| | Water-based PV/T (round tube absorber and square/ rectangular tube absorber) | Food processing systems, Space heating, Water distillation, (Domestic/ industrial) water heating systems | 69–71 |
| | Bifluid-based PV/T (air and water) (two absorbers, free flow, and channel) | Agriculture process, Industrial processes, Space hearting system | 72–74 |
| Concentrator type of PV/T systems | Single-cell concentrator | | 75,76 |
| | Linear geometry concentrator | | 77,78 |
| | Densely packed modules concentrator | | 79,80 |
| Novel PV/T systems | PV/T nanofluid-based | PV thermal management systems, Water heating | 81 |
| | PV/T based on phase change material | Building-integrated systems, PV thermal management systems | 82 |
| | PV/T refrigerant-based | Drying systems, Space cooling systems, Space heating systems | 83,55 |
| | PV/T heat pipe-based | Building applications, PV thermal management systems | 84,85 |
| | PV/T with heat pump | PV thermal management, Space cooling, Space heating | 86,87 |

### *Photovoltaic power converter*

The solar PV panel naturally generates a stochastic out-put direct current (DC) voltage due to the daily instability of solar irradiation and the cell temperature. The voltage stability in the output of the PV system, as presented in Fig. 4, requires a regulator before being supplied to the loads. Therefore, DC-DC power converters applied in the PV systems mainly regulate the system voltage. In addition, due to the voltage standardisation of the load to be supplied by the PV panel, a boost converter is necessary to regulate and adjust the voltage level using a pulse width modulation (PWM) to a maximum power point (MPP)[66].

The philosophy of green energy generation from the Sun increasingly leads to large-scale solar PV systems implementation. Large solar power plants challenge the current architectures of the PV system because they require higher and stable power ratings and voltage levels at the point of common coupling (PCC)[88]. Therefore, the converter section is an essential factor to consider for the overall performance of the PV system. The DC-DC converter can be non-isolated[89] or isolated[90]. The system configuration that classifies the converter for the PV module depends on full and partial power processing converters, with subcategories connected in series and parallel[91]. A section of a DC-DC converter for a PV system needs a detailed assessment of the type of voltage (high voltage (HV), medium voltage (MV), etc.), configuration and system applications[2]. In[89], a comparative assessment is presented to detail various possibilities of the DC-DC converter selection for a large-scale PV system based on the HV gain technique. Table 6 summarises different types of isolated and non-isolated converters. It is observed that the HV converter applications are different from the MV. SEPIC and ZVS stand for single-ended primary induction converter and zero-voltage switching.

**Table 6**. Classification of DC-DC Converters.



| **Type** | **Isolated** | | **Non-Isolated** | |
|---|---|---|---|---|
| **Configuration** | **Single-Phase** | **Multi-phase** | **MV Gain** | **HV Gain** |
| Application | Flyback | Dual Active Bridge | Buck | Cascade Boost |
| | Forward | ZVS PWM | Boost | A couple Induction |
| | Push-Pull | V6 Converter | Buck-Boost | A Switched Capacitor |
| | Half-Bride | Step-UP | Cuk | Interleaved Converter |
| | Full-Bride | Boost Half-Bridge | SEPIC | Dual Active Bridge |
| | – | – | Zeta | – |

### *Photovoltaic power inverter*

The energy produced by the PV panel requires an inverter before deployment to AC load and/or connection to the utility grid. This device facilitates an asymmetric voltage with the necessary magnitude and frequency in the output[2]. For grid-connected PV systems, either single or three-phase inverters can be utilised to convert the power. The harmonic limit in the three-phase inverters is one of the essential factors to consider at the design stage to meet the grid requirement[26].

There are different approaches to inverter classification. Two main classes are broadly selected to classify the inverters. These are line-commutated and self-commutated, which contain impedance-source inverters, current-source inverters and voltage source inverters (including voltage-controlled and current-controlled schemes). It has also been observed that the inverter can be subcategorised based on the connection methods, the number of output voltage levels, PWM switching techniques, types of input source, type of load and output characteristics[2]. Figure 5 details different inverter topologies to be implemented in PV systems[26]. The selected topologies to organise the power inverter, as detailed in Figure 5, represent all the inverter categories. In[92], a multilevel multifunctional grid-connected inverter topology is presented. These are classified based on power circuit structure to mitigate *PQ* problems. Therefore, the multilevel inverter topologies are often classed in current and voltage sources[92], and it can also be a voltage orientation control[93].

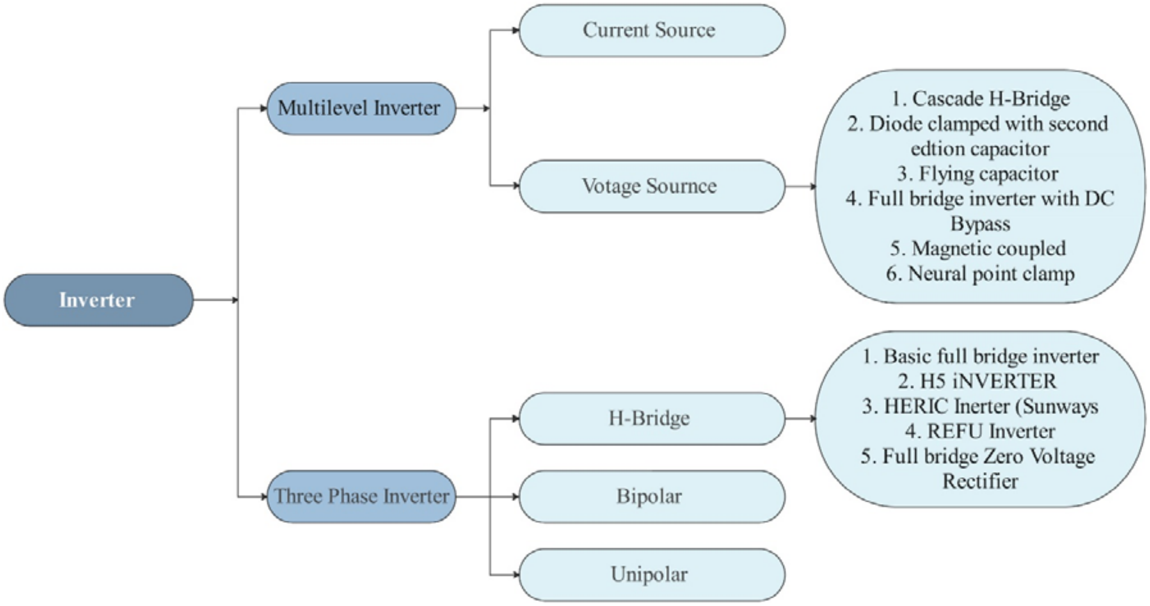


**Figure 5**. Various types of solar PV inverter topologies.

## Grid-connected solar photovoltaic system

Solar power is one of the fastest-growing RERs to be effectively integrated into the distributed power grid on different scales, from small to large and even extremely large. The main component of the solar PV and/or PV/T systems, as discussed in Section Section 3, can be operated in an islanded-mode[94] and/or connected to the main grid mode[95]. A user-friendly concept used to express different operation modes of solar PV systems is called a microgrid[52,96]. Figure 4 demonstrates that the PV/T system provides two operating output possibilities (electricity and heat). The grid-tied PV/T system focuses on the electricity output option in this research work. The microgrid concept is used in different VREs and/or DEG applications to supply electricity[97]. Therefore, the microgrid concept is limited to applying the DERs based on RERs[96]. The term microgrid is unused in several research works, or it is intentionally avoided to describe the grid-connected VRE system[98]. This research work also deals with grid-connected VRE systems (PV and PV/T) in the microgrid environment without exploiting the target concept term “Microgrid”.

The promotion of the feed-in tariff strategies and PV system has aggressively increased in several countries. The objective of this promotion is based on a perspective impact that can fasten the grid-connected RERs growth[99]. Figure 6 classifies various configurations of grid-connected PV in terms of their structural arrangement[26,100]. For an effective operation, the grid-integrating solar PV and PV/T systems require a filter and coupling transformer to deal with different power quality glitches[2]. Regardless of inverters classification detailed in Figures 5 and 6, a new generation of single-phase transformer inverters is currently being developed to increase the efficiency of the PV system, minimise investment and operation costs and reduce the size of the system. This system is increasingly gaining the interest of residential PV system markets[101]. Grid-tied PV and PV/T systems have various problems, from solar resources to system operation efficiency. Figure 7 presents major problems affecting grid-connected solar PV’s optimal operation[12]. From these identified problems, some of the challenging questions of the grid-tied PV system can be analysed.

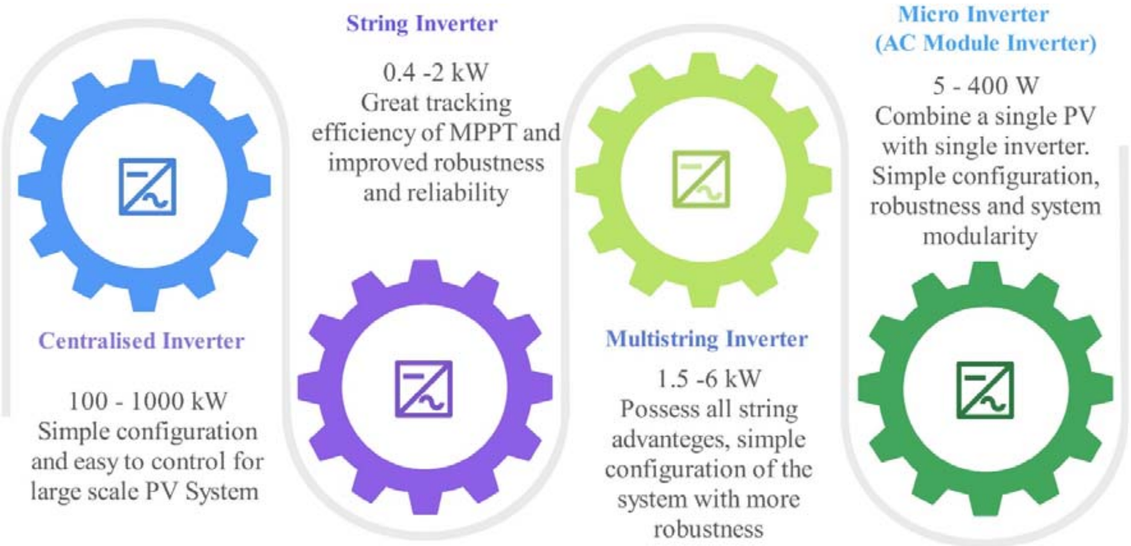


**Figure 6.** Grid-connected solar PV inverter classification.

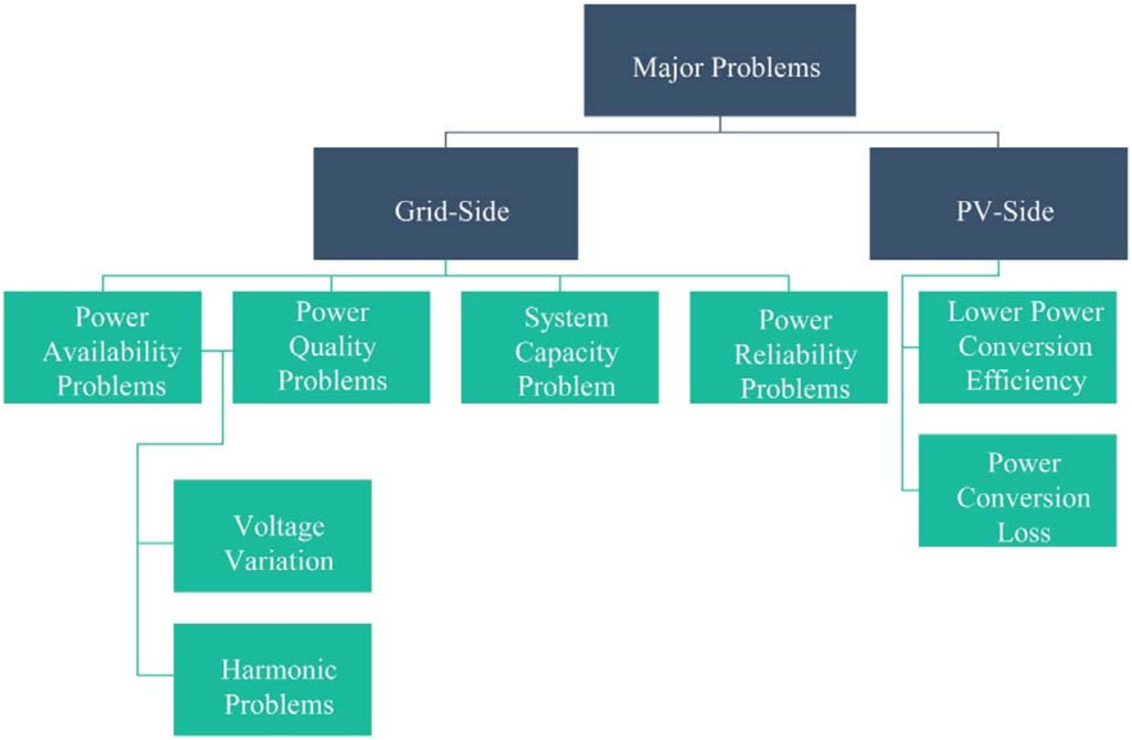


**Figure 7.** Principal problem of grid-tied PV systems.

### *Maximum power point tracking*

Tracking varying power from the PV panel is efficient by combining a DC-DC converter and maximum power point tracking (MPPT)[102,90,103]. The MPPT is synchronised with the power converter, DC-DC converter and/or DC-AC inverter, to improve the high-power arrays of the PV modules. However, the PV curve of power and voltage characteristic which defines the MPP is nonlinear due to changing ecological conditions which affect temperature and solar irradiation and challenge the tracking system of the PV panel[104]. Therefore, MPPTs have several applications within the solar technologies environment, such as grid-tied power supply systems, satellite power supply, solar vehicles, solar water pumping systems, small electronic devices (mobile charging), etc.

Various techniques for MPPT have been detailed in[2,105]. A summary of MPPT in grid-tied PV mode is presented in Table 7. All the MPPT techniques, as described in Table 7, are expensive except the one-cycle control (OCC) technique. While all the MPPT techniques require a tuning parameter, the sliding-mode-based MPPT technique does not need it[66]. The intelligent MPPT techniques contain various strategies to track the MPP. The most well-known of these techniques is the fuzzy logic (FL)-based MPPT technique, artificial neural network (ANN)-based MPPT technique, and particle swarm optimisation-based MPPT (PSO-MPPT) technique[2,66]. The intelligent MPPT techniques are promising approaches developed under various smart grid technologies based on optimal control conceptual framework.

**Table 7.** Grid-connected MPPT techniques.

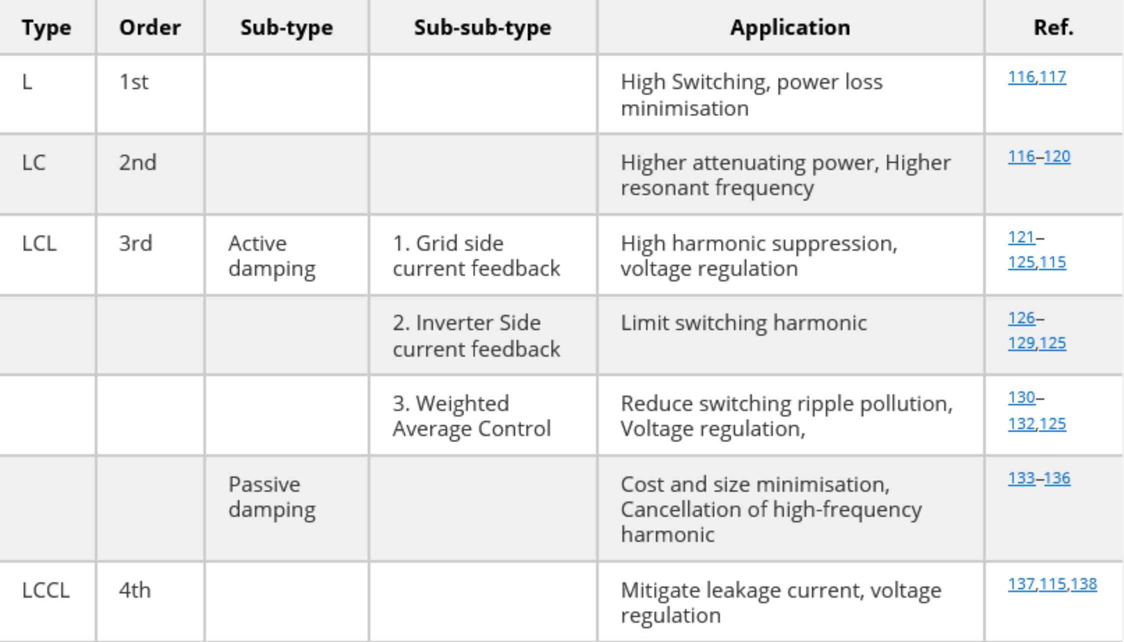
| MPPT Technique | Control Strategy | Control Variable | Circuitry | Complexity Level | Converter (DC-DC or DC-AC) | Commercial Products |
|---|---|---|---|---|---|---|
| One-Cycle Control (OCC) Technique | Sampling method | Current | Analogue/ Digital | Simple | DC-AC | Model Enphase, Enphase Energy (Petaluma, CA) |
| Current sweet Technique | Modulation method | Current | Digital | Complex | DC-AC | |
| DC-Link Capacitor Droop Control Technique | Modulation method | Voltage | Analogue/ Digital | Simple | Two-stages DC-DC DC-AC | |
| Intelligence MPPT Techniques | Indirect control | Voltage or Current | Digital | Medium | Both | Morning-star - Trakstart MPPT charge controller, Solar Electric Supply (USA) |
| Sliding-Model-Based MPPT Technique | Sampling method | Voltage or Current | Digital | Complex | Both | |
| Hybrid MPPT (HMPPT) Technique | Sampling method | Voltage or Current | Digital | Medium/ Complex | Both | |
| MPPT technique for Mismatched Conditions | Indirect Control | Voltage or Current | Digital | Medium | Both | Semiconductor, (America), Maximizer-Es and Maximizer-EP, Tigo Energy and Sun Mizer, Xander, (California) |

It is important to note that the MPPT technologies, as described in Table 7, can be called the MPPT algorithm[106]. Furthermore, these can be categorised into three principal aspects: conventional structure, advanced soft computing approach, and hybrid strategies[107–109]. Therefore, several optimal control strategies can be developed to meticulously handle the PV system's dynamic behaviour to operate at MPP with significant efficiency. In[110], the most popular algorithms applied in the MPPT are detailed. Besides, it is observed that all algorithms that can be developed to handle the MPPT behaviour for maximum power production from solar PV depend on the classification of techniques which are a function of the above three principal aspects[111].

### *Filter*

The power quality of the utility grid is negatively impacted by flowing harmonic pollution during the integration of the PV systems[112]. This originates from the high order harmonics produced by the power electronic devices, as detailed in Table 6, Figs. 5 and 6. The passive and active harmonic filters reduce the harmonic distortion and guarantee the quality of the power flow into the electrical network[113,114]. These devices also act as reactive power compensation during the low power factor within distributed generation networks[2]. The main passive elements of the passive filter used in a grid-connected PV system are a capacitor (C) and inductor (L)[26]. A resistor is also considered a potential element for implementing and designing a passive filter[2]. Several filters can be implemented to deal with harmonic pollution in grid-connected PV systems. Table 8 describes different types of filters, their applications and order, respectively. The combinations of the various filters are increasingly being implemented to reduce the total inductance and minimise the system costs[26]. This strategy creates a high-order power filter[115].

**Table 8**. Various types of filters.



| Type | Order | Sub-type | Sub-sub-type | Application | Ref. |
|---|---|---|---|---|---|
| L | 1st | | | High Switching, power loss minimisation | 116,117 |
| LC | 2nd | | | Higher attenuating power, Higher resonant frequency | 116–120 |
| LCL | 3rd | Active damping | 1. Grid side current feedback | High harmonic suppression, voltage regulation | 121–125,115 |
| | | | 2. Inverter Side current feedback | Limit switching harmonic | 126–129,125 |
| | | | 3. Weighted Average Control | Reduce switching ripple pollution, Voltage regulation, | 130–132,125 |
| | | Passive damping | | Cost and size minimisation, Cancellation of high-frequency harmonic | 133–136 |
| LCCL | 4th | | | Mitigate leakage current, voltage regulation | 137,115,138 |

### *Coupling transformer*

There are two principal reasons to justify implementing the coupling transformer in the grid-connected PV systems. First, the transformer is implemented at a low frequency (LF) between the inverter and the power grid. This LF device serves as galvanic isolation and protects the system against the DC injection that can negatively affect the distributed network[2]. Second, the LF transformer is sometimes optimal for an off-grid PV system[139]. Therefore, several transformerless inverters for grid-connected PV systems are beginning to be widely utilised in the energy market[101].

On the other hand, a transformerless grid-integrated PV system creates leakage current components that complicate the electrical network[2]. Therefore, three categories have been identified in classifying the Grid-tied PV system based on whether a transformer is used or not. These are the grid size LF transformer including the filter and converter; DC side high-frequency (HF) transformer containing converter and filter; and a transformerless system with only the converter and filter. Furthermore, in[140], a new solution is designed to manage the power quality for solar PV power plants connected to the grid. The strategy uses the filtering scheme based on a box-type transformer and grid-connected transformer that acts as inductive filtering.

### *Synchronisation system*

The grid-connected PV system can be implemented in different voltage levels and the size of the electrical network, which can be in HV, MV and low voltage (LV). The common term used to describe the electrical system with diverse power generation is microgrid. In[52], an overview of an energy management system for a microgrid is presented. This research study also defines various microgrids based on their size, capacity and voltage level in the electrical network. Figure 8 depicts four critical parameters to consider for efficient grid-tied synchronisation[2,26]. The better synchronisation system stabilises reactive powers (*PQ*) and voltage and frequency (*Vf*) of the network[37]. The direction of the power flow in grid-tied mode during synchronisation is one of the critical aspects to consider for optimal power system coordination. The power flow direction depends on phase difference and voltage magnitude, detailed in Figure 8. Both active and reactive powers can have two flow directions between the grid and the inverter. Therefore, when the phase difference is negative, the real power flows from the inverter to the grid, while for a positive phase difference, the active circulates from the grid to the inverter.

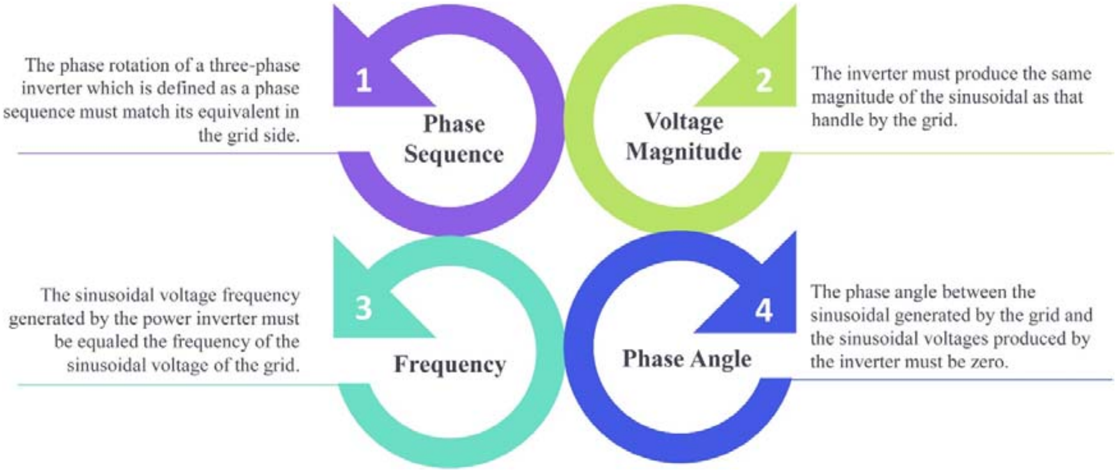
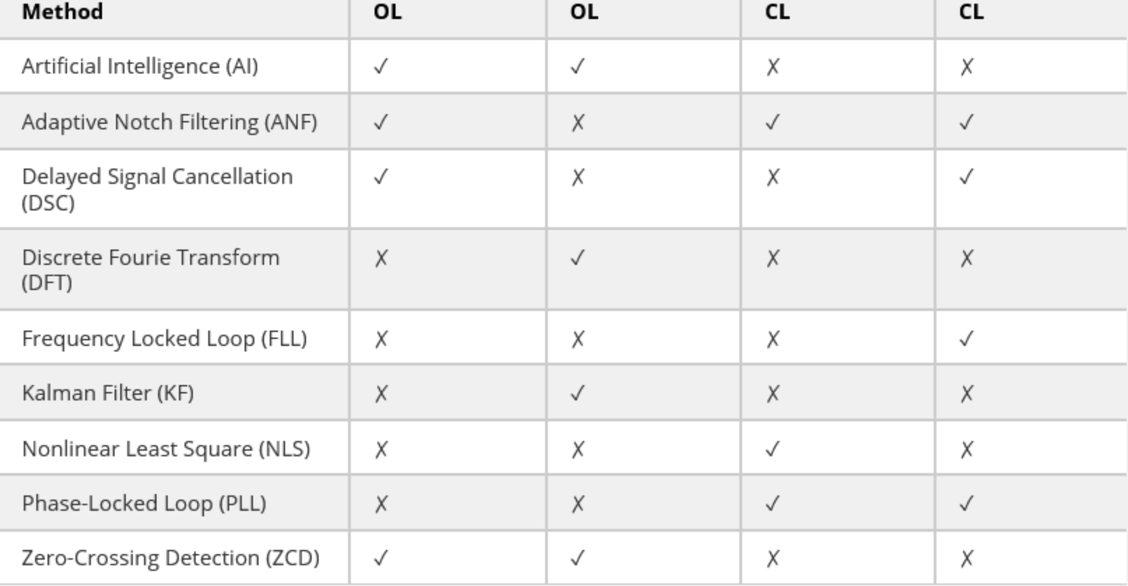


**Figure 8**. Grid synchronisation parameters.

On the one hand, the voltage magnitude influences the direction of the reactive power. For the inverter voltage magnitude superior to the grid voltage magnitude, the reactive power flows from the inverter to the grid. On the other hand, when the inverter voltage magnitude is less than the grid voltage magnitude, the reactive power flows from the grid to the inverter[2,22]. When dealing with grid-tied PV systems, synchronisation requires adequate dynamic behaviours to handle the steady-state of the *PQ* and *Vf* parameters. These variables can be coordinated mainly by an appropriate strategy to coordinate the phase difference and voltage magnitude. In[26], a classification of the grid synchronisation technique is detailed. The grid synchronisation can be split into two domains of the system analysis. These are frequency domain analysis and time-domain analysis. The frequency technique contains three Fourier methods: Fourier analysis, discrete Fourier transform, and recursive discrete Fourier transform. The time-domain analysis is based on a phase-locked loop (PLL) and frequency-locked loop (FLL). Therefore, several methods can be developed from the two essential domains of grid-tied PV synchronisation to ensure power grid stability. Table 9 narrows down the two domains of grid synchronisation into their applications (single-phase or three-phase system) and the type of control schemes, namely open-loop (OL) or closed-loop (CL)[2,22]. The OP schemes can swiftly detect the magnitude, phase and frequency of the control variable signal. In contrast, the CL schemes adaptively update the detected parameters through a loop mechanism[22].

**Table 9.** Various grid synchronization methods.



| **Grid Synchronisaiton Method** | **Single Phase OL** | **Three Phase OL** | **Single Phase CL** | **Three Phase CL** |
|---|---|---|---|---|
| Artificial Intelligence (AI) | ✓ | ✓ | ✗ | ✗ |
| Adaptive Notch Filtering (ANF) | ✓ | ✗ | ✓ | ✓ |
| Delayed Signal Cancellation (DSC) | ✓ | ✗ | ✗ | ✓ |
| Discrete Fourie Transform (DFT) | ✗ | ✓ | ✗ | ✗ |
| Frequency Locked Loop (FLL) | ✗ | ✗ | ✗ | ✓ |
| Kalman Filter (KF) | ✗ | ✓ | ✗ | ✗ |
| Nonlinear Least Square (NLS) | ✗ | ✗ | ✓ | ✗ |
| Phase-Locked Loop (PLL) | ✗ | ✗ | ✓ | ✓ |
| Zero-Crossing Detection (ZCD) | ✓ | ✓ | ✗ | ✗ |

Figure 9 depicts different topologies of PLL that can be used on grid-tied PV systems[2,26,141]. The PLL method is one of the most critical strategies in a grid-connected distributed power generation system. Several techniques have been implemented worldwide to create derivative versions of PLL methods for grid-connected power inverters[2]. The selected different topologies of PLL in Figure 9 are the most used to synchronise PV systems connected to the main grid.

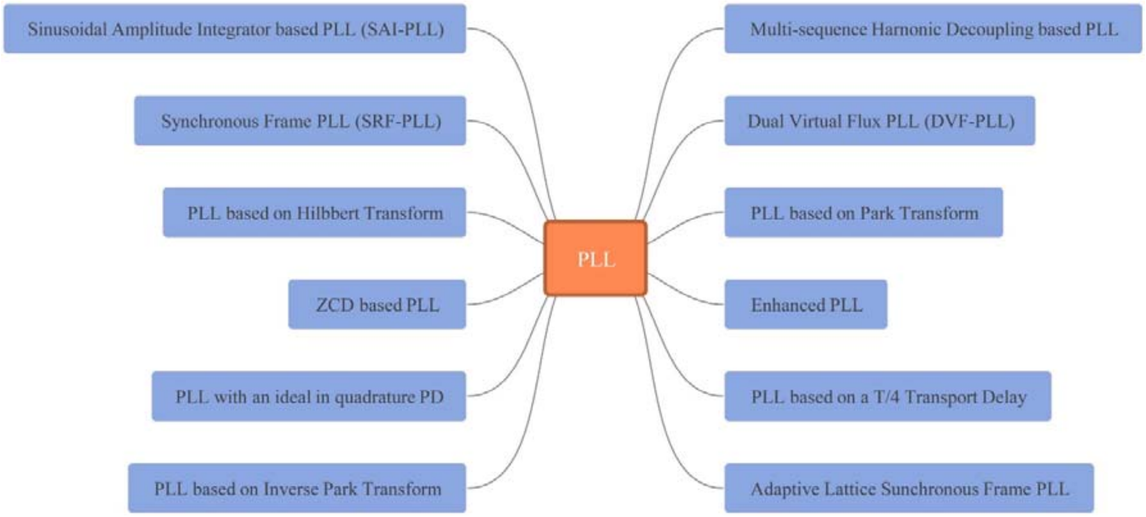


**Figure 9.** Various PLL topologies for grid-tied system.

### *Control scheme of grid-connected PVs*

The control of grid-tied DERs handles the reliability and resilience of the network[142]. An excellent dynamic of power coordination depends on the robustness of the control methods[143]. Several control strategies have been developed to ensure grid-connected PV systems' optimal operation[144–152]. The structure of different topologies presented in Figure 6, centralised, micro, multi-string and string inverters, is the main conceptual framework that can assist in developing the control scheme for grid-tied PV systems[31]. The control of PV systems microgrid possesses four principal architecture categories: centralised control, decentralised control, hierarchical control, and multi-agent control[12]. The total optimal operation of a given microgrid contains three layouts of a dynamic control scheme. The first level is the primary control layout, which functions the local *PQ* sharing and *Vf* control. The secondary control level is the second layout that restores the frequency and voltage at the PCC. Finally, the tertiary control level optimally coordinates the real and reactive power exchange and controls the power flow within the network[153].

Figure 10 categorises the controllers' strategies to be used in a grid-connected PV system into six groups. PID, PI, PD and P stand for Proportional-Integral-Derivative, Proportional-Integral, Proportional-Derivative, and Proportional controllers[139]. The most popular controllers in grid-integrated VRE are PR controllers. The PR controllers are preferable to the classic controllers (PI) because they provide ease of tuning, elimination of selective harmonics, perfect decoupling, reduced steady-state error, robustness, and sinusoidal voltage regulation[26]. However, it is essential to note that the single-phase controller and three-phase controller of the grid-tied PV system can differ, as detailed in Table 9. In[20], it is demonstrated that the control objective of a grid-connected single-PV system is based on PWM and MPPT. Therefore, the control blocks contain three main functions: basic control functions, PV system specification functions, and advanced functions (ancillary services). The first block (basic control functions) deals with current/voltage control, DC-link DC voltage control and grid synchronisation. The PV system specification functions coordinate the MPPT, anti-islanding protection and PV panel/plant monitoring. Lastly, the advanced functions deal with the grid support($V$, $f$, $Q$), fault ride through, energy storage, harmonic compensation, flexible power control and reliability.

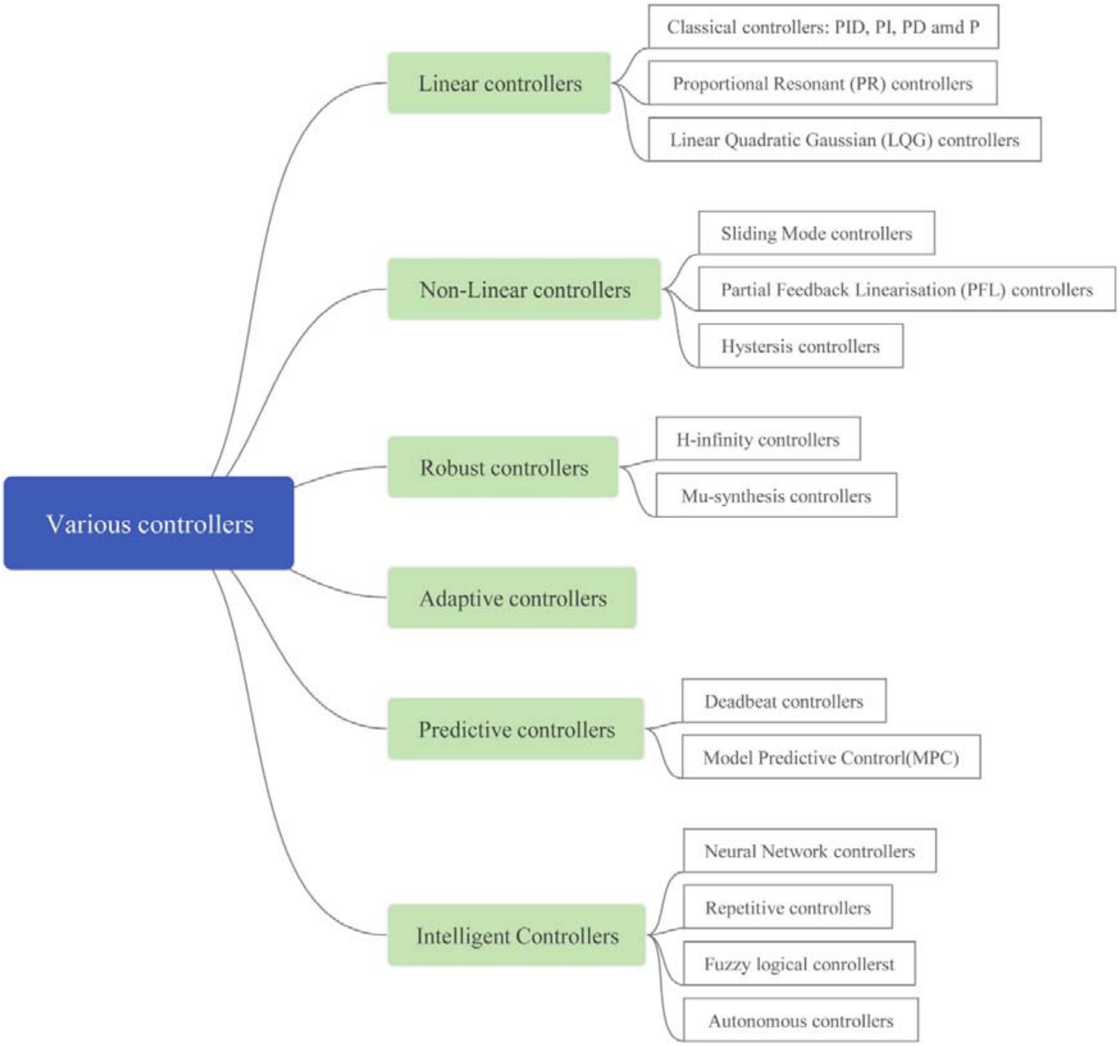


**Figure 10**. Various controllers for the grid-tied PV system.

### *Islanding detection*

The operation of a grid-tied PV system must be designed to handle the isolated running of a portion of the area. These operating conditions are realised using an islanding environment. Two scenarios can create this event, namely, intentional and unintentional methods. Accidental islands come with high risks that can tangibly damage different electrical devices. Thus, islanding detection is one of the essential strategies to avoid failure. Islanding detection methods are based on two principal schemes: local and remote. The local schemes are split into two. The first tactic deals with inverter-based generation and rotating-based generation methodologies. The second local method consists of passive approaches based on conventional passive and modified passive. Alternatively, the remote schemes bear communication-based methods, signal processing techniques and intelligence-based methods. Each of these methods holds several strategies that can handle islanding detection[2]. In addition, improving system performance may necessitate using hybrid methodologies that can increase detection efficiency[26]. Other classifications of islanding detection methods are proposed in[154]. These schemes are based on three particular strategies around the inverters and one on communication schemes that maintain a relationship between the power grid and the power inverter.

### *Main standards of grid-tied PVs*

A grid-connected PV system is a microgrid. The micropower grid was one of the first power plants developed by Thomas Edison in 1882. However, the advancement of power services and regulation of energy monopoly did not permit a microgrid to evolve across generations from the early age of the electricity market[155]. The advent and need for VRE in this modern generation provide an opportunity to develop microgrids operating in islanded and/or grid-connected mode. Several important factors, such as energy disturbance, environment, reliability and resilience of integrated power system[52] and safety, need to be considered for adequate monitoring to prevent and protect equipment[2]. Therefore, several standards have been developed to deploy microgrids in their controllers, operation modes, protections, and specifications[156–158]. The standardisation of the microgrid systems assists in deploying the DERs in various power system sizes.

The synchronisation of the utility grid with the PV panels requires the congruence of the electrical parameters, as illustrated in Figure 8. The main objective of this philosophy is to resolve the significant system problems, presented in Figure 7. The standard and guidelines are the essential tools that offer a mutual technical understanding for interconnecting PV systems to the utility grid. The Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC) provide the most widely recognised standards under IEEE 1547:2003 and IEC 61727:2002, respectively. These two standards, IEEE 1547:2003 and IEC 61727:2002, deal with specifications and tests of the interconnection of DER and grid-tied PV systems for a rated capacity of less than 10 kVA[2]. There are standards for grid-connected PV systems, and Table 10 summarises the most important standards[26]. Mohammed et al. in[2] state that IEEE 929:2000 is a specific standard for grid-connected PV systems. It is essential to specify that some standards can be used for other purposes based on the system specifications and requirements, regardless of the summary provided in Table 10. For example, IEEE 519:1992 is a standard for voltage limitations and requested time for islanding operation[12].

**Table 10**. Grid-connected PV systems: List of most essential standards[26].

| **Categories** | **Standards** | **Summary (Applications & Objectives)** |
|---|---|---|
| Design and Testing Procedure Verification | CEI 62124:2004 | Off-grid PV systems: Conception verification |
| | DIN EN 6210 (VDE 0126-33):2008-07 | CPV modules and assemblies (design and approval) |
| | IEEE 1547.1:2005 | Conformance testing for integrated DERs' equipment |
| Islanding | DIN EN 62116 (VDE 0126-2):2012-01 | Test procedure to prevent grid-tied PV inverters measures |
| | IEC 60364-7-712:2002 | PV supply: Special installation or locations requirement |
| | IE 62116:2008 | Grid-tied PV: Test procedure for prevention measures |
| Grid Connection | DIN EN 0530:2011 | Grid-tied PV inverters: Overall efficiency |
| | IEC 62446:2009 | Minimum requirements: Documentation, inspection and test |

| | | |
|---|---|---|
| | IEEE 1547:2003 | Interconnecting DERs with Electrical power systems |
| | IEEE 2030:2011 | Smart grid interpretability: Overall power system |
| Measurement and Analysis | IEC 601829-8:2014 | PV devices: Measurement of spectral responsively of a PV |
| | IEC 61000-4-15:2010 | Electromagnetic compatibility: Test & technical measurement |
| | IEC 61724:1998 | PV system: Performance monitoring (measurement & analysis) |
| | IEC 61829:2015 | PV array: Current and voltage characteristics measurement |
| | IEEE 512: 1999 | Harmonic control: Recommended practices and requirements |
| | IEEE 929:2000 | Utility interface of PV system: Recommended practice |
| | EN 50160: 1999 | Voltage quality: Public distribution |
| PV power converters | DIN EN 61683:2000-08 | Power conditioners: Procedure for measuring efficiency |
| | IEC 61727:2002 | PV system: Characteristic of the utility interface |
| | IEEE 921: 2010, UL1741 | Independent power system: Inverters, converters and controller |
| Safety | DIN EN 61730-2:2007-10 | PV module: Safety qualification (requirement for testing) |
| | IEC 60269-6:2014 | LV fuses: Supplementary requirement for the protection of PV |
| | IEC 62109-1: 2010 | Power converters: Safety in a PV system (general requirements) |
| | VDE 0126-1-1:2006 | Automatic disconnection device: Generator and pubic LV grid |

## Key discussion of system components

The visions of grid-tied solar PV systems are a function of the improvement approaches throughout the network operation. This starts from power sources (utility and solar energy) to the end-users. Sections 2–4 provide an excellent understanding of these critical visions. Section 5 discusses the grid-tied PV and/or PV/T components in function of the system benefits, challenges and mitigation. Figure 11 presents different landscapes to consider in assessing the benefits, challenges and possibility of mitigating various boundaries and issues in integrating solar energy (PV and PV/T systems) into the power grid. Table 11 presents some recently published research works that deal with grid-tied solar power systems. This looks to identify the challenge, benefits and mitigation of each relevant implementation strategy.

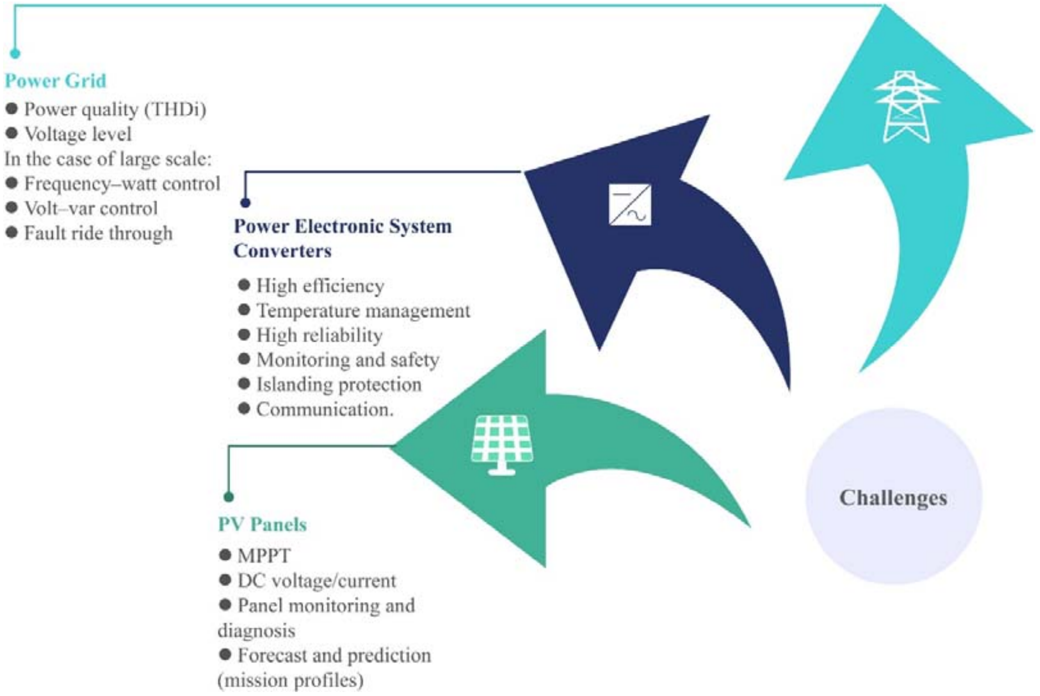
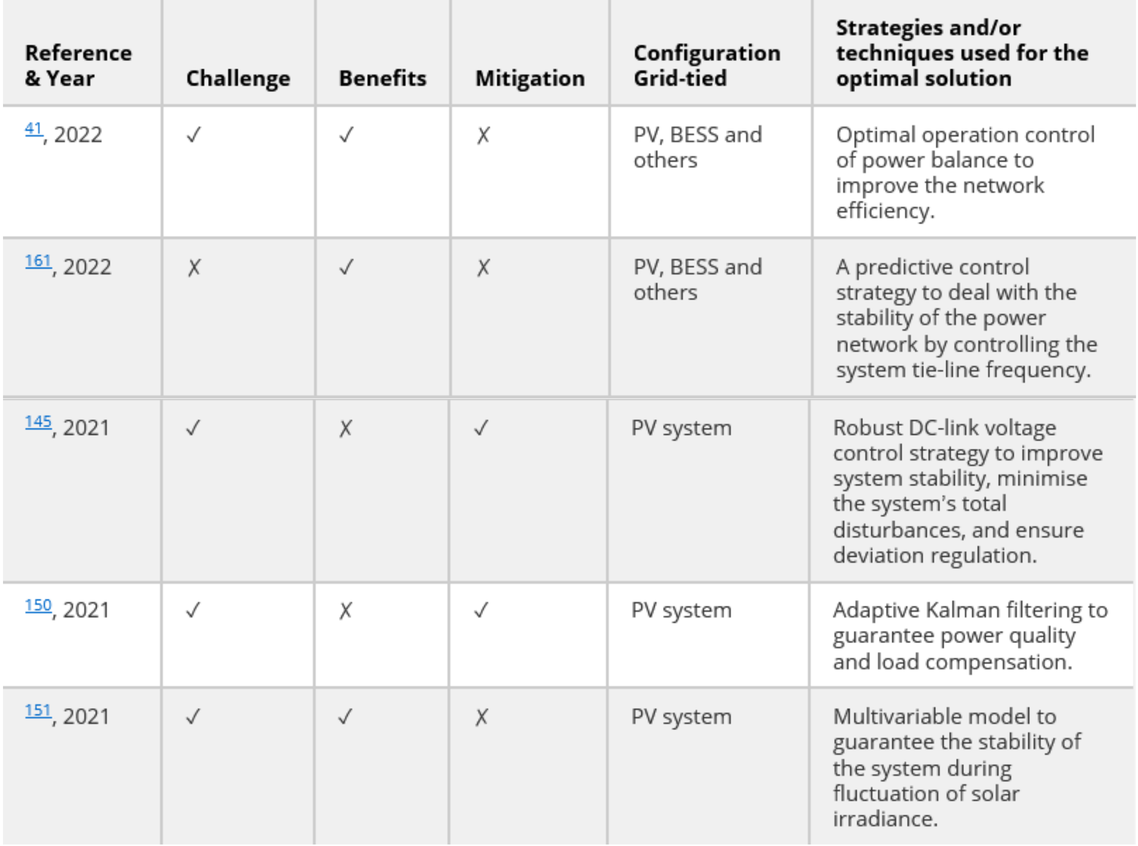


**Figure 11**. Challenges for the grid-tied PV system.

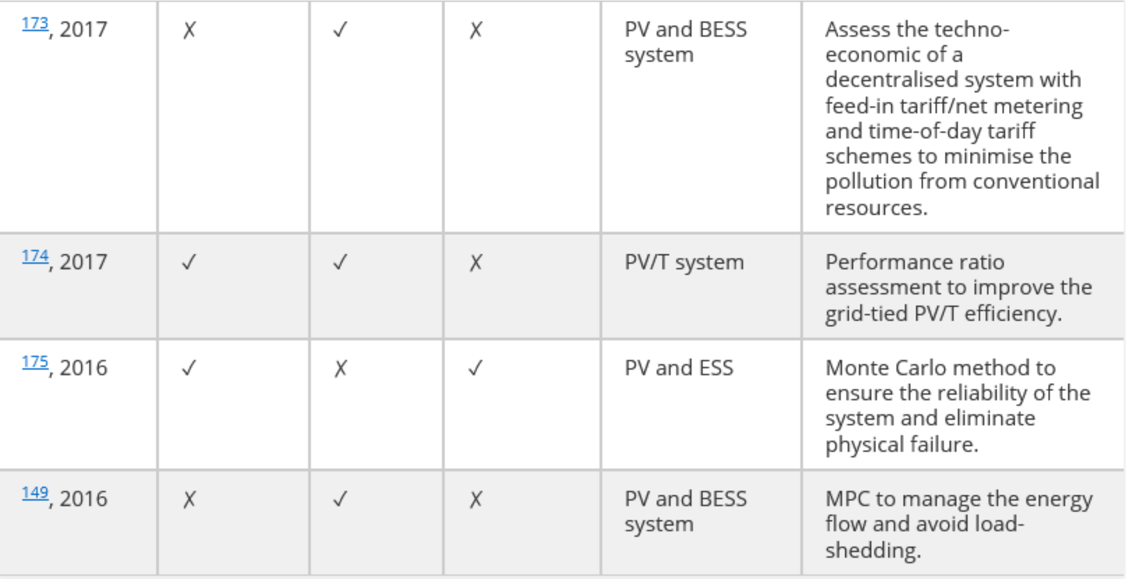
**Table 11.** Discussion on Key implementation schemes.



| Reference & Year | Challenge | Benefits | Mitigation | Configuration Grid-tied | Strategies and/or techniques used for the optimal solution |
|---|---|---|---|---|---|
| [41], 2022 | ✓ | ✓ | ✗ | PV, BESS and others | Optimal operation control of power balance to improve the network efficiency. |
| [161], 2022 | ✗ | ✓ | ✗ | PV, BESS and others | A predictive control strategy to deal with the stability of the power network by controlling the system tie-line frequency. |
| [145], 2021 | ✓ | ✗ | ✓ | PV system | Robust DC-link voltage control strategy to improve system stability, minimise the system's total disturbances, and ensure deviation regulation. |
| [150], 2021 | ✓ | ✗ | ✓ | PV system | Adaptive Kalman filtering to guarantee power quality and load compensation. |
| [151], 2021 | ✓ | ✓ | ✗ | PV system | Multivariable model to guarantee the stability of the system during fluctuation of solar irradiance. |

| | | | | | |
|---|---|---|---|---|---|
| [152], 2021 | ✓ | ✓ | ✗ | PV system | Monitor and measure the energy yield and the capacity utilisation factor to contribute to the reduction of $CO_2$ emission. |
| [162], 2021 | ✗ | ✓ | ✓ | PV system | Particle swarm optimisation and intermediate power point tracker algorithms to stabilise the DC bus voltage and inject the power to the grid. |
| [163], 2021 | ✓ | ✓ | ✗ | PV/T, and others | Energy performance modelling to deal with the environment and economic aspects of grid-tied PV/T, wind turbine and heat storage systems. |
| [164], 2021 | ✓ | ✓ | ✗ | PV/T | Energy performance modelling to deal with a concentrating PV/T for electricity and hot water production in the residential building environment. |
| [165], 2021 | ✓ | ✗ | ✗ | PV/T | Assessment of thermal and collector efficiencies for optimal operation of the grid-tied PV/T system. |
| [166], 2021 | ✗ | ✗ | ✓ | PV/T | Apply water to cool the temperature increase of the solar panels to guarantee the efficiency of the system operation. |
| [137], 2020 | ✓ | ✗ | ✓ | PV system | Common-mode resonance and damping and neutral-point voltage balancing strategy for transformerless PV inverter. |
| [167], 2020 | ✓ | ✗ | ✗ | PV, BESS and others | Robust optimisation and economic dispatch for the microgrid. |
| [142], 2020 | ✓ | ✓ | ✗ | PV and ESS | Applied predictive control to manage the power flow on the system. |
| [148], 2020 | ✗ | ✓ | ✓ | PV system | Fractional-order proportional integral and integer-order proportional-integral to enhance stability and system robustness, MPPT and total harmonic minimisation. |

| | | | | | |
|---|---|---|---|---|---|
| [168], 2020 | ✓ | ✓ | ✗ | PV/T system | Artificial neural network to assess the system's technical and economic criteria and improves the thermal and electrical efficiencies of the PV/T. |
| [169], 2020 | ✓ | ✓ | ✗ | PV/T, BESS system | Real-time performance and energy prediction with exergy generation for thermal and electrical components are developed to maximise heat and power production. |
| [138], 2019 | ✓ | ✗ | ✓ | PV system | Active damping technique with a common-mode current closed-loop control for leakage current suppression. |
| [107], 2019 | ✓ | ✗ | ✗ | PV system | Adaptive neuro-fuzzy interface system (ANFIS) to draw much energy and fast response for MPPT. |
| [98], 2018 | ✗ | ✓ | ✗ | PV system | Fractional Nonlinear Synergetic Control to regulate the voltage at DC-link and ensure a fast transient response. |
| [140], 2018 | ✗ | ✓ | ✓ | PV system | Two-stage filtering station to eliminate the harmonics of the output signal from each PV inverter and enhance the power quality of the entire network. |
| [146], 2018 | ✗ | ✓ | ✗ | PV system | Hysteresis band current controller under a modified $p-q$ theory to control the power flow. |
| [170], 2018 | ✗ | ✓ | ✓ | PV/T system | Cost of energy and payback period easements to draw the capacity factor, yield factor and efficiency of the system while providing a stable voltage and balancing power of the network. |
| [171], 2018 | ✓ | ✗ | ✓ | PV/T system | New thermal absorber configuration to deal with the thermal efficiency of PV/T. |
| [172], 2017 | ✓ | ✗ | ✗ | PV, ESS and others | Coordinated control strategies to tackle the trade-off between performance and safety. |



| | | | | | |
|---|---|---|---|---|---|
| [173], 2017 | ✗ | ✓ | ✗ | PV and BESS system | Assess the techno-economic of a decentralised system with feed-in tariff/net metering and time-of-day tariff schemes to minimise the pollution from conventional resources. |
| [174], 2017 | ✓ | ✓ | ✗ | PV/T system | Performance ratio assessment to improve the grid-tied PV/T efficiency. |
| [175], 2016 | ✓ | ✗ | ✓ | PV and ESS | Monte Carlo method to ensure the reliability of the system and eliminate physical failure. |
| [149], 2016 | ✗ | ✓ | ✗ | PV and BESS system | MPC to manage the energy flow and avoid load-shedding. |

### *Benefits*

Several benefits can be observed throughout the implementation of grid-tied PV and PV/T systems. The structure supports cost-effective energy storage, harmonic compensation, flexible power control and reliability. Therefore, this system is beneficial in regulating the voltage and frequency and compensating for the power factor in the electrical power network. The advantages of such a model can be observed from the generation to the end-user, where the power flow stability within the network is a significant value[159]. Environmental concerns address the VREs revolution during the past and current decades. Therefore, PV technologies have become a feasible solution and supporting energy player in the power sector[160]. This is based on being an environmentally friendly DEG to reduce the carbon emission from the traditional power resources.

As detailed in Figure 1, the PV system connected to the grid can be implemented as a virtual power plant using the aggregators. This can be applied in various scales of electricity markets with several types of consumers. In[176], an assessment of the economic benefits of grid-tied PV systems for residential usage within two independent energy markets (India and the UK) is presented. It is observed that the minimisation cost for the energy market when the PV module is connected to the grid can be optimally even for a lower solar resource with excellent location-specific system planning. However, this also depends on load generation matching, primarily achieved through an optimal system modelling approach based on intelligent applications.

The sustenance of suitable control schemes, as seen in Figures 9 and 10, is their influence in coordinating the system operation that respectably epitomises various equipment. For example, in[162], a high-efficiency control is devised to handle optimally coordinated grid-connected PV. The boost converter is controlled through PSO and intermediate PPT algorithms. On the other hand, the inverter control model combines the voltage-oriented technique with the PLL algorithm to synchronise the system. The advantages of these two levels of the collective controllers are: guarantee ease of insertion into different operating modes of microgrid; increase the efficiency of PV module regardless of partial shading; accurate control response; voltage stability on the DC bus; power factor improvement; and a user-friendly system. In[149], it is demonstrated that the predictive controller offers an opportunity to correctly manage the energy flow from PV and battery energy storage system (BESS) connected to the utility grid during an intensive periodic load shedding. The optimal design of BESS to support the total operation of the solar PV system is a function of several parameters, such as the size of power, maximum generating energy from the PV[177], the budget of ESS, etc.

The integration of the PV/T system into the utility grid significantly reduces the overall costs of energy consumption. This system generates both electricity and heat Figure 4. Implementing the traditional PV system connected to the main grid requires several efforts to satisfy the thermal load for a given electrical system (or microgrid). Therefore, the conventional PV module impedes system improvement in grid-connected and off-grid modes compared to the PV/T system[178]. Rahaie et al. in[179] state that the PVT system presents higher electrical efficiencies than traditional PV panels. The strong point of this model is that it increases the water flow rate that cools down the system and augments the overall efficiency for both electricity and thermal, as presented in Figure 4. This is in contrast with the cooling methods of conventional PV panels[180].

### *Challenges*

A grid-tied PV system faces various challenges, from solar resources passing through the interconnecting devices of the grid to the end-users. Due to sources of uncertainty of generated energy from the PV systems, solar resources are among the most significant difficulties that the PV system can have. As detailed in Figure 2, the solar resource plays a substantial role throughout the implementation strategies of the PV system. Table 5 details different challenging questions of PVT systems. Table 7 shows various techniques that assist in responding to uncertainty issues using MPPT strategies effectively. Finally, Figures 7 and 8 depict the key factors that challenge the effectiveness of grid-tied solar panels.

The critical challenges of the grid-tied PV and PV/T systems are summarised in Figure 11[20]. This contains three principal aspects: resource transformation, electricity conversion and utility grid stability questions. Table 11 shows that the most challenging problems can be an opportunity for mitigation techniques. In[181], five top challenges and their possible solutions are detailed. These are voltage fluctuation caused by irregular solar radiation, frequency fluctuation due to variation of active load demand, harmonics due to power electronic and non-linear devices, energy security and system synchronisation. Islanding detection is also one of the critical challenges to consider for optimal operation and protection of the system[2]. The economic challenges are; higher investment, operation and maintenance costs. The most important economic challenges depend on the cost of operation and maintenance, which can negatively affect the cost of generated energy from the PV panels[155]. The intermittent nature of power generated from solar devices leads to the need for BESS[182], as shown in Table 3. The necessity of the ESS to optimise the system's operation implies a high investment cost for the system[183]. The technology development of the entire structure needs to meet different requirements at several levels, which complicates the hardware design of system implementation[5].

### *Mitigation*

The grid-tied PV system can secure the energy supply to the end-users when coordinated with the ESS[53]. The effectiveness of such a system relies on an adequate control scheme, as developed in Figure 10, to handle the flow of the system. This is a benchmark of various control philosophies designed to coordinate the grid-connected PV panels. Traditional energy management strategies and control schemes cannot efficiently coordinate a hybrid grid, PV and ESS due to three significant challenges. First, the vulnerability of the system due to the weather can create either loss of load due to energy shortage or the need for energy storage which increases capital and operation maintenance costs. Secondly, a curtailment that can lead to wastage of surplus energy from the PV system can be caused. Finally, the energy cost can be higher due to the unnecessary charging of ESS from the utility grid. It is important to note that the conventional control strategy to manage the energy negatively instigates the system loss of load and the surplus energy wastage from the PV when there is various stress on the utility side with load shedding[149].

The synchronisation of the PV systems with the utility grid requires a reliable and safe interconnection operation and high-quality power based on AC to the utility with optimal costs. The inverter technologies of a grid-connected PV system, as detailed in Figures 5 and 6, support the system's stability. Power electronic technologies have been applied to the PV inverters to guarantee the system requirement. The application combines HF switching of semiconductor devices with PWM technologies. Therefore, the connected system can generate high-efficiency conversion with a substantial power factor value and minimal harmonic distortion power[26]. Table 10 introduces some vital standards for an excellent operation process of the grid-connected PV system. These standards are based on the mitigation vision that opts to improve the operation efficiency of the grid-connected PV system. Figure 11 depicts the relevant challenges to esteem as appeasement scopes. The bulk of the significant problems detailed in Figure 7 reveals a gap in several mitigation schemes. Table 11 demonstrates that the mitigations of the electrical problems for grid-tied solar panels are primarily implemented in a grid-connected PV system. Therefore, these strategies are also valuable for grid-tied PV/T systems.

## Future perspective

The impacts of grid-connected PV and PV/T systems in this research work are mainly based on the system's electrical parts. Figure 11 presents the necessary components of grid-tied PV and PV/T systems to be considered for future perspectives. The PV/T also offers an opportunity to use the wasted energy from the conventional solar panel to produce heat, as detailed in Figure 4. This is one of the essential benefits that the PV/T thermal has over the traditional PV system, as described in subsections 3.2 and 5.2. Therefore, the significant perspective for this research work can be summarised as follows:

- The assessment and monitoring of secure energy related to environmental policies are important factors in measuring sustainable development goals. However, the deployment of VREs does not always guarantee the development of secure and reliable power plants due to the diverse challenges that come with the implementation and operation of grid-connected PV systems. Hence, IoT technologies offer real-time measurement of different vital parameters of the RERs.
- Apply smart grid technologies to coordinate various challenging problems of the system, as presented in Figures 7 and 11. Figure 1 depicts some essential applications and strategies that intelligent technologies may bring to implement VREs. This is regarding technologies, business models, energy market and system operation.
- Microgrids play a significant role in enabling the widespread adoption of DERs based on VRE. However, as the power generated from solar PV systems is naturally unsteady, the dynamic and stability of grid-tied PV systems can be negatively affected. Thus, their integration needs new approaches for coordination and control system performance. Moreover, as detailed in Sections 3–5, the existing systems lack run-time

adaptive behaviour. Therefore, the electric energy system must adapt by integrating Information and Communication Technologies (ICT) to face these constraints. The emerging integrated strategy to solve this problem can be a multi-agent system. This scheme effectively deals with distributed communication, computing and data integration assessment within the smart grid environment[184].

- Apply the IoT technologies and energy monitoring digitisation to develop a real-time data transfer based on various control strategies of the power inverters to monitor and commercialise microgrids.
- The integration of DERs based on PV panels in the existing network can be facilitated using transactive energy. This is a novel strategy to coordinate and trade the power flow in the electrical system, and its key feature is designed under market-based solutions for energy management. An adequate transactive energy market framework can then be devised to enable and incentivise PV owners to participate in different markets.
- A peer-to-peer interaction based on an energy router can be addressed by integrating diverse autonomous PV systems into the utility grid to form a multi-microgrid system. In addition, this approach can control network congestion and some local issues within the electrical system.
- Develop an intelligent control scheme that can autonomously coordinate both types of generated energy in the PV/T. The performance of this intelligent scheme is based on maintaining or increasing the PV/T system efficiency for the manipulated variables (electricity and heat). Energy harvesting from PV devices is one of the pertinent research topics increasingly gaining interest within the solar power research community[179]. Therefore, it is also estimated that an intelligent approach based on IoT for PV and PV/T environmental energy harvesting can increase system efficiency.

## Conclusion

Green energy power plants and strong energy security policies enable adequate supply to the current generation to meet energy demand growth. Secure energy guarantees the stability of a power network in the presence of uncertainty from the generation and consumer sides. Integrating a PV and PV/T system into the utility grid assists firstly in securing the energy and sustains Paris' agreement on sustainable development goals. Therefore, this research assesses different scopes for this type of interconnecting power grid regarding benefits, challenges and mitigation. This paper systematically reviews the essential systems and/or components that effectively connect the PV and PV/T to the DSO. This consists of analysing different fundamental aspects (technical, economic, environmental, etc.) to support creating a green planet.

RERs assist humanity with mitigation against various types of pollution from conventional power resources. Nevertheless, the effective operation of generated power from RERs requires ESSs to underpin the total power supply in the presence of the source uncertainty from renewable energy. VREs are the most popular among green power plants based on RERs that fascinate the energy markets. Solar and wind resources are the prominent VREs worldwide. Solar power holds the total source capacity for the bulk RERs and VREs. The solar irradiation that falls on the earth in one hour can meet the total estimated energy for humanity for a year. Therefore, solar is the powerhouse and future of the energy system for green planet development. The PV system is one of the salient devices that transform the energy from the Sun into electricity. Nevertheless, the PV panel cannot generate electricity from the total solar energy received on the panel. The inefficiency of the conventional PV module wastes more than 50% of solar energy to heat. Therefore, the PV/T concept was introduced to use the lost power from the Sun that could not be transformed into electricity to generate heat.

This work shows that the transformation process of solar energy, either from PV or PV/T system to electricity, passes through several steps to guarantee effective operation. First, it is found that the synchronisation of the utility grid with solar panels needs to meet specific standards that can optimally ensure adequate coordination of the power network. Second, the heat produced from the PV/T does not affect its connection to the power network. Therefore, technologies and control approaches have been developed to maximise solar energy conversion to electricity for both PV systems. Third, power electronic converters play a significant role in exploiting VRE from the Sun. Finally, the power quality flow between the utility grid and the PV inverters requires an accurate match of the electrical parameters concerning the energy market standards. This prorates the system with specific benefits regarding overall cost minimisation, power quality and green environment. Besides, The system uncertainty may lead to various challenges, from VRE sources to the power network connection. This is a juncture for possible mitigation approaches that can optimally stabilise the system. Smart grids are the fundamental vision to overcome different boundaries and issues for integrating solar power systems into the grid using innovative applications and technologies in a real-time environment. Therefore, the performance improvement of grid-tied PVs can be guaranteed in a real-time environment by using intelligent approaches to evaluate and control various systems from solar generation to end-users. Several challenges and mitigation problems in grid-connected PV mode are effectively resolved with ICT integration, where multi-subsystems are coordinated and monitored. Furthermore, through this emerging integration, the benefits of grid-tied PVs increase with suitable and secure power to support the utility grid.

## Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## Nomenclature

AC - Alternative Current
AI - Artificial Intelligence
ANF- Adaptive Notch Filtering
ANN - Artificial Neural Network
BESS - Battery Energy Storage System
CPV/T- Concentrated Photovoltaic Thermal
CSP - Concentrated Solar Power
CL- Closed-Loop
DC- Direct Current
DCS - Direct Concentrated Solar
DES - Distributed Energy Resources
DFT - Discrete Fourie Transform

DR - Demand Response
DSC- Delayed Signal Cancellation
DSSC- Dye Sensitized Solar Cell
DSO- Distributed System Operator
ESS- Energy Storage System
EV- Electric Vehicles
FL - Fuzzy Logic
FLL - Frequency Locked Loop
ICT - Information and Communication Technologies
IEA - International Energy Agency
IEC - International Electrotechnical Commission
IEEE - Electrical and Electronics Engineers
IRES - Intermittent Renewable Energy Sources
IoT - Internet of Things
HF - High-frequency
HV - High voltage
KF - Kalman Filter
LF - Low-frequency
LQG - Linear Quadratic Gaussian
LV - Low voltage
MCES - Multicarrier Energy System
MPC - Model Predictive Control
MPP - Maximum Power Point
MPPT- Maximum Power Point Tracking
MV - Medium voltage
OCC - Once-Cycle Control
OL - Open-LOOP
P - Proportional
PCC - Point of Common Coupling
PD - Proportional Derivative
PI - Proportional Integral
PID - Proportional Integral Derivative
PLL - Phase-Locked Loop
PR - Proportional Resonant
PSO - Particle Swarm Optimization
PV - Photovoltaic
PV/T - Photovoltaic thermal
PWM - Pulse Width Modulation
RER - Renewable Energy Resource
RES - Renewable Energy System (or source)
SEPIC - Single Ended Primary Induction Converter
STE - Solar Thermoelectricity
TSO - Transmission System Operators
UPS - Uninterruptible Power Supply
VR - Voltage Regulation
VRE - Variable Renewable Energy
ZCD - Zero-Crossing Detection
ZVS - Zero-Voltage Switching

## Biographies

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