Topologies for Large Scale Photovoltaic Power Plants

Ana Cabrera-Tobar[a,*], Eduard Bullich-Massagué[a], Mònica Aragüés-Peñalba[a], Oriol Gomis-Bellmunt[a,b]

[a] *Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionamients (CITCEA-UPC), Department d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya, UPC. Av. Diagonal 647, Pl. 2. 08028, Barcelona, Spain*
[b] *Catalonia Institute for Energy Research, IREC, Jardins de les Dones de Negre,1,Pl.2a,08930 Sant Adrià del Besòs,Spain*

Abstract

The concern of increasing renewable energy penetration into the grid together with the reduction of prices of photovoltaic solar panels during the last decade have enabled the development of large scale solar power plants connected to the medium and high voltage grid. Photovoltaic generation components, the internal layout and the ac collection grid are being investigated for ensuring the best design, operation and control of these power plants. This article addresses the review of components as photovoltaic panels, converters and transformers utilized in large scale photovoltaic power plants. In addition, the distribution of these components along this type of power plant and the collection grid topologies are also presented and discussed.

Keywords: Photovoltaic Power Plants, Photovoltaic panels, transformers, Renewable energy, PV inverter, PV layout.

1. Introduction

The energy demand worldwide is expected to grow by 41 % during the next 20 years due to industrial and residential needs [1]. Commonly, the electricity demand was supplied by fossil fuels as oil, natural gas and coal; but the variability of electricity price, the rise of CO_2 emissions and the reduction of

*Corresponding author
Email address: ana.cabrera@citcea.upc.edu (Ana Cabrera-Tobar)

fossil fuel reserves have caused that different countries and organizations focus on renewable energy as a solution to supply the future and the present demand [2].

Therefore, the use of renewable energies to supply electricity has grown in the last years, especially wind and photovoltaic power. Wind power plants had the fastest growth during the last years. In fact, the cumulative wind power installation in the European Union at the end of 2014 was 128.8 GW [3], while in Asia, US, and South America was 115 GW [4], 65 GW [5] and 4 GW [4] respectively. In contrast, photovoltaic (PV) power installations did not have the same growth, due to prices of photovoltaic panels, technology used and social opposition. In fact, the cumulative power installation of photovoltaic for residential and utility purpose connected to the grid in 2014 was 81 GW in Europe, 37 GW in Asia [4], 13 GW in USA [6] and only 104 MW in South America [4]. According to the European Photovoltaic Industry Association $EPIA$, the total installed capacity of photovoltaic power in Europe will reach 156 GW, and for Asia will be 184.9 GW until 2018 [7]. US, South America and South Africa show a drastic increment on the development of PV power plants (PVPPs) adding several GWs to the worldwide PV generation, in fact US has 21.8 GW of PVPPs under development [8].

Because of this trend, different PV panels, inverters, transformers, protections and storage systems have been developed to improve the overall performance of PVPPs for small, large (LS-PVPPs) and very large scale (VLS-PVPPs)[1]. Accordingly, this article focuses on two main objectives; former, the introduction of the main characteristics of the basic components for LS-PVPPs; and the latter, the definition and discussion of internal disposition of PV panels, inverters and transformers considering also the ac collection grid topologies for LS-PVPPs.

[1]In this article we consider small scale if the power rate of the PVPP is in the range of 250 kW to 1 MW, LS-PVPP from 1 MW to 100 MW and according to the International Energy Agency [9], VLS-PVPP has a rate capacity from 100 MW to GW.

Numerous publications regarding the review of suitable technology for small PVPPs are found in the literature. The explanation of the components, topology and the control of small PVPPs for houses and buildings are studied in [10, 11, 12, 13]. Meanwhile, [14] and [15] focus on problems related to large scale integration of PV generation into the distribution system as voltage drop and network losses. The topologies used to interconnect PV panels with the inverters, for small PVPPs interconnected to the grid, are studied by [16] and [17]. Besides, Salas, V. and et al. [18] study the technology used by inverters in small PV application comparing efficiency, control, cost, weight, and its future trend.

In contrast, there are few publications regarding the review of the electrical layout and the suitable technology for LS-PVPPs and VLS-PVPPs. Stranix et al. [19] and Simburger et al. [20] review the design of LS-PVPPs considering electronic devices, wiring, protections, PV panels, mounting characteristics, installation, maintenance and cost according to the technology used in 1980s. Alternative configurations are studied in [21], comparing technical advantages and disadvantages, but these configurations are only based on central inverters topologies. Ito Masakazu and et al. [22] present how different types of PV panels affect to the area occupied by a VLS-PVPP . In [23] and [24], a summary of the problems related to the integration of LS-PVPPs to the grid considering electrical grid codes is described. The control and the implementation of LS-PVPPs are studied on [25, 26, 27] with specific examples. Despite the extensive literature review, there is a lack of information about the internal topology and the ac collection grid for LS-PVPPs. Therefore, the development of this review is critically important in order to describe the components, their internal disposition and the ac collection grid topology used in LS-PVPPs. To accomplish the objectives of this paper an extensive literature review is developed considering publications of the last 30 years presented in journals and magazines. Besides, an extensive review of the technical data of real LS-PVPPs developed around the world is developed to do a deeper analysis of the current trend.

The remainder of this paper is structured as follows. Section 2 presents a review of the main electrical components used in LS-PVPPs. Section 3 is dedicated to the analysis of the internal disposition of the components in a LS-PVPP. Section 4 presents the analysis and discussion about the ac collection grid topologies in LS-PVPPs. Finally, the conclusions are presented in Section 5.

2. Electrical components

The electrical components of LS-PVPPs have three tasks: i) to convert solar energy into electricity, ii) to connect the LS-PVPP to the grid, iii) to assure an adequate performance. The basic components involved in these tasks are: PV panels, PV inverters and transformers. In this section, a review of these components is developed considering their operating principles, the current technology used, and their future trend.

2.1. PV panels

Solar cells are the basis of the PV panel. The function of the solar cells is the conversion of solar energy into electricity [28]. A number of solar cells are connected in series and then encapsulated in an especial frame to construct the PV panel [29].

There are different materials of solar cells affecting to the overall efficiency of the PV panels. The basic types, crystalline ($c - Si$) and multicrystalline ($m - Si$) silicon, present efficiency values around 20 % [30]. Other types as the thin film solar cells using amorphous silicon ($a - Si$) have an efficiency around 6.9 % to 9 % [22, 30] . Thin film solar cells are also using other materials as copper indium diselenide ($CuInSe_2$-CIS), and Cadmiun telluride ($CdTe$) with efficiencies around 15 % [28] and 12 % [30] respectively. Other materials are in research with the aim to improve efficiency and costs as it is summarized in [31] and [32].

The $c - Si$ and $m - Si$ has dominated the utility market during the last years due to its efficiency , the land used, and its stability during time, reliability and abundant primary resource. The main drawback of this technology is the price due to manufacturing and the quantity of material used [33], [34]. In contrast, thin film solar cells has some benefits as the price, the efficiency of sun light in low radiation and low temperature coefficient. But the main drawback for its utilization on LS-PVPPs is the land occupied, lower efficiency, low stability during time [35], [36] and the scarcity of materials [37]

The efficiency of the solar panels affects to the overall dimension of the LS-PVPP, as it is explained in [22]. For the same power, if the efficiency reduces, the area occupied by the LS-PVPP is major. The total cost is also affected not only by the land occupied but also because of installation, transportation, maintenance and mounting characteristics [38]. Fig. 1. illustrates the relationship between the efficiency of the different types of solar cells with the size of the PVPP according to the available data in [22] for a LS-PVPP of 100 MW. The Fig. 1 shows that the multicristalline silicon solar cells ($m - Si$) has larger efficiencies (10-12%) than the case of thin film solar cells (7-9%). The area occupied by the silicon solar cells is less than twice the area used in thin film solar cells when amorphous silicon is used. This is also validated by Yimaz at et al. [39] using a small system of 33 kW to compare the performance of ($c - Si$), ($m - Si$) and thin film solar cells.

Researchers are still looking forward the improvement of solar cell characteristics by the increment of the efficiency, the decay of prices and the long-term stability [40]. For LS-PVPPs, other solar cell characteristics are also becoming necessaries as sustainability, recycling and reduction of CO_2 production during its life cycle [41].

2.2. PV inverters

The PV inverters are electronic devices that permit the conversion from dc to ac power and are used in different applications. In the case of LS-PVPPs, the PV panels generate dc power, then these panels are connected to a PV inverter to generate ac power [28], permitting its connection to the internal ac grid.

The PV inverter has one or two stages of conversion. In one stage, a single

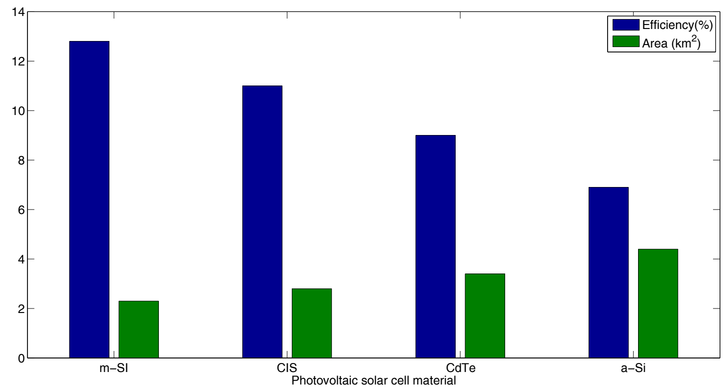

Figure 1: Efficiency and Area occupied by PV panels with different types of solar cells for a LS-PVPP of 100MW [22]

inverter (dc-ac) is commonly used, and in two stages an additional dc-dc converter is connected [42, 43]. The use of dc-dc converter in LS-PVPPs is still on research. A review of the state of the art of non-isolated dc-dc converters is studied in [44, 45] and isolated dc-dc converters are analyzed in [46]. In non-isolated converters, the configuration used are boost, buck, buck & boost, Cûk or SEPIC. The leakage current, the voltage stress and the current ripple are a drawback of non-isolated dc-dc converters. Therefore, isolated configuration is considered appropriate for LS-PVPPs. The isolation is commonly obtained by a high frequency transformer. The typical configurations are flyback, forward, push-pull and boost-half-bridge [47]. The switching stress, the cost and the efficiency are typical issues on these configurations [46].

The choice of the dc-dc converter depends on the dc-ac inverter used at the next stage. The typical inverters used are Neutral Point Clamped (NPC) and Cascade H-Bridge (CHB) [48]. If a dc-dc stage is connected, an isolated converter suites better for CHB as it needs independent dc input for each CHB used [49]. In the case of a NPC, non-isolated converter is connected in a previous stage [50].

In any case, one or two stages of conversion, the PV inverters used in LS-PVPPs must overcome issues related to the technology of the PV panels and electrical requirements. First, PV inverters must have galvanic isolation to overcome any issue related to the leakage current from the PV panels interconnection [46]. Second, due to the non-linear characteristics of the voltage and current of the PV inverter, a tracker of the maximum power point (MPPT) for any radiation and temperature is needed [51]. Third, the power quality and the operational characteristics of the PV inverters must obey any of the electrical standards applicable to the country.

Photovoltaic power initially became important in Distribution generation for which some of the applicable standards for PV inverters are IEEE 1547, UL1741 and ANSI C84. These electrical standards permit that the PV inverter disconnects in any case of faults, low voltage or disturbance into the grid. However, an immediate disconnection is counterproductive for a large facility as a LS-PVPP. Dedicated standards for the interconnection of LS-PVPPs to the grid are the ones presented in Germany (BDEW), US (FERC LGIA) and Puerto Rico (PREPA). According to these standards, not only inverter's disconnections is forbidden, but they also have to provide grid support functions as voltage and frequency regulation as well as fault ride through capability [52], [53]. To help to comply these requirements FACTS and capacitor banks are included, but they are not part of these review.

2.3. Transformers

In LS-PVPPs, there are two types of transformers installed (Fig. 2). The first one (Tn), steps up the voltage from the PV inverters to the range of 13.8 kV to 46 kV [54]. The second one (T-HV) has two functions: i) to provide galvanic isolation for LS-PVPPs from the electrical grid and ii) to step up the voltage from the LS-PVPP [21]. In the LS-PVPP detailed in [55], forty transformers are used to step up the voltage of the PV inverters from 0.4 kV to 30 kV. In this case, another transformer is used for the complete LS-PVPP to step up the voltage from 30 kV to 110 kV.

If the PV inverter has a power rating higher than 500 kW, three winding transformer is commonly used [56]. This transformer has two windings for low

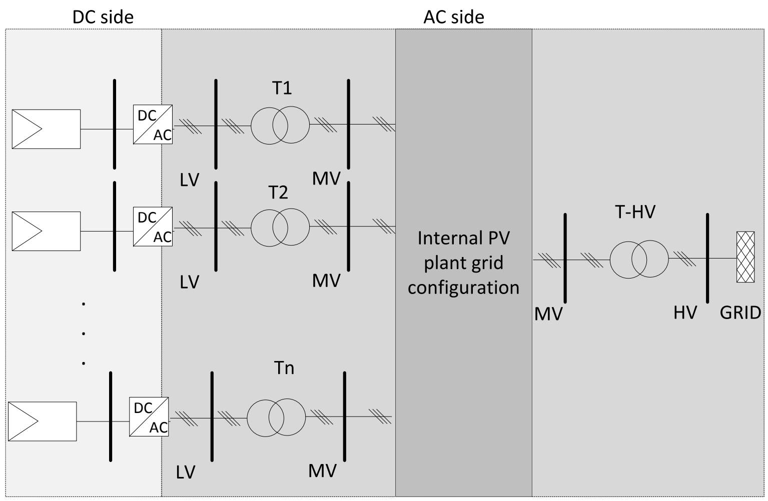

Figure 2: Location of the transformers in the LS-PVPP

voltage (LV), to connect two inverters, and the third one for medium voltage connection (MV) [57, 58]. The existing vector groups for this transformer are: $Dy_ny_n, Dd_nd_n, YNy_ny_n, YNd_nd_n, YNy_nd_n$ [59]. In the case of PV inverters with a power rating less than 500 kW, transformers of two windings are used [60]. These transformers have two windings, one for low voltage (LV) and other for high voltage (HV). The transformer T-HV has also two windings, one for medium voltage (MV) and the other one for high voltage (HV). The existing vector group for this transformer is Yy.

Any of these transformers (Tn or T-HV) is elected according to the rated power, efficiency, and cost. The transformer could become a bottleneck, if the rated power is smaller than the normal operation of the LS-PVPP. If the rated power is too large, there could be some instabilities that cause problems with the overall performance [54, 57]. To overcome this issue, a technique has been designed by A. Testa and et al. [61] to choose the transformer according to the power, the efficiency, the cost and the operation of a LS-PVPP.

Currently, researchers are looking for other type of transformers to reduce the area occupied and to improve the reliability of LS-PVPPs. The work developed by Bahha Hafez and et al. proposes the use of medium frequency transformers at LS-PVPPs [62]. According to this work, the efficiency of the overall power plant improves by 2 % in comparison with a LS-PVPP developed in Eggebek that uses multistring inverters, but an ac-ac converter is added to the topology.

After the understanding of the definition, function, characteristics and the future trend of the main components in LS-PVPPs, the following section studies the distribution of these components for this type of application.

3. Internal PV plant configuration

The connection of PV inverters with PV panels (Fig. 3) and transformers (Fig. 4) in LS-PVPPs considers three basic topologies: i) central, ii) string, and iii) multistring [16], [17]. There is a fourth basic topology, the ac module integrated, but its application in LS-PVPPs has not been developed yet. The power produced by the different topologies is affected by solar radiation and shading effect, becoming very important the correct choice of the topology according to the power output, location, reliability, cost and efficiency [10].

In this section, a review of these configurations is developed, describing and analysing their main characteristics, advantages, disadvantages, applications and future trend. To overview a summary of the configurations presented in this section, some tables (see Tables 1 to 3) and graphics (see Fig. 3 to 7) are developed according to the data collected from several publications and manufacturers.

3.1. Description of internal topologies

The interconnection between PV panels and the inverters is illustrated in Fig. 3. The central topology (Fig. 3(a)) interconnects several thousands of PV panels to one inverter. The disposition of these PV panels are clustered into PV arrays. Each array has hundreds of PV strings connected in parallel, and each string has hundreds of PV panels connected in series. The string topology (Fig. 3(b)) connects one PV string with one inverter. The multistring topology (Fig. 3(c)) connects one PV string to a dc-dc converter, then 4 or 5 dc-dc

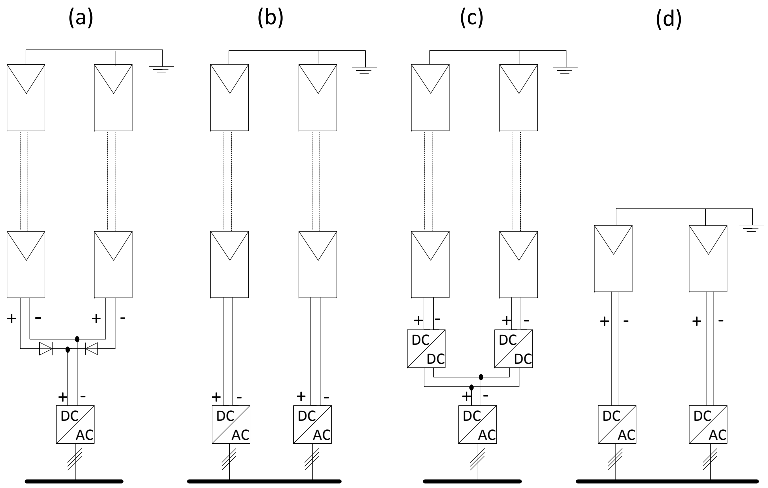

Figure 3: PV inverter topologies. (a) Central, (b) String, (c) Multistring, (d) Module integrated

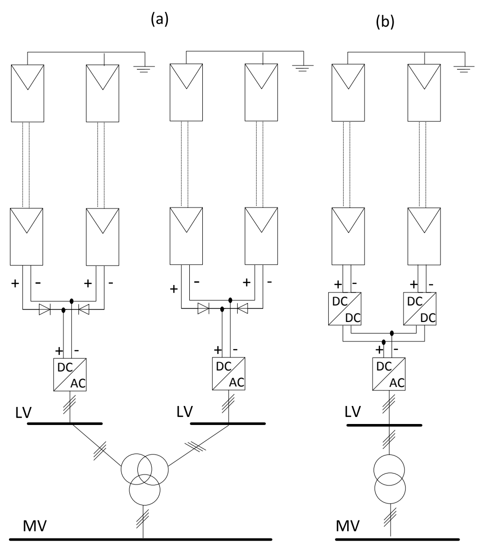

Figure 4: Connection of Transformers at Medium Voltage. (a) Central PV inverter with three winding transformer, (b) Multistring PV inverter with two winding transformer.

converters are connected to one inverter which may or may not be closed to the dc-dc converter. The fourth topology, the ac module integrated (Fig. 3(d))

Table 1: Electrical characteristics of PV inverter topologies

Inverter topology	P (kW)	Vin mppt dc (V)	Vout ac(V)	f (Hz)
Central	100-1500	400-1000	270-400	50, 60
String	0.4-5	200-500	110-230	50, 60
Multistring	2-30	200-800	270-400	50, 60
Module Integrated	0.06-0.4	20-100	110-230	50, 60

has one inverter per each PV panel. The inverters utilized on these topologies takes the name of the topology used: central, string, multistring and ac module integrated. The electrical characteristics of these inverters are described in Table 1.

These topologies are differentiated by four categories: general characteristics, power losses, power quality and cost (Table 2[2]). The first category, general characteristics, considers the robustness, reliability, flexibility and MPPT efficiency [63, 64, 65]. Each topology presents its own general characteristics that depends specially on the power rating, number of PV inverters and number of PV strings. For instance, the central topology has low levels (L) of reliability, flexibility and MPPT efficiency but its robustness is higher than other topologies.

The second category, power losses, considers mismatching, switching, ac and dc losses. Mismatching losses are inevitable in any PV array. These depends on uneven degradation along the PV string, shading, cloud coverage, dust, cooling, MPPT efficiency, among others [66, 67]. In this case, central topology presents higher (H) mismatching losses because several strings are connected to a single inverter. The switching losses are also a concern that depends on the devices and the control of the PV inverter. The length of the cables in the dc or the ac side influences the cumulative losses of LS-PVPPs. Central inverters have very

[2]The following nomenclature is used: H-H: very high, H: High, M: Medium, L: Low, L-L: very low

high (H-H) losses at the dc side as many strings are connected in parallel. In contrast, the ac losses in the central inverter are low (L), as the transformers (Tn) are connected very close to the inverter.

The third category, power quality, is influenced by the dc and ac voltage variations and voltage balance. In the case of central topology, the dc voltage variation is very high (H-H) because many strings are connected in parallel. In this case, the ac voltage variation is low (L) and the voltage balance is high (H) as it has only one inverter. The voltage is unbalanced specially when many inverters are connected in parallel as the case of module integrated. Due to losses, distances and voltage sags, the three phase voltage balance at the point of connection with the transformer (Tn) could be affected. Therefore, when several inverters are connected in parallel, is necessary to develop a master control for a group of PV inverters to reduce the ac voltage variation and to improve the voltage balance.

The fourth category, the cost, involves the installation, maintenance, land cost and length of cables in the dc or the ac side [63, 68, 69]. The comparison of costs for each topology is detailed in Table 2, but the land cost is not included as it depends on the location of the LS-PVPP.

Because of comparison analysis, Fig. 5 is developed considering each characteristic for every topology presented in Table 2. It can be stated that the central topology has the following advantages: robustness, low ac power losses, low ac voltage variation and a reasonable installation and maintenance cost in contrast with the other topologies. The general characteristics of string and multistring topologies [63] are very attractive, but the main drawback is the installation and the maintenance cost as the number of inverter increases. String topology has similar characteristics as the multistring topology, but it is recommended to use it when each PV string has different orientation angle [69, 70]. In real LS-PVPPs, module integrated has not been implemented, but it can be concluded that has good characteristics considering flexibility, MPPT efficiency and reliability. The robustness, power losses, power quality and the general cost are several drawbacks for the module integrated topology.

Table 2: Main characteristics of PV inverter topologies

		Central	String	Multistring	Module integrated
General characteristics	Reliability	L	H	M	H-H
	Robustness	H	L	M	L-L
	Flexibility	L	H	M	H-H
	MPPT efficiency	L	H	M	H-H
Power losses	Mismatching	H	L	L	L-L
	Switching	H	L	M	L-L
	ac power losses	L	M	M	H
	dc power losses	H	L	M	L-L
Power quality	ac voltage variation	L	H	M	H-H
	dc voltage variation	H-H	M	H	L-L
	voltage balance	H	M	L	L
Cost	Installation cost	M	H	M	H-H
	dc cables	H	L	M	L-L
	ac cables	H	M	M	H
	Maintenance	L	M	H	H-H

3.2. Analysis in real LS-PVPPs

In this subsection an analysis of real LS-PVPPs is developed to see the applicability of the topologies studied before. A comparison of three different topologies available in the market considering cost, efficiency and area is illustrated in Fig. 6. The topologies compared are central, multistring and an additional topology called multicentral inverter. This topology encapsulates in one cabinet several central inverters with a power rating less than 100 kW. In the cabinet, there are at least three different PV inverters with the same characteristics. Each of them has its individual MPPT control. The output of each inverter is connected in parallel with the adequate protections to have only one output for the complete cabinet. Fig. 6 shows that multicentral inverter has better characteristics on price and efficiency in comparison with central and multistring inverter.

Additionally, Fig. 7 compares 22 LS-PVPPs of different power from 6 to 90 MW, where 17 of them have PV inverters connected in central topology.

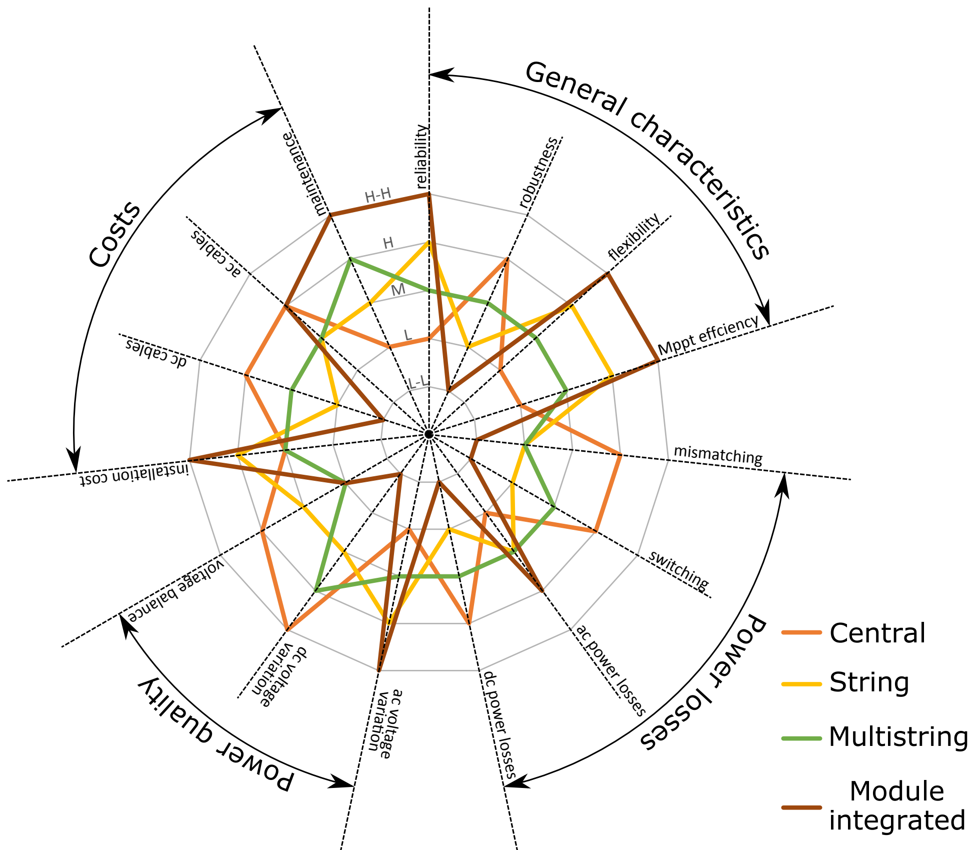

Figure 5: Comparison between different PV inverter topologies characterisitcs for LS-PVPPs

The comparison is made between the area occupied and the number of PV modules in contrast of the capacity rating of the LS-PVPP for central and multistring topology. This graph shows that the central topology is the most used technology due to its feasibility and the small number of inverters used in the power plant. Multistring topology is barely used in LS-PVPPs and the area occupied according to the evaluated data is almost the same as the area used for central topology.

In any of these cases at large scale, string topology has not been used. The work developed by Syafaruddin and et al. [71] analyses that an array of PV panels connected to central inverter generates less power than string topology

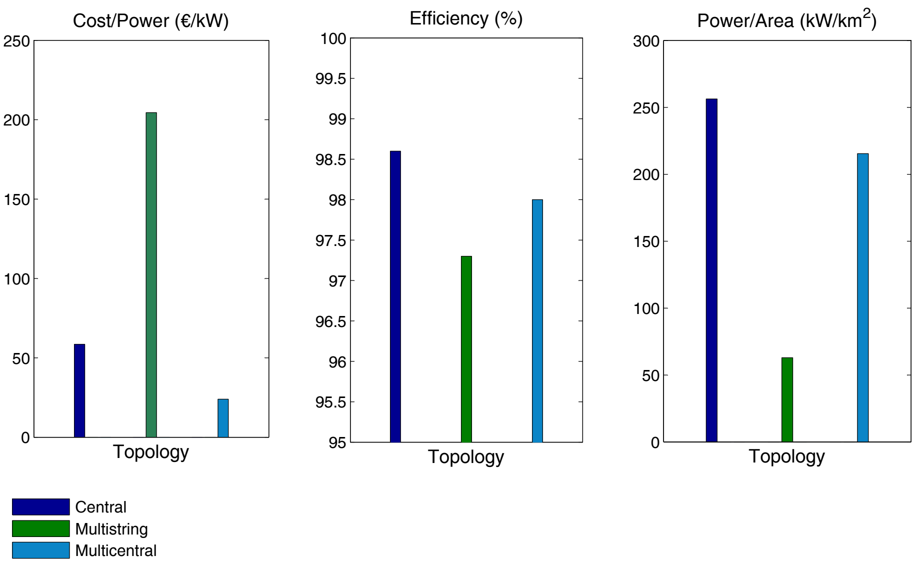

Figure 6: Comparison between different PV inverter topologies available in the market for LS-PVPPs

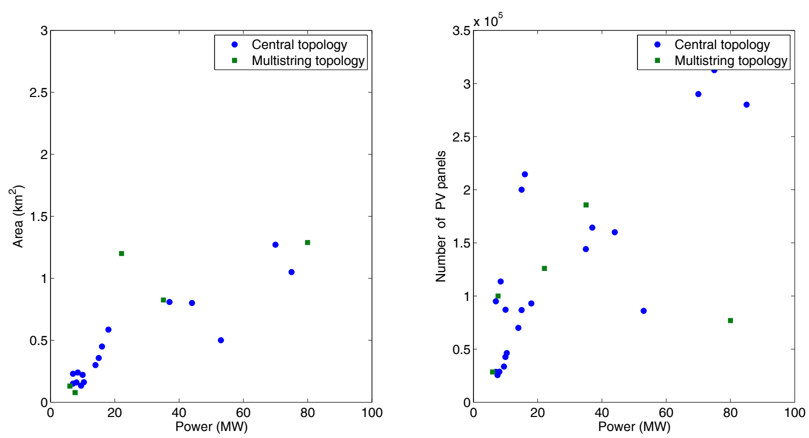

Figure 7: Comparison of area and number of PV panels used between different real LS-PVPPs

295 for the same PV array considering non-uniform irradiance condition and a novel MPPT control based on artificial neural network. The study developed by A. Woyte and et al. [72] concludes that there is not a considerable difference among central and string inverter with a similar annual yield, thus the performance

Table 3: Details of some operational LS-PVPPs

Photovoltaic Power Plant	Power (MWp)	Area (km^2)	Panels ($*10^3$)	Panel type	Inverters Number	Topology
Korat I	6.0	0.13	29	m-Si	540	M
Narbonne	7.0	0.23	95	Thin film	19	C
Rapale	7.7	0.49	100	Thin film	900	M
Airport, Athens	8.1	0.16	29	m-Si	12	C
Saint Amadou	8.5	0.24	113	Thin film	16	C
Volkswagen Chattanoga	9.5	0.13	33	m-Si	10	C
Masdar	10	0.22	87	m-Si, Thin film	16	C
Adelanto	10.4	0.16	46	m-Si	13	C
Taean	14	0.30	70	m-Si	28	C
Jacksonville	15	0.40	200	Thin film	20	C
San Antonio	16.0	0.45	214	Thin film	22	C
Cotton Center	18.0	0.58	93	m-Si	36	C
Almaraz	22.1	1.2	126	m-Si	6697	M
Veprek	35.1	0.83	185	c-Si	3069	M
Long Island	37.0	0.80	164	m-Si	50	C
Reckahn	37.8	0.98	487	Thin film	43	C
Ban Pa-In	44.0	0.80	160	m-Si	61	C
Lieberose	71.0	2.2	900	Thin Film	38	C
Kalkbult	75.0	1.05	312	m-Si	84	C
Eggebek	80.0	1.29	76	m-Si	3200	M
Montalto di Castro	85.0	2.83	280	c-Si	124	C
Templin	128	2.14	1500	Thin Film	114	C
California Valley Ranch	250	6.01	749	c-Si	500	C
Agua Caliente	290	9.71	5200	Thin Film	400	C

ratio during the year is similar.

Table 3 summarizes the main characteristics of some LS-PVPPs developed by SMA, ABB, SunPower and Danfoss. This table indicates the area, the number of PV panels, the panel type, the PV inverters and the topology[3] used in operating LS-PVPPs. Other components are still necessary for the design, implementation and operation of LS-PVPPs, as junction boxes for dc and ac side, sensors [73, 74] and protection devices that are not part of this review.

The data detailed in Table 3 shows that the preferred material of PV panel is m-Si and thin film. In LS-PVPPs that uses thin film solar panels occupies twice the area than the PVPPs that uses m-Si. Only, three PVPPs of the table below uses c-Si, and these show less number of PV panels and less area occupied. Furthermore, the number of PV inverters depends on the topology used, a large number of PV inverters is common in multistring topology. For instance, in the

[3] M=Multilevel, C=Central

cases of Veprek and Long Island solar plant with a corresponding power of 35 MW and 37 MW respectively, have similar area occupied, though the topology is different. The number of PV panels used in the case of Long Island is twenty thousand less than Veprek solar plant, though the power is higher in the first case. The number of multistring inverters, in the case of Veprek, has a total number of 3069 in contrast with 50 inverters used in the case of Long Island. Despite the topology used, the area and the number of PV panels does not seem to have any relation with the topology chosen. However, the area occupied and the number of PV panels has a relation with the type of material used in the PV panel. In Veprek PV plant, c-Si is used, in contrast m-Si is used in Long Island. In the case that thin film solar cells is chosen for similar power as Reckahn power plant, the area occupied increases in 20 % and the number of PV panels is almost three times than the case of Long Island PV plant. However, in both cases the internal configuration chosen is central and the number of inverters is almost similar.

The cost influences in the decision of the topology and the technology used as well as the efficiency required, the performance, the area, the price of land and the location. Despite the importance of the internal distribution of the PV panels, inverters and transformers, the following section studies the general configuration of the overall plant without considering the PV inverter topology chosen for the PV arrays.

4. Collection grid topologies

Collection grid topologies are considered for internal dc or ac power. Very little information has been documented about the ac collection grid topologies for LS-PVPPs and none has been presented for the dc collection grid. This section explains some possible AC collection grid topologies described by some manufacturers as radial, ring, star and their variations considering their advantages and disadvantages. In this explanation, an array of PV panels together with its inverter and transformer is considered as PV generator.

4.1. Radial

The radial collection system considers several numbers of PV generators connected to one feeder, developing one string, as shown in Fig. 8. The majority of LS-PVPPs uses this topology because it is cheapest and simplest, but its low reliability makes it less attractive. If the first generator connected to the feeder is lost, all the string is lost. One example of this configuration is detailed by Danfoss using one of their Multistring inverters. In this case a LS-PVPP of 15 MW is proposed. It has two feeders of 7.5 MW, and each of them has 5 transformer stations of 1.5 MW. The low voltage side of the transformer is connected to 88 multistring inverters that are connected in parallel between them [75]. In the case a PV inverter is lost, the total power production will not be affected significantly, but, if one transformer station is lost, all the feeders can be lost in the worst case scenario. In this case the power produced will reduce by 50 %.

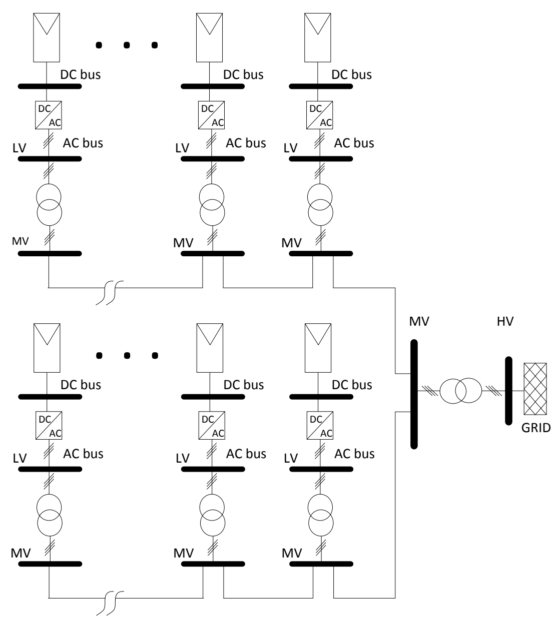

Figure 8: Radial collection configuration

4.2. Ring

The ring collection topology is the one used to improve the reliability of LS-PVPPs. The connection is based on radial design but it adds another feeder in the other side of the string (Fig. 9). If one of the PV generators is lost, then the PV generators connected to the other side of the feeder can still give power to the LS-PVPP. The drawback is the cost and the complexity of the installation. A LS-PVPP of 10 MW proposed by Danfoss uses this configuration considering 15 transformer stations. The low voltage side of these transformers is connected to 42 multistring inverters. In this case, if there is any failure in one of the inverters just a small part of the LS-PVPP is lost (less than 1 %) [76]. In this case, if any transformer station is lost, there is a reduction of power production of 6.3 %.

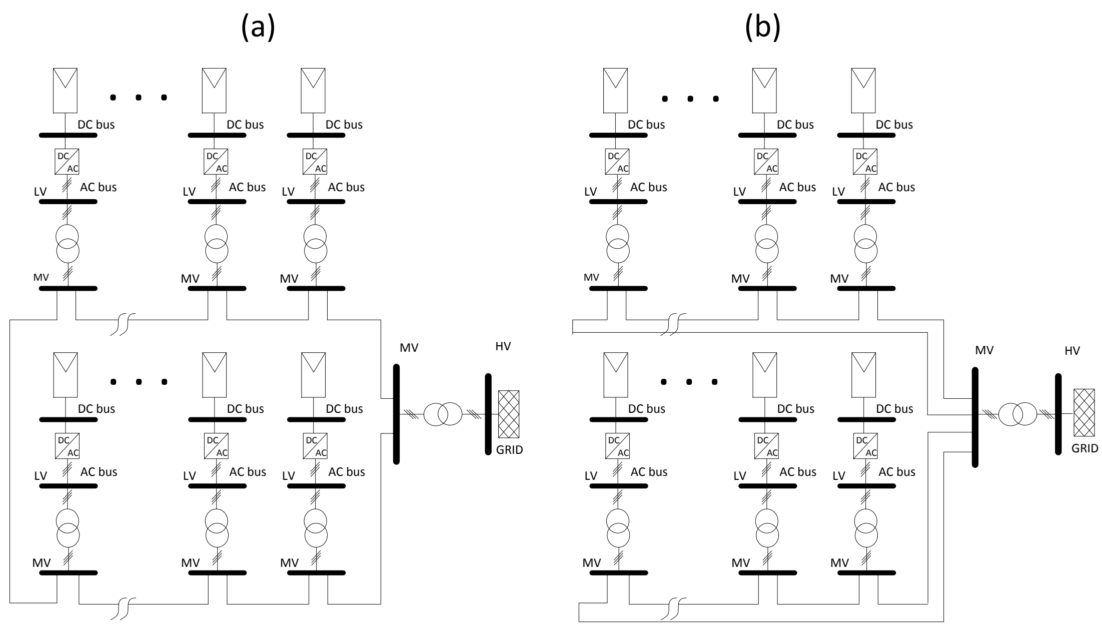

Figure 9: Ring collection configuration. (a) case 1 and (b) case 2

4.3. Star

This collection topology has one PV generator connected to the main collector. Commonly, this collector is in the middle of the LS-PVPP to reduce the distances of the cables and to have the same losses between them (Fig.10). This solution offers higher reliability than the other cases. On the downside, there is one feeder for each PV generator that increases the total cost. An example of 21 MW LS-PVPP is explained by Abraham Ellis for the integration of Renewable Energy in South Africa [77]. The star configuration proposed considers 8 transformer stations. Each of these transformers is linked to 3 central inverters on the low voltage side. In this case, if a transformer station is lost, 14 % of the power production will be affected. This can be reduced if multistring inverters are used. It will have a power reduction of 4% if any of the central inverters fails.

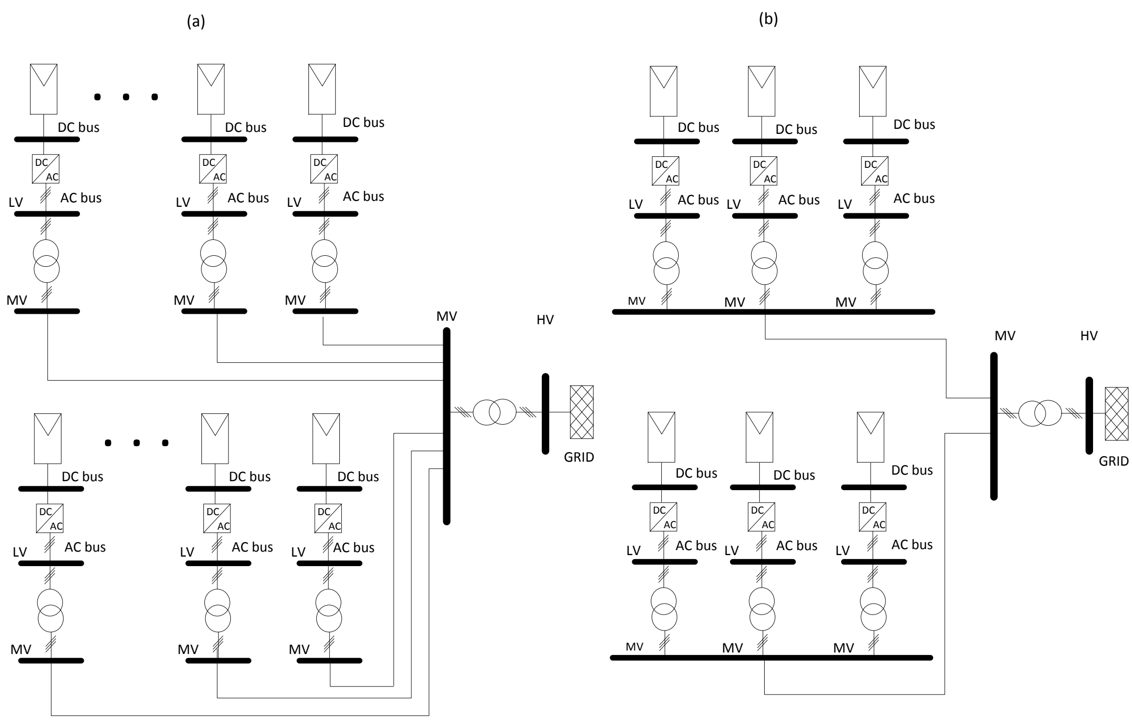

Figure 10: Star collection configuration. (a) case 1, (b) case 2

Table 4: Summary of basic elements, internal configuration and topologies for LS-PVPPs

	Basic elements			Configuration and topologies	
	PV panels	PV inverters	Transformers	Internal configuration	Collection grid topologies
Technology	m-Si c-Si Thin film solar cells	one stage (dc-ac) two stages (dc-dc-ac) galvanic isolated or non-isolated	Two windings Three windings	Central String Multistring ac module	Radial Ring Star
Most used tecnology	m-Si and Thin film	One stage dc-ac	Three winding	Central	Not enough documented PVPPs
Concerns	Effciency Price Manufacturing stability	Switching losses Effciency Adequate control Compliment of grid codes Galvanic isolation Price	Size Price Power	Power effciency Voltage variation Installation cost Maintenance cost	Reliability Losses Cost

The ac collection grid topologies presented here have different problems about reliability, cost and efficiency. These issues are overcome if there is a complete analysis about these configurations in one case scenario, very few cases have been published making impossible the comparison among them. Finally, we present a table (Table 4) that summarizes the technology, the internal topology and the ac collection grid configurations used in LS-PVPPs, considering what has been discussed before.

5. Conclusions

In this paper, the main characteristics of the basic components for LS-PVPP have been detailed. In addition, the internal disposition and ac collection grid topologies have been described considering real LS-PVPPs implemented around the world. The tables 1 to 4 present a general summary of the different topics discussed in this review. It is worth pointing out the right choice of the components affects the area occupied, the efficiency and the reliability of LS-PVPPs. From this review, some conclusions can be argued:

- The material used in the PV panels makes a big difference in the area occupied. Better materials of PV panels makes possible the reduction of the area used by LS-PVPPs. PV panels with higher power and less size must be developed specifically for LS-PVPPs. This will help to reduce the installation costs and the area used. In this sense, silicon solar cells is more suitable for large installations as it has higher efficiency and the land used is less than the case of thin film solar cells. Also, the prices are expected to decay in the future years which will help to the development of LS-PVPPs. However, thin film solar cells technology is still improving and it is expected that more LS-PVPPs will use it, as the price is less than crystaline or multicrystaline solar cells.

- The most widely used PV inverters in LS-PVPPs have one stage of inversion (dc-ac), as it is a known technology and has been deeply applied on the integration of renewable energy into the grid. However, two stages are attractive for the future of LS-PVPPs to improve the control of the PV generator at the dc side which permits to reduce the dc variations. Besides, the addition of galvanic isolation in any of these cases depends broadly on the PV panel type and the electrical characteristics required by the LS-PVPP. Deeper studies are necessary considering real cases scenarios to understand the advantages and disadvantages of the use of converters with one or two stages, galvanic isolated or not.

- The performance of a LS-PVPP depends mostly on the operation and control of the PV inverters. Until now the PV inverters have broadly developed to comply electrical standards to support the consumer without providing grid support functions. Due to the future trend of the development of LS-PVPPs that have to behave as similar as possible as the conventional power plants, PV inverters have to improve their operational and control characteristics. However, not many studies about the improvement of PV inverters technology and control have been developed for LS-PVPPs.

- The internal topology is critical for the performance of the LS-PVPPs. Central topology has been preferred by the majority of LS-PVPPs developed in the world. This may obey to the simplicity of installation and to the small number of components in the overall power plant. The drawback of the central topology is the mismatching losses caused by the change of radiation reducing the effectiveness of the MPPT control and affecting to the output power. Multistring topology has better characteristics of efficiency because it has a dedicated MPPT control per string. The complexity of installation and the large number of inverters installed, makes this topology less attractive to investors. The multistring inverter topology has a big potential on LS-PVPPs, but deeper research on cost, efficiency and behavior is necessary.

- According to the topology chosen and the rated power of the inverter, the transformer is elected. Two windings transformer was commonly used in PVPPs developed in the 90s due to the power of central inverter. However, the development of central inverters with higher rating has increased the necessity to have an improved transformer. Today, one of the transformers most used in real LS-PVPPs has three windings that permits to link two central PV inverters with their independent control. But in the case of multistring inverters, two windings transformers is still used. The future trend of the transformers for LS-PVPPs depends specially on how the inverter improves its technology and control. Their size, operation, maintenance, power quality are the current concern in LS-PVPPs and deeply research on new transformer's generation is still emerging.

- A comparison of various conceptual designs for the ac collector system options in terms of losses, reliability and economics has been presented in this review. In real LS-PVPPs radial configuration is the most used as it has the lowest cable cost. Currently, there is any study comparing the collector system options for this type of application and how the variation of solar radiation and temperature affects to the performance of any configuration. In future years the use of radial or ring configuration will be the most used and not so many changes will occur in this area. However, as the PV array supplies dc power will be more attractive to have dc collection grid instead of ac. This will depend on how the dc-dc converters and protections will develop in the future years and how the price for dc technology will drop.

- The future of LS-PVPPs depends on the decay of prices, size reduction, efficiency improvement of the different elements used in its development (PV panels, transformers and inverters). After the prices will be sufficiently reduced, the internal configuration and the collection grid are part of the future concern in LS-PVPPs considering cost, robustness, reliability and flexibility. Together with the concern of the elements and the configuration, the necessity to improve the control and the energy management of LS-PVPPs is increasing. The trend is to control the LS-PVPPs to behave as similar as possible as conventional power plants considering grid codes requirements.

References

[1] Bp Energy outlook 2035, Tech. rep. (2014).
URL http://www.bp.com

[2] L. C. Lau, K. T. Lee, A. R. Mohamed, Global warming mitigation and renewable energy policy development from the Kyoto Protocol to the Copenhagen AccordA comment, Renew. Sustain. Energy Rev. 16 (7) (2012) 5280–5284. doi:10.1016/j.rser.2012.04.006.

[3] EWEA, The European Wind Energy Association — EWEA.
URL http://www.ewea.org/

[4] IRENA Resource.
URL http://resourceirena.irena.org/gateway/index

[5] Wind Energy Facts at a Glance.
URL http://www.awea.org

[6] U.S. Solar Market Insight — SEIA.
URL http://www.seia.org

[7] Global market outlook for Photovoltaics 2014-2018.
URL http://www.epia.org/fileadmin/user_upload/Publications/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf

[8] Major Solar Projects in the United States Operating, Under construction or under development.
URL http://www.seia.org

[9] K. Komoto, K. Kurokawa, Nishimura, et al., IEA PVPS Task 8: Project Proposals on Very Large Scale Photovoltaic Power Generation (VLS-PV) Systems in Deserts, in: 2006 IEEE 4th World Conf. Photovolt. Energy Conf., Vol. 2, IEEE, 2006, pp. 2359–2362. doi:10.1109/WCPEC.2006.279665.
URL http://ieeexplore.ieee.org

[10] D. Picault, B. Raison, S. Bacha, Guidelines for evaluating grid connected PV system topologies, in: 2009 IEEE Int. Conf. Ind. Technol., IEEE, 2009, pp. 1–5. doi:10.1109/ICIT.2009.4939505.
URL http://ieeexplore.ieee.org

[11] A. Ghafoor, A. Munir, Design and economics analysis of an off-grid PV system for household electrification, Renew. Sustain. Energy Rev. 42 (2015) 496–502. doi:10.1016/j.rser.2014.10.012.
URL http://www.sciencedirect.com

[12] A. Cabrera-Tobar, H. U. Banna, C. Koch-ciobotarus, G. Siddharta, Optimization of an Air Conditioning Unit according to Renewable Energy availability and Users Comfort, in: ISGT, 2014, Istanbul, 2014. doi:10.1109/ISGTEurope.2014.7028866.
URL http://ieeexplore.ieee.org/

[13] J. Weniger, T. Tjaden, V. Quaschning, Sizing of Residential PV Battery Systems, Energy Procedia 46 (2014) 78–87. doi:10.1016/j.egypro.2014.01.160.
URL http://www.sciencedirect.com

[14] J. Widén, E. Wäckelgå rd, J. Paatero, P. Lund, Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids, Electr. Power Syst. Res. 80 (12) (2010) 1562–1571. doi:10.1016/j.epsr.2010.07.007.

[15] J. V. Paatero, P. D. Lund, Effects of large-scale photovoltaic power integration on electricity distribution networks, Renew. Energy 32 (2) (2007) 216–234. doi:10.1016/j.renene.2006.01.005.
URL http://www.sciencedirect.com

[16] L. Hassaine, E. OLias, J. Quintero, V. Salas, Overview of power inverter topologies and control structures for grid connected photovoltaic systems, Renew. Sustain. Energy Rev. 30 (2014) 796–807. doi:10.1016/j.rser.2013.11.005.
URL http://www.sciencedirect.com

[17] Z. Zeng, H. Yang, R. Zhao, C. Cheng, Topologies and control strategies of multi-functional grid-connected inverters for power quality enhancement: A comprehensive review, Renew. Sustain. Energy Rev. 24 (2013) 223–270. doi:10.1016/j.rser.2013.03.033.
URL http://www.sciencedirect.com

[18] V. Salas, E. Olías, Overview of the state of technique for PV inverters used in low voltage grid-connected PV systems: Inverters above 10kW, Renew. Sustain. Energy Rev. 15 (2) (2011) 1250–1257. doi:10.1016/j.rser.2010.09.051.
URL http://www.sciencedirect.com/science/article/pii/S1364032110003382

[19] A. Stranix, A. Firester, Conceptual Design Of A 50 Mw Central Station Photovoltaic Power Plant, IEEE Trans. Power Appar. Syst. PAS-102 (9) (1983) 3218–3225. doi:10.1109/TPAS.1983.318132.
URL http://ieeexplore.ieee.org

[20] E. Simburger, R. Fling, Engineering Design for a Central Station Photovoltaic Power Plant, IEEE Trans. Power Appar. Syst. PAS-102 (6) (1983) 1668–1677. doi:10.1109/TPAS.1983.317904.
URL http://ieeexplore.ieee.org

[21] K. Papastergiou, P. Bakas, A. Marinopoulos, Overview of Alternative System Configurations for Very Large Scale PV Power Plants, 27th Eur. Photovolt. Sol. Energy Conf. Exhib. (2012) 3805–3810doi:10.4229/27thEUPVSEC2012-5CO.8.1.
URL http://www.eupvsec-proceedings.com

[22] M. Ito, K. Kato, K. Komoto, T. Kichimi, K. Kurokawa, A comparative study on cost and life-cycle analysis for 100MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules, Prog. Photovoltaics Res. Appl. 16 (1) (2008) 17–30. doi:10.1002/pip.770.
URL http://doi.wiley.com/10.1002/pip.770

[23] D. Gallo, R. Langella, A. Testa, J. C. Hernandez, I. Papic, B. Blazic, J. Meyer, Case studies on large PV plants: Harmonic distortion, unbalance and their effects, in: 2013 IEEE Power Energy Soc. Gen. Meet., IEEE, 2013, pp. 1–5. doi:10.1109/PESMG.2013.6672271.
URL http://ieeexplore.ieee.org

[24] A. Marinopoulos, F. Papandrea, M. Reza, S. Norrga, F. Spertino, R. Napoli, Grid integration aspects of large solar PV installations: LVRT capability and reactive power/voltage support requirements, in: 2011 IEEE Trondheim PowerTech, IEEE, 2011, pp. 1–8. doi:10.1109/PTC.2011.6019324.
URL http://ieeexplore.ieee.org

[25] M. Morjaria, D. Anichkov, V. Chadliev, S. Soni, A Grid-Friendly Plant: The Role of Utility-Scale Photovoltaic Plants in Grid Stability and Reliability, IEEE Power Energy Mag. 12 (3) (2014) 87–95. doi:10.1109/MPE.2014.2302221.
URL http://ieeexplore.ieee.org

[26] A. Hoke, D. Maksimovic, Active power control of photovoltaic power systems, in: 2013 1st IEEE Conf. Technol. Sustain., IEEE, 2013, pp. 70–77. doi:10.1109/SusTech.2013.6617300.
URL http://ieeexplore.ieee.org

[27] E. Bullich-Massagué, M. Aragüès-Peñalba, L. Serrano, P. Carlos, R. Ferrer-San-José, O. Gomis, Power Plant Control Experience in Large Scale PV Plant . Modelling, Control, Simulation and Implementation., in: 4th Sol. Integr. Work. 2014, Berlin, 2014.

[28] T. Markvart, Solar electricity, 2nd Edition, Wiley, Southampton, 2009.

[29] T. Markvart, Practical Handbook of Photovoltaics, Elsevier, 2012. doi:10.1016/B978-0-12-385934-1.00020-9.

[30] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, E. D. Dunlop, Solar cell efficiency tables (version 39), Prog. Photovoltaics Res. Appl. 20 (1) (2012) 12–20. doi:10.1002/pip.2163.
URL http://doi.wiley.com/10.1002/pip.2163

[31] L. Stolt, J. Hedstrom, J. Kessler, M. Ruckh, K.-O. Velthaus, H.-W. Schock, ZnO/CdS/CuInSe2 thin-film solar cells with improved performance, Appl. Phys. Lett. 62 (6) (1993) 597. doi:10.1063/1.108867.
URL http://scitation.aip.org

[32] V. Tyagi, N. A. Rahim, N. Rahim, J. A. Selvaraj, Progress in solar PV technology: Research and achievement, Renew. Sustain. Energy Rev. 20 (2013) 443–461. doi:10.1016/j.rser.2012.09.028.

URL http://www.sciencedirect.com/science/article/pii/S1364032112005291

[33] M. Z. Rahman, Advances in surface passivation and emitter optimization techniques of c-Si solar cells, Renew. Sustain. Energy Rev. 30 (2014) 734–742. doi:10.1016/j.rser.2013.11.025.
URL http://www.sciencedirect.com/science/article/pii/S1364032113007740

[34] A. Metz, D. Adler, S. Bagus, H. Blanke, M. Bothar, E. Brouwer, S. Dauwe, K. Dressler, R. Droessler, T. Droste, M. Fiedler, Y. Gassenbauer, T. Grahl, N. Hermert, W. Kuzminski, A. Lachowicz, T. Lauinger, N. Lenck, M. Manole, M. Martini, R. Messmer, C. Meyer, J. Moschner, K. Ramspeck, P. Roth, R. Schönfelder, B. Schum, J. Sticksel, K. Vaas, M. Volk, K. Wangemann, Industrial high performance crystalline silicon solar cells and modules based on rear surface passivation technology, Sol. Energy Mater. Sol. Cells 120 (2014) 417–425. doi:10.1016/j.solmat.2013.06.025.
URL http://www.sciencedirect.com/science/article/pii/S0927024813003103

[35] W. Hoffmann, T. Pellkofer, Thin films in photovoltaics: Technologies and perspectives, Thin Solid Films 520 (12) (2012) 4094–4100. doi:10.1016/j.tsf.2011.04.146.
URL http://www.sciencedirect.com/science/article/pii/S0040609011009874

[36] M. Hussin, S. Shaari, A. Omar, Z. Zain, Amorphous silicon thin-film: Behaviour of light-induced degradation, Renew. Sustain. Energy Rev. 43 (2015) 388–402. doi:10.1016/j.rser.2014.10.093.
URL http://www.sciencedirect.com/science/article/pii/S1364032114009186

[37] C. Candelise, J. F. Speirs, R. J. Gross, Materials availability for thin film (TF) PV technologies development: A real concern?, Renew. Sustain. En-

ergy Rev. 15 (9) (2011) 4972–4981. doi:10.1016/j.rser.2011.06.012.
URL http://www.sciencedirect.com/science/article/pii/S136403211100298X

[38] T. Hoff, J. Iannucci, Maximizing the benefits derived from PV plants: Selecting the best plant design and plant location, in: IEEE Conf. Photovolt. Spec., IEEE, 1990, pp. 892–897. doi:10.1109/PVSC.1990.111749.
URL http://ieeexplore.ieee.org

[39] S. Yilmaz, H. R. Ozcalik, S. Kesler, F. Dincer, B. Yelmen, The analysis of different PV power systems for the determination of optimal PV panels and system installationA case study in Kahramanmaras, Turkey, Renew. Sustain. Energy Rev. 52 (2015) 1015–1024. doi:10.1016/j.rser.2015.07.146.
URL http://www.sciencedirect.com/science/article/pii/S1364032115007935

[40] IRENA, Renewable Energy technologies: cost analysis series (Solar Photovoltaics), Tech. rep., IRENA (2012).
URL https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf

[41] J. Tao, S. Yu, Review on feasible recycling pathways and technologies of solar photovoltaic modules, Sol. Energy Mater. Sol. Cells 141 (2015) 108–124. doi:10.1016/j.solmat.2015.05.005.
URL http://www.sciencedirect.com/science/article/pii/S092702481500210X

[42] S. Kjaer, J. Pedersen, F. Blaabjerg, A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules, IEEE Trans. Ind. Appl. 41 (5) (2005) 1292–1306. doi:10.1109/TIA.2005.853371.
URL http://ieeexplore.ieee.org

[43] M. S. Agamy, M. Harfman-Todorovic, A. Elasser, R. L. Steigerwald, J. A. Sabate, S. Chi, A. J. McCann, L. Zhang, F. Mueller, A high efficiency

DC-DC converter topology suitable for distributed large commercial and utility scale PV systems, in: 2012 15th Int. Power Electron. Motion Control Conf., IEEE, 2012, pp. LS2d.3–1–LS2d.3–6. doi:10.1109/EPEPEMC.2012.6397420.
URL http://ieeexplore.ieee.org

[44] M. Taghvaee, M. Radzi, S. Moosavain, H. Hizam, M. Hamiruce Marhaban, A current and future study on non-isolated DCDC converters for photovoltaic applications, Renew. Sustain. Energy Rev. 17 (2013) 216–227. doi:10.1016/j.rser.2012.09.023.
URL http://www.sciencedirect.com

[45] W. Li, X. He, Review of Nonisolated High-Step-Up DC/DC Converters in Photovoltaic Grid-Connected Applications, IEEE Trans. Ind. Electron. 58 (4) (2011) 1239–1250. doi:10.1109/TIE.2010.2049715.
URL http://ieeexplore.ieee.org

[46] M. Ciobotaru, V. G. Agelidis, Large-scale PV system based on the multiphase isolated DC/DC converter, in: 2012 3rd IEEE Int. Symp. Power Electron. Distrib. Gener. Syst., IEEE, 2012, pp. 801–807. doi:10.1109/PEDG.2012.6254093.
URL http://ieeexplore.ieee.org

[47] M. Rashid, Power electronics handbook., 2001.

[48] J. Rodriguez, L. Franquelo, S. Kouro, J. Leon, R. Portillo, M. Prats, M. Perez, Multilevel Converters: An Enabling Technology for High-Power Applications, Proc. IEEE 97 (11) (2009) 1786–1817. doi:10.1109/JPROC.2009.2030235.
URL http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=5290111

[49] S. Rivera, S. Kouro, B. Wu, J. I. Leon, J. Rodriguez, L. G. Franquelo, Cascaded H-bridge multilevel converter multistring topology for large scale

photovoltaic systems, in: 2011 IEEE Int. Symp. Ind. Electron., IEEE, 2011, pp. 1837–1844. doi:10.1109/ISIE.2011.5984437.
URL http://ieeexplore.ieee.org

[50] S. Kouro, K. Asfaw, R. Goldman, R. Snow, B. Wu, J. Rodriguez, NPC multilevel multistring topology for large scale grid connected photovoltaic systems, in: 2nd Int. Symp. Power Electron. Distrib. Gener. Syst., IEEE, 2010, pp. 400–405. doi:10.1109/PEDG.2010.5545744.
URL http://ieeexplore.ieee.org/

[51] S. Ozdemir, N. Altin, I. Sefa, Single stage three level grid interactive MPPT inverter for PV systems, Energy Convers. Manag. 80 (2014) 561–572. doi:10.1016/j.enconman.2014.01.048.
URL http://www.sciencedirect.com

[52] O. Gomis-Bellmunt, L. Serrano-Salamanca, R. Ferrer-San-José, C. Pacheco-Navas, M. Aragüés-Peñalba, E. Bullich-Massagué, Power plant control in large-scale photovoltaic plants: design, implementation and validation in a 9.4 MW photovoltaic plant, IET Renew. Power Gener.doi:10.1049/iet-rpg.2015.0113.
URL http://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2015.0113

[53] R. Shah, N. Mithulananthan, R. Bansal, V. Ramachandaramurthy, A review of key power system stability challenges for large-scale PV integration, Renew. Sustain. Energy Rev. 41 (2015) 1423–1436. doi:10.1016/j.rser.2014.09.027.
URL http://www.sciencedirect.com/science/article/pii/S1364032114008004

[54] S. Testa, A. De Caro, T. Scimone, Sizing of step-up transformers for PV plants through a Probabilistic Approach.
URL http://www.wseas.org

[55] B. Engel, G. Bettenwort, V. Sakschewski, O. Glitza, T. Fawzy, D. Premm, How to Represent PV Plants in Grid Integration Studies - A Generic Approach, 26th Eur. Photovolt. Sol. Energy Conf. Exhib. (2011) 3862–3868doi:10.4229/26thEUPVSEC2011-5AO.4.2.

[56] D. A. Trevas, A. Peterson, K. J. Rapp, J. Luksich, Optimal sizing of solar energy transformers using natural ester fluid, in: 2012 11th Int. Conf. Environ. Electr. Eng., IEEE, 2012, pp. 1006–1010. doi:10.1109/EEEIC.2012.6221525.
URL http://ieeexplore.ieee.org

[57] Transformers for Solar Power Solutions.
URL http://www.energy.siemens.com

[58] DunHuang China Solar Power, Gansu Dunhuang 50MWp Solar PV Power Station Project, Tech. rep., China (2006).
URL http://cdm.unfccc.int/Projects/DB/TECO1348832160.15/view

[59] Requirements for Medium-Voltage Transformers and Transformers for Internal Power Supply for the SUNNY CENTRAL Series CP XT and CP-JP and for Sunny Central Storage.
URL http://files.sma.de/dl/7356/SC_Trafo-TI-en-51.pdf

[60] Application paper tripple linx inverter for large rooftop.
URL http://www.danfoss.com

[61] A. Testa, S. De Caro, R. La Torre, T. Scimone, Optimal size selection of step-up transformers in PV plants, in: XIX Int. Conf. Electr. Mach. - ICEM 2010, IEEE, 2010, pp. 1–6. doi:10.1109/ICELMACH.2010.5607819.
URL http://ieeexplore.ieee.org

[62] B. Hafez, H. S. Krishnamoorthy, P. Enjeti, U. Borup, S. Ahmed, Medium voltage AC collection grid for large scale photovoltaic plants based on medium frequency transformers, in: 2014 IEEE Energy Convers. Congr.

Expo., IEEE, 2014, pp. 5304–5311. doi:10.1109/ECCE.2014.6954128.
URL http://ieeexplore.ieee.org

[63] M. Meinhardt, G. Cramer, B. Burger, P. Zacharias, Multi-string-converter with reduced specific costs and enhanced functionality, Sol. Energy 69 (2001) 217–227. doi:10.1016/S0038-092X(01)00067-6.
URL http://www.sciencedirect.com

[64] M. Ciobotaru, V. G. Agelidis, High gain DC/DC converter for the grid integration of large-scale PV systems, in: 2012 IEEE Int. Symp. Ind. Electron., IEEE, 2012, pp. 1011–1016. doi:10.1109/ISIE.2012.6237227.
URL http://ieeexplore.ieee.org

[65] M. Díez-Mediavilla, M. Dieste-Velasco, M. Rodríguez-Amigo, T. García-Calderón, C. Alonso-Tristán, Performance of grid-tied PV facilities based on real data in Spain: Central inverter versus string system, Energy Convers. Manag. 86 (2014) 1128–1133. doi:10.1016/j.enconman.2014.06.087.
URL http://www.sciencedirect.com

[66] M. Brenna, R. Faranda, S. Leva, Dynamic analysis of a new network topology for high power grid connected PV systems, in: IEEE PES Gen. Meet., IEEE, 2010, pp. 1–7. doi:10.1109/PES.2010.5589768.
URL http://ieeexplore.ieee.org

[67] S. Brenna, Morris and Dolara, Alberto and Foiadelli, Federica and Lazaroiu, George C. and Leva, Transient Analysis of Large Scale PV systems with Floating DC section, Energies 5 (10) (2012) 3736–3752.
URL http://econpapers.repec.org/RePEc:gam:jeners:v:5:y:2012:i:10:p:3736-3752:d:20344

[68] G. Cramer, M. Ibrahim, W. Kleinkauf, PV system technologies, Refocus 5 (1) (2004) 38–42. doi:10.1016/S1471-0846(04)00076-9.
URL http://www.sciencedirect.com

[69] B. Lave, H. Grau, U. Borup, String Inverters for PV Power Plants, 24th Eur. Photovolt. Sol. Energy Conf. 21-25 Sept. 2009, Hamburg, Ger. (2009) 4173–4175doi:10.4229/24thEUPVSEC2009-5BV.2.44.
URL http://www.eupvsec-proceedings.com/proceedings?paper=4618

[70] PV power plants 2014. Industry guide.
URL http://www.pv-power-plants.com/

[71] E. Karatepe, T. Hiyama, Performance enhancement of photovoltaic array through string and central based MPPT system under non-uniform irradiance conditions, Energy Convers. Manag. 62 (2012) 131–140. doi:10.1016/j.enconman.2012.03.028.
URL http://www.sciencedirect.com

[72] A. Woyte, J. Nijs, R. Belmans, Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results, Sol. Energy 74 (3) (2003) 217–233. doi:10.1016/S0038-092X(03)00155-5.
URL http://www.sciencedirect.com

[73] M. Pau, N. Locci, C. Muscas, A tool to define the position and the number of irradiance sensors in large PV plants, in: 2014 IEEE Int. Energy Conf., IEEE, 2014, pp. 374–379. doi:10.1109/ENERGYCON.2014.6850454.
URL http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=6850454

[74] P. Guerriero, V. D'Alessandro, L. Petrazzuoli, G. Vallone, S. Daliento, Effective real-time performance monitoring and diagnostics of individual panels in PV plants, in: 2013 Int. Conf. Clean Electr. Power, IEEE, 2013, pp. 14–19. doi:10.1109/ICCEP.2013.6586958.
URL http://ieeexplore.ieee.org/articleDetails.jsp?arnumber=6586958

[75] Danfoss, Danfoss FLX String Inverters for PV power Plants, Tech. rep.,

Danfoss, Denmark (2014).
URL http://www.danfoss.com

[76] Danfoss, String inverters for PV power plants, Tech. rep., Danfoss, Denmark (2009).
URL http://www.danfoss.com

[77] A. Elis, Y. Kazachkov, et al., IEC TF88-WG27-Oct 2009 Wind Modeling Update, Tech. rep. (2009).
URL https://www.wecc.biz