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Review

A comprehensive review of future photovoltaic systems

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ABSTRACT

This paper presents a comprehensive review of photovoltaic (PV) systems with more focus on PV inverters. At this stage, there is no consensus that this technology will play a major role or will be the first choice for energy generation in the future because of many reasons, the most important of which is its lack of efficiency. Different materials are used and other materials are expected to be used for developing PV cells, modules and power electronic devices in order to increase their efficiency and lifetime, and to reduce their costs. Future power electronic devices are expected to have reduced chip thickness, more specific converter topologies, better control of types of materials, improved nanotechnology, and inbuilt current bi-directionality. Different aspects will be discussed in this paper related to PV inverters including power electronic materials, topologies, grid codes, storage systems, and others.

1. Introduction

In recent years the world has seen a marked growth in photovoltaic (PV) generation (Fraunhofer ISE). PV generation is currently significant in many regions and it is expected to continue its exponential growth and to play a major role to meet renewable energy targets as set up by local authorities, national governments and international agreements to meet CO_2 reductions. Inverters have a major function in PV systems since they both optimise the power generated from solar panels via their inbuilt controller, and efficiently transform the electrical power to the necessary format for injecting into the grid supply. PV inverters are divided into three types according to their power rating. The highest power type is the centralised inverter. A PV array is made of several PV strings with modules connected in series. These can be connected to a centralised inverter which provides three phase power to the grid. At a much lower power level of a few kW, inverters are known as string inverters, since they are supplied by a single string of PV panels (or sometimes two or more strings). The string inverter output can be three-phase or single-phase depending upon its power level. The third inverter type is the micro inverter. The micro inverter is connected to a single PV panel, and provides a single phase output power.

This paper discusses available to date PV systems, with particular reference to inverters, and moves on to discuss the future of PV materials and PV inverters, summarising the factors that will influence future designs such grid codes and storage systems.

2. The future of PV technology

There is no general consensus on the future of PV technology as there are obstacles to its implementation. Non-technical barriers include factors like long lived fossil power plants, unfavourable pricing rules, supply of raw materials, land availability and geographical constraints (Bosetti et al., 2012). In Raugei and Frankl (2009), the authors listed four factors that must be considered to draft possible future cost and environmental performance scenarios for PV technology. These factors are cost reduction, increase of efficiency, integration into buildings and energy storage technologies. Other factors (Frankl et al., 2006a) are the maturity of each technology in terms of its degree of industrialization and module manufacturing cost, energy pay-back time, and additional issues related to “Balance of System” (BOS) costs.

Because of these obstacles, there is no general consensus on the future of PV technology. Frankl et al. (2006a) drafted three long term road maps for the future development of PV technology up to 2050.

- “Very Optimistic/Technological Breakthrough” scenario: the growth of world PV technology will increase in a quadratic fashion to reach almost 9000 GW by 2050. This implies that by the middle of the 2030 s several energy storage systems (e.g. Hydrogen Gas, pumped hydroelectric, compressed air energy storage and efficient high-speed flywheel systems) and the infrastructure required to enable the storage of mass PV energy in these storage systems will be developed. The scenario is dominated by the expected expansion of PV systems following development of new technologies and materials post 2025. These technologies and materials are expected to

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constitute approximately 50% of the total PV market by 2050. To ensure PV moves from a limited share (3% of world electricity generation in 2025) to a major energy source provider in 2050, the PV sector will require the realization and diffusion of new PV materials and devices, and high increases in efficiency and lifetime for all PV technologies.

- "Optimistic" scenario: this scenario assumes that the predicted growth in the world PV market made by the European Photovoltaic Industry Association together with Greenpeace will be valid up to 2025 as mentioned in their latest Solar Generation Report (EPIA 2006), with the expected annual installed capacity reaching to 55 GW; crystalline Si, thin films and novel devices will likely co-exist all the way through, each expanding especially within its own most suitable market sector. After 2025 it is assumed that the growth rate of the PV market will be less, eventually leading to a linear trend whereby the cumulative installed capacity will grow steadily. In this scenario the global installed capacity will double each decade and reach 2400 GW by 2050.
- "Pessimistic" scenario: this scenario assumes that at best PV will provide approximately 13% (Fraunhofer ISE, 2015a) of total world electricity by 2050 (the estimated total energy in 2050 is 35,000 TWh per annum). In this scenario, novel technologies are postponed to a much later time, and by 2050 only a small percentage of novel technologies will take part in the total cumulative installed power and new devices will be used in limited applications.

Fig. 1 shows the expected growth of the world PV market according to the three scenarios discussed (Frankl et al., 2006a).

3. Technical influencing factors for new PV cell materials

3.1. Future PV cell materials

A PV cell is a semiconductor diode that can convert the energy from sunlight into direct current electricity. Individual PV cells produce low voltage of approximately 0.5 V, but at a high current of Approximately 3 A. A PV module comprises several PV cells connected in series. In addition, bypass diodes are used to connect some sections of the series in parallel to create some redundancy and additional electricity paths. The peak power of a commercial PV panel is around 50–360 W and in some cases reaches to 405 W (http://www.solardesigntool.com/components/module-panel-solar/Helios-Solar/1649/9T6-405/specification-data-sheet.html, a.N.).

Table 1
PV cell technical barriers.

Technology	Drawbacks to future use
Crystalline-silicon	Efficiency, materials
Thin-film	Efficiency, stability, toxicity, lifetime
Concentrating PV	Stability, complexity, high cost
Organic PV	Efficiency, stability, lifetime
Third Generation PV	Efficiency, proof of concept only

The different PV cell characteristics (efficiency, lifetime, I-V curve) depend on the material used. Each material or technology has drawbacks such as those shown in Table 1, some materials have serious drawbacks that put these materials out of competition for future of PV technology. Other materials will be used up to at least the middle of the 2030s. After 2030 it is predicted that there is a need for new materials to increase PV system efficiency and to reduce costs. Various high efficiency PV cells are now being developed such as PERC cells, N-type bifacial cells, IBC cells, HJT cells and TOPCON cells (Solar, 2016).

In Goetzberger et al. (2002) and Goetzberger and Hebling (2000), for the future of solar energy materials three scenarios are envisioned:

i. Mono-crystalline and multi-crystalline silicon is relatively mature but several studies have shown that it still has a high cost reduction potential; fifty percent of the cost of a silicon module is due to the cost of processed silicon wafers. A major new development that may occur is the low cost production of solar grade silicon.
ii. New crystalline film *Si* materials of medium thickness either as ribbons or on foreign substrates.
iii. A breakthrough may occur in the production of true thin film materials such as amorphous silicon (*a-Si)* or Copper Indium diSelenide (*CIS*) or Cadmium Telluride (*CdTe*).

The authors in Frankl et al. (2006b) state that to achieve the ambitious target of high PV market penetration and cost reduction, there is a need for significant PV module technology improvement. Other improvements in terms of "Balance of systems" (BOS), system reliability, maintenance and overall system performance are necessary as well. It is expected that the long-term future PV technology spectrum will be very different from that of today. At present crystalline silicon is the dominant PV cell material and will be used for many years to come. However for the longer term (2030 and beyond), its share in the PV market is will be likely progressively reduced. It is believed that several different

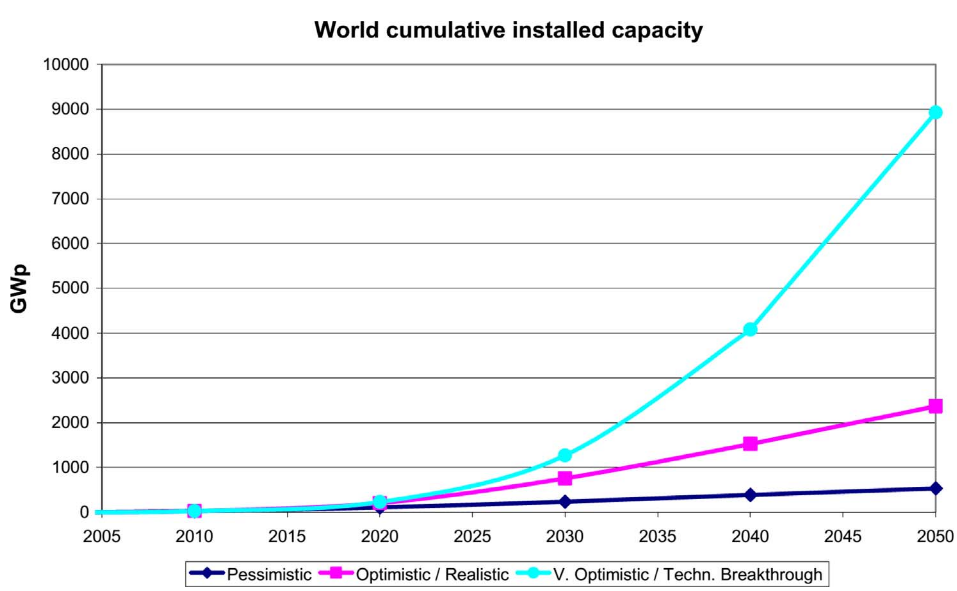

Fig. 1. World cumulative installed capacity according to the three scenarios (Frankl et al., 2006a).