Modern manufacturing technology for modular photovoltaic panels: State-of-the-art and future trends

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Abstract. The technological advancement of the recent years has triggered a significant increase in the global energy consumption. Within this frame, the fossil fuels still account for most of the energy consumption as the renewable energy systems often lack reliability and predictability in terms of total energy supply. These shortcomings may be overcome if various design and manufacturing process optimization methods are applied so as to gain more benefits from the current solar power systems. A modern modular photovoltaic (PV) panel is an assembly of photovoltaic cells mounted in an adaptable framework for quick installation. The photo-voltaic cells use sunlight as source of energy and generate current electricity, which can be harvested directly or through an existing grid. A collection of PV modules can be arranged in any desirable manner to form a PV panel. Also, the implementation of such modern modular systems brings numerous advantages, including the reduction of power transmission cost and the minimization of the global warming problems. This work presents the latest findings related to the manufacturing technology and the equipment train used in the production of modern photovoltaic systems.

1. Introduction
The demand for electricity supply for commercial, domestic and industrial purposes is increasing due to the infrastructural development and the economic expansion. Nowadays, the electricity requirement is higher than the quantity the utility companies can generate and thus, the service delivery is, in many cases, unreliable [1]. It is well known that supplying reliable energy to costumers is, generally, associated with increasing the living standards of education, micro-economy and healthcare. Unfortunately, this rising energy demand is mainly provided by burning fossil fuels such as coal, natural gas, oil and bituminous rocks. In addition, the discovery of conventional energy resources is getting very rare and the energy supplies of organic origin slightly grow around the world [2]. The intemperate use of organic origin energy involves higher rates of gas emissions such as nitrogen dioxide, carbon dioxide and methane in the air that negatively influence the greenhouse effect [3]. In time, the exploitation of these non-renewable resources may unavoidably lead to their total consumption, which might further raise an energy crisis [4]. According to the latest energy policies, the alternative energy sources should be considered as a responsibility for both industries and governments with respect to the protection of the environment. Recent studies have established that the new cost-effective energy strategies may lower the electricity use by 27% to 75%, within 10-20 years, without threatening the manufacturing output or the quality of life [5]. An eloquent example of alternative energy source is the solar energy. The energy harvested from the solar radiation can be
used to heat buildings (through passive solar hot water systems), to produce hot water (through solar hot water systems) and to satisfy the electricity demand (through photovoltaics - PV systems). For instance, when compared to fossil fuel-generated electricity, each kilowatt of PV electricity offsets 9 kilograms of sulphur dioxides, up to 16 kilograms of nitrogen oxides and 2300 kilograms of carbon dioxide (CO2) annually [6].

The term photovoltaics derives from the Greek word ϕώς meaning light and the word volt, named after the Italian physicist Alessandro Volta (1745-1827). Photovoltaics is the science that deals with the light-electricity conversion, namely the photon energy-electric current conversion. In other words, it stands for light-current conversion. First use of the word photovoltaic was mentioned in the book “Elements of Electro-biology, Or the Voltaic Mechanism of Man of Electro-pathology, Especially of the Nervous System and of Electro-therapeutics” written by Alfred Smee (1818-1877) in 1849 [7]. The Photovoltaic solar systems typically contain several panels (wired together in an array), an overcurrent protection (circuit breakers or fuses), several electrical disconnects, a junction box, an inverter and other specialized equipment depending on the type of application (off-grid, grid-tied, battery-backup). The outdoor performance of a PV panel depends on the availability of the incoming solar radiation and on the panel junction temperature. The challenging part consists in ensuring a satisfactory efficiency of the absorption process (of the radiant energy) in case of unwanted natural elements [8].

This work presents the fabrication steps of a modern photovoltaic panel, the latest findings related to the manufacturing technology and the equipment train that are used in the production of modern photovoltaic systems.

2. Photovoltaic panels

A solar photovoltaic panel (figure 1) is composed of glass, solar cells, back sheet and ethylene vinyl acetate (EVA), all mounted within a frame. On the market there are three categories of solar panels available: thin film, monocrystalline and polycrystalline photovoltaic panels. At the level of the cell structure, various materials can be identified, such as amorphous silicon, mono silicon or polysilicon [9].

Figure 1. Solar photovoltaic panel [10].
3. Materials and manufacturing process
Sand is the main raw material used in the manufacturing of solar panels. Most photovoltaic panels are made of silicon, which is the primary component in sand. The latter is plentifully available, being the second accessible element on Earth [11]. Nonetheless, transforming sand into silicon is achieved at a higher cost and it is an energy demanding process. High-purity silicon is created from quartz sand at high temperatures in an arc furnace. The silicon is amassed, usually as solid rocks. The rocks are melted together at high temperatures with the purpose of forming cylinder shaped ingots. In the melting process, all atoms are aligned in the orientation and structure needed. In order to obtain positive electrical polarity, boron is included in the process.

Mono crystalline cells (figure 2) are synthesized from a single silicon crystal. The latter has better capability in transforming solar energy into electricity, yet the monocrystalline panels are more expensive.

![Figure 2. A mono crystalline silicon photovoltaic wafer [12].](image)

Polysilicon cells are created by melting various silicon crystals together. The distinct silicon crystals give a shattered glass look. Polishing and grinding are being done after cooling of the ingot, leaving them with flat sides. Next, the wafers are fabricated by slicing the silicon ingot into thin disks. A wire saw is used for precision cuttings so the final wafer thinness is comparable to that of a paper. Afterwards, due to silicon shining property, an anti-reflective coating is placed on the wafer to reduce the volume of sunlight lost.

The next step in the manufacturing process consists in adding conductors on each wafer’s surface. The conductors will ensure the conversion of solar energy and grants the wafer’s surface a grid-like matrix. The coating ensures the absorption of sunlight, instead of reflecting it. In an oven-like chamber, over the wafers’ surface, phosphorous is being dispersed in a thin layer. This process will electrically charge the surface negatively. A paramount condition for the proper function of the photovoltaic cell is the positive-negative junction, which is produced by the combination between phosphorous and boron. The photovoltaic cells are joined together into a matrix-like structure with the use of metal connectors. The available arrangements that can be found on the market include: 48 cell
panels - convenient for small residential roofs, 60 cell panels – standard size, 72 cell panels – adopted for sizable installations [13]. Thereafter the cells are inserted together and a 6-7 mm thick layer of glass placed on the front side, opposing the sun.

The back sheet is manufactured from polymer-based, highly durable material. Thence the penetration of soil particles, water and other materials on the back of the panel will be prevented. Recently the junction box has been installed in order to implement connections for the module. The frame also provides protection against weather and accidental impacts. Furthermore, using a frame will allow for various ways of mounting the panel. Ethylene Vinyl Acetate (EVA) is the glue that connects everything together. The encapsulation must be performed at the highest quality control in order to prevent any possible damaging of the cells under severe weather conditions.

4. Photovoltaic panel testing and quality control
As soon as the module is completed, tests are performed to ensure the photovoltaic cells operate as expected. Standard Test Conditions (STC) are applied as a reference point. The photovoltaic panel is inserted in a flash tester. The tester will produce a 25°C cell temperature, an air mass of 1.5g and 1000W/m² equivalent irradiance [14]. The electrical parameters are determined and the results are written down on the technical specification sheet for every photovoltaic panel. This test will reveal the efficiency, power output, current, voltage and temperature tolerance of the product. Besides the STC, nominal operating cell temperature (NOCT) test is performed. The specifications used are close to real life scenarios:
- operation temperature of the open-circuit module is at 800W/m² irradiance,
- 1m/s wind speed,
- 20°C cell ambient temperature.

The NOCT ratings are specified on the technical data sheet. Inspection and cleaning are the final steps of the manufacturing before the module is available for selling.

5. Photovoltaic panels manufacturing evolution
Commercial manufacturing of crystalline silicon modules began in 1963 in Japan when Sharp Corporation patented the photovoltaic module [15]. The latter is a 242 W photovoltaic module that was installed on a lighthouse, the biggest commercial photovoltaic installation in the world at that time. It has been noticed that the quantity of photovoltaic modules produced in Japan increased significantly between 1997 and 2004 [16]. After 2004, the production capacity reduced drastically. The same tendency was observed in photovoltaic module manufacture in Europe up to 2008, after that the production volume has decreased.

In 1997, the photovoltaic module manufacturing capacity of the US was at its best, then the production capacity has been reduced every year. Insomuch as the photovoltaic modules fabrication in China was just the opposite compared to US. The worldwide production of photovoltaic modules has accelerated over last few years due to the far-reaching potential, with China taking the supremacy in total manufacture volume [17].

Germany and other European countries promoted the global cumulative photovoltaic installation up to 70% until 2011 [18]. Therefore, till now, the photovoltaic installation market has been very promising in Europe compared to other continents. More than 85% of the solar cell manufacture depends on crystalline silicon, based on the scenario that was commonly agreed by the European countries in 2011 [19].

6. Advantages and disadvantages of modern manufacturing technologies
Monocrystalline silicon cells photovoltaic panels are one of the first types of solar panels that were accessible on the market [20]. They are used both for industrial and home applications. The benefits of adopting this technology consist in:
- use of high-quality silicon;
- high-performance rates of 20%;
- convenient use of roof space;
- more solar power collected in a battery bank;
- longer warranties (up to 25 years) [21];
- harvest more solar energy per square foot.

On the other hand, the shortcomings of using monocrystalline silicon cells technology are:
- expensive production cost;
- circuit breakdown can occur at times when the solar panels are shaded;
- significant waste amounts results during manufacturing [22];
- potential damage over time due to high temperatures (they perform at their top only in warm weather conditions).

When it comes to economic benefits, polycrystalline silicon solar panels are recommended [23]. They have a speckled look, which is very different from a monocrystalline silicon module because of the molten silicon used in the manufacturing process. Therefore, these types of photovoltaic panels are cheaper [24] than the monocrystalline silicon solar panels. The advantages using this technology are:
- less expensive;
- easy and quick installation;
- easy to acquire;
- few fossil fuels are required in the manufacturing process;
- the modules perform reasonably well, in various weather conditions, in comparison with other crystalline photovoltaic panels [25].
- the polycrystalline silicon modules can be used both with batteries and inverter technology.

However, the disadvantages of this technology include:
- harvest less solar power;
- more space requirement on the roof;
- potential durability issues;
- easily damaged when exposed to high temperatures.

Thin-film solar panels are manufactured with second-generation solar cells technology, also made from silicon. These types of photovoltaic panels are less expensive than monocrystalline solar cell panels and they can be easily manufactured. This class of solar cells are convenient for a solar array, but they acquire more energy during manufacture, thus, more burning of fossil fuels [26]. The main advantages of using thin-film photovoltaic panels are:
- flexible;
- lightweight;
- high temperatures does not affect the performance over time;
- they can be integrated in any part of the façades or on the roof;
- uncomplicated manufacture process.

More than that, this class of photovoltaic panels work in low light environment and are an affordable substitute to monocrystalline solar panels. On the other hand, thin-film photovoltaic modules have limited efficiency between 7 and 13% [27] and the power output is low. More than that, they are not ideal for residential use because of a lot of space occupation and they have short warranty and life span.

Another way of thin-film solar panel manufacturing is using amorphous silicon. The latter use triple layered technology which improves the performance and strengthens the photovoltaic panel [28]. Amorphous solar panels are relatively new technology and their energy efficiency is still at the research level. However, they are frequently used to produce biohybrid solar cells panels that emulate the natural part of photosynthesis [29] and possess the thin-film panels’ advantages.

The multi-junction photovoltaic cells may achieve an efficiency rating of up to 41% [30]. Nevertheless, they also use a lot of advanced technology and materials, including curved mirror surfaces, cooling systems, and lenses. Even though concentrated solar photovoltaic modules are more efficient, the manufacturing cost is higher.
7. Future trends in photovoltaic panel manufacturing

Development and research in the solar energy field focus on increasing the efficiency of the photovoltaic panels and the reduction of the production cost [31]. The photovoltaic panel fabrication industry is developing more convenient alternatives than traditional sources of energy, for instance fossil fuels. The early supremacy of silicon in the research programs has nowadays spread out to the wholesale of commercial modules. If there is to eliminate electronics and characterize the market as electricity distribution system of 1 kW or more, current manufacturing is monopolized by polycrystalline and single-crystal silicon modules that serve up to 94% of the demand [32]. There is a vast range of distinct photovoltaic cells on the market using various types of materials and an even preponderant number will be developed in the near future.

Photovoltaic cell technologies are categorized into three generations, according to the commercial debut and component materials. First-generation photovoltaic systems are fully commercial and they use wafer-based crystalline silicon (c-Si) high tech, either multicrystalline (mc-Si) or single crystalline (sc-Si). The second-generation photovoltaic systems (early market distribution) are based on thin-film photovoltaic technologies and include three main categories: micromorph silicon (a-Si/g2020c-Si)/amorphous (a-Si), cadmium telluride (CdTe) and copper indium-gallium diselenide (CIGS)/copper indium selenide (CIS). The third-generation photovoltaic systems include organic photovoltaic cells (figure 3).

![Figure 3. Organic photovoltaic cells [33].](image)

8. New photovoltaic products

After more than two decades of research and development, thin-film solar cells (figure 4) are starting to be promoted and developed in significant quantities. The high potential of thin-film solar cells to supply lower cost electricity compared to the crystalline silicon wafer-based photovoltaic cells is already acknowledged. Thin-film photovoltaic cells comprised subsequent thin layers, 1 μm to 4 μm thick, of photovoltaic cells arranged onto an inexpensive, large substrate such as polymer, glass or metal. As a result, a substantially less semiconductor material is required for absorbing the same quantity of sunlight (approximately 99% less material when compared with crystalline solar cells) [34]. Further, thin films can be encased into lightweight and flexible structures, which can be conveniently integrated into the components of a building (building-integrated photovoltaic, BIPV).
Figure 4. Thin-film solar cells [35].

9. Conclusions
Photovoltaic technology is to become a considerable supplier of electricity in the 21st century due to its affordable cost (cheaper than fossil fuels) and lower environmental impact. One of the most promoted applications of photovoltaic panels consists in various arrangements installed on roofs and facades. Therefore, the PV modules may be considered as a building material in itself. However, even if it is designed as a regular construction material, the manufacturing process of PV panels should be addressed according to the newest technology advancements and quality control techniques. From this point of view, in this work, the manufacturing technology and the equipment train used for modern photovoltaic systems have been described and discussed.

In the final part of this paper, several future trends in PV manufacturing and development were pointed out. Overall, the future of photovoltaics continues to be one of intense development and research where thin films will overcome crystalline silicon in efficiency and cost. Also, it is expected that the role of PV in the generation of electricity will come up with other forms of renewable energy and that half of all new buildings will include PV in their design.

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