Solar Photovoltaic and Thermal Energy Systems: Current Technology and Future Trends

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Abstract—Solar systems have become very competitive solutions for residential, commercial and industrial applications for both stand-alone and grid connected operations. This paper presents an overview of the current status and future perspectives of solar energy (mainly photovoltaic) technology and the required conversion systems. The focus in the paper is put on the current technology, installations challenges, and future expectations. Various aspects related to the global solar market, the PV modules cost and technology, and the power electronics converter systems are addressed. Research trends and recommendations for each of the PV system sectors are also discussed.

Index Terms—Photovoltaic systems, Renewable energy sources, Solar power generation.

Fig. 1: Global electricity generation

I. INTRODUCTION

CURRENTLY, the reliable and resilient energy systems are based on fossil fuels burning which are still dominating worldwide. However, fossil fuels are non-renewable and directly emit greenhouse gases to the environment. This has been leading to serious environmental and health impacts. Furthermore, the fluctuating price of the fossil fuels has serious impact on the energy security.

There are several alternative resources that can provide clean, continuous, and renewable energies such as hydropower, solar, wind, biomass, and geothermal. Nuclear energy is potential, however its use brings huge safety risks, therefore as this, it can not be deemed as clean or safe source.

Renewable energy sources (RES) are receiving significant attention worldwide as a sustainable alternative type of energy supply being an important sector of the global energy generation [1]. Renewable energies are expected to overtake coal around 2030 to become the largest power source and achieving 34% of total energy generation on 2040 as shown in Fig. 1 [2]. The renewable energy growth rate in different
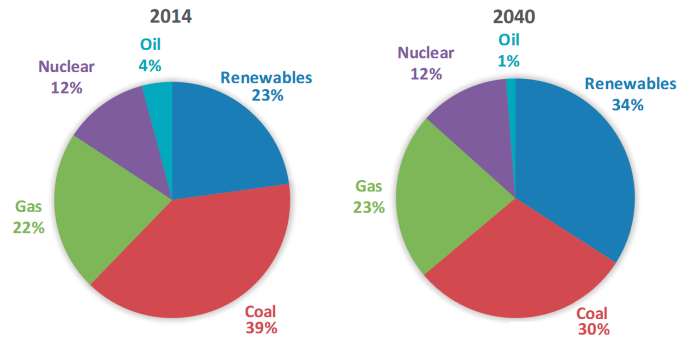
areas is increasing sharply with promising target as shown in Fig. 2.

RES are clean and environmental friendly resources, hence play an important role in reducing greenhouse gas emissions. Investing in RES would help in reaching little to no global warming effects and gas emissions, which helps in improving public health and in protecting our environment [3]. This improves human life quality by providing enormous and inexhaustible energy supply, with more jobs, and other economic benefits such as stable energy prices. Wide spread of RES has more benefits than aforementioned economic, health and environmental aspects [4]. There are many political, social and technical advantages of adopting renewable energies. Among those are: energy security and self-sufficiency, industry development, local ownership and public decision making, community building and empowerment. Energy security is priceless; it justifies all efforts and expenditures being put for adopting the renewables and in particular the distributed form of them [5].

RES have gone a rapid growth in the last ten years and are forecasted to lead world power market growth to 2020 [4]. Solar energy has gained the highest attention (highest growth rate) worldwide in the last years. This is because of potential availability, good visibility, and safe use for small and large scales by residential, commercial, and utility-scale users. From 2009 to 2015, the solar power capacity has been multiplied by a factor around 100 [6].

The highest addition rate among the renewables is the solar PV as seen from Fig. 2 [7]. PV power installations and the related research are increasing rapidly. Some market analysts expect the PV installation could reach 25% of generated energy by 2050 [8]. The price of PV systems has decreased above 50% in five years [9]. Figure 3 shows trends of installation
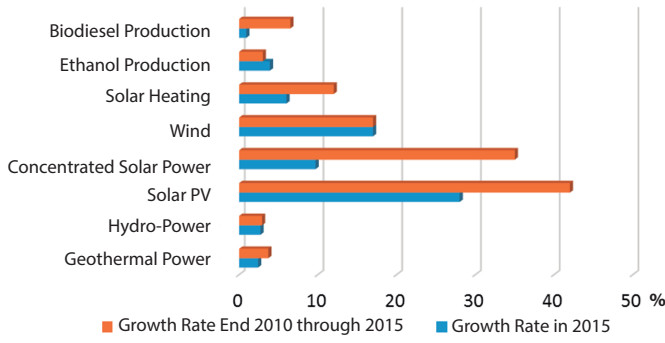
Fig. 2: Average annual growth rates of solar energy production - 2010 to 2015
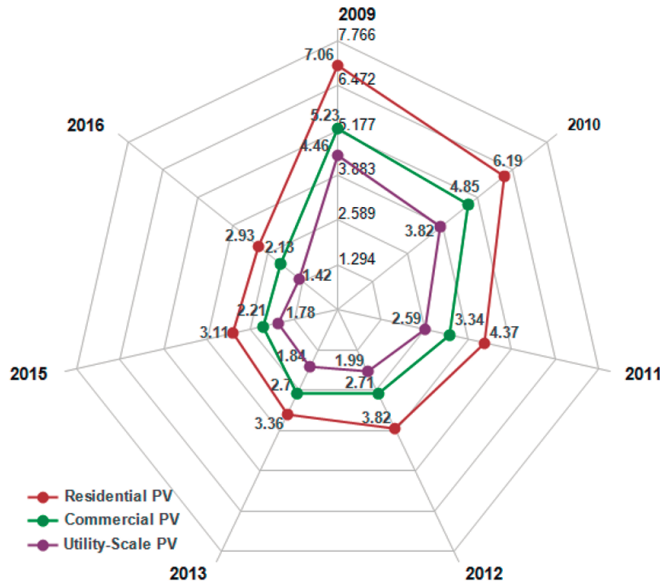

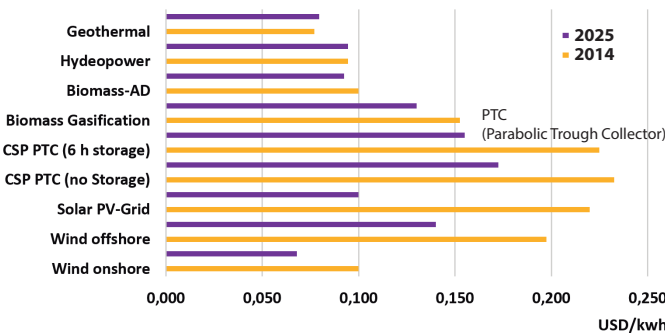Fig. 3: Installation prices of residential, commercial and utility scale PV systems

Fig. 4: Worldwide capital costs expectations of various energy resources in 2025 compared to 2014

prices of residential and commercial PV systems [10]. For the installation of large-scale PV power systems, prices are commonly below 1.79 USD/W now. In particular places and times, the cost of PV power may be competitive with the generated from coal or gas. For instance, the capital costs per watt of building various power plants is shown in Table I for

TABLE I: US Capital Costs of Different Energy Resources in 2016

Energy Sources	Capacity (MW)	Capital cost (USD/kW)
COAL		
Ultra Supercritical Coal (USC)	650	3636
USC with CCS (USC/CCS)	650	5084
Pulverized Coal (PC) Conversion to Natural Gas	300	226
PC Greenfield with 10-15% biomass (GCBC)	300	4620
PC Conversion to 10% biomass - 30 MW (CTCB)	300	537
NATURAL GAS (NG)		
NG Combined Cycle (NGCC)	702	978
Advanced NG Combined Cycle (ANGCC)	429	1104
Combustion Turbine (CT)	100	1101
Advanced Combustion Turbine (ACT)	237	678
Reciprocating Internal Combustion Engine (RICE)	85	1342
URANIUM		
Advanced Nuclear (AN)	2234	5945
BIOMASS		
Biomass (BBFB)	50	4985
WIND ENERGY		
Onshore Wind	100	1877
SOLAR ENERGY		
Photovoltaic - Fixed	20	2671
Photovoltaic - Tracking	20	2644
Photovoltaic - Tracking	150	2534

data from 2016 based on the US market [11]. The worldwide cost reduction of PV systems since that made the PV system an economically competitive investment for longer run. Figure 4 shows the worldwide capital costs expectations of various energy resources in 2025 compared to those in 2014 [12]. The grid-connected solar PV system has promising reduction to be competitive with most of energy sources.

The main application of solar energy systems is to act as clean power source connected to the electrical grid [13]. However, there are many additional applications of solar energy such as, solar water pumps in stand-alone and grid interfaced systems [14], solar feeding of the telecommunication base towers which is cost effective particularly for remote areas [15], [16], solar energy in building managements systems [17]–[19], solar energy in micro-grids, smart grid and distributed generation [20], [21], charging infrastructures of electric vehicles [22], solar energy for marine, satellite, and many other applications.

II. TYPES OF SOLAR ENERGY SYSTEMS

Today's market of the solar power systems can be categorized into two types: the thermal and PV solar power. Direct use of thermal energy for water heating is very mature and relatively old technology with global capacity over 400 GW-thermal. For electricity generation, the concentrated solar power (CSP) is a promising technology indirectly generating
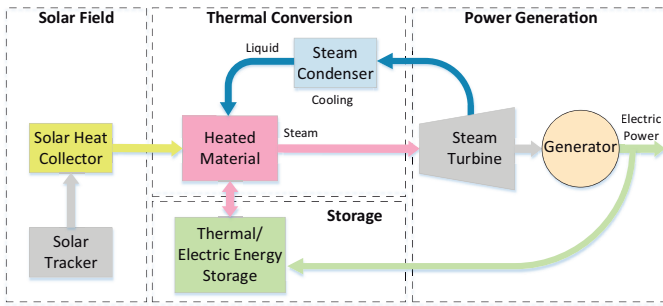
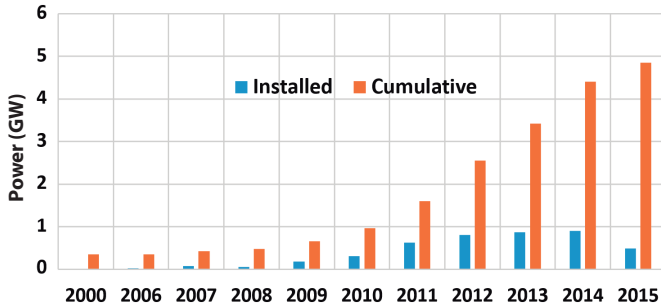Fig. 5: Block diagram of a concentrated solar power system

Fig. 6: Evolution of worldwide CSP electrical generated energy

electricity, which is adopted particularly in high power generation plants.

A. Concentrated Solar Power

Concentrated solar power (CSP) could be categorized as indirect. The first type of CSP converts the solar energy first to heat and then to electricity, which is the thermal CSP. This technology uses lenses or mirrors and tracking systems to concentrate solar irradiance to heat a solid, liquid, or gas. It directs the large area of sunlight into a small area (focal point) to produce heat and/or electricity. The block diagram of a CSP system is presented in Fig. 5. Examples of concentrating technologies include parabolic trough and power tower, dish stirling, concentrating linear fresnel reflector, and solar chimney [23]. Over 60% of the applications use long parabolic trough systems. Such plants may achieve at least 25% efficiency. Power Tower based plants may have a capacity factor around 40% [24].

The second type of CSP systems is the photovoltaic. Concentrating photovoltaic (CPV) systems concentrate the sunlight into PV surfaces for producing electricity. It is categorized as indirect method because the sunlight is first concentrated, then converted into electricity.

A hybrid method is a combination (photovoltaics and thermal) that is used to produce electricity in addition to thermal heat.

Thermal heat can be used for water heating, solar cooling (heat-powered air conditioning), and water desalination. Solar thermal processes have various temperature and pressure requirements with different heat conducting and storing materials, such as steam, hot water, and thermal oil. CSP technology

is now acquiring an increasing interest, especially if built with thermal energy storage. Thermal systems allow storing energy for several hours longer than other technologies.

Figure 6 shows the worldwide CSP electrical generated energy [7], [25]. It can be observed that the global generated capacity is relatively low. Regardless the relatively higher efficiency of the CSP systems, they have been and being deemphasized by the PV systems for many reasons, such as significantly higher installation and running costs, continuous decrease of the PV panels cost, and higher sensitivity of CSP system than of the PV to the environmental conditions such as dust and humidity. Some particles of the dust may affect not only the efficiency but also directions of solar beams to the focal point of the plant. Furthermore, the CSP systems are mainly applicable for higher power generation which requires special attention, location, cleaning, and investment [26].

B. Solar PV Technology

The direct solar power or solar PV power refers to a system that converts solar radiation directly to electrical form of energy using PV cells [27]–[29]. This type of renewables presents the highest global attention because of its numerous advantages. The advantages of this technology are: quiet energy conversion, easy design and installation, nice architectural visibility, long lifetime with less maintenance requirement, easy transportation and light weight, and acceptable price with significant dropping rate.

The cost of the PV systems has dropped dramatically in the last years and expected to continue dropping (see Fig. 7) [30]. From 2009 to 2015, there was 56% reduction in the total cost, 77% in the PV modules, 45% in inverter cost, and 44% in installation-related costs. All this helped in promoting this technology worldwide as a possible alternative to all other energy sources, renewables and traditional. Figure 8 and Fig. 9 show the world trend in adopting this area of clean and renewable energy [6], [31], [32].

The globally installed PV power capacity has had a remarkable increase since 2009. The PV penetration of total electricity generating capacity is gradually rising in several countries with expectations through 2018, except a sharp increase in Japan since 2012, as shown in Fig. 9 [32].

The grid-connected solar PV is the most promising technology for solving future energy demands. The research related to PV is currently concentrated on the improvement and solutions for higher efficiency and lower price of the PV panels and systems, capturing the maximum possible amount of energy from the PV panels using efficient maximum power point tracking (MPPT) methods [33], power electronics converters for stand-alone and grid connections, developing efficient PV power converter topologies, solving the power quality challenges with grid-tie systems, reliable and cost effective storage, and integrating with smart grid systems [34]–[36].

III. THE SOLAR CELL

The solar cell is made from solid state material that converts the energy of light (photons) into electric form using the photovoltaic effect. Solar cells are also called PV cells and

TABLE II: Top Ten Largest Solar PV Plants in the World [37]

Ranking	Power (MW)	Project	Location	On Grid
1	579	Solar Star Projects	Rosamond, California, USA	2015
2	550	Desert Sunlight Solar Farm	Riverside County, California, USA	2015
3	550	Topaz Solar Farm	San Luis Obispo County, California, USA	2015
4	530	Longyangxia Dam Solar Park facility	Qinghai, China	2013
5	500	Golmud Solar park	Qinghai, China	2011
6	458	Copper Mountain Solar Facility	Boulder City, Nevada, USA	2015
7	345	Charanka Solar Park	Gujurat, India	2012
8	300	Cestas Solar Farm	Bordeaux, France	2015
9	290	Agua Caliente Solar	Yuma County, Arizona, USA	2014
10	250	California Valley Solar Ranch	San Luis Obispo, California, USA	2013

photoelectric cells. As an example, the characteristic curves of a commercial PV module is represented in Fig. 10 where the behavior with the solar irradiance of one PV module is highlighted. The short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) are the main basic parameters of the PV module. In any case, taking into account the actual solar irradiation (W/m^2) and the temperature, the optimum operation point of the PV module is the point with maximum extracted power (P_{mp}). Capturing the maximum power in any condition (temperature and irradiation) is essential and is achieved by efficient maximum power point tracking (MPPT) algorithms.

There are different types of materials used for the design of PV cells. The crystalline materials used for cells design are single crystalline (sc-Si) with a Czochralski (CZ) float zone (FZ) technology, multicrystalline (mc-Si) with a cast, sheet, ribbon growth technology, polycrystalline (pc-Si) with a chemical-vapour deposition technology, and microcrystalline (mc-Si) with a plasma deposition. One main difference between those materials is the regularity level and structure, which affects the size of the crystals making such material.

There are other types of solar cells such as thin film, including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CI(G)S) [38]. Additional types may be also found such as desensitized solar cell (DSSC), gallium arsenide germanium solar cell (GaAs), luminescent solar concentrator cell (LSC), multi-junction solar cell (MJ), organic solar cell (OPV), perovskite solar cells, photoelectron chemical cells (PEC), plasmonic solar cells, plastic solar cells, polymer solar cells, quantum dot solar cells, etc.

Efficiencies of solar PV cells converting the energy of light's photons to electric energy are different [24]. However, the output power of PV panels is sensitive to the environmental conditions such as solar irradiation intensity, ambient temperature, and dust. The efficiency of commercial PV panels is still relatively low but in the last decade the efficiency of average commercial wafer-based silicon modules have increased for about 5% (from about 12% to 17%) [39]. Commercial thin film solar cells have increased significantly. As an example, CdTe modules efficiency have raised from 9% to 18.6% (commercialized by First Solar in 2015).

Nevertheless, there are promising data on the available and foreseen technologies. Figure 11 shows the progress in PV cells efficiency development using laboratory solar cells as example [24]. In the laboratory, the best performing monocrystalline silicon models are with about 25.6% efficiency. Also in the laboratory, the high concentration multi-junction solar cells achieved up to 46.0% efficiency. Figure 11 indicated some improvement trend but this is not enough. There is still much research and development needed in this direction. Recorded efficiencies demonstrate the need for further efficiency improvement at the production level. This is a major
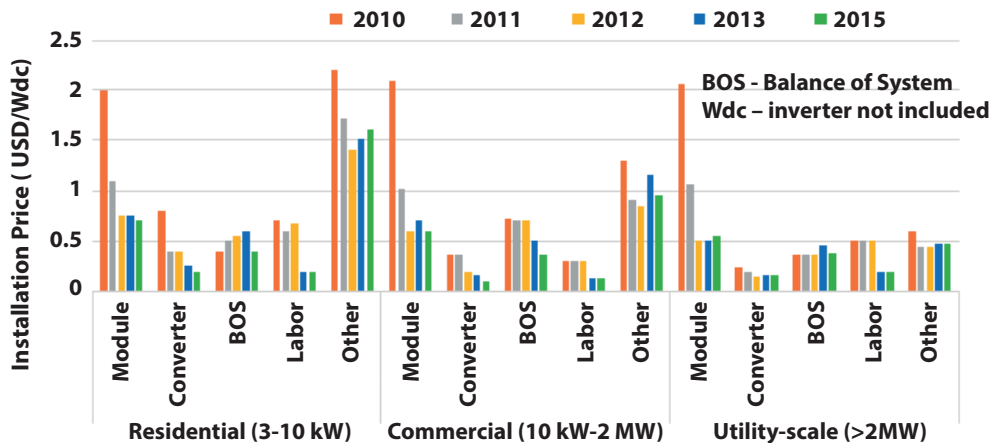

Fig. 7: The evolution of the cost distribution of residential, commercial and utility-scale PV systems
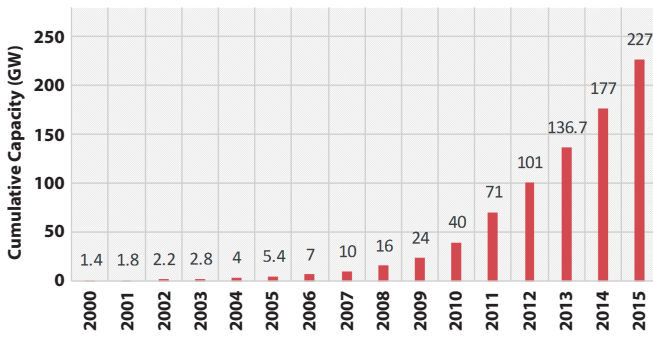
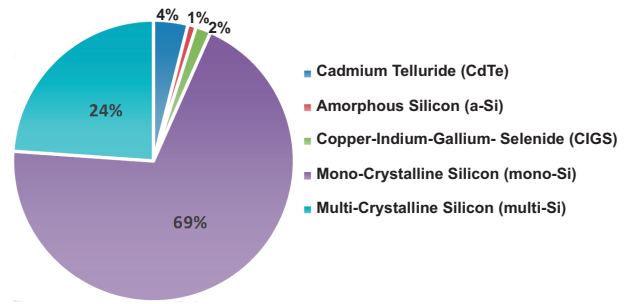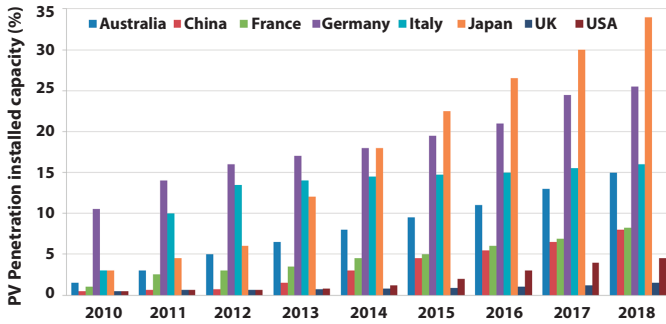Fig. 8: Globally installed PV power capacity (until 2015)

Fig. 9: PV penetration of total electricity generating capacity (expected since 2015)
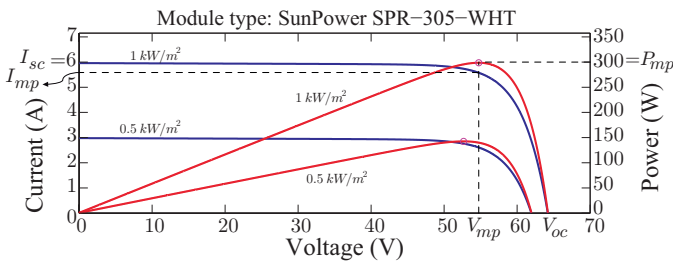

Fig. 10: Characteristic curves of a commercial PV panel including the solar irradiance variation
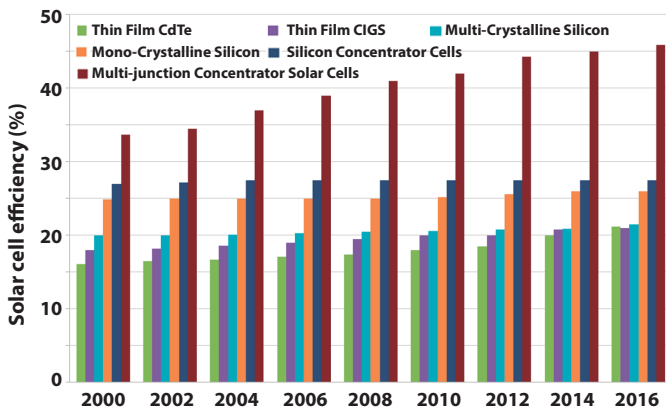

Fig. 11: Development of laboratory solar cell efficiencies

challenge for future research that to potentially increase the efficiency of PV panels at production scale with a reasonable price.

Fig. 12: Global PV market by technology in 2015

Fig. 13: Price history of silicon solar cells

For the global PV market, thin-film technologies took up around 7% of worldwide disposition, including 4% in CdTe and 2% in CIGS and 1% in a-Si; while 93% was held by crystalline silicon (mono-Si and multi-Si) in 2015, as shown in Fig. 12 [39]. In addition, mono-Si is still dominant in 69%.

With the improving technology in semiconductors, there has been a significant drop for the price per watt of solar cells over the last two decades. Figure 13 shows the price history of silicon solar cells. The price for crystalline silicon cells was about 76 USD/W in 1977 prices, while average prices in 2015 was as low as 0.30 USD/W, which is 200 times less than forty years ago. Prices for thin-film solar cells were around 0.55 USD/W in 2016 [40].

IV. GENERAL SCHEME OF A SOLAR PV SYSTEM

The PV cells arranged into panels could be used in large-scale PV projects. A rooftop PV system may be comprised of tens or hundreds of panels, while a large-scale project may consist of thousands or even millions of panels.

Utility-scale PV plants are commonly installed in remote areas, as Table II lists for the top ten large-scale PV farms [37]. Large-scale PV systems have been a major part of PV's growth in recent years. They contributed above 50% of all solar capacity assembled from 2010 to 2014, with overall capacity quadrupling from 2012 to 2014 [41].

Rooftop systems as distributed generation sources are excellent tools for creating future smart grid systems. Such kind of systems have the chance to grow most over the world at residential and commercial scales.

The typical power configuration of a PV system (for stand-alone or grid-connected applications) is represented in Fig. 14 [42]. The solar photovoltaic cells, arranged forming
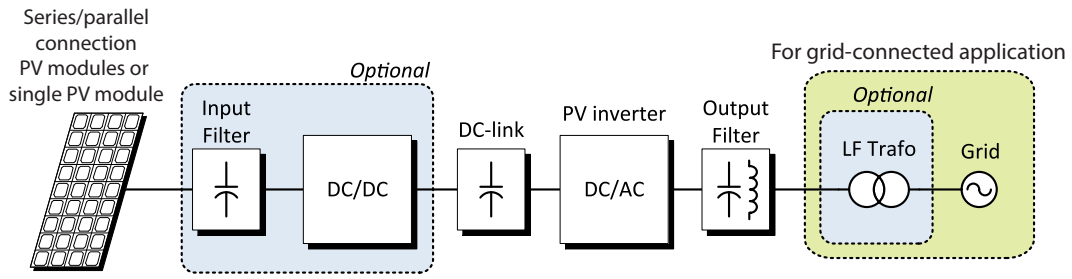
Fig. 14: General scheme of a PV system for grid-connected or stand-alone applications
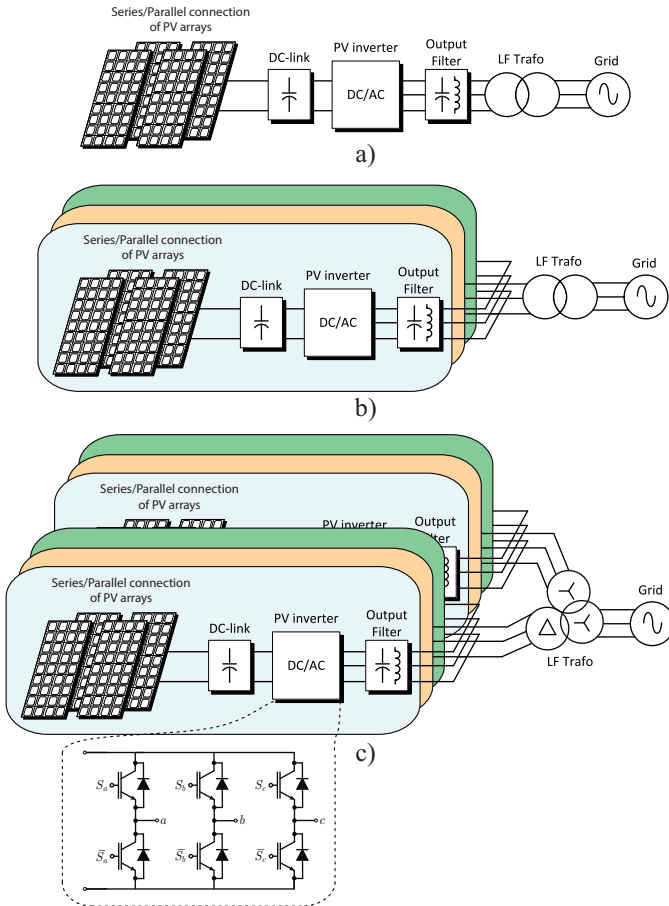

Fig. 15: General schemes of high-power PV system based on central inverters a) single-channel central inverter b) multi-channel central inverter c) dual central inverter

PV arrays generate a dc voltage/current that is usually transferred by one step-up dc/dc converter to boost low PV voltage as well as track maximum power point. A dc/ac inverter connects the system to the grid or end-user (stand-alone systems) fulfilling existing grid codes (required national and international standards and regulations).

V. GRID-CONNECTED PV SYSTEMS

In general, the structure of a PV system can be derived from the nominal power of the system looking at highest efficiency with lowest costs [43]. Following this rule, actual PV systems can be divided into three different groups: high-power PV plants, residential and industrial PV installations, and low-power PV systems.

A. PV power plants

High-power PV plants are now being installed extensively worldwide representing a 61% of the PV market during 2015. In the last decade, the maximum power of a single PV plant has increased from 50 MW up to more than 500 MW in 2015 (Table II).

For high-power PV plants, the mainstream solution is to use a central three-phase inverter to connect the PV panels to the grid using a low frequency transformer. The solar panels are connected in series and in parallel in order to reach convenient values of dc voltage and nominal power respectively. The maximum dc voltage is forced by the maximum isolation allowed by the solar panel taking into account current technology and regulation (recently upgraded up to 1500 V). The maximum nominal power is limited by the maximum dc voltage and the maximum current supported by the power switches. With the current PV and power switches technology and grid codes, the maximum power of a PV central inverter is around 1 MW using a conventional two-level 1700 V IGBT-based three-phase inverter with a low frequency transformer (see Fig. 15a). However, some newer central inverters are based on multilevel topologies such as the TMEIC Solar Ware Samurai which is based on a T-Type three-level three phase topology in order to achieve high quality output waveforms with reduced power losses.

If the PV plant provides more power, the plant is divided to several areas, each one is managed by a central inverter independently. This solution is the most convenient from the economical point of view but the system efficiency is poor because only one MPPT controller is used for a big area of solar panels leading to a power efficiency reduction with potential partial shading and mismatch phenomena. In order to minimize this problem, a global MPPT algorithm can be specifically developed to look for the maximum power generation in the presence of other local maxima produced by partial shading phenomenon.

In order to reduce the cost of the overall installation, it is usual to arrange several central inverters in the same cabinet connecting their outputs to the same LV side of the low-frequency transformer as represented in Fig. 15b. If a single dc voltage from the PV arrays of a large area is used as single input to the group of PV central inverters (arranged in the same cabinet), all inverters in the cabinet are not always working
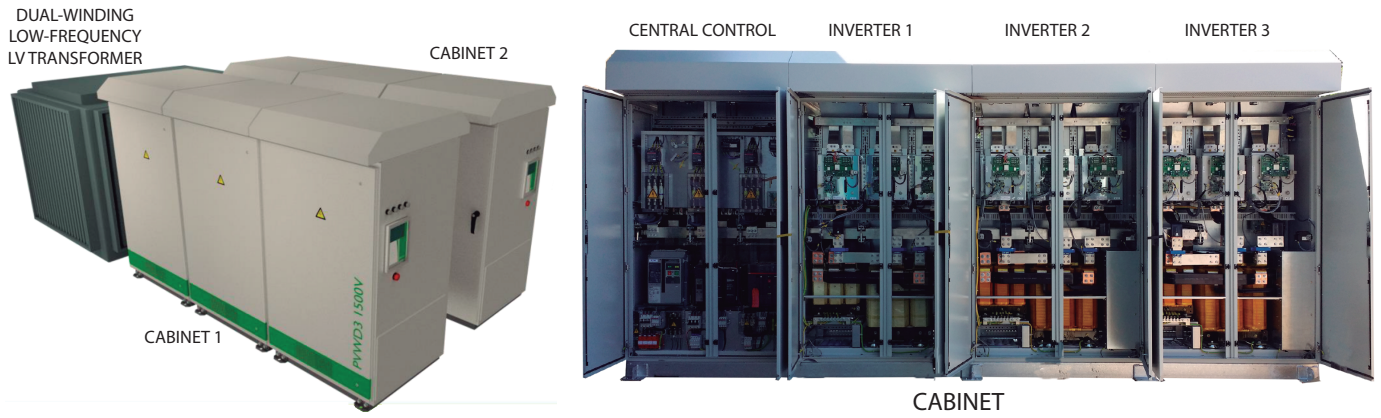
Fig. 16: 3.3 MW Multi-channel 1500 V central inverter PV3000WD3HV550 by GPTech based on two cabinets connected to the dual-input LV low-frequency transformer. Each cabinet is formed by three independent central inverters which can have independent dc inputs
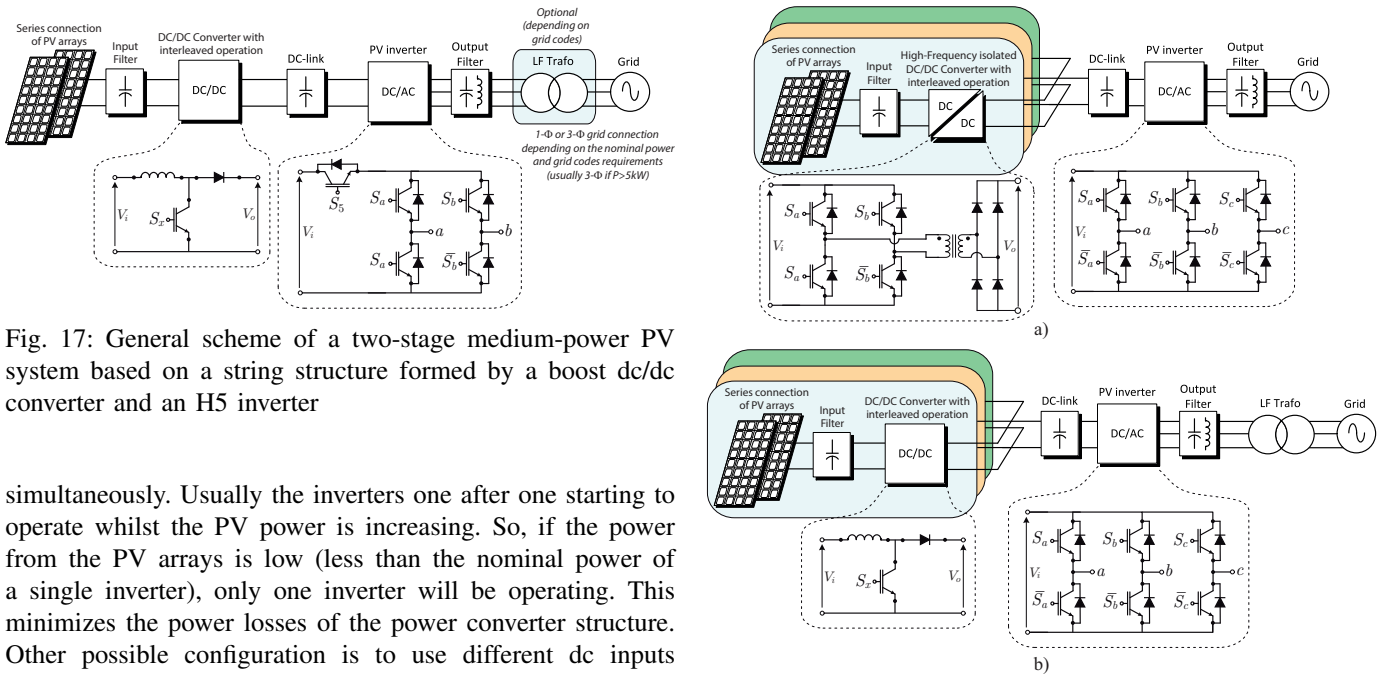

Fig. 17: General scheme of a two-stage medium-power PV system based on a string structure formed by a boost dc/dc converter and an H5 inverter

Fig. 18: General schemes of a medium-power PV system based on a multi-string structure a) with high-frequency isolated dc/dc stage b) with non-isolated dc/dc stage with low frequency grid-connected transformer

simultaneously. Usually the inverters one after one starting to operate whilst the PV power is increasing. So, if the power from the PV arrays is low (less than the nominal power of a single inverter), only one inverter will be operating. This minimizes the power losses of the power converter structure. Other possible configuration is to use different dc inputs for each central inverter inside the cabinet. If this option is chosen, each PV central inverter inside the cabinet applies an independent MPPT controller leading to higher energy yield.

In order to achieve even higher nominal power, the trend is to connect several groups of central inverters to a sole multi-winding low frequency transformer even avoiding the use of a cabinet to reduce the price as much as possible (see Fig. 15c). For instance, this is the case of the PV3000WD3HV550 modular inverter by GPTech depicted in Fig. 16 [44].

B. Residential and Industrial PV applications

When the power of the PV system is lower than 50 kW approximately, the cost of the power converter is still the key but other issues such as efficiency, energy yield and distributed operation gain importance. These applications represented a 37% of the PV market in 2015. In this case, a typical structure of the PV system is the string configuration where no PV strings are connected in parallel. The converter is usually a

two-stage structure formed by one step-up converter connected to each PV string and one grid-tied inverter. In the string configuration, the MPPT controller is related to a reduced PV area extracting power with higher efficiency compared with the central inverter structure. This is achieved at the expense of the increase of cost of the overall PV installation. This fact conventionally limits the string configuration to small scale PV systems (typically residential applications with power less than 25 kW). Typical structure of a string PV converter is represented in Fig. 17 where for instance the H5 converter is a suitable solution. H5 (by SMA), H6 (by Ingeteam), or HERIC inverters are based on the H-bridge structure but usually

adding extra switches in order to avoid undesirable leakage currents in the transformerless system. The H5 converter could be replaced with an h-bridge if galvanic isolation is required by the national grid code or with a conventional three-phase inverter if the nominal power is above the maximum single-phase grid connection limits imposed by the grid codes.

When the power is higher than 25 kW, the mainstream solution is to use of multi-string solution usually built ad-hoc taking into account the actual operational conditions of the PV system. The multi-string configuration merges the advantages of the central inverter and the string configurations. A typical structure of a PV multi-string solution is represented in Fig. 18. Multi-string structure presents multiple PV strings and a dedicated dc/dc converter connected to each one. A single central inverter (typically three-phase) connects all dc/dc converters to the grid. Using this configuration, each dc/dc converter can obtain maximum power from the PV string with dedicated MPPT controllers with reduced overall system cost. The reason is that usually the cost of dc/dc converters is lower than the cost of three-phase grid-tied inverters. In addition, the isolation of the power system can be achieved with a grid-tied low frequency transformer or with high-frequency transformers in the dc/dc stage which helps reducing the cost, weight and volume of the power system. This modular solution is popular for low- and medium-power applications (usually from 10 to 50 kW) such as industrial, residential or roof-top PV systems.

Recently, the multi-string configuration has been also applied to PV systems in the range of hundreds of kilowatts [45]. In the multi-string PV system design there is a trade-off between maximum power tracking, isolation issues and economical cost of the PV installation. The reduction of the cost of the power devices has led to make profitable this solution compared with the conventional one that is based on a central inverter but only for small PV plants. Besides, the high cost of the bulky low frequency transformer can be reduced using high-frequency transformers in the dc/dc converter. In this case, a PV plant with multi-string converters becomes a very decentralized power system leading to advantages and disadvantages. Examples of advantages are higher yield due to multiple MPP trackers, high plant availability due to high modularity (leading to a natural fault-tolerant capability), maximum flexibility in the plant design, easy transportation and fast installation. As disadvantages can be cited the initial high-cost investment for the power system, more complex communication and monitoring issues and higher power losses.

In both cases (multi-string or string configurations), if required a step-up converter, for transformerless systems the boost converter is the easiest solution (interleaved if a multi-string PV system is considered) for the dc/dc stage. For the inverter stage, several solutions have found industrial impact depending on the grid code of each country. Usually, grid codes do not allow single-phase connection to the grid if the nominal power of the PV system is above several kilowatts (5 kW in the Spanish regulation for instance). So, for PV systems with nominal power above this limitation, the mainstream solution for the inverter is the conventional two-level 1200 V

IGBT-based three-phase converter. However, other solutions based on multilevel converters (neutral-point clamped or t-type) could be also found (PVS300 by ABB, not yet in the market). The advantages of using a multilevel converter topology are the higher quality of the output waveforms leading to a smaller output filter and therefore to a compact size. For PV systems with nominal power below the three-phase connection grid code requirement, PV inverters are based on the extended versions of the H-bridge structure such as the H5, H6 or HERIC inverters [46]–[49].

C. Low-power PV systems

Roof-top PV applications are usually in the hundreds of watts (or even in the kW) range and the PV converter design has to be in this case mainly focused to achieve very high efficiency with galvanic isolation and connection to a single-phase grid. Usually, the power converter is directly connected to a single PV module or a small PV array achieving 100 V maximum (usually the converters are installed close to the PV module working in potential harsh weather conditions). As this PV nominal voltage is low, it is required a two-stage power system formed by a step-up dc/dc converter and a single-phase inverter. Both converters can have different topologies and several solutions can be found in the market [50], [51]. For the dc/dc converter, high-frequency interleaved (or not) flyback or full-bridge resonant converters can be found as industrial products. For the inverter, the mainstream solution is to use a conventional 600 V MOSFET-based H-bridge but other power converter topologies can be also found. In Fig. 19, the typical configurations of a module-based PV system are shown. These converters can be found achieving nominal power around 250 W with efficiency higher than 99%. As the converter is very small-size, it is usually located just back of the PV array or the PV module reducing the cabling and making easier the installation becoming a "plug&play" system. This solution is the most efficient in terms of perfect tracking the maximum existing power from the PV module at the expense of high cost because of the high number of used power converters. Although the impact of low-power PV systems in the PV market is very limited (2% of the PV market in 2015), the growth of module-based PV systems (microinverters) is large in the last years with high future impact.

VI. Control of Grid-Connected PV systems

The control structure of a grid-connected PV system depends on the converter topology used to integrate the PV arrays/modules to the grid [52], [53]. The PV converter structure, as mentioned in Fig. 14, can be single-stage based if a central inverter is used (typical for large PV power plants) or two-stage based if a first dc/dc stage is required (typical for industrial or domestic PV systems). A summary of the control scheme for a single-stage or two-stage PV converter structures is presented in Fig. 20.

In both cases (single- or two-stage), the grid-tied inverter control scheme is in most cases based on the well-known voltage-oriented control (VOC) technique normally using the
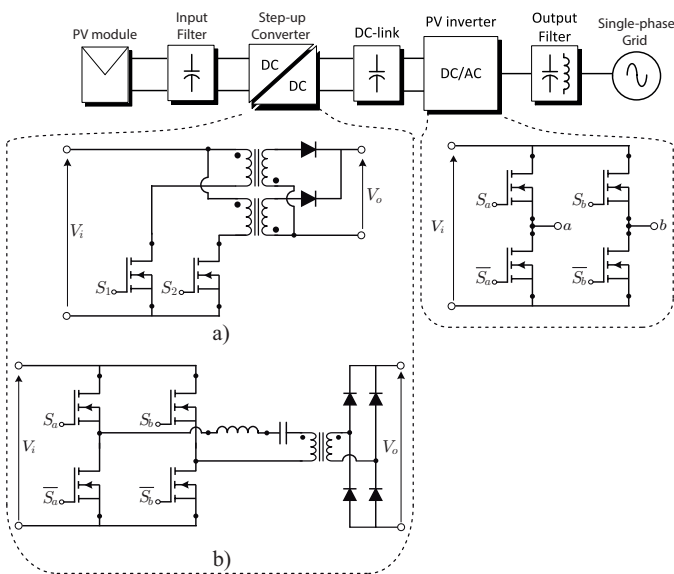
Fig. 19: General schemes of a low-power PV system based high-frequency isolated dc/dc converter and a single-phase inverter a) interleaved dc/dc high-frequency flyback converter b) resonant H-bridge and diode bridge rectifier

synchronous d-q frame (note that this is not the case in single-phase inverters) [13]. The MPPT method is executed by the inverter in the single-stage case. In the two-stage case, the MPPT is achieved by the dc-dc converter whilst the inverter accurately controls the dc-link voltage which is fixed value.

VII. STAND-ALONE PV SYSTEMS

Stand-alone (off-grid) PV power systems lose their share in total cumulative PV capacity of global market due to dynamic development of grid-connected systems. Market share of stand-alone PV systems over the last 15 years has been reduced from 15% in 2000 to below 0.5% in 2015 [6]. However, this part of PV application has important social aspects because still there are 1.2 billion of people all over the world living without access to the electric grid and PV is most important power source for them [54]. For these people, particularly stand-alone PV installations have become a viable solution for creating hybrid systems with energy storage and gas/diesel generators as part of bigger islanded microgrids [55], [56]. This issue is becoming more attractive for research and deployment toward transforming to smart grid and solving the problems of rural areas.

Generally, stand-alone PV applications can be divided into:

- Pico PV systems (P≤10Wp)
- Domestic PV systems (10Wp<P≤10kWp)
- Commercial/Institutional PV systems (P>10kWp)

Pico PV systems are the only fast developing part of stand-alone applications taking into account the number of produced devices, which gave impressive multiple market growth during the past five years [54]. The other off-grid domestic and commercial PV installations are not similarly impressive. Their share was 70 MW in 2015 while the cumulative capacity was 1 GW. This share is very low in comparison

TABLE III: 2015 Cumulative Capacity of Stand-Alone Solar PV Systems Worldwide [6]

Ranking	Power	Country
1	350 MW	China
2	173 MW	Australia
3	127 MW	Japan
4	124 MW	Spain
5	61 MW	Canada
6	50 MW	Germany
–	135 MW	All other countries
–	1020 MW	TOTAL

to 195 GW of total cumulative capacity of grid-connected installations. Leading countries in stand-alone systems are presented in Table III.

Power electronics converters used in stand-alone domestic and commercial PV systems are available in the portfolio of most producers and can be used in dc (only domestic) or ac (domestic and commercial) systems what is shown in Fig. 21 [57]–[60]. AC system shown in Fig. 21a is more popular because it is easily scalable, has a similar structure to public grid, its installation is simple, and extendable (gives the possibility to add other elements of smart grid like wind turbines or gas/diesel generators). It is worth mentioning that the dominant majority of installations include energy storage as a mandatory part of stand-alone system. Not least because it stores energy when there is low demand and provides more energy at peak time, but also it brings better voltage and frequency stabilization of the ac system.

One of most important parts of stand-alone PV systems is the control method of the dc/ac converter (shown in Fig. 21b). Usually, droop control is applied similarly to other well-known methods for islanded grids [61]. It assumes that converter output is inductive and the active (P) and reactive power (Q) to be calculated as [62]:

$$P = \frac{EV}{X} sin\varphi$$
$$Q = \frac{EV cos\varphi - V^2}{X}, \qquad (1)$$

where E is the converter voltage amplitude, V is the filtered output voltage amplitude, X is the coupling impedance and φ is the angle between E and V.

From equation (1), it is possible to assume that the active power depends mainly on the angle φ, which changes indirectly by the converter voltage pulsation error $\Delta\omega$. On the other hand, the reactive power depends on the converter voltage amplitude E as seen from Fig. 22.

VIII. ENERGY STORAGE SYSTEMS FOR PV APPLICATIONS

Since solar energy is not always available, it should be partially stored in an efficient manner. Energy Storage Systems (ESS) can be classified as small local (up to 50 kWh) and distributed (with capacity above 50 kWh). Usage of ESS supporting power system in year 2012 (besides pumped hydro)
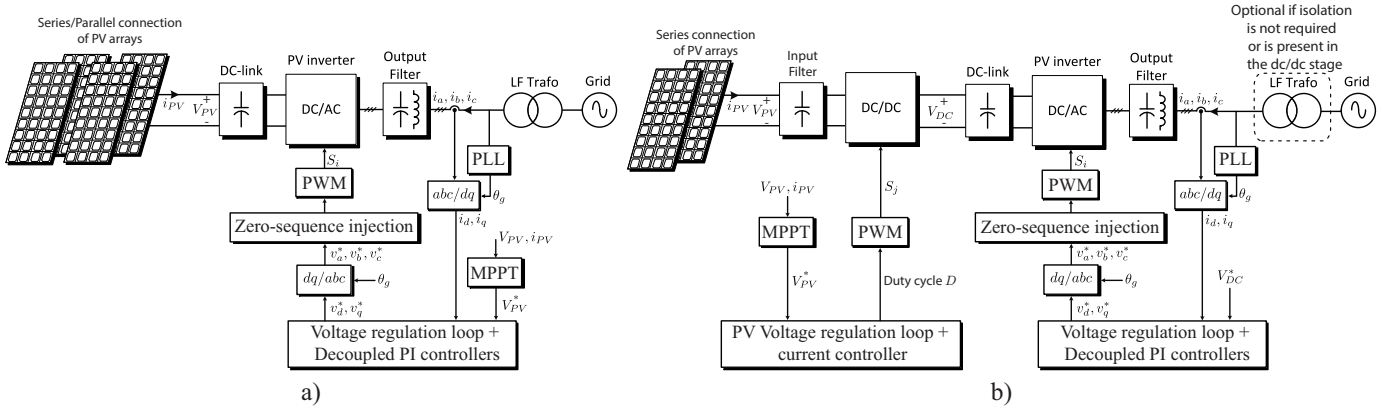
Fig. 20: Control scheme of a) typical single-stage PV system for a large PV power plant b) typical two-stage PV system for industrial or domestic applications
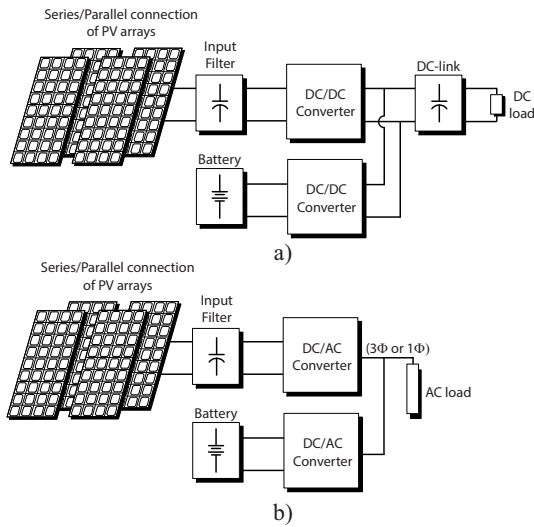

Fig. 21: Configuration examples of domestic and commercial stand-alone PV systems a) simple dc based b) single or three-phase ac based

Fig. 22: Droop characteristics

was based respectively on sodium-sulphur, lithium-ion, advanced lead-acid, redox-flow, and nickel-cadmium batteries. In recent years the situation changed with significantly increased installations based on lithium-ion batteries comparing to others [63], but existing capacity is still low.

Future investment and installation in energy storage is promising. The forecast shown in [63] expects a multiple annual power market capacity increase in the next years. One of significant reasons for that is the dynamic market

development of electric vehicles (EV) and the utilization necessity for chemical batteries removed from EV, which can be still used (as secondary life) in ESS applied for RES or power systems. According to the scenario described in [64], cumulative installed capacity of secondary live batteries will reach 230 GWh and 1000 GWh in 2025 and 2030 respectively. This situation is observed by power electronics companies which currently provide plenty of converters dedicated to the ESS, what is shown in Table IV [65]–[68].

ESS installed directly to support high power PV power plants are still not common but the situation is changing due to the continuous cost reduction of battery stacks and new hard restrictions imposed by the grid codes. Examples presenting first installations are collected in Table V [69].

IX. Operational Issues of PV Systems

The extensive installation of PV systems has come hand by hand with concerns about grid stability, grid quality and recovery, and safety of the grid maintenance staff. Requisites imposed by the grid codes of the local utility grid are known as minimum technical requirements, and renewable energy systems must comply with them to be authorized for the connection to the electric power grid. Depending on each country regulation, some standards are mandatory while others are just best practices recommendations. The standards can be classified depending on the organizations involved in its development (IEC: International Electro-technical Commission, UL: Underwriter Laboratories Inc., IEEE: Institute of Electrical and Electronics Engineers and CEN: European Committee for Standardization). A summary of standards to be fulfilled by PV converters are summarized in Table VI.

Some of the specific regulation of PV systems have been created using modified versions of regulations applied to wind power systems but other grid codes have been especially developed for PV systems. Main grid code to be fulfilled for PV systems is IEEE 1547 which is the standard for interconnecting distributed resources with electric power systems. However, it has to be noticed that nowadays regulations for PV systems vary from country to country and a worldwide standardization is still under development.
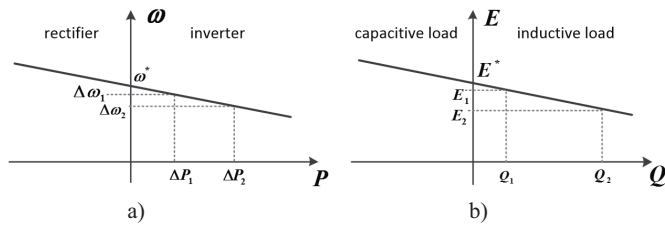
TABLE IV: Examples of Commercial High-Power Energy Storage Systems

Parameter	Belectric EBU 1200	Belectric EBU Lion	ABB ESM	Siemens Siestorage	SMA sunny central storage
Capacity	1202 kWh	4016 kWh	6000 kWh	500 kWh	up to 1.6 MW
Battery Technology	Lead acid	Lithium-ion	Lithium-ion	Lithium-ion	Lead acid / Lithium-ion
Life Cycles	up to 2000	up to 8000	up to 2000	-	-
Max. dc voltage (V)	1500	1500	1200	-	900
Special functions	Black start Island operation	Black start Island operation	Black start Island operation	Black start	Black start Island operation

TABLE V: Largest Energy Storage Installations Directly Supporting Solar PV Plants

Ranking	Power/Capacity	Type of Energy Storage	Location	Solar park	On grid
1	15 MW / 60 MWh	Redox flow batteries	Hokkaido (Japan)	SoftBank Tomatoh Abira Solar Park (111MWp)	2015
2	14 MW/53 MWh	Lithium-ion batteries	Hebei (China)	140 MW of renewable energy generation	2011
	2 MW / 8 MWh	Redox flow batteries		(100 MW wind and 40MWp solar)	2016
3	15 MW / 60 MWh	Sodium-sulfur batteries	California (USA)	Vaca Dixon Solar Plant of Vacaville (2MWp)	2012
4	0.5 MW / 2 MWh	Lead-acid batteries	New Mexico (USA)	Albuquerque PV park (0.5 MWp)	2011

TABLE VI: Summary of International Standards and Recommendations for PV Systems

Standard	Focus
$EN50524$	Data sheet and name plate for photovoltaic inverters in grid parallel operation
$EN50530$	Overall efficiency of photovoltaic inverters including the procedure to measure the accuracy of the MPPT
$UL1741$	Inverters, converters, controllers and interconnection system equipment for use in stand-alone or grid-connected power systems
$IEEE1547$	Interconnecting distributed resources with electric power systems including voltage and frequency regulation, power quality, ride-through capability and anti-islanding operation
$IEC61683$	Power conditioners - Procedure for measuring efficiency
$IEC62109-1$	Safety of Power Converters for Use in Photovoltaic Power Systems - Part 1: General Requirements
$IEC62109-2$	Safety of Power Converters for Use in Photovoltaic Power Systems - Part 2: Particular Requirements for Inverters

Grid codes regulate a lot of different aspects related to the PV power plants operation: total harmonic distortion thresholds; grounding and isolation unit faults; behavior against external conditions (dust, humidity, etc.); behavior against electric power grid faults; arc-fault detection and protection; and others. Specifically, the behavior against electric power grid faults has had a significant relevance in last years. The growth of the penetration factor of renewable energy systems in the electric power grid makes it critical to support the grid by several ancillary services preventing the total blackout of the electrical service.

Important ancillary services to the grid are the voltage and frequency excursions (deviations of the measured grid frequency or voltage in respect with its nominal value). Frequency regulation service is also a requirement defining the droop curve to be applied over the active power reference to help the system recovery to the nominal grid frequency. On the other hand, voltage regulation methods are applied when a voltage excursion is detected. In this case, the regulation is carried out by the PV system with the injection of reactive power making a contribution to the stabilization of the grid voltage at the interconnection point.

In addition, associated to the potential grid faults, frequency and voltage ride through protection methods are of concern. Ride through regulations impose that if the measured frequency or voltage reaches an error threshold continuously during a predefined time, the PV system will produce a controlled disconnection from the electric power grid. In this way, the PV power plant must keep operating to avoid a domino effect with all renewable energy systems becoming disconnected during the grid fault destabilizing the grid. And on the other hand, the PV system still connected to the grid supporting the grid by a reactive current during the grid fault.

One of the most important requirements for PV systems is the anti-islanding protection. The islanding phenomenon appears under certain conditions when a grid blackout happens and the PV system keeps operating feeding local loads without noticing the shutdown of the main grid. In this case, the PV system has to be disconnected from the grid in order to prevent hazards for the grid utility staff. In addition, it is a requirement to prevent overcurrents in the PV customer system when the grid recovers. So, anti-islanding grid codes impose that the PV control unit has to provide a disconnection before a pre-defined time after the occurrence of the fault. Detection methods of islanding condition can be divided into three main categories, which are passive inverter-resident methods, active inverter-resident methods, and methods not part of the inverter structure such as the communications between the utility and the PV inverter. Active inverter-resident solutions based on methods to attempt to cause an abnormal condition in the grid voltage have gain importance in the last years reducing the power losses and the required communication between the PV system and the

utility grid [70].

Other recent regulation for PV systems is related to a limitation of active power delivered to the grid. This requirement, also known as power curtailment, is imposed by the grid when an excess of power is present leading to a potential blackout of the system. Grid codes impose that PV systems must be equipped with a means to curtail power by remote control or to reduce drastically the active power feed-in. The PV plant operator is normally compensated for this loss but energy storage systems are now being studied to minimize the energy lost. However, nowadays there are still financial and technical barriers to be overcome as the costs for storage systems are high.

X. Future Perspective of Solar Energy

Research trends are mainly focused on improving the reliability, efficiency and power quality, reducing the cost, integrating with the grid at various scales and contributing in building microgrid and smart grid paradigms.

Environmental concerns have pushed up renewable energy sources revolution in the last decades, mainly wind and solar. Concentrated solar and solar photovoltaic technology are now a mature solution to obtain energy from the sun irradiation which is a free and almost endless energy source. Both concentrated or photovoltaic systems have been developed deeply in the last 25 years becoming nowadays a supporting energy player in the energy sector. The future trend of solar energy is promising with the objective of becoming one of the first energy producers of the world hand by hand with other renewable energy sources.

This future development depends on several factors. First of all, the effort of researchers will be focused on increasing the efficiency of the solar modules and reducing their cost. The use of new materials to create multi-junction solar cells will lead the future in this field.

About the solar photovoltaic power converters, the focus always will be located on maximizing the converter efficiency with minimum costs. Reliability, fault tolerant operation, easy maintenance and reduced transportation and installation costs are also factors to develop new power converter topologies for PV systems, from low to high-power. These topologies will be following the solar cells development (for instance recently PV systems isolation was upgraded to 1500 V leading to the appearance of a new version of commercial PV inverters). Recently, some multilevel converter topologies are already in the market and represent a promising advance in the development for PV system looking for high quality output waveforms, reduced size and cost output filters and higher efficiency. A vast use of multilevel converters for utility-scale PV systems will probably happen, if the voltage isolation regulation of the PV panels is to be revised in the future achieving central multilevel PV inverters with direct medium-voltage connection avoiding the use of low-voltage transformers and associated switchgear costs. Another trend in the new generation of PV converters will be the use of new wide band-gap power semiconductors such as SiC or GaN devices (as long as they become competitive in price) to improve the power density and power efficiency.

In addition, the stochastic behavior of the sun irradiation, the grid stability requirements and the maximization of economical profits will possibly force to use energy storage installations supporting PV installations to save extra energy if a power curtailment is required or adding active or reactive power if the grid demands. The development of batteries technology by improving their life-time and reducing the costs will walk hand by hand with this hybrid solution.

Therefore, R&D sector is strongly focused to elaborate new high energy density batteries with reduced price below 150 Euro/kWh. New promising technologies of batteries which are currently under research and development are: future Li-ion (300Wh/kg), Zn-air (400Wh/kg), Li-S (600Wh/kg) and Li-air (800Wh/kg) [64].

Another aspect, which can significantly improve future perspective of solar energy is broad development of dc smart grids (SG) as well as research of smart transformers (ST) [71]. This trend makes it possible for easy integration and fully utilization of PV energy and storage elements which eliminates additional power converters and improves overall efficiency and energy security.

Finally, but also important, the vast development of solar energy systems also depends strongly on the governments and the required strong support to develop and implement renewable energy sources. This was in the past based on feed-in tariff policies to accelerate the development of renewable energy source technology, which now can be considered mature. Now, the politician efforts have to be focused on creating a friendly scenario to create a distributed electrical grid system not very dependant on gas/coal-based or nuclear plants.

XI. Conclusions

Solar energy systems (photovoltaic and concentrated) have become a mature and promising technology worldwide. The paper has shown that the solar energy has been shaped to be an essential element of the present and future energy scenarios. The continuous development of materials have led to new families of solar systems that are more efficient, compact, and cheap. This have led to profitable installations and investments to take advantage of the endless sun power. This paper summarizes the current status of solar energy technology and provides a comprehensive overview of this vital sector by addressing the facts, challenges, and solutions from the past, present and future projection.

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