Solar photovoltaic technology as a smart alternative to replace conventional fossil fuels

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Resumen– *Este trabajo presenta un estudio de los problemas del cambio climático y cómo las energías verdes pueden ayudar a reducir las consecuencias negativas del calentamiento global y los efectos invernadero en la tierra. El sol es considerado una de las fuentes más importantes y abundantes de energías renovables por lo que está cerca de ser la fuente de electricidad más grande del mundo para 2050. Además, la mayoría de las formas de energía disponibles en la tierra surgen directamente de la energía solar, incluidos el viento, la energía hidroeléctrica, la biomasa y los combustibles fósiles, con algunas excepciones como la energías nuclear y geotérmica. En consecuencia, la energía solar fotovoltaica (SPV) es una tecnología capaz de convertir la inagotable energía solar en electricidad, empleando las propiedades electrónicas de los materiales semiconductores que representan una de las formas más prometedoras de generación de electricidad, como una opción alcanzable e inteligente para reemplazar los combustibles fósiles convencionales. La tecnología de células solares está experimentando la transición a una nueva generación de productos eficientes y de bajo costo basados en ciertos materiales semiconductores y fotoactivos. Además, tiene ventajas ambientales definidas sobre las tecnologías de generación de electricidad competidoras, y la industria fotovoltaica sigue un enfoque de ciclo de vida proactivo para prevenir el daño ambiental futuro y sustentar estas ventajas.*

Palabras claves– *calentamiento global, células solares IBC, combustibles fósiles, efecto invernadero, energía solar, fotovoltaico, renovable, Oblea c-Si.*

Abstract– *This work presents a study of the climate change issues and how green energies can help to reduce the negative consequences of global warming and greenhouse effects on earth. The sun is considered one of the most important and plentiful sources of renewable energies reason why it is close to being the largest source of electricity in the world by 2050. Furthermore, most of the energy forms available on earth arise directly from the solar energy, including wind, hydro, biomass and fossil fuels, with some exceptions like nuclear and geothermal energies. Accordingly, solar photovoltaic (SPV) is a technology capable of converting the inexhaustible solar energy into electricity by employing the electronic properties of semiconductor materials, representing one of the most promising ways for generating electricity, as an attainable and smart option to replace conventional fossil fuels. Solar cell technology is undergoing a transition to a new generation of efficient, low-cost products based on certain semiconductor and photoactive materials. Furthermore, it has definite environmental advantages over competing electricity generation technologies, and the PV industry follows a pro-active life-cycle approach to prevent future environmental damage and to sustain these advantages.*

Keywords– *c-Si wafer-based, fossil fuels, global warming, greenhouse effect, IBC solar cells, photovoltaic, renewable, solar energy.*

1. Introduction

Nowadays renewable energies are becoming an essential part of our daily life thanks to the new governmental agreements and policies that pursue at least partially replacing fossil fuels, reducing global warming below 2°C, and achieving additional benefits. By implementing an action plan to protect our environment and by fulfilling established targets to develop renewable-energy systems we can greatly contribute to the security of the global energy supply, the reducing of greenhouse gas (GHG_s) emissions, an the solving of the climate crisis and related health issues. Since non-renewable energy sources as well-known as fossil fuels are limited and have contributed negatively to global warming through the dramatic increment of greenhouse gas emissions, energy security has a role to play in meeting the fast and constant demand of electricity supply. Clean energies like solar power represent the best alternative to overcome the challenge of meeting a growing energy demand, which includes populations from both industrialized cities and remote areas (with long distances to a basic distribution grid electricity and where communication is not available but it is also necessary). To give a general idea of the enormous potential of the sun, consider that one ten-thousandth of the solar radiation that reaches the earth's surface is enough to cover the yearly global energy consumption. This potential capability of sun power has been well used by the denominated photovoltaic (PV) energy. PV technology consists of solar cells that directly convert sunlight into electricity at the atomic level. This can be obtained through the photovoltaic effect by using the electronic properties of semiconductor materials, which is one of the most promising energy conversion process. PV systems offer many attractive features, including pollution-free operation, very low GHGs emissions, relatively low maintenance costs, and economical feasibility in urban and rural areas. Definitively, PV solar cells will foster many aspects related to energy supply security and industrial development by providing improved access to electricity, job opportunities welfare, increased health, and a better quality of life while reducing the negative impact of massive burning fossil fuels. This work presents a concise study about the problem of steadily growing energy consumption and the dramatic situation of global warming due to the greenhouse gas emissions. Additionally, we will review a summary of the technological developments made in the photovoltaic industry since the middle of the 20th century.

2. Global warming and the energetic paradigm

Currently, our planet is facing enormous environmental challenges. The disorder of the greenhouse effect (GHE) is a major threat to the global climate. The GHE is a natural process that typically plays a critical role in regulating global temperature. It warms the earth's surface and contributes to maintaining the temperature approximately 15°C in average, allowing sustained life [5] on earth. Without this, the overall temperature would be much colder (i.e. -18°C average) and life on our planet would be impossible [8], [28]. This natural phenomenon was discovered in 1827 by Joseph Fourier and quantified in 1896 by Svante Arrhenius [13]. The GHE is mainly caused by the interaction of sunlight with greenhouse gases (GHG / GHG_s) and present components of the atmosphere, which can be both anthropogenic and natural gases. The main mixture of gases (also known as trace gases) related to the GHE are carbon dioxide (CO_2), methane (CH_4), water vapour (H_2O) and ozone (O_3). A helpful comparison is to compare a greenhouse (where a trace gas acts) to a glass that allows sunlight to pass into it, but keeps the resulting heat radiation inside. These gases contributes to warming up the glass, which is similar to how the greenhouse effect works. Nonetheless, an uncontrolled concentration of GHG_s in the atmosphere can highly increase the average global temperature. In 2016, Nerilie Abram, a researcher at the Australian National University (ANU), published an article [24] revealing robust evidence about the impact of anthropogenic sources (i.e. CO_2, CO and CH_4) on climate, for more than 170 years that exactly match with the boom of the industrial revolution. Actually, many research publications state that human activities and industrial developments are responsible for the steep rise in concentrations of greenhouse gases. Carbon dioxide, which comes out to the atmosphere because of the fossil fuel combustion (coal, gas, natural gas, or petroleum), is major contributor as result of our relentless pursuit of energy. These massive emissions probably represent the main threat for the planet's ecosystem.

In fact, according to IEA the permanent use of fossil energy is responsible for approximately 85% of the high anthropogenic CO_2 emissions produced annually. Other activities such as agriculture, land clearing and deforestation also contribute negatively to the global warming [16].To clarify the greenhouse effect on earth, examine and consider Figure 1, where ⓐ sunlight (visible and infrared radiation) crosses the atmosphere almost unobstructed and is ⓑ absorbed by the ground. This warms the surface ⓒ and ⓓ emits heat radiation (also called *black body*) which once again is ⓔ absorbed by the trace gases and ⓕ set free into the environment as heat. Only a small portion of this heat energy gets back into space whereas the majority remains in the atmosphere and increases the earth's temperature [15].

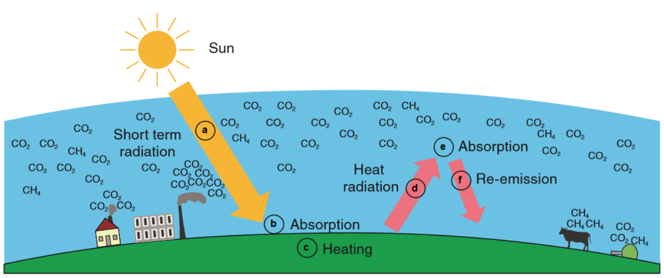

Figura 1. Greenhouse effect schematic. The heat radiation reflected from the earth surface is held back into the atmosphere by the greenhouse gases. Taken from [15].

In 2013, the concentration of CO_2 in the atmosphere reached 396-ppm (parts per million) average, a value that was never reached during millions of years, and representing 142% of the rate reported before the Industrial era (1750, taken as the reference year) [18]. Additionally, a study about the global distribution of greenhouse gas emissions that covered a timeframe from the late-20th century until 2014 shows that the annual CO_2 levels were almost exclusively from the United States and Europe, however, since 2006 China became the main CO_2 emitter, and accounted for 30% of the global emissions as depicted in Figure 2 [21].

According to Japan Meteorological Agency (JMA) global warming is a reality and the day by day, increase in temperature levels and their effects is noticeable [40]. Likewise, in January 2017 NASA & NOAA confirmed that since the 19th century, Earth's average temperature has increased

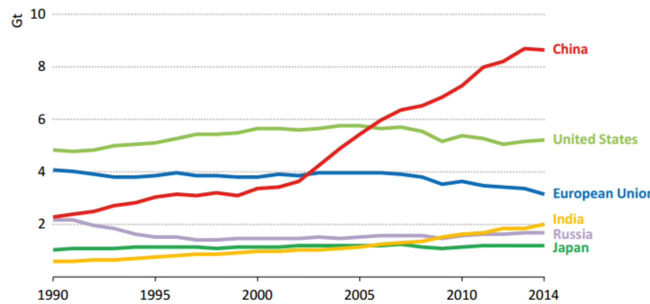

Figura 2. Energy and industrial production-related CO_2 emissions by selected region [21].

to 1.1°C (2° Fahrenheit) because of the extra trapping of heat released into the atmosphere, a result of the additional emission of trace gases caused by the so-called anthropogenic greenhouse effect [39]. Moreover, a recent monthly analysis of global temperatures revealed that February 2017 was the second warmest February in 137 years of modern record-keeping (shown in Figure 3). For this reason, NASA's actions are fundamental to properly facing the challenge of climate change of this generation, as stated by Charles Bolden, former NASA administrator (until January 2017) [38].

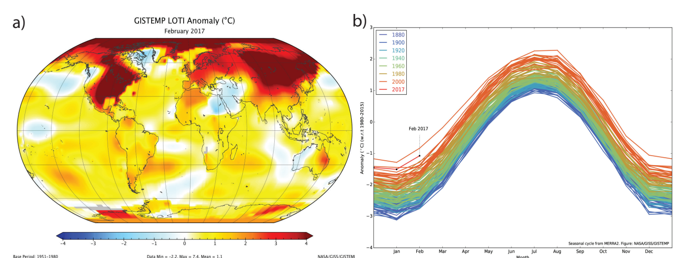

Figura 3. a) Representation of global map for February 2017 LOTI (land-ocean temperature index) anomaly evidencing that Northern countries were much warmer than they were in the 1951-1980 base period, b) GISTEMP monthly global temperature anomalies for the 1980-2017 period [38].

3. The general action plan to face climate change effects

Consequently, governments are currently building greater commitments in order to face climate change through new global agreement policies. Opposite to the limited participation of the countries in the Protocol of Kyoto in 2005, the European Union (EU) proposed a new strategy to mitigate global warming and communicated it in December 2015 at the Paris Climate Conference (COP21), which became effective in November 2016 [31]. The Paris agreement established a global action plan to keep the long-term global mean temperature below 2°C (postulated in the Copenhagen Accord of the UN-FCCC) [30] and reducing future internal GHGs emissions (i.e. CO_2), to at least 40% average, within the next thirteen years, regarding the levels reported in 1990 [23]. Furthermore, it highlights the EU commitment of increasing the green energy quote and improving the energetic efficiency. However, in 2015 through the strategy "Europe 2020", the EU GHG_s emissions were 22% below the 1990 level. Actually, after the 20th-century emissions continue to decline over time, and a significant drop of 18% is expected by 2030 (as illustrated in Figure 4) [25]. Therefore, all of these guidelines are aimed at implementing a sustainable energy model where both developing and developed countries are collectively undertaking appropriate actions to avoid harmful environmental impacts, and thus, the energy sector will change to the extent necessary to meet the internationally agreed objectives.

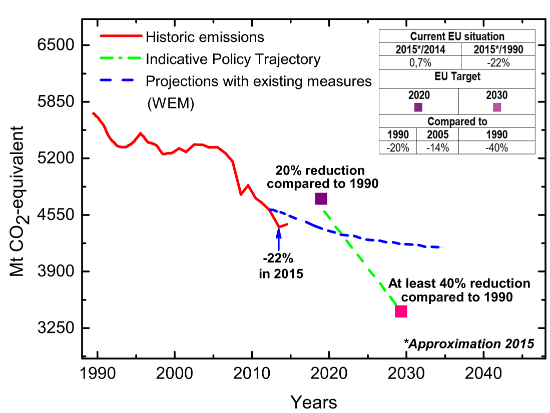

Figura 4. Progress towards the achievement of the Europe 2020 targets [25].

These government efforts are focused on specific priorities as climate protection through the reduction of carbon dioxide intensity (by 2030), and carry out a transition plan toward a new renewable energy supply system capable of meeting the energetic needs of an ever increasing population. The following is an interesting analysis based on the currently implemented policies by the International Energy Agency (IEA). After the first quarter of the 21th century, world energy demand is expected to increase by about 50% every 10 years until 2050. Figure 5 is a graph, which depicts the present situation and the possible future scenario for global energy supply with respect to the constant rise in energy demands and the associated dramatic increment of CO_2 emissions.

Contributions from various primary energy sources (particularly coal, oil, gas, nuclear, hydro, bio-energy, among other renewable ones) are shown [21]. This shows that fossil fuels will remain as base-load electricity production, working together with renewable energy sources until 2030, and regulated by the Europe 2020 target policies. Afterwards, the expected scenario consists of boosting alternative clean energy investments in order to furnish future energy demands, as well as overcoming fossil fuel dependence whereas energy-related CO_2 emissions will keep constant after 2040 with a possible decline of 39% over the same period. However, the fossil fuels industry continues to lead the global energy supply and to be primarily subsidized by governments (see Figure 6), gathering high economic incomes that probably overcome other types of technologies. This is expected despite the fact that their prices tend to increase, and renewable energy prices tend to decrease because of continued productivity improvements and economies of scale.

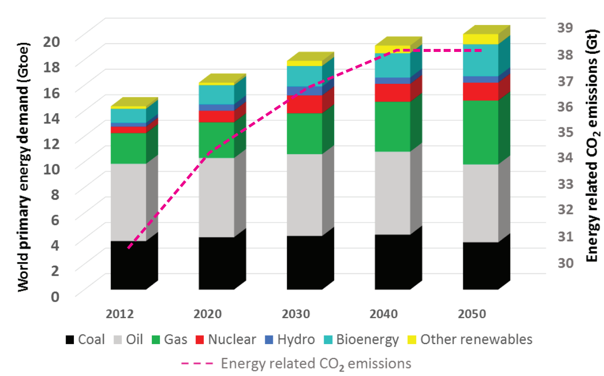

Figura 5. Estimated global primary energy supply scenario by IEA policies [21].

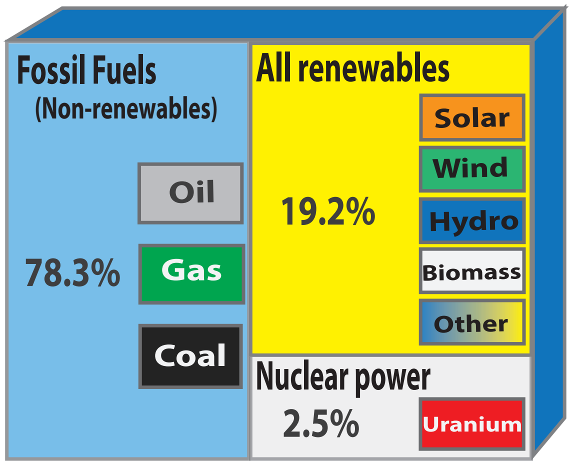

Figura 6. Estimated renewable energy share of global final energy consumption, 2014 [29].

4. Facing the global energy demand by adopting renewable energy supply technologies

In this matter, a change in the way of producing and using energy is fundamental. In particular, the industry must be concerned about reducing the dependence on fossil fuels to generate electricity (coal, gas, and oil), and instead, substitute them for the development and use of eco-friendly and sustainable energy sources such as solar and wind. Among the viable options, solar energy by far represents the largest energy resource capable of fulfilling the whole energy demand of humankind (by just using one ten-thousandth part of the incoming sunlight), compared to other non-renewable sources. Thus, as being an inexhaustible and sustainable energy source that cannot be over-consumed, solar energy can easily become the world's primary energy supply. This relationship is clearly described in the schematic of the energy cube values depicted in Figure 7. There is a comparison between the annual solar incidental radiation, and the available reserves of fossil fuels, and nuclear energy carriers regarding the world annual energy demand. The current limited non-renewable energy sources are represented by the small boxes at the bottom-left. The solar radiation is sketched by the biggest yellow cube, representing its vast power available every new year. Conversely, at the bottom-right there is a small box of the global annual energy usage, which appears to be very small when compared to the large solar box. This is because sunlight potential is proportionally more than ten thousand times the current yearly global energy consumption.

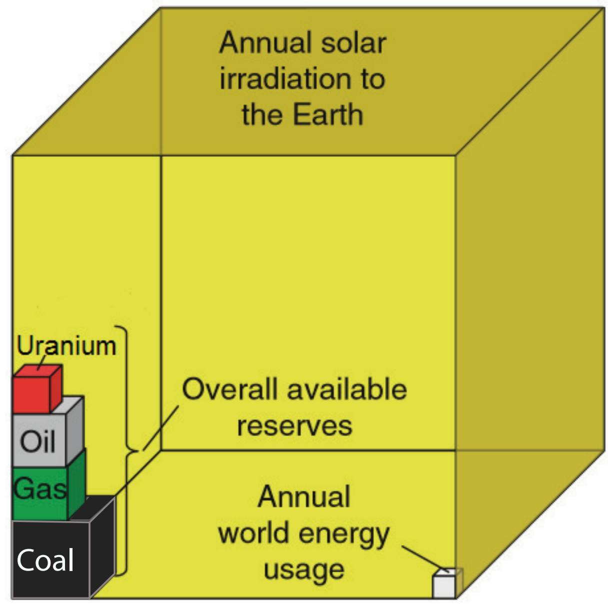

Figura 7. Schematic of the energy cubes: an estimate of the potential of solar energy. The annual solar irradiation exceeds several times the total world energy demand as well as the whole fossil fuel energy reserves. [15], [28].

Additionally, solar energy helps society to meet its increasing energy needs, reducing electricity costs as well as being environmentally friendly. It provides solutions for decreasing or even stopping the global warming crisis because harnessing it does not generally cause pollution, which is different and better than conventional and non-renewable energy sources. Its end wastes are already handled by current pollution controls and regulations. On the other hand, most of the today's solar power systems (including photovoltaic and solar thermal) are easily deployable at the consumer level, requiring low maintenance. The primary maintenance focuses on cleaning the solar panel a couple of times per year. Since the early 1980's technological advancements have consistently been made in the photovoltaic industry. In particular, research groups have greatly contributed to enhancing the power density and general performance of solar cell systems by exploiting the potential of nanotechnology and quantum physics. Thus, solar power clearly represents the solution of satisfying the world's future energy necessities while also significantly reducing the production of GHG emissions and negative implications for our global climate. It provides energy security and the offer of an independent way to produce electricity, because it is free and available to everyone all over the world. For these reasons, solar energy has been established as "The People's Power supply". The map sketched in Figure 8 shows the solar energy potential of the European Union (EU). Despite the fact that Northern regions do not have the best location for maximum solar PV potential, the EU as a whole is producing a significant electricity quota from solar power. For instance, Germany is dominating the EU installed PV capacity, due mainly to the environmental concern supported by generous subsides. However, a couple of Southern countries with even greater solar potential are also making efforts to improve and accelerate actions for the sake of a low carbon society. This is the case of Italy and Greece, countries that are currently dependent on fossil fuel as the primary energy supply, but their geographic location is rather favorable for the exploitation of PV technologies.

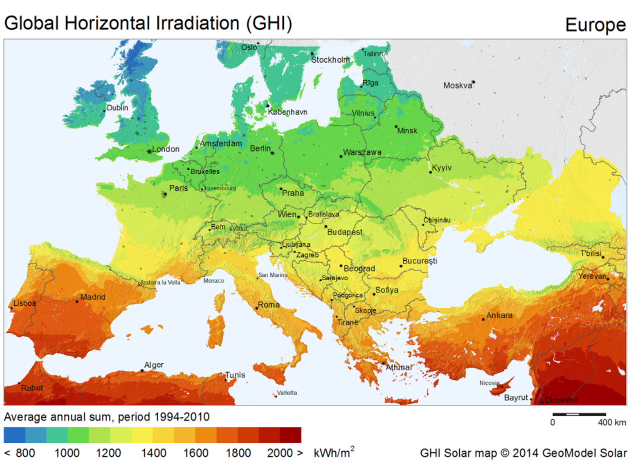

Figura 8. Global solar irradiation in European countries published by SolarGIS: Geographic Information System data and maps [35].

In effect, photovoltaic systems are becoming a strategic real choice, and in the case of the European Union (EU), the solar cell production supplies nearly 4% of its whole electricity demand (see Figure 9). This has been possible thanks to the solar contributions of 17 of the European Union's 28 members to more than 1% of their power needs. Actually, Italy, Greece and Germany have been established as the top solar electricity consumers, each producing more than 7% of their energy usage. It is worth mentioning that, in Italy around 8% of the power consumption is entirely covered by its own solar PV production. Accordingly, at the end of 2015, the production of photovoltaic plants in Italy reached 22.942 GWh. As it is shown in Figure 10 the increase compared to 2014 (+ 2.9%) is lower than that recorded in previous years. Looking at the performance of PV plant production throughout 2015, July recorded the largest solar capacity with nearly 3 TWh of energy produced in Italy.

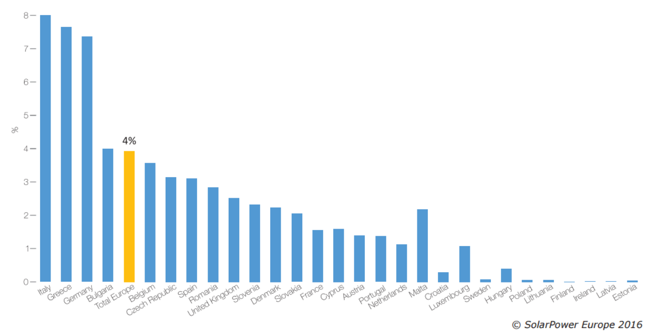

Figura 9. Share of electricity demand covered by solar photovoltaic production in European countries, 2015 [34].

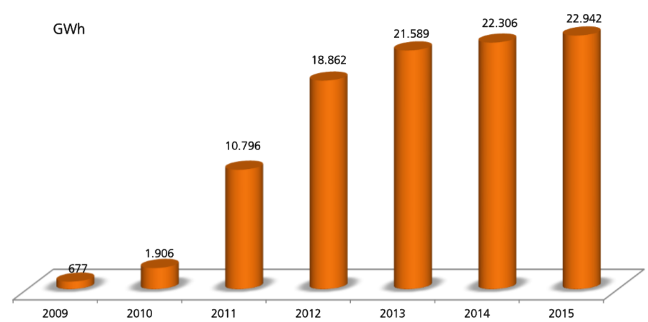

Figura 10. Annual production of photovoltaic plants in Italy (2009-2015) published by the energy service manager agency (GSE, Italy) [20], [36].

Actually, the chart of Figure 11 illustrates the daily average of solar irradiation stating that July was the sunniest month of 2015. Besides, in the same month, the highest peak reached 874 W/m^2 average.

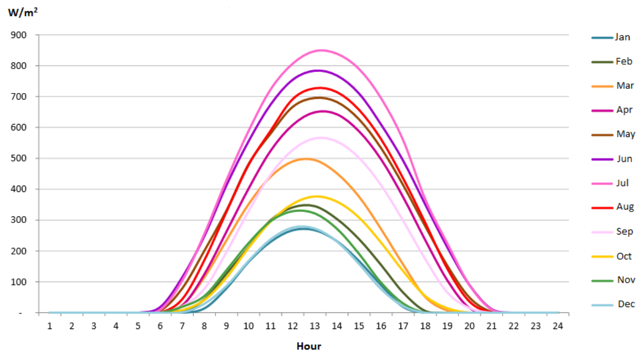

Figura 11. Hourly average of solar radiation in Italy, published by the energy service manager agency (GSE, Italy), 2015. [20].

Conversely, November, December, and January had the lowest solar irradiation; and the maximum value of daylight hours was recorded in June, as it can be seen in the bell curve. Indeed, in the specific case of Southern Italy, solar production is offering a significant contribution to the alternative energy supply with the presence of companies dedicated to the development of PV solutions, such as Omnia Energia (oe), certificated as the best eco-sustainable urban building in the EU (A+). In terms of fuel consumption, oe saves around 70% energy compared to traditional buildings, as well as, 83 Ton CO_2 avoided in a solar year [14]. Hence, as the benefits accomplished by implementing energy solutions based on solar power are clear in Europe, PV systems have reached an important position among the green energies portfolio of this generation.

5. Overview of PV recycling

The deployment of PV technology has grown dramatically in recent years, reaching a cumulative global installed capacity of 222 *GW* at the end of 2015. PV offers economic and environmentally friendly electricity production but like any technology, it ages and ultimately requires decommissioning (which includes dismantling, recycling, and disposal). As PV increasingly becomes a global commodity, and to ensure its sustainable future, stakeholders involved with each step of the product life-cycle must implement sound environmental processes and policies, including responsible *end-of-life* treatment. Regulatory frameworks that support the early development of life-cycle management techniques and technologies will foster such processes and policies [37].

The PV industry has adopted a pro-active and longterm strategy to preserve the environmentally friendly nature of the industry. Manufacturing solar panels presents some health, safety and environmental *HSE* concerns which were the focus of numerous studies at *Brookhaven National Laboratory*, under the auspices of the US Department of Energy's National Photovoltaic Program [6], [7], [10]. One issue is what to do with PV modules at the end of their use?. Modules are expected to last about 30 years, and, then will have to be decommissioned and disposed or re-used in some ways. There is a concern about disposing them in municipal landfills because they may contain small amounts of regulated materials. Environmental regulations can determine the cost and complexity of dealing with end-of-life PV modules. At present, only the European Union *EU* has adopted PV-specific waste regulations. Most countries around the world classify PV panels as general or industrial waste.

In limited cases, such as in Japan or the US, general waste regulations may include panel testing for hazardous material content as well as prescription or prohibition of specific shipment, treatment, recycling and disposal pathways. The *EU*, however, has pioneered PV electronic waste *e-waste* regulations, which cover PV-specific collection, recovery and recycling targets. Based on the extended producer responsibility principle, the EU Waste Electrical and Electronic Equipment *WEEE* Directive requires all producers supplying PV panels to the EU market (wherever they may be based) to finance the costs of collecting and recycling *end-of-life* PV panels put on the market in Europe. Lessons can be learned from the experience of the *EU* in creating its regulatory framework to help other countries develop locally appropriate approaches. The PV recycling industry is expected to expand significantly over the next 10-15 years. Annual *end-of-life* PV panel waste is projected to increase to more than $60 - 78$ million metric tonnes cumulatively by 2050 according to [37] (see Fig. 12). This increasing scale should improve the cost-effectiveness and energy/resource efficiency of recycling while stimulating the technical innovations needed to handle the wide variety of materials used in fast-evolving PV technologies.

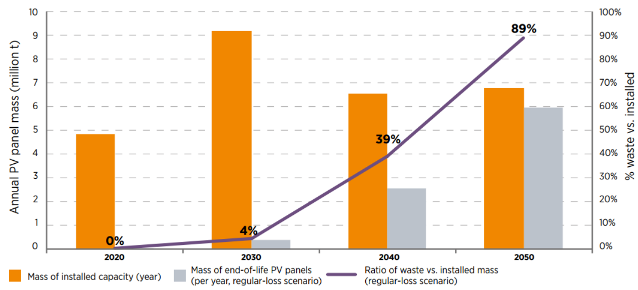

Figura 12. Annually installed and end-of-life PV panels 2020-2050 (in % waste vs. t installed) by a regular-loss scenario. Based on [21], [37].

Based on the best available information today and according to [21], [37] the next graphic suggests the actual future PV panel waste volumes considering a regular-loss scenario. Regarding to the probability of PV panels becoming waste before reaching their estimated end-of-life targets, the potential origin of failures for rooftop and ground-mounted PV panels has been analyzed independently from the PV technology and application field [21], [37]. Basically, the three main panel failure phases detected are the following (see Fig. 13):

- Infant failures defined as occurring up to four years after installation (average two years),
- Midlife failures defined as occurring about five to eleven years after installation,
- Wear-out failures defined as occurring about 12 years after installation until the assumed end-of-life at 30 years.

The main infant failure causes include light-induced degradation (observed in $0.5\% - 5\%$ of cases), poor planning, incompetent mounting work and bad support constructions. On the other hand, causes of midlife failures are mostly related to the degradation of the anti-reflective coating of the glass, discoloration of the ethylene vinyl acetate, delamination and cracked cell isolation. And the causes of frequently observed failures within all phases in the first 12 years after exposure to mechanical load cycles (e.g. wind and snow loads) and temperatures changes include potential induced degradation, contact failures in the junction box, glass breakage, loose frames, cell interconnect breakages and diode defects.

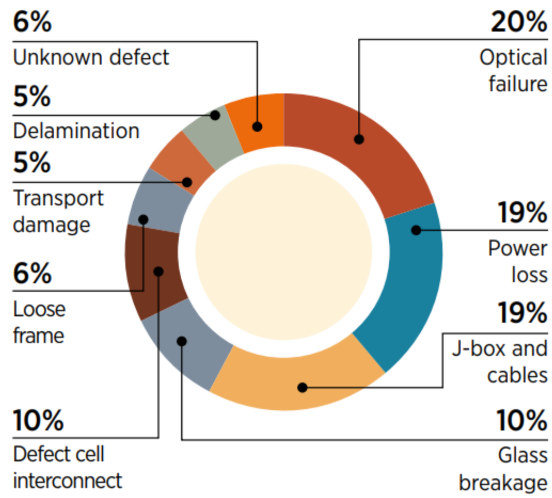

Figura 13. Failure rates on PV panels according to customer complaints. Based on [21], [37].

The operation of PV systems does not produce any noise, toxic-gas emissions, nor greenhouse gases as exposed in section **??**. PV energy not only can help meeting the growing worldwide demand for electricity, but it can do so without incurring the high environmental costs of burning fossil fuels. Relative to burning coal, every gigawatt-hour of electricity generated by PV would prevent the emission of up to $10ton$ of sulfur dioxide, $4ton$ of nitrogen oxides, $0.7ton$ of particulates (including $1kg$ of Cd and $120kg$ of As), and up to $1000ton$ of carbon dioxide [4]. Recycling PV systems at the end of their useful life adds to the environmental benefits and can further enhance market support. Subsequently, recycling answers public concerns about hazardous materials in PV modules which can create barriers to market penetration.

6. Review of PV technology developments

Photovoltaic technology is one of the foremost ways to harness solar energy. A PV cell consists of an electrical device made out of certain semiconductor materials such as Silicon, that exhibit a particular property known as the *bulk photovoltaic effect*. The PV effect is a process that causes the absorption of photons of light and releases electrons, and when these free electrons are captured, an electric current is obtained. In other words, the PV conversion directly converts sunlight (photons) into electricity (voltage) without an intermediate heat engine. The PV effect was accidentally discovered in 1839 by the French physicist Alexander-Edmond Becquerel at the age of 19 years old when he observed a light-dependent voltage between electrodes immersed in an electrolyte [32]. Nonetheless, it was not until 1954 when the scientists Daryl M. Chapin, Calvin S. Fuller and Gerald L. Pearson built the first modern silicon-based photovoltaic cell at Bell Laboratories in the United States. Practically, they discovered that silicon material can create an electric charge when exposed to sunlight. Thus, their solar cell registered an efficiency of about 6% [1].

This paramount invention defines a new era for the current and future developments in the PV industry by offering advantages as described in Table 1. Note that the list includes technical and environmental parameters, taking as a reference the positive and negative issues of conventional fossil-fuel power plants. Later on, laboratories started developing the first silicon solar cells to power space satellites and solar cells are considered essential in this type of application. Moreover, in the late 1970s and 1980s, the developed PV systems were focused on terrestrial applications, and the first thin-film solar cell based on copper-sulphide/ cadmium-sulphide junction amounted to an efficiency (η) above 10%. In contrast to this invention, in 1975 R. Schwartz initiated research of a new architecture known as back-contact solar cells, considered an alternative to photovoltaic cells, featuring both a front and rear contact [2]. In 1985, the University of New South Wales (UNSW) built crystalline silicon (*c*-Si) solar cells and reached efficiencies above 20%, and in 1999 they stated a new record of 25%, considered the world highest efficiency [9], [12]. The structure was also *c*-Si-based. In 1994, the National Renewable Energy Laboratory (NREL) from Colorado, U.S.A, built a solar cell based on indium-gallium-phosphide/gallium-arsenide tandem junction that exceeded 30% efficiency.

Until the late 1990s, solar cell innovations continued to be introduced, pushing up the photovoltaic industry and the related manufacturing processes. Consequently, PV research and developments of solar cell systems were notably growing interest in North America, Europe, and Asia. To confirm this, the world total installed PV power systems in 1999 outstripped the 1 GW, defining a renewed beginning for the public discussion of solar energy, bearing in mind essential aspects such as the environment and the climate change, economy, health and the common welfare. Afterwards, many laboratories and companies continued developing silicon photovoltaic cells, achieving new conversion efficiency records of approximately 25% as in the case of SunPower & Panasonic in 2014 [17], [19]. Over the same year, the Australian National University designed an interdigitated back contact (IBC) solar cell featuring point contacts on the rear side achieving an efficiency of 24.4%, the highest reported value to date for this promising back contact architecture [26]. Furthermore, at the end of 2016 Yoshikawa et. al from Kaneka Corporation built an interdigitated back contact (IBC) *c*-Si-based solar cell, obtaining the world's highest conversion efficiency of 26.33% [41]. Additionally, it is important to highlight that this kind of back contact-back junction (BC-BJ) solar cell structures are recognized by the many advantages over the conventional PV cells, but more complex configuration implies specific fabrication processes and higher costs. Anyhow, point contact cells have shown a pledging performance, thus representing a potential architecture to optimize by the extensive study carried out in this work

Advantages of PV technology
Quite evenly distributed energy across the planet and essentially infinite
Low emissions, no combustion or radioactive fuel for disposal
Ambient temperature operation (no high-temperature corrosion)
Low operating cost (no fuel)
Low maintenance cost
No moving parts
Quick installation
High public acceptance
High reliability in modules (≥20 years)
Modular (small or large increments)
Economically feasible in urban and rural areas
Integrated into new or existing building structures
Installed at nearly any point-of-use
Daily output peak may match local demand

Tabla 1. Advantages of photovoltaic technology [11].

[3]. It is worth mentioning, that each of these innovations have contributed significantly to the worldwide record growth of the photovoltaic market during the last years. In particular, the global cumulative capacity of PV systems have been fitting an exponential curve in the last twenty-five years, amounting from less than 1 GW at the beginning of the 1990s to a steadily rise of 242 GW reported by 2015, 302 GW in 2016 and an expected future projection of 368 GW of solar power capacity at the end of 2017, as sketched in Figure 14 a).

Therefore, according to data compiled by the Institute for Solar Energy (Fraunhofer, ISE), it is evident that the installation of PV systems will spread rapidly to the emerging markets all over the world in the next ten years. In fact, the installed renewable electric capacity by the end of 2015 was mainly driven by leaders such as China, Japan, United States, and the pioneering European countries as Germany, Italy, and Greece. In fact, it seems that these countries will remain a considerable influence on the worldwide renewable energy market, especially in the solar PV installations (see Figure 14 b)) [27], [33].

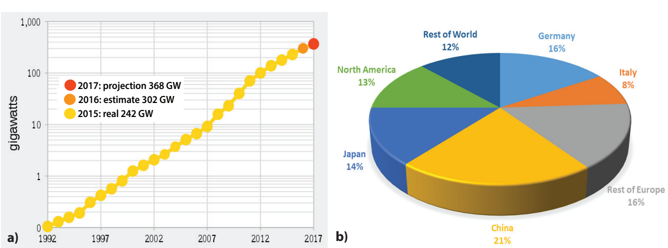

Figura 14. a) Global cumulative PV capacity, period 1992-2017, b) Global PV system installation by region, status 2015 [27], [33].

Accordingly, PV will play a significant role in the world future energy supply, as one of the best renewable sources to meet the alarming and growing energy demand. Although different types of solar cells with various kinds of semiconductor materials have been studied and produced, crystalline silicon wafer-based cells accounted for about 93% of the total production reported in 2015. It was stated as the cheaper way to produce on mass-scale, given the diffusion of facilities dedicated to the fabrication of diverse silicon applications [27]. Silicon is the second most abundant element in the Earth's crust (about 28%) after oxygen, and it is also a non-toxic material and represents a fundamental component in the microelectronic industry.

As silicon solar cells have shown satisfactory properties in creating an electric charge when exposed to sunlight, it has led the PV industry for more than the three decades and is still improving. Actually, this valuable semiconductor material offers a reliable technology that can easily achieve a large-scale deployment [22]. However, the key to accomplishing this objective is based on the understanding of the device operation and the reduction of the related loss mechanism, focusing on the optimization of the process design, increasing the conversion efficiencies, as well as, reducing manufacturing complexity and cost.

7. Conclusion

Nowadays, adopting new ways of green energy become an important matter of study to face the current global warming effects with a particular attention to the solar power. The sun is a remarkably renewable source of energy that we can freely harness on without fear of it ends one day. Photovoltaic (PV) research groups are focused on developing technical and economically feasible manufacturing technology to enhance the performance of solar cell modules and thus, commercialize it as a real alternative to supply electrical power to rural and urban communities and hence replace non-renewable fossil fuels. It is evident that the photovoltaic market is dominated by the crystalline silicon c-Si solar cell devices because of the specific and beneficial characteristics of this semiconductor material in the electronics industry. Therefore, the research on c-Si has a fundamental importance especially due to the low-costs achieved and the promising wide enhancements on the future electronic applications. Finally, due to the vast potential of PV technology, the global production of terrestrial solar cell modules has been growing over the last decades, with China recently taking the lead in total production volume.

8. References

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