Renewable and Sustainable Energy Reviews 74 (2017) 590–601

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Photovoltaic solar energy: Conceptual framework

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ARTICLE INFO

Keywords:
Photovoltaic solar energy
Systematic literature research

ABSTRACT

The purpose of this article is to understand the state of art of photovoltaic solar energy through a systematic literature research, in which the following themes are approached: ways of obtaining the energy, its advantages and disadvantages, applications, current market, costs and technologies according to what has been approached in the scientific researches published until 2016. For this research, we performed a qualitative and quantitative approach with a non-probabilistic sample size, obtaining 142 articles published since 1996–2016 with a slitting cut. The analysis result of this research shows that studies about photovoltaic energy are rising and may perform an important role in reaching a high-energy demand around the world. To increase the participation of photovoltaic energy in the renewable energy market requires, first, to raise awareness regarding its benefits; to increase the research and development of new technologies; to implement public policies a programs that will encourage photovoltaic energy generation. Although crystal silicon solar cells were predominant, other types of cells have been developed, which can compete, both in terms of cost reduction of production, or in terms of greater efficiency. The main applications are dominated by telecommunications, water pumping, public lighting, BIPV, agriculture, water heating, grain drying, water desalination, space vehicles and satellites. The studies found on photovoltaic solar energy are all technical, thus creating the need for future research related to the economic viability, chain supply coordination, analysis of barriers and incentives to photovoltaic solar energy and deeper studies about the factors that influence the position of such technologies in the market.

1. Introduction

With the increase of population and technologic and economic development, human beings need more energy to create a better life environment. However, burning traditional fossil fuels is causing a series of environmental problems, such as climate change, global warming, air pollution and acid rain [1–3].

Therefore, there is an urgent need for the development of renewable energy Technologies, in order to deal with the political, economic and environmental challenges that are involved in generate electricity. The appearance of such energies in the last years has largely propelled the interest among investigators, politics and industry leaders in understanding the economic viability of the new energy source [2,4].

Capturing solar energy through photovoltaic panels, in order to produce electricity is considered one of the most promising markets in the field of renewable energy. Due to its fast growth perspective and high levels of investment involved, the photovoltaic market is now being more disputed around the world, especially in Europe, China and in the United States. In Brazil, the advances are starting to be significant, especially after the insertion of solar energy in Brazil's energy matrix, and the beginning of solar energy auctions at a time in which the energy sector is facing difficulties due to the reduction of hydroelectric energy, which is currently Brazil's main energy matrix, and the increase in electricity prices.

Research on photovoltaic solar energy has increased in recent years, as has the number of publications in journals. Based on what has been exposed, this study aims to answer the following question: "How does photovoltaic solar energy has been approached in scientific studies published between 1996 until 2016?" For such, we performed a systematic literature research followed by a structured of the contents published on photovoltaic solar energy.

Besides the ongoing introduction, the article is structured from a division dedicated to showing the research method adopted in the study. Posteriorly, we will expose the classification of the articles, followed by the analysis of the themes (definition, mean of obtaining, advantages, disadvantages, applications, current state in the market, costs and technologies) discussed in the analyzed pieces, at last, in the final section we have the conclusion regarding the theme and a suggestions for possible future studies.

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http://dx.doi.org/10.1016/j.rser.2017.02.081
Received 17 June 2016; Received in revised form 31 December 2016; Accepted 22 February 2017
Available online 02 March 2017
1364-0321/

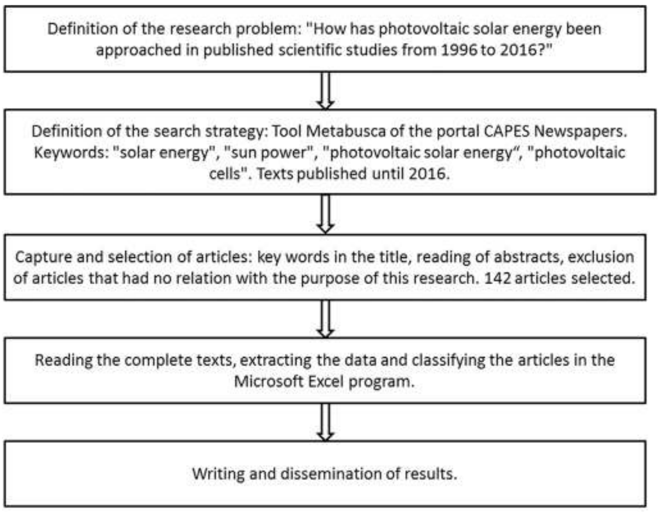

Fig. 1. Stages the research.

2. Research method

This research can be characterized, regarding its object, as a systematic literature research. In [5] a systematic literature research is defined as a trustworthy research approach, due to fact that it is broad and explicitly presents the utilized means and obtained results. Corroborating with this idea [6] register that systematic literature review has the goal of generating structure knowledge about a research theme.

The research was conducted in five stages. Fig. 1.

During the first stage, we defined the problem of our research as: “How does photovoltaic solar energy has been approached in scientific studies published between 1996 until 2016?”. From that definition, we then went to the second stage, which was consisted of finding articles through the Metasearch of CAPES (Brazil's Higher Education Coordination of Personnel Perfecting) Periodicals portal through the utilization of the following keywords: “solar energy”, “sun power”, “photovoltaic solar energy” “photovoltaic cells”. No filters were used to limit the period of years of the research, which was made among all the texts published until 2016.

In the third stage was made the capture of the articles that contained in their title these key words. Then the selection of the articles was done from the reading of the abstracts. During the development of this stage, articles that had no relationship with the objective of this research were excluded. In this way, 142 articles were selected. In the fourth stage of the research the texts were read and extracted, as well as their classification in terms of structure and content through the elaboration of a spreadsheet database in the Microsoft Excel program. In the fifth stage, the results were drafted for subsequent publication.

3. Classification of the analyzed articles

The study research included the reading of 142 articles, which were published in a time interval between 1996 and 2016. The year with the largest number of publications was 2014, with 26 items. In second place, with 15 publications, it was the year 2011.

As regards to the Journals of the publications, out of the 142 articles, the most important one was the Renewable and Sustainable Energy Reviews, with about 22% of publications followed by Solar Energy, Solar Energy Materials & Solar Cells, Energy Policy and Renewable Energy which together add up to 35% of the publications. On the issue of countries with more publications on the key words of this research, the prevalence was the United States, with 26 publications, China (15) and Germany (14). Other countries such as Japan, Italy, Spain, Denmark, South Korea, Belgium, Croatia, Belgium, Lithuania, Scotland, Greece, UAE, Singapore, Spain, Australia, Australia, Brazil, India, Poland, Switzerland, Sweden, Thailand, Poland, Australia, Pakistan, Israel, Morocco, Mexico, Malaysia, Chile, Turkey, United Kingdom and Taiwan, Norway got together 87 published texts.

Table 1
Classification of the type of research.

Type research	Amount	Type research	Amount
CS	23	S	2
EX	38	LR-EX	2
AR	1	LR-S	1
LR	75		

CS: Case Study; EX: Experimental; AR: Action Research; LR: Literature Review; S: Survey.

When classifying the texts, we took into account 5 items, which are: type of study, approach, goals, object and focus of the research. As to the type of study that was used in the articles, the literature review was predominant, with 75 texts, followed by the experimental study with 31, as seen in Table 1.

The majority of the articles were classified, according to the approach, as being qualitative, with 59% of the total amount, being followed by the qualitative and quantitative (31%) and quantitative (10%). As for the goals, the exploratory and exploratory-descriptive classifications prevailed with 75 and 58 texts, respectively, followed by the explanatory classification (5), descriptive (3) and exploratory-descriptive (1).

When analyzing the focus of the research, we could see that the theoretical focus obtained a rate of 87%. As for the theoretical-industrial focus, as well as the industrial focus had a rate of 6% of the texts, followed by the domestic focus, research center and theoretical-domestic focus (3%, 3% and 1%, respectively).

When it comes to the object, 84 analyzed articles were characterized as literature research. Next, we have the texts classified as laboratory research (34), field research (20), literature and field research (3) and literature and laboratory research (1).

Among the 142 articles read in this study, 74 served as basis for item 4. Photovoltaic solar energy.

4. Photovoltaic solar energy

The photovoltaic solar energy (PV) is one of the most growing industries all over the world, and in order to keep that pace, new developments has been rising when it comes to material use, energy consumption to manufacture these materials, device design, production technologies, as well as new concepts to enhance the global efficiency of the cells [7–9]. The understanding of photovoltaic solar energy from the point of view of the authors consulted in the first stage of this research is presented in Table 2.

It can be observed that the definitions presented by the authors on photovoltaic solar energy have terms in common, being them: “electricity”, “solar radiation”, “direct generation”, “conversion”. Thus, we can adopt as a concept of photovoltaic solar energy the following definition: electricity obtained directly from the conversion of solar energy.

The conversion of solar radiation into electricity occurs due to the photovoltaic effect, which was observed by the first time by Becquerel in 1839 [8,9,17–23]. This effect occurs in materials known as semiconductors, which present two energy bands, in one of them the presence of electrons is allowed (valence bad) and in the other there is no presence of them, i.e., the band in completely “empty” (conduction band), see Fig. 2. The semiconductor material more commonly used is the silicon, second most abundant element on Earth. Its atoms are

Table 2
Definition of solar photovoltaics.

Author	Definition of solar PV
[10]	It is the direct conversion of sunlight into electricity.
[11]	Energy based on semiconductor technology that converts sunlight into electricity.
[12]	It is the most elegant method to produce electricity by converting abundant sunlight.
[13]	Energy that converts sunlight into electricity by means of a single junction LED (or several junctions).
[14]	Direct generation of electricity from sunlight.
[15]	Renewable source of energy by converting solar light into electricity.
[1]	Energy that generates electricity from solar energy.
[3]	Direct conversion of radiation into electricity.
[16]	Energy source that converts light directly into electricity without gas emissions or noise.
[17]	It is the direct conversion system that converts sunlight into electricity without the help of machines or mobile devices.

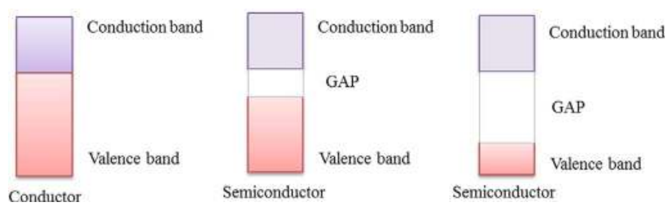

Fig. 2. Band of valence, band gap (GAP) and the conduction band: insulator, conductor and semiconductor.

characterized by having four electrons that connect to its neighbors, creating a crystal network.

The function of sunlight on the photovoltaic effect is to supply an amount of energy to the outermost electron to make it possible for him to move from the valence band to the conduction band in the material, thereby generating electricity. As [14] in the case of silicon, specifically, it is needed 1.12 eV (electro volts) for electrons to exceed the GAP. Further, according to [19], the semiconductor material must be able to absorb a large part of the solar spectrum.

Virtually all photovoltaic devices incorporate a PN junction in a semiconductor, which through a photo voltage is developed. These devices are also known as solar cells or photovoltaic cells [19]. A typical solar cell is shown in Fig. 3. The PN junction is the main part of the cell where the light receiving portion is the N-type material in the part below this the material is P-type.

The main advantages and disadvantages of photovoltaic solar energy are described in Table 3.

Compared to conventional power generation sources, such as those using fossil fuels, photovoltaic technology does not bring the serious environmental problems that these sources cause during generation, such as climate change, global warming, air pollution, acid rain and so on. Another advantage in relation to fossil fuels is that solar energy

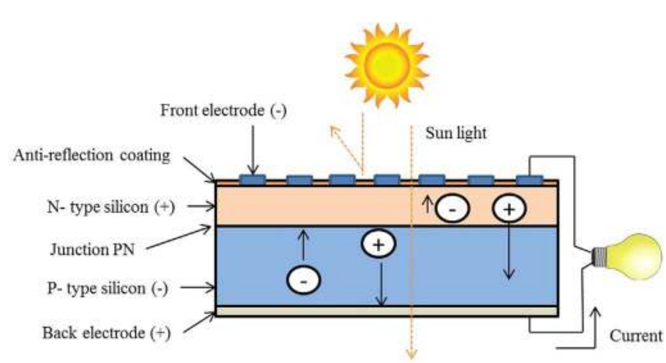

Fig. 3. Photovoltaic cell.

Table 3
Advantages and disadvantages of solar photovoltaics.

		Authors
Advantages	Reliable system	[15,24]
	Low cost of operation and maintenance	[15–17,23]
	Low maintenance	[23,24]
	Free energy source	[15,17]
	Clean Energy	[1,2,4,15,17,24–26]
	High Availability	[2,15,24]
	The generation can be made closer to the consumer	[15]
	Does not cause environmental impacts /Environmental friendly	[1,17,23,26]
	Potential to mitigate emissions of greenhouse gases	[1,17]
	Noiseless	[16,17]
Disadvantages	Limitations in the availability of systems on the market	[15]
	High initial cost	[15,16,20,23,25]
	Needs a relatively large area of installation	[15]
	High dependence on technology development	[16]
	Geographical conditions (solar irradiation)	[16]

does not need to be extracted, refined or transported to the generation site, which is close to the load. However, during its life cycle, it consumes a large amount of energy and emits some greenhouse gases in some stages (manufacturing process of solar cells, assembly of photovoltaic modules and transport of material, among others) [5,9,17,27].

Photovoltaic technologies, consume per unit of electricity produced, 64 times more material resources, 7 times more human resources and 10 times more capital than nuclear technology. Although this data is biased, this is a clear indication of the extreme inefficiency of PV technologies in regions of moderate sunshine to help achieve the goal of providing a resource-efficient, efficient electricity supply system. Due to the intermittent nature of electricity production in these regions, parallel electricity supply infrastructure needs to be provided [28].

In relation to other renewable sources, photovoltaic solar energy presents a lower incidence of damages to the environment where it is being generated, which does not occur with the energy produced by the hydroelectric plants, where for the construction of hydroelectric plants the course of the river is changed and extensive areas of production of food and forests are flooded. Another important factor is the cost of operation, which for hydraulic power generation is high compared to the cost of operating a solar plant. Despite the decrease in generation during cloudy days, energy from the sun is abundant, while the volume of water in the dams during periods of drought is limited. If compared to wind energy, photovoltaic solar energy is silent and can be generated in urban areas since panels can be installed on the roof.

Despite its limitations, the photovoltaic power generation systems allow the installation of a short-term power plant, with the possibility to generate several MW in less than a year. As the environmental impacts, they are minimal, photovoltaic systems remove the need for preliminary studies that require long-term assessment, unlike the highly polluting systems [15].

Using photovoltaic solar energy is used in both spatial and Earth applications, as seen in Table 4.

The large-scale photovoltaic application occurs through photovoltaic plants installed in both water and land. To conserve valuable land and water, installing solar photovoltaic systems in water bodies such as oceans, lakes, reservoirs, irrigation ponds, wastewater treatment plants, wineries, fish farms, dams and canals may be an option attractive. Floating type photovoltaic solar panels have numerous advantages compared to grounded solar panels, including fewer

Table 4
Applications of solar photovoltaics.

Applications	Description	Authors
Spacecraft	Photovoltaic energy is converted into electrical energy to be applied in on-board equipment of the spacecraft. The main technology used in this application are gallium arsenide cells which, despite having a high cost compared to silicon cells, shows good efficiency	[8,17,22,29,30].
Water pumping	Water pumping of wells and rivers used in farms for irrigation of plantations, for livestock and for domestic consumption	[8,17,22,29–33].
Lighting street	Used to illuminate parking spaces, signage and other outdoor areas. Photovoltaic panels are usually mounted in the lighting structure or integrated in the pole itself and carry a rechargeable battery, which powers the lamps. For installation there is no need to open ditches, wiring and similar preparations needed for traditional lighting systems	[22,29–32].
Building integrated photovoltaic systems (BIPV)	It is a set of photovoltaic systems and technologies that are integrated into the building, forming part of its external covering like roofs and facades. Are considered as a functional part of the building structure, being architecturally integrated into the building design. Simultaneously serving as building envelope material and power generator	[8,16,29,30,33,34].
Telecommunications	It is used in the generation of electricity in isolated telecommunication stations for the operation of equipment such as communication radios, radio communication devices, telemetry stations, public telephones, PLCs and video cameras. Provides reliability and low maintenance level	[8,17,29–32].
Water desalination	Desalination (transformation of seawater into drinking water) is done using batteries charged during the day with photovoltaic panels	[8,32].
Satellites	Solar panels used in satellites are composed of solar cells located on the outer parts of satellites that can be attached to the satellite body or open and oriented to the Sun. Three-junction solar cells are currently used in series (called a triple junction) With germanium base. Because of their location they are able to receive even more photons than the panels installed on Earth and produce even more energy to keep the electrical equipment on the satellite running.	[8,17]
Weather monitoring	The solar panel provides the energy required to power all measuring equipment, weather sensors, processing and communication	[29,30].

obstacles to block sunlight, convenient energy efficiency, and higher power generation efficiency due to their lower temperature under panels. In addition, the solar installation brings benefits to the aquatic environment because shading of the plant prevents excessive evaporation of water, limits algae growth and potentially improves water quality [35].

The installation of photovoltaic plants in the desert may be one of the most suitable places for the use of photovoltaic solar energy due to the high levels of solar radiation. In the Atacama desert in Chile, for example, it is a viable option capable of contributing to the continued supply of sustainable electricity in the north of the country, contributing to the stabilization of electricity prices, thus benefiting the Chilean mining industry [36,37].

4.1. Elements of the photovoltaic solar energy system

A typical photovoltaic solar system consists of four basic elements: Photovoltaic module, charge controller, the inverter and battery when necessary (Fig. 4).

The photovoltaic module consists of photovoltaic cells, i.e., the surfaces that generate electricity, which convert directly solar energy into electricity. These surfaces have no moving parts to wear out or suffer breakdowns and works without the use of fuel without vibrations without noise and without harming the environment [15–17,24].

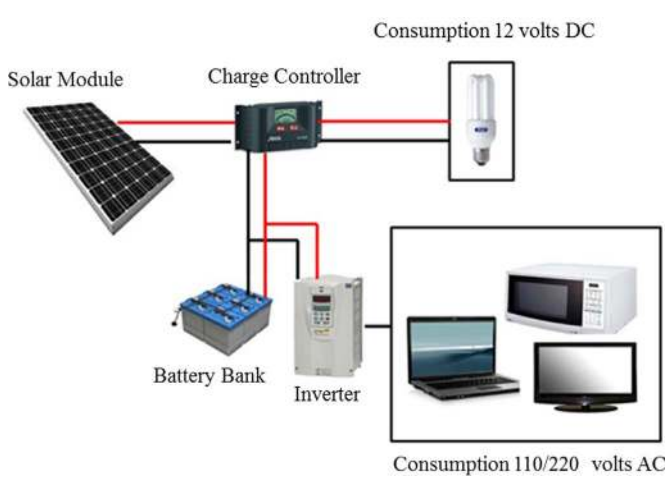

Fig. 4. Typical System of photovoltaic solar energy.

As for the charge controller, it has the function to preserve the batteries from being overcharged or discharged completely, increasing its useful life. The inverter, in turn, is responsible for converting the power generated by photovoltaic panels (electricity generating DC – DC) to alternating current – AC voltage levels and network frequency. Batteries are used in photovoltaic systems to store the surplus produced by the modules to be utilized at night or on days with low sunshine or overcast [15,17].

4.2. Photovoltaic technologies

According to [38,39], there is a wide variety of photovoltaic cell technologies in the marketplace today, using different types of materials, and an even larger number will be available in the future. Photovoltaic cell technologies are generally categorized into three generations, depending on the raw material used and the level of commercial maturity.

- First generation Photovoltaic systems (fully commercial) that use the technology of crystalline silicon (*c*-Si) both in its simple crystalline form (sc-Si) as well as in the multicrystalline form (mc-Si).
- Second generation photovoltaic systems are based on thin film photovoltaic technologies and generally include three main families: (1) Amorphous silicon (*a*-Si) and micro amorphous silicon (a-Si /μc-Si); (2) cadmium telluride (CdTe); and (3) copper indium selenide (CIS) and copper, indium gallium dieseline (CIGS).
- Third generation photovoltaic systems include organic photovoltaics technologies that are still in demonstration or have not been widely marketed and new concepts in development.

There are some requirements for a solar cell material to be considered ideal: bandgap between 1.1 and 1.7 eV, because the smaller the gap, the easier it is to promote an electron from one band to the other and thereby increase the conduction of this material; consisting of readily available materials, non-toxic; easy fabrication technique, suitable for large production volumes; good photovoltaic conversion efficiency; long-term stability. A material fulfilling all the requirements has not yet been found [18,19,40].

4.2.1. Silicon cells

Silicon is the most popular material in commercial solar cell modules, accounting for about 90% of the photovoltaic cell market. This success is due to several beneficial characteristics of silicon: (1) is abundant, being the second most abundant element on Earth; (2) is generally stable and non-toxic; (3) bandgap of 1.12 eV, almost ideally adapted to the terrestrial solar spectrum, that is, the silicon is sensitized within the range of electromagnetic spectrum emitted by the sun; And (4) silicon photovoltaic cells are readily compatible with the silicon-based microelectronics (transistor and integrated circuits manufacturing) industry [14,17,38].

The monocrystalline (*m*-Si), polycrystalline (p-Si, also referred to as multicrystalline, mc-Si) cells are cells under the aegis of crystalline silicon structures [24,41]. Cells from a single silicon crystal are cultured by the Czochralski process [19,22]. These cells have excellent conversion efficiency, however, they have high manufacturing costs, higher energy requirements during their life cycle, longer energy return time, and require the use of very pure materials (solar grade silicon) and with the perfect crystal structure [1,3,19,22,23,39,42].

The efforts of the photovoltaic industry to reduce costs and increase the rate of production led to the development of new crystallization techniques. In this way the cells based on multicrystals appeared. Such technology is becoming more attractive because the cost of production is lower, even though these cells are somewhat less efficient than monocrystalline cells [23]. In addition to lower manufacturing costs, polycrystalline cells offer other advantages compared to monocrystalline cells, such as: better aesthetic appearance, less energy consumed during its life cycle, shorter energy return time, lower Greenhouse effect, requires less energy in its manufacture, the crystal structure does not have to be perfect [1,3,19,22,23,39,42].

Silicon cells are not restricted only to cells based on the crystal structure. There are also silicon nanowire cells (SiNWs), which are under intense investigation for photovoltaic applications, as they can allow a new way of converting solar to electric energy with high efficiency and low cost. This attractiveness is attributed to its original geometric characteristics [14].

Firstly, SiNW solar cells exhibit better optical absorption of the solar spectrum, ie in comparison to other traditional technologies, it requires less silicon to obtain the same amount of absorption. The energy losses that occur when light passes through a photovoltaic cell without being absorbed is smaller in silicon nanowire cells. Second, SiNW solar cells allow the use of silicon of inferior quality to solar grade silicon. Thirdly, SiNWs can be produced with excellent electrical characteristics. These advantages can substantially reduce the cost of production of SiNW-based solar cells by keeping these cells competitive [14].

4.2.2. Thin film cells

In the search for cost reduction, the need for research on thin film solar cells has arisen. Thin-film solar cells require much less material from the semiconductor to be manufactured in order to absorb the same amount of sunlight, up to 99% less material than crystalline solar cells [39]. The use of this technology has increased in recent years due to its high flexibility, easy installation, diffuse light efficiency of approximately 12% and a service life of 25 years [16]. The main approaches are based on amorphous silicon cells (a-Si); Microamorphic silicon (a-Si /μc-Si); Cadmium telluride (CdTe); Copper indium selenide (CIS) and copper, indium and gallium-diselenide (CIGS).

The manufacturing methods are similar to those used in the production of flat panel monitors for computer monitors, cell phones and televisions. A thin photoactive film is deposited on a substrate, which may be either glass or a transparent film. Then the film is structured into cells. Unlike crystalline modules, thin film modules are manufactured in one step. Thin film systems generally cost less to be produced than crystalline silicon systems, but have substantially lower efficiency rates. On average, thin film cells convert from 5% to 13% of solar radiation into electricity, compared to 11–20% for crystalline silicon cells. However, since thin films are relatively new, they may offer greater opportunities for technological improvement [39].

The first amorphous silicon (a-Si) publications relevant to the manufacture of solar cells appeared after the 1960s. The first amorphous silicon solar cell was reported by Carlson in 1976. In the market the same arose in 1981. The high expectation In this material was contained by the relatively low efficiency obtained so far and by the initial degradation induced by light [17,18,43].

This technology diverges from crystalline silicon in the fact that the silicon atoms are located at random with each other. This randomness in the atomic structure has an important effect on the electronic properties of the material, causing a larger gap (1.7 eV) while that of crystalline silicon is 1.1 eV [23].

Another configuration is the microamorph silicon cells, which combine two different types of silicon, amorphous and microcrystalline, one on top of the other in a single device, where the upper layer consists of an ultra thin layer of a-Si, which converts The shorter wavelengths of the visible solar spectrum and the lower layer have the microcrystalline silicon which is most effective in converting the longer wavelengths. This results in higher efficiency gains of about 8–9% more than amorphous silicon cells depending on the cell structure and the thickness of the layers [23,44].

One of the most promising approaches to manufacturing low cost and high efficiency involves the use of cadmium telluride. The CdTe has been known to have the ideal gap (1.45 eV) with a high coefficient of absorption of the solar spectrum being one of the most promising photovoltaic materials for thin film cells. However, the toxicity of cadmium (Cd) and environmental issues related to the use of this material pose a problem for this technology. Therefore, First Solar, one of the world's largest manufacturers of photovoltaic solar modules, has launched a recycling program for deactivated PV cells, extremely popular in the field of thin films because of the efficiency of its process, which has the capacity to reduce the Cost of production to make the cost of this technology more competitive. The other potential problem is the availability of Te, which can lead to scarcity of raw materials, thus affecting the cost of the modules [17,23,43–46].

Copper and indium diselenide ($CuInSe_2$) or indium copper selenide (CIS), as is sometimes known, and copper-indium-gallium selenide (CIGS) are photovoltaic devices containing semiconductor elements of groups I, III and VI of the periodic table which are Beneficial because of their high optical absorption coefficients and their electrical characteristics that allow the adjustment of the device [17,23,44]. Some of the major challenges of these technologies have been limited ability to expand the process of high yield and low cost, degradation under wet conditions, as it promotes changes in the properties of the material and the shortage of Indian in nature [23,42,47].

4.2.3. Organic photovoltaic cells

Organic photovoltaic cells offer the long-term potential of achieving the goal of a PV technology that is economically viable for large-scale power generation [3], since organic semiconductors are a less expensive alternative to Than inorganic semiconductors, such as silicon. In addition, organic molecules can be processed by simpler techniques that are not suitable for crystalline inorganic semiconductors [21,48].

Almost all organic solar cells have a flat layered structure, wherein the light absorbing layer is sandwiched between two different electrodes. One of the electrodes has to be (semi) transparent, the indium tin oxide (ITO) is normally used, however a thin layer of metal can also be used. Calcium, magnesium, gold and aluminum can also be used as electrodes, the latter being the most used [21,48].

Organic solar cells are constructed from thin films (typically 100 nm) of organic semiconductors, such as polymers. They are composed of small molecules such as pentacene, polyphenylene vinylene, copper phthalocyanine (a blue or green organic pigment) and carbon-based nanostructures (fullerenes, nanotubes, graphene). This type of cell is largely made of plastic, contrary to traditional silicon, the manufacturing process is less expensive, since it uses low cost material and high production throughput, and presents limited technical challenges, ie no Requires high temperature or vacuum conditions [23,48].

Organic photovoltaic cells have characteristics that make them very attractive, among them the potential to be flexible and semitransparent, potential to be manufactured in a continuous printing process, wide area of coating, easy integration in different devices, significant cost reduction in comparison With traditional solutions, ecological and economic advantages. These characteristics allow a significant reduction in installation costs, accounting for up to 70% of the total cost of traditional photovoltaic systems. However, organic photovoltaic cells have limited durability, they are not yet capable of converting sunlight into electricity, with the same efficiency as silicon cells (the low efficiency is due to the low absorption of incident sunlight due to the organic cells presenting A large energy gap. Most semiconductor polymers have a power gap greater than 2.0 eV (620 nm), which limits the absorption of solar photons around 30% [3,9,20,49].

Research on organic solar cells aims to increase the conversion efficiency of solar energy, since the total energy output of a solar cell is equal to the product of its efficiency and lifetime. Therefore, the stability, directly related to the life time, is an important property for this type of cell, since it impacts the value (yield on the cost) of an energy production system based on this technology [50].

Over the past few years, many aspects of organic solar cells have been extensively studied, including the synthesis and application of new materials, physical process modeling, large-scale manufacturing, improved stability, and so on [50]. However, the research and development of organic solar cells still have a long way to go to compete with inorganic solar cells [48].

As with carbon nanotubes and fullerenes, graphene is a type of nanostructured material that has been considered highly promising in many applications due to its excellent electronic, optical, thermal and mechanical properties. Among the various possible applications graphene can be used in the manufacture of carbon-based organic photovoltaic cells [51–57].

Initially derived from graphite graphene is an artificially modified material to have unique properties that are not normally found in nature. Graphene is extremely strong, lightweight, flexible, great conductor of electricity, almost totally transparent and has been considered the biggest revolution in metamaterials research in the last five years. Its developers received the Nobel Prize for Physics in 2010, and high funding has been directed to experimental research based on graphene in recent years. In 2012, graphene was one of two award-winning projects Future and Emerging Technologies Flagship Initiative, a multi-billion dollar competition organized by the European Commission as part of an innovative research funding program. This grant (which was the largest financial incentive - € 1 billion - for a single research project in the history of modern science) is expected to lead to an exponential growth in the amount of research on graphene in the near future [57,58].

4.2.4. Dye-sensitized solar cells

The first dye sensitized solar cell (DSSC) were proposed in 1991 by Michael Grätzel and Brian O'Regan. These cells belong to the group of hybrid solar cells, since they are formed by organic and inorganic materials [18,59]. DSSCs have been extensively studied to minimize problems related to efficiency, cost of production and environmental issues [3,9,49,59].

The main difference of this type of cell compared to conventional solar cells is that the functional element which is responsible for the absorption of light (the dye) is separated from the transport mechanism of the charge carriers. Thus impure raw materials and simple cell processing are allowed, which reduces the cost of the device. However, promising efficiencies on the order of 7–11% can be obtained. An important feature of DSSCs is stability over time [18,60]. DSSCs utilize low-cost titanium dioxide (TiO_2) in their manufacture compared to silicon that is used in conventional solar cells [59].

To date, DSSCs based on organometallic dyes such as ruthenium and porphyrins (zinc complexes) have shown excellent conversion efficiency from solar to electric. However, large-scale application of them is limited due to practical issues. For example, the difficulty of synthesis and purification of ruthenium and porphyrins and, especially, the issues of ruthenium limited availability [49].

Semiconductors in the class of perovskite organometallic trialkyls ($(CH_3NH_3)PbX_3$, at where X may be iodo, bromo or chloro) can be used as light collecting components in dye-sensitized solar cells giving rise to perovskite solar cells. Because they are very thin these cells are highly flexible and transparent [61]. The conversion of solar energy through organometallic perovskite has recently emerged as arguably the most promising of all thin-film solar cell technologies. Efficiency of energy conversion reached 20% in less than 5 years [62].

Many efforts have been devoted to the development of metal-free organic dyes. Among them are: squaraine, coumarin, indoline, phenothiazine, triphenylamine, fluorene, thienopyrazine, carbazole and tetrahydroquinoline [59].

4.2.5. Compounds III–V

In the field of nanotechnology applied to the development of solar cells, in addition to the carbon-based nanostructures and the polymeric materials, there are also compounds III-V. Cells based on these compounds, such as GaAs, InP (indium phosphide) and GaSb (gallium antimonide) have direct bandgaps of energy, ie they emit only light as a way to release the energy absorbed at the passage of the electron Of the band of valence for the conduction band, present high coefficients of optical absorption, high cost of production, better resistance to irradiation, better weight/power ratio in space applications [22,29,30].

4.3. Photovoltaic market

The photovoltaic market is a rapidly growing. During the period between 2000 and 2015 the growth rate of photovoltaic installations was of 41%. It is observed in Fig. 5 that China and Taiwan since 2006 have been increasing the photovoltaic industry with strong growth rates. At the end of 2015, its market share was about 71% of global sales.

The market for photovoltaic systems will likely continue to grow in the future as strongly as so far, due to the thrust of subsidies, tax breaks and other financial incentives [12,33,42]. Support for R & D and photovoltaic technology change are crucial aspects in accelerating the widespread adoption of photovoltaic systems. These two aspects play a key role in climate policy [63].

Some of the largest countries in Europe, such as Germany, Denmark and Spain, in addition to Asian countries China and Taiwan, have used feed-in tariff (FIT) which is a political mechanism to encourage consumers to invest in renewable microgeneration. On the other hand, the United States, United Kingdom, Japan and Sweden, have used the RPS (Renewable Portfolio Standard), which is a regulation that requires that part of the energy consumed comes from renewable sources. Meanwhile, South Korea has changed its plans for renewable energy technologies from a RPS setting to minimize the financial burden on the government [4,64].

Based on Fig. 6 Europe contributed 40% of total cumulative PV installations in 2015 (in 2014 it was 48%). The facilities in China and Taiwan accounted for 21% of total cumulative installations (in 2014 was 17%). In 2015, Germany accounted for about 16% (39.6 GWp) of

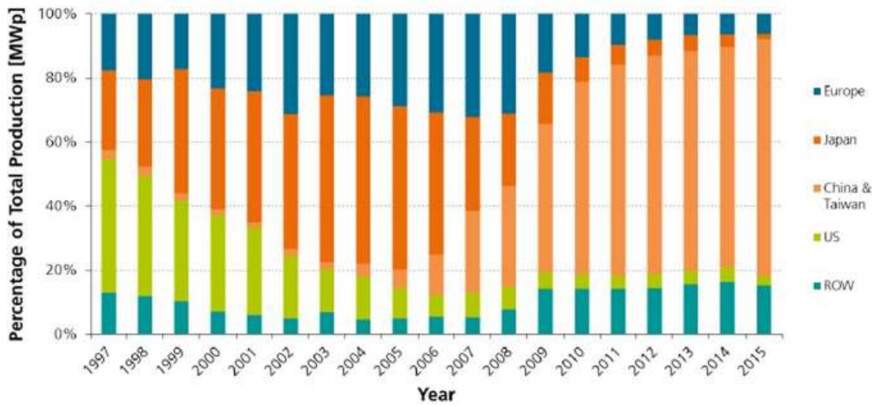

Fig. 5. Percentage of total production (MWp) over the years.
Source: Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE AG 2016.

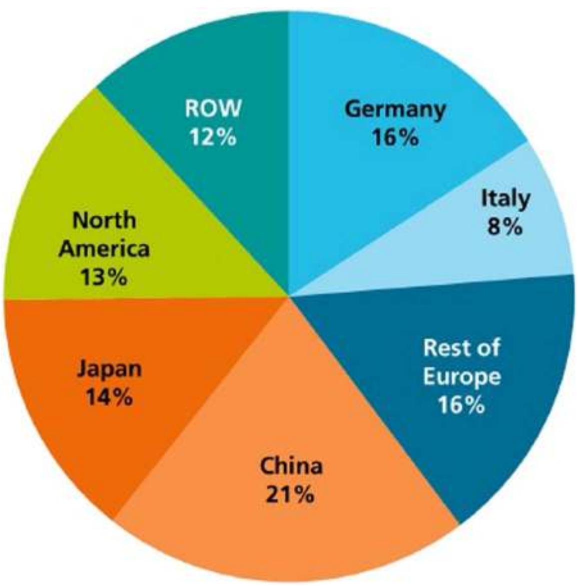

Fig. 6. Cumulative global photovoltaic installation by 2015.
Source: Data: EPIA (2000–2011); IHS and Photon (2012–2013). Graphic: PSE AG 2016.

cumulative installed PV capacity worldwide (242 GWp). In 2015, the newly installed capacity in Germany was about 1.4 GWP; in 2014 it was 1.9 GWp. In total, 1.5 million photovoltaic systems were installed in Germany.

The different rates of technological progress of photovoltaic technologies affect the dynamics of the market [38]. The photovoltaic technology based on crystalline silicon accounted for about 93% of the total production in 2015. The participation of multicrystalline silicon technology was about 69% of total production (Fig. 7).

Among the thin-film technologies in 2015, CdTe cells led with an annual output of 2.5 GWp. In 2015, the participation of all thin film technologies market amounted to about 7% of the total annual production (Fig. 8).

The lab cell efficiency record is of 25.6% to monocrystalline silicon and 21.3% to silicon multicrystalline based technology. The higher efficiency of thin film technology lab is 21% for CIGS and CdTe solar cells (Fig. 9).

In the laboratory, modules with better performance are based on monocrystalline silicon with an efficiency of almost 23% (Fig. 9).

Fig. 10 indicates that in the laboratory solar cells multi- junction high concentration reached a 46% efficiency today.

4.4. Conceptual framework

Despite the remarkable technological improvements achieved by PV technology, the research of the factors that directly influence the competitive position of each photovoltaic technology in the energy market is of considerable interest. In this regard, a conceptual model was elaborated, which consists of four main factors (Fig. 11).

Successful marketing can only be performed if aspects such as efficiency, cost, lifetime and sustainability are met simultaneously. Whether a cell type succeeds in only two ways, as, for example, competitive costs and a reasonable efficiency, will only make this cell address very specific niche markets unless other parameters are also optimized [11,20,42].

4.4.1. Efficiency

The solar cell efficiency depends on the temperature, solar irra-

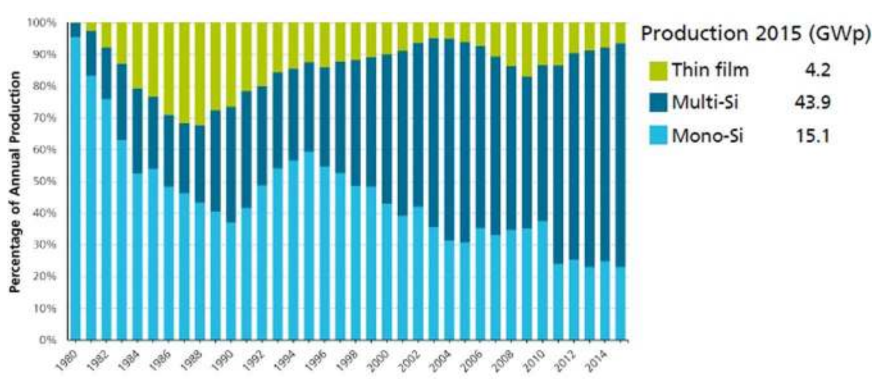

Fig. 7. Percentage of annual production of the main photovoltaic technologies.
Source: Data: Navigant Consulting (1980–2010); from 2011: HIS. Graphic: PSE AG 2016.

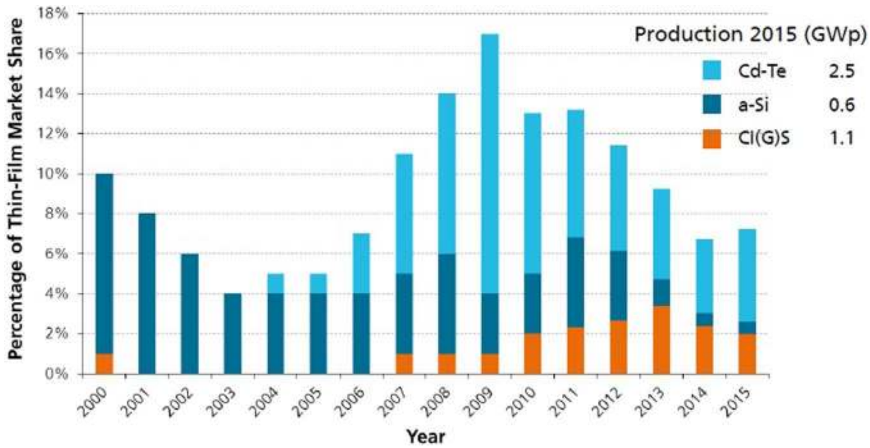

Fig. 8. Total annual output of the main thin film technologies.
Source: Data: Navigant Consulting (1980–2010); from 2011: HIS. Graphic: PSE AG 2016.

diance and dust. The temperature can affect cell performance drastically and, due to this fact, studies have focused on reducing the temperature by means of heat extraction and then utilizing it for other purposes, such as heating water or air heating. For the problem of dust, it is advisable that the PV surface is cleaned frequently to maintain the performance, since the accumulation of dust can block the irradiance on the photovoltaic modules. This block is not interesting, because the lower the irradiance is, the lowest cell efficiency are due to a reduced amount of photons that reach it [2,3,36,65,66].

4.4.2. Cost

The cost aspect of photovoltaic electricity is influenced by the location, i.e., less sunny locations require larger systems to generate the same amount of electricity that a smaller system in a sunny location can produce, and more distant places require larger transmission lines to connect the power produced to the grid. The type of technology used and the complexity of the system also influence the costs [3,33,42,67,68].

Thus, a strategy to reduce costs is to obtain economies of scale. This was evident with the development of crystalline silicon cells and is likely to be true for other technologies when their production volumes increase. In addition to economies of scale a combination of technological innovation, research in this field and improvement in learning are likely to reduce costs significantly This is shown by the learning curve of the PV modules in Fig. 12 [29,39,69,70].

It is observed that in the last 35 years, the module price decreased by about 19.1% at every duplication of cumulative production modules. Many scientists and engineers familiar with the variety of materials and PV technology concluded that photovoltaic materials of thin film and the third generation ones are the most likely candidates to continue the 80% price reduction [41].

4.4.3. Life time and ecological aspect

The lifetime aspect is related to degradation that the photovoltaic cells are subjected to. Degradation causes the reduction of its useful life and is characterized by loss of cell efficiency in converting sunlight into electricity. The long-term reliability of photovoltaic modules is needed to make photovoltaic technology a commercially viable option for power generation. The reliability of photovoltaic modules can be assessed by understanding the degradation phenomenon and degradation mechanism during outdoor operation. The main factors responsible for the degradation of photovoltaic cells are: solar radiation, humidity, temperature and dust [66,71].

Currently PV plant suppliers cite an operating lifetime of a 30 year PV installation, but the warranty for the material is usually limited to 5 years due to damaging events such as damage from improper installation or maintenance, hail, Snow and storm, etc. In Europe, modules that have failed during transportation, installation or operation are

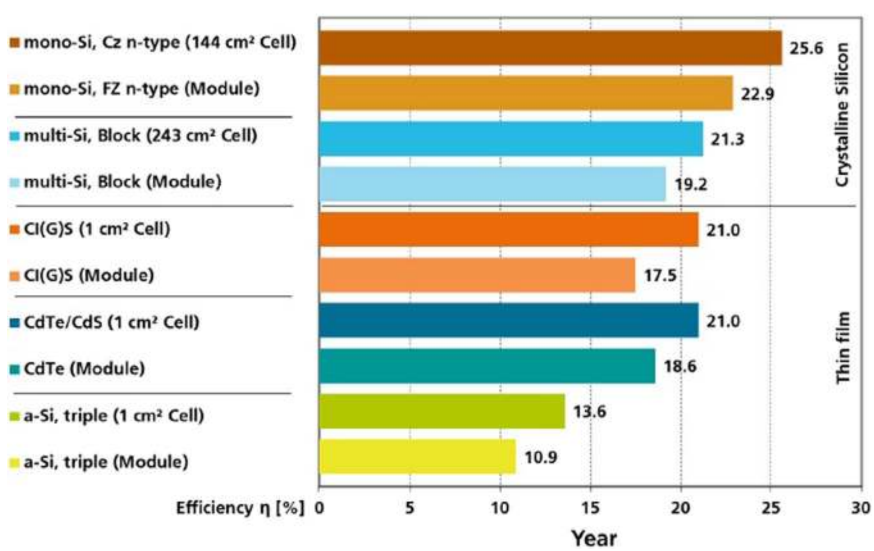

Fig. 9. Efficiency of cells.
Source: Data: Green et al.: Solar Cell Efficiency Tables (Version 47), Progress in PV: Research and Applications 2016. Graph: PSE AG 2016

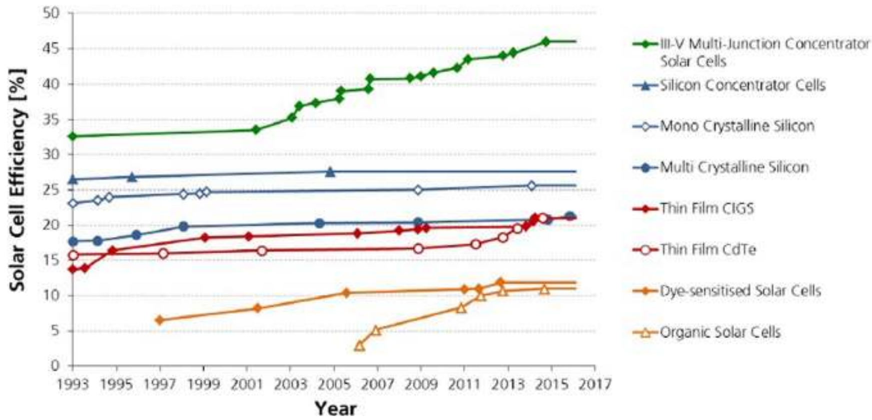

Fig. 10. Efficiency of solar cells.
Source: Data: Solar Cell Efficiency Tables (Versions 1–47), Progress in Photovoltaics: Research and Applications, 1993–2016. Graph: Simon Philipps, Fraunhofer ISE 2016

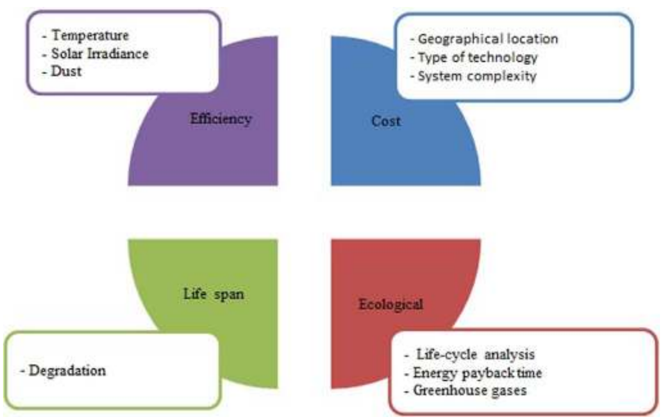

Fig. 11. Conceptual model of the aspects that influence the competitive position of photovoltaics in the energy market.
Source: Prepared by the authors.

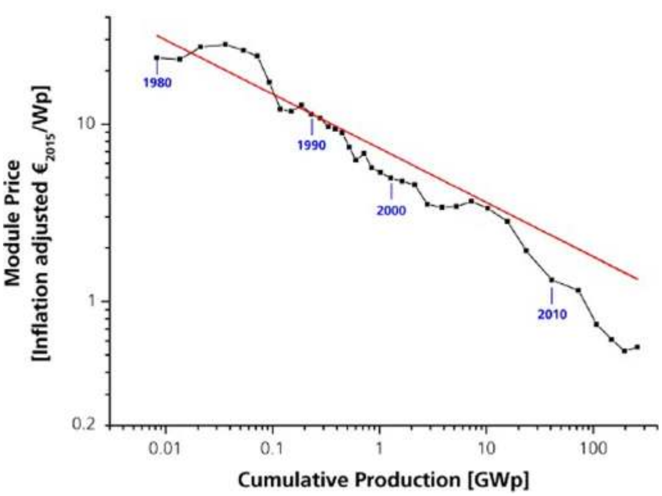

Fig. 12. Learning curve of the PV modules.
Source: Data: from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2015: IHS. Graph: PSE AG 2016.

collected for disposal by the European Association PV CYCLE. Across Europe, by the end of December 2015, 13,239 t of failed or depleted modules have been collected [72].

The environmental aspect is also an important criterion to be taken into account in determining the position of a technology in the market, since there are materials that are highly efficient, but have a great toxic potential such as arsenic used in the manufacture of GaAs cells (Gallium Arsenide) [34]. Studies on the generated waste suggest that it is possible that by 2035 the total number of photovoltaic panels will be about 3,000,000 t, of which about 800,000 t belong to CdTe technology and 45,000 t for CIGS technology [73].

Life cycle analysis (LCA) is a framework for considering the environmental inputs and outputs of a product or process from its inception to its disposal. The stages of the life cycle of PV systems involve (1) the production of raw materials, (2) the purification and processing, (3) the fabrication of modules, (4) the installation and use of the system, and (5) its decommissioning and disposal or recycling. LCA is used to assess the environmental impacts of energy technologies, and the results are increasingly used in decisions on the financing of R & D and the formulation of energy policies [1,4,74].

Informative publications for decision makers in the European Community (European Commission, 2003) and Australia (Australian Coal Association Research Program (ACARP), 2004) indicated that the photovoltaics, despite being environmentally friendly in the category generation, present some environmental impact compared to other technologies. These impacts reflect the energy based on fossil fuels used in the production of materials for solar cells, modules and systems [1,74].

The lifecycle metrics most often measured for environmental analysis of the PV system is the energy payback time (EPBT) and GHG (Greenhouse Gases). Energy payback time is defined as the time required for a renewable energy system, to generate the same amount of energy that was used in its production [1,4,12,74].

The greenhouse gases (GHG) during the stages of the life cycle of a photovoltaic system are estimated as a CO_2 equivalent through an integrated time horizon of 100 years. The use of fossil fuels during the production of photovoltaic materials are the main sources of GHG emissions for PV cycles. Upstream energy production methods also play an important role in determining the total GHG emissions [1,12,74].

The use of photovoltaic systems can reduce 69–100 million tons of CO_2, 68,000–99,000 t of NO_X and 126,000–184,000 t of SO_2 by 2030 (HOSENUZZAMAN et al., 2015). The results of a study on the life cycle assessment of the production of monocrystalline silicon photovoltaic (PV) solar cells in China showed that the emission of greenhouse gases ranged from 5.60 to 12.07 g CO_2 eq/kWh [75]. A 62.7 kW photovoltaic system has a life-cycle emission rate of 50 g CO_2 eq/kWh. The GWP of this proposed system varies from 4307 to 5400 kg of eq CO_2 [76].

A photovoltaic system located in southern Europe, with multicrystalline silicon modules have an energy payback time (EPBT) of about one year. Depending on the technology and the location of the PV system, the EPBT today ranges from 0.7 to 2 years [1]. Photovoltaic systems in Northern Europe, for example, need about 2.5 years to balance the input power, while the PV system in the south, the EPBT equals 1.5 years or less, depending on the technology installed. Figs. 13

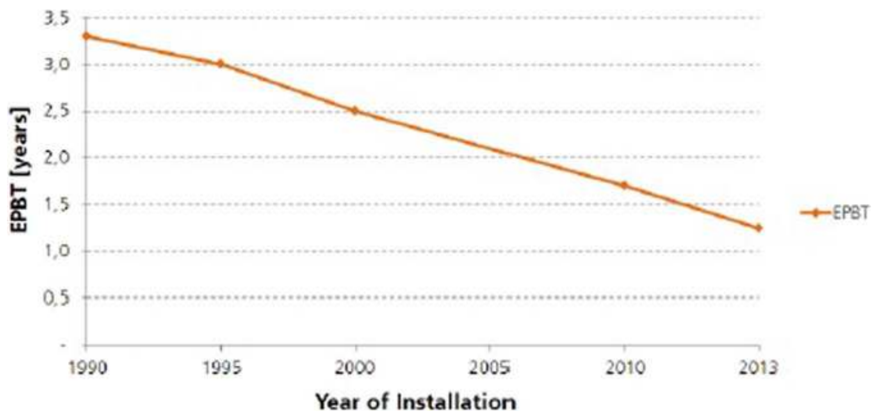

Fig. 13. Historical trend in times of Energy Return (EPBT) of photovoltaic modules of crystalline silicon.
Source: Data: EPIA Sustainability Working Group Fact Sheet 2011; since 2010: M.J. de Wild-Scholten 2013. Graph: PSE AG 2014.

and 14 show the historical trend of EPBT of photovoltaic modules of crystalline silicon and EPBT photovoltaic systems multicrystalline silicon in some regions, respectively.

Emission rates of greenhouse gases and EPBT can be mitigated from the reduction in the use of the glass (used in the protection of photovoltaic cells against bad weather, temperature fluctuations and mechanical impacts) and aluminum (used in the frames of the modules) since they reduce the energy requirement to produce these materials [1].

5. Conclusions

Photovoltaic solar energy, a renewable energy source, seen as an alternative to dealing with the challenges of shortage of energy generated from traditional sources. Until the mid-2000s aroused relatively little interest from the academic community, taking into account the number of articles published on this topic. This scenario of scientific interest has come to change from the second half of the 2000s, with a significant increase in the number of published articles.

As for the definition of solar photovoltaic energy, it is observed that the authors make use of terms in common, namely: "electricity", "sunlight", "direct generation", and "conversion". In this article we suggest a consensual conceptualization between these terms which say that the photovoltaic solar energy is the energy obtained directly from solar radiation conversion.

It is argued in several articles, among them [4,16,32], the power consumption worldwide is increasing every year and among different technologies that are competing for power generation we can highlight the renewable energies, especially photovoltaic solar technology that is growing rapidly in recent decades and can play an important role in achieving the high demand for energy worldwide. A huge amount of annual installed photovoltaic systems shows the seriousness and responsibility of each country on the subject to save the Earth by using renewable energy.

In some articles [7,9], it is reported that in order to increase PV participation of the renewable energy market we need to increase awareness about the benefits (social, economic and environmental); increase research and development of new technologies (to obtain

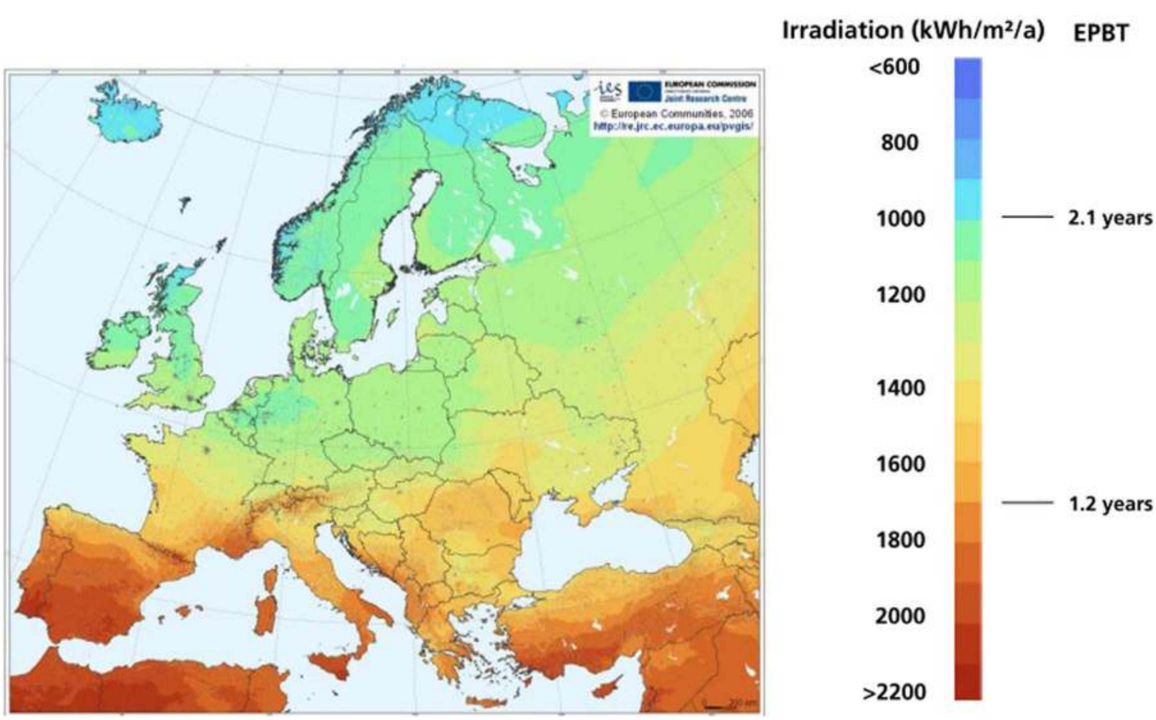

Fig. 14. EPBT of multicrystalline silicon photovoltaic systems – geographical comparison.
Source: Data: M.J. de Wild-Scholten 2013. Image: JRC European Commission. Graph: PSE AG 2014 (Modified scale with updated data from PSE AG and FraunhoferISE).

cheaper and more efficient cells); implement policies and programs that would encourage the generation PV; train more qualified professionals for this market and that the photovoltaic industry needs to improve not only the reliable political framework conditions to ensure a return on investment, but also the innovation and continuous research.

Authors like [11,20,42] point out that in the energy market the competitive position of each solar technology is determined by the efficiency factors, lifetime, cost and the environmental factor [9,19,23,74]. state that currently there are several types of solar cells industrially available, however, there is a continuous effort in improving efficiency and reducing costs.

Although the crystalline silicon solar cells were predominantly the cell type used for most of the second half of last century, other cell types have been developed, which compete in terms of production costs reduction (solar cell based on the use of multicrystalline silicon, and the thin film cells (amorphous silicon, CdTe or CIGS)) in terms of greater efficiency (based on the use of III–V compounds).

Technologies, as mentioned by [1,12,74] also need to have acceptable energy payback times. Monocrystalline and multicrystalline silicon cells typically have power recovery times of 3–4 years and thin film technologies, of 12–18 months. After years of moderate growth of the photovoltaic market, the evolution of applications has increased [8,16,22,29–34]. presents as the main applications of solar photovoltaics energy the telecommunication, water pumping, street lighting, BIPV, agriculture, water desalination, weather monitoring and spacecraft and satellites.

It is recommended that the ones interested in the topic of solar photovoltaics to invest in future studies related to inverter optimization strategies, network connection scenarios, detailing of photovoltaic applications, economic viability, formatting of the supply chain, analysis of barriers and incentives for photovoltaic solar energy and the deepening of the knowledge of the factors that influence the position of the technologies in the market.

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