Sustainability in Solar Cells

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R. Gupta, (ed.), *Handbook of Energy Materials*,
https://doi.org/10.1007/978-981-16-4480-1_33-1

Abstract

Sustainability means “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Solar energy is a widely accepted definition of sustainability because energy from the sun can be used indefinitely without decreasing its future availability. Although solar energy itself is sustainable, its use is not entirely free from disadvantages, and some of them are related to its degree of sustainability. For example, solar cells (SCs) are not sustainable because they are built with rare minerals such as selenium, which will eventually run out if solar panel manufacturers continue to extract them at an accelerated rate. However, these disadvantages pale in comparison to the positive potential of solar energy as a sustainable energy source. It is expected that solar energy will become more economical than non-renewable energy sources, which, by nature, become more expensive as their availability decreases. Even with the broad scope of the theme, it is essential to review the strategies currently studied since it encompasses questions about cheaper and more sustainable alternatives for the manufacture of SCs that meet environmental requirements. In this chapter, we also discuss issues to reduce the negative environmental impact, such as encapsulation and recycling to expand SCs materials’ life.

Keywords

Sustainability · Solar cells · Three generations of solar cells · The market value of solar cells · Recycling · Reuse of solar cell materials

Introduction

Energy is essential for humanity. Currently, the two most popular energy sources are used to satisfy human necessities: fuel fossil and nuclear. However, the implication of these sources is increasingly clear for climate change. Accordingly, considerable effort has been made to explore new renewable energy sources, like solar energy (Hou et al. 2019).

Solar energy has been considered cleaner than fossil fuel and more environmentally friendly. Its adoption can lessen greenhouse effects and the global warming phenomenon, the main concerns right now. Nevertheless, the manufacturing of solar panels is still expensive, and the process uses lot of energy, high-value materials, and even a significant CO_2 footprint emission. For that reason, it is not sufficient to be inexhaustible as solar energy to solve climate variability. Being entirely sustainable is an important requisite right now (Fthenakis 2009; Ahmad et al. 2021).

Hence, this chapter deals with sustainability in using solar cells (SCs) as source of energy. The cost, efficiency, recycling, and environmental impact are points to be discussed in terms of sustainability. Some questions will be briefly clarified: (i) how to define whether the source of energy is sustainable?; (ii) how sustainable is it?; (iii) is it feasible to apply it even in regions of energy poverty?

Moreover, trying to clarify these issues, we will address topics such as the degree of sustainability of SCs and the cost-benefit point of this energy matrix. A brief but concise overview will also be presented on various photovoltaic system technologies, including first-, second-, and third-generation of SCs (the detailed definitions of such generations of SCs are given in section "Sustainability of SC Types" of this review). Plans to reduce the price of cutting-edge technologies such as recycling SC components, processes evolving components' encapsulating and processes that use nanotechnology are also discussed here. These alternatives should be considered, as they represent ways to extend the use and reuse of photovoltaic (PV) components, reducing the environmental impacts of using this energy source and making it more sustainable.

The sustainability of solar panels is also discussed considering current technological developments, which will be able to guide the evolution of solutions to further reduce any negative impact of their building, setting up, and use. The environmental results of mining can be used as an illustration of the adverse effects of the production and use of SCs. Several rare metals are used in photovoltaic components. A typical example is selenium, which is extensively used in SCs and can become a limiting factor in using this energy matrix since there will be a shortage of this raw material in the long term due to its low abundance in the earth's crust (about 10^{-5} to 10^{-6} percent). Finally, throughout the text, several examples of technological developments and scientific innovations in SCs are provided. The objectives are to guide and map technologies with the potential reducing costs and increasing sustainability in the production and using of SCs and of photovoltaic materials related to this energy matrix.

Growth of Global SC Use

The sun is abundant and renewable energy source. Due to its abundance and possibility of being converted into electricity, solar energy is widely employed as a sustainable global energy source. SCs use the photovoltaic effect to convert directly into electricity the solar radiation arriving on them. Hence they are also known as PV panels (Maghami et al. 2016). From 1992 to 2021 the worldwide growth of PV has been almost exponential. During this period, SCs experimented significant transformation, from an initially market's niche, with small-scaled applications, to achieve nowadays almost conventional and large-scaled electricity source. It demonstrated the second-largest absolute generation growth of all renewable technologies in 2020, slightly behind wind and ahead of hydropower (Böhmeke and Koch 2021).

Annual solar installations grow by over 30% in 2021 after a volatile demand in 2020, triggered by restrictions caused by the COVID-19 pandemic. In 2021 occurred

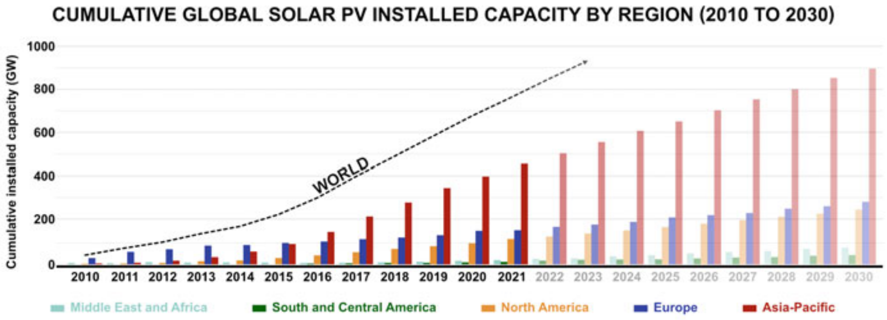


Fig. 1 Growth of SC use in the planet

an increase of 22% in the global installed capacity of solar photovoltaic energy, reaching the mark of 713.2 GW by the termination of 2020 (Fig. 1) (OWData 2021).

According to the International Energy Agency (IEA), after 2022 SCs will get new global yearly records on deployments. The global increase in capacity is expected to be around 125 GW in 2030, relative to 2021. In the last decade, growth was mainly driven by China, Europe, North America, and Asia-Pacific (PPSP 2018).

The production costs of SCs are expected to drop in the second half of 2022 due to the perspective increasing in supply chain. According to Statkraft Low Emissions – 2020 Scenario report, energy from sun is awaited to become the most powerful technology used for energy generation on the earth from 2035 onwards. In summary, the sun energy through PV system will surpass wind, hydroelectric, coal, and gas sources (Böhmeke and Koch 2021).

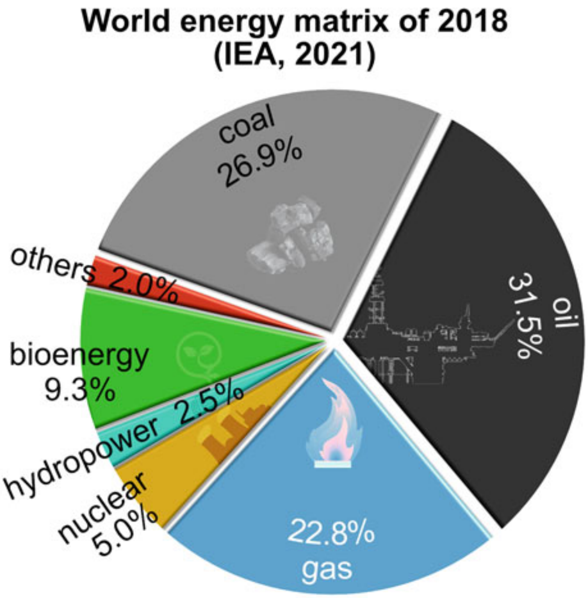
Another analysis by the IEA indicates that, after 2025, the average cost of electricity generated by a PV system awaits to drop. Besides, reducing the price of solar energy technology facilitates consumer access and drives increased the employ of the system (Vartiainen et al. 2020). The route to the growing SCs market is to target their efficiency for better converting sunlight energy into electricity and decrease their cost. Even though silicon processing has become cheaper over the past few decades, due to advances in technology, it still contributes significantly to the cost of producing SCs, especially in the first generation. However, new technologies employing different materials are being studied and aimed at a more sustainable world.

What Does Sustainability Mean?

Currently, inexhaustible sources like solar, wind, hydraulic, geothermal, and biomass represent only 16.8% of all energy matrices. The non-renewable sources, coal, natural gas, oil, and derivatives represent around 81.2%. The remaining 2% are characterized by other energy matrices, as shown in Fig. 2 (IEA 2021).

Observing these data, it is understandable that only a small energy portion used in all the world is renewable, which leaves us far from complying with the 2015's Paris

Fig. 2 World energy matrix of 2018



Agreement (CMA1), which exactly provided for a boost in the use of renewable sources to promote sustainability (Mostafaeipour et al. 2021). The consumption of fossil fuel resources guide to environmental impacts and natural disasters worldwide. Among the major consequences, glaciers' melting, rising sea levels, desertification, change in rainfall, floods, and reduced biodiversity can be highlighted (Mostafaeipour et al. 2021). Undoubtedly, such environmental disasters generally have the most significant impact on the poorest countries (Dey and Lewis 2021).

These facts have led many countries to express the urgency of implementing clear goals to reduce gas emissions. There is an urgent necessity to implement sustainable solutions that supply the diversification of energy matrices and, consequently, reduce overheating. For this, the United Nations (UN) organized the Conference on Climate Change (COP26) that was held in Glasgow, Scotland, in 2021. COP26 also incorporates the 15th Kyoto Protocol and the second Paris Agreement meetings (CCConference 2021). At the event, sustainability was one of the central themes, especially to decide targets for reducing greenhouse gases emission, reducing deforestation, and implementing alternative and sustainable energy matrices (CCConference 2021). Another goal of COP26 was to discuss replacing the employ of mineral coal, and 77 countries signed a treaty with this intention at the end of Conference (CCSustainability 2021). This treaty suggested that the most sustainable energy sources will demand in great scale, as around 27% of the total energy consumed is obtained from coal burning. Thus, the requirement to advance and use more sustainable technologies for energy production is evident. However, what exactly is a sustainable energy source?

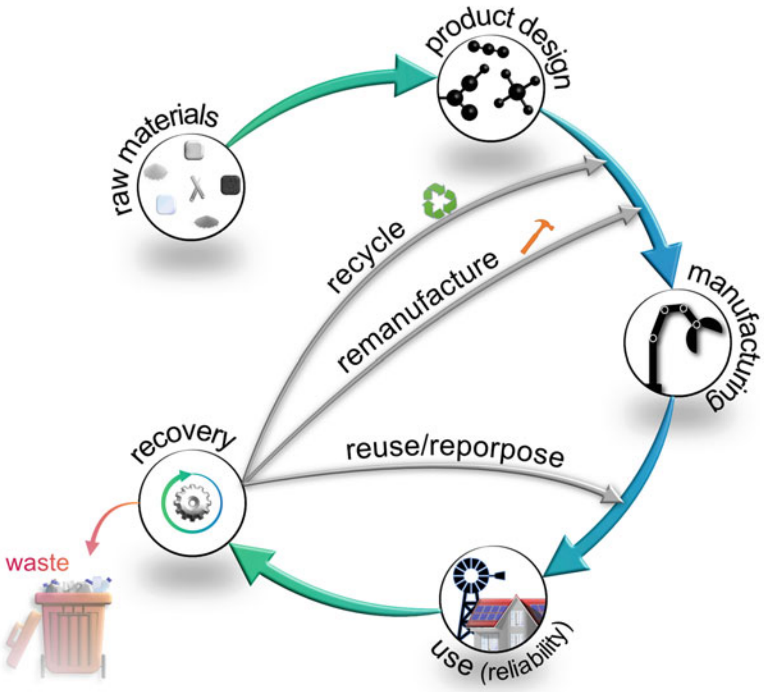


Fig. 3 The factors that influence the SCs sustainability: raw material acquisition, manufacturing, use/maintenance, and final disposal

To answer this question, it is first necessary to understand the sustainability view. Sustainability means “development that meets the needs of the present without, however, compromising the ability of future generations to meet their own needs.” In 2015, the UN defined seventeen (17) Sustainable Development Goals SDGs) that must be followed as part of the global effort to battle climate variations. Among the SDGs, the main is the SDG7, which ensures access to stable, sustainable, sustainable prices and modern energy for all (United Nations 2021). In this context, some factors have been considered, such as the raw material acquisition cost, manufacturing, use/maintenance, and final disposal of SCs (see scheme in Fig. 3). These factors cannot always be met by each energy matrix alone. However, each of them must be individually evaluated regarding its sustainability.

How to Measure Sustainability in SCs?

Our planet receives immense amount of solar radiation that can be transformed into electrical energy, and the sun can be considered, for practical effects, an almost infinite energy source (Radosevic et al. 2020). But other factors interfere in the

Fig. 4 Dimensions of sustainability

degree of sustainability of SCs as component of energy matrix. So, how could we measure the sustainability of solar energy?

First, we must consider that sustainability also means achieving viable development in three dimensions: environmental, social, and economic (Fig. 4) (Daniela-Abigail et al. 2022).

Thus, the use of SCs needs to be evaluated from these three dimensions so that it is possible to measure their degree of sustainability (Daniela-Abigail et al. 2022). Even because the cost for an energy source can be very relative according to the country considered. So, in the case of sustainable sources, we cannot measure only the monetary value, but the cost-benefit, economic impacts, environmental impacts, and social impacts (Wei et al. 2021).

Considering the environmental view, SCs are renewable and sustainable. It contributes to the maintenance of natural resources, does not harm the environment, and does not emit greenhouse gases. Energy generation is done by transforming solar irradiation into electrical energy through a photochemical process and PV equipment (Kwak et al. 2020).

In mid-2010, there were few isolated projects in the area, all dependent on government projects (Kwan 2012). However, today, solar energy is installed in thousands of places around the world, and, with the advancement of technologies and the reduction of costs, the growth is highly significant and imminent (Kwan 2012). The price is on top of sustainability, and solar panels need to be available for all people, even in poverty countries. Although PV energy is cheaper than other renewable sources, it is still a luxury for hundreds of millions. The cost of production is still so high that it reproduces the final price, making it impractical for most consumers. Thus, it is crucial to have low-cost solar panels to change the culture of

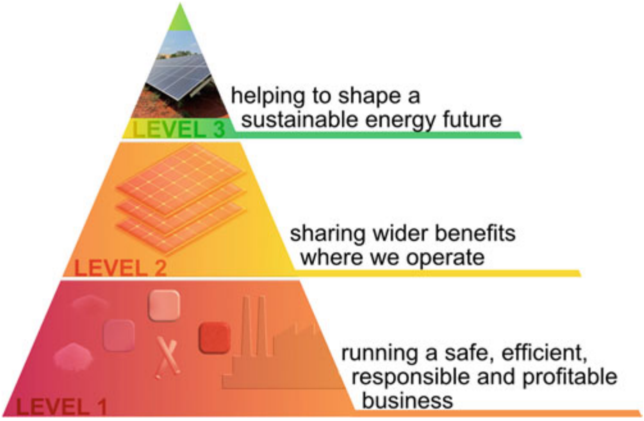


Fig. 5 Different levels for sustainability

non-renewable energy source using. There are predictions that by 2030 solar energy will become the most important energy source on the planet (Tulus et al. 2019). It should also be considered that the diffusion of solar energy as a safe energy source can stimulate economic growth, creating new jobs and becoming a pillar for economic growth in industries and services. These factors can significantly contribute to economic improvement, especially in developing countries (Mostafaeipour et al. 2021).

Finally, from a social point, it would be reflected that one of the greatest challenges in the world is to ensure universal access to electricity. One should particularly think about the influence that the lack of energy has on hospitals, schools, and emergency systems specially from emerging countries and rural regions worldwide (Wassie and Adaramola 2021). That is why it is vital the advances in the sector and the expansion of PV systems and of related materials continue, leading to the greater economic viability of SCs, which can contribute to the access of society as a whole (Kwak et al. 2020). Thus, three levels of development must be traced so that SCs have greater viability and a greater degree of sustainability. These levels are displayed in Fig. 5.

On a first level, SCs must be considered a safe, efficient, responsible, and profitable business to be economically favorable to their dissemination and use. Solar energy must be shared and disseminated with access even to the poorest on a second level. Finally, on the third level, SCs can contribute to a better future using more sustainable energies that help the local, regional, and global environments.

In this way, solar energy can be one of the greatest promising energy matrices, with the real potential to meet demands, boost economies, be sustainable, and, above all, its capacity to transform people's lives based on energy security (Radosevic et al. 2020). In addition, it will bring livelihood opportunities, especially for the poorest countries, which have been hardest hit by global warming (Mostafaeipour et al. 2021).

Sustainability of SC Types

When we think of SCs, the first image that comes to mind is solar panels on rooftops or in a solar farm. In fact, this sort of solar panel has dominated the market. Nevertheless, there are promising technologies in study to become SCs cheaper, lighter, flexible, efficient, and applicable everywhere. Scientists work tirelessly to create new pathways to produce more sustainable SCs with the advances in nanotechnology.

SCs are categorized into three main generations due to the different semiconducting materials used for their fabrication. The first-generation SCs called conventional, traditional, or wafer-based cells are most widely used and manufactured globally, showing well-matured in terms of their technology and fabrication process. The second generation of SCs was introduced to reduce the high cost of the raised process related to crystalline silicon SCs, providing a possible route to increased throughput and fully integrated operations. The second-generation photovoltaic devices share several standard features, such as long-term stability under outdoor conditions, minimal energy inputs, and small amounts of semiconductor material. Figure 6 shows the main examples of the first- and second-generation types of SCs. The new (third) generation of materials for SCs has emerged as an alternative to first- and second-generation SCs, seeking to overcome challenges such as high cost and efficiency (Ahmad et al. 2021).

First-Generation SCs

The first-generation SCs are subdivided into monocrystalline and polycrystalline cells. The cells are composed, basically, of silicon, the most abundant element on earth (Ranabhat et al. 2016). Figure 6a, b show a simple silicon SC and a diagram of a usual Si PV-based and Si module. The crystalline SC consists of two layers of semiconductor material, a p-n junction diode which induces an electric field across the junctions. When the semiconductor absorbs photons, they transfer energy to their electrons to move through the material. They are designed to maximize the effective contact area and reduce contact resistance losses. There are several SCs types; nonetheless, silicon-based SCs are used to construct about 90% of total SCs (Khatibi et al. 2019).

The most common SCs currently available in the market comprise single and multi-crystalline silicon with 93%, and other types of photovoltaics represent 7% of the market (Jlanka 2021). Bell Laboratories have developed the first silicon SCs in 1954 with efficiency of 6%. Since then, many efforts to improve the efficiency and cost of these materials for SCs have been realized. Silicon has indirect bandgap of 1.12 eV, which allows the material to absorb solar radiation in the UV-Vis region that has multiple reflections and allows strong light capture, which results in optical reflection different from widespread, generating high efficiency. Nowadays, the efficiencies for first generation range from 14% to 18% in production and ~25%

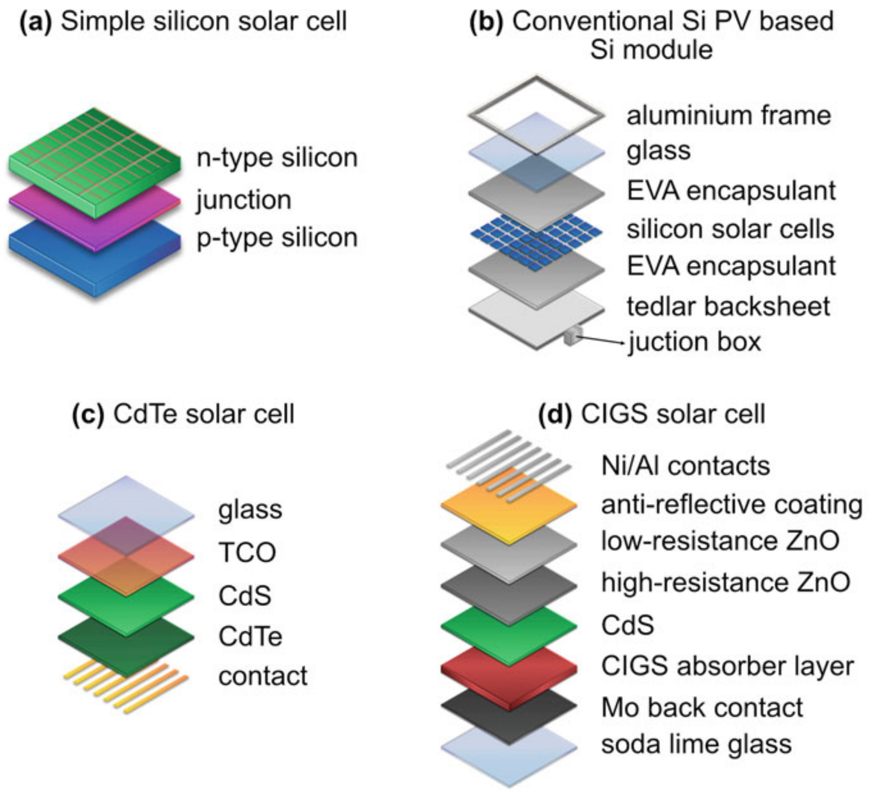


Fig. 6 (**a**) Schematic of a simple silicon SC (**b**) conventional Si PV-based Si module. (**c**) The basic structure of a CdTe SC; (**d**) the basic structure of a CIGS SC

on laboratory scale cell, with theoretical maximum efficiency of 26–28% (McIntyre 2010).

Monocrystalline silicon is made up through the Czochralski method, consisting of a crystal that grows in a single direction. First, raw silicon is melted up to 1500 °C in a crucible. Eventually, traces of different atoms are added to dope the silicon and make it p or n-type. After complete melting, the seed crystal shaft is dipped and withdrawn, controlling the rotation speed, temperature, and traction rate. Afterward, they are cut into small slices from ingots. The production cost is very high but presents high power conversion efficiency (PCE) (Simya et al. 2018).

Multicrystalline silicon is made by raw silicon that is melted and poured in a square mold, cooled, and cut into perfect thin wafers resulting in a large column grain of crystallinity. The production method showed some limitations associated with low purity and less efficiency (Kibria et al. 2014). This process is less expensive and straightforward than producing a single crystal. Multicrystalline silicon is commonly used commercially due to its relatively high efficiency and low cost than single crystalline silicon (Ranabhat et al. 2016).

From the sustainable levels, first-generation SCs are still far from reaching the three levels. Although silicon SCs have had an 80–90% market in the last 40 years, they are still expensive to produce, and their production has not zero emissions, is not clean, or 100% green. In addition, the consequence of the exponential increase of SCs installation is a high level of panels waste. At the end of SCs life, most photovoltaic panels end up in landfills when it is not sustainable and not an environmentally friendly option. It is estimated in 2050, 60–78 million tons of SC waste. On the other hand, different materials such as metal, glass, and polymer layers with bound laminate and semiconductors are used for first-generation cell manufacturing. Tin and lead, for example, can be leached or contaminate the soil, resulting in exponential environmental pollution.

Even so, various local state policies have been created to treat end-of-life (EOL) solar panels. Physical treatment by crushing and milling is the more conventional method to recycle PV because the emission linked with these steps is not considerable. Another method that can be highlighted is the physical-thermal process. After grinding, the material is subjected to heat treatment and sieved, allowing the recovery of around 85% of the panel as glass. The chemical recycling to recover metals is performed mainly by three main routes: precipitation, metal replacements, and electrolysis (Farrell et al. 2020).

Second-Generation SCs

The second generation of SCs exhibits high solar absorption coefficient with thinner layer than silicon cells. The main types are amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) based thin films. They present slightly less efficient than crystalline silicon but require less surface area to generate the same energy (McIntyre 2010; Ranabhat et al. 2016). Table 1 compares the main first and second generation of SCs in terms of advantages and disadvantages.

Table 1 Advantages and disadvantages of first- and second-generation of SCs

Materials	Advantages	Disadvantages
Monocrystalline silicon	Pure material with high efficiency on a commercial scale	High cost to production and installations
Multicrystalline silicon	Process cheaper and simple to produce a single crystal Relative high efficiency	Low purity, less efficiency compared to monocrystalline
Amorphous silicon	Thin layer/less material Cheaper compared to crystalline silicon	More space on the roof to achieve the same energy Low efficiency
CdTe	Relative high efficiency Thin layer/less material	Cd is toxic, affects health and the environment
CIGS	Relative high efficiency Thin layer/less material	High cost Toxic materials

Amorphous Silicon SCs

They are made up of a thin layer of silicon atoms. However, they do not form specific crystalline structure. These cells work best at high temperatures and need more space on the roof to achieve the same energy presented by crystalline silicon. They are commercially significant in utility-scale photovoltaic power stations, integrated PV, or a small stand-alone power system. SCs composed of amorphous silicon is cheaper than crystalline SCs. However, they also have low efficiency compared to crystalline cells (Simya et al. 2018).

Cadmium Telluride (CdTe)

The first CdTe/CdS SC was reported in 1972. CdTe is formed by a reaction between Te vapors and Cd and deposited on the surface using physical vapor deposition techniques. The CdTe/CdS SC is constituted by a heterojunction between n-type CdS and p-type CdTe, Fig. 6c. It is considered an exciting alternative to replace conventional crystalline silicon PV devices. After research for several decades, structured SCs based on CdTe thin films achieved the highest cell efficiency of 22.1% (Simya et al. 2015).

The process fabrication of these cell types is much cheaper than bulk silicon using polycrystalline materials and glass. CdTe has bandgap close to the theoretically calculated SC value and high absorption coefficient. Approximately 99% of incident light is absorbed by a layer of thickness of 1 mm compared to 10 mm of Si, significantly decreasing the quantity of used materials. The negative point of using CdTe for SCs is the effect on health and the environment since using cadmium. However, the amount of active material used is quite small, considering that CdTe SCs provided 10% of the world's energy; this accounts for less than a tenth of the world's cadmium usage (McIntyre 2010).

Copper Indium Gallium Selenide (CIGS)

Copper indium gallium selenide is polycrystalline and considered as an attractive material for PV SCs due to several characteristics, such as the absorption coefficient with 99% of the light being absorbed in the first micrometer-depth. It also produced a thin film for SCs due to their high efficiency comparing other thin films and low-cost potentials. The solar conversion efficiency of CIGS SCs achieved the highest cell efficiency of 22.6%. The construction of CIGS SC is shown in Fig. 6d. The operation is like a crystalline silicon SC that creates free electrons and holes. The electrons diffuse into CIGS in the electric field within the junction region. This point is guided to the CdS/ZnO layer, resulting in a voltage increase between the back and the front contacts (McIntyre 2010). However, the efficiency levels compared to crystalline silicon are still lagging, and a replacement by CIGS is necessary to reduce costs and use abundant but non-toxic materials (Simya et al. 2015).

As well as the first-generation, second-generation SCs are not entirely sustainable. The cost is still high, hazardous metals are used, and the efficiency is not so good. In addition to these drawbacks, the recycling of second-generation SCs has several environmental impacts. The process like film delamination (chemical and thermal) uses lot of energy, and chemical components have higher impact on the planet than the synthesis process (Maani et al. 2020). Additionally, silicon SCs also have limited efficiency, around 20%. Accordingly, new technologies have been widely studied to replace the traditional silicon SC, improving efficiency, and using sustainable materials and processes.

Third-Generation SCs

The third generation of SCs has begun as an alternative to replace the traditional silicon SCs. However, most of them are still in the research phase due to their lower efficiency than silicon SCs. Figure 7 displays the widely studied types of third-generation SCs, including the dye-sensitized SC (DSSC), organic SC (OSC), perovskite SC (PSC), and quantum dots (QDs).

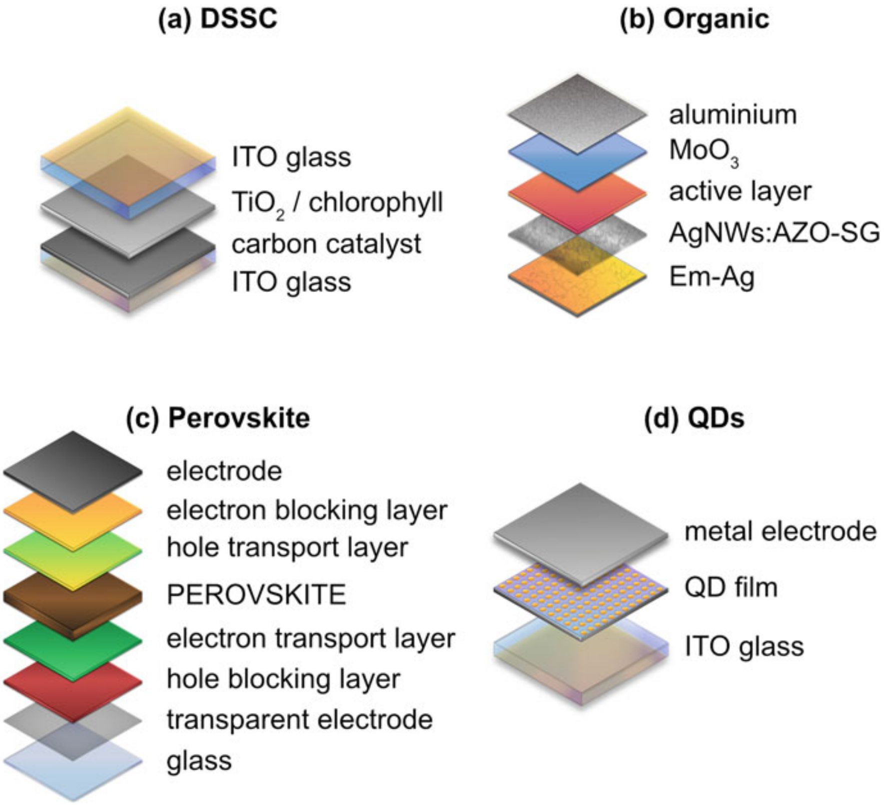


Fig. 7 Third-generation SCs. (**a**) DSSC, (**b**) OSC, (**c**) PSC, and (**d**) QDs

DSSC

DSSC first appeared in 1991 with O'Regan and Michael Gratzel, so they are also called Gratzel cells. These devices work like photovoltaic semiconductors that convert solar radiation into electrical current in an oxidation-reduction reaction, so organic dyes are illuminated with solar radiation in electrochemical cells. Brian O'Regan and Michael Grätzel used a transparent film of nanoporous titanium dioxide, TiO_2, to improve the electrode performance due to porosity. The first DSSC had a PCE of 7% (O'Regan and Grätzel 1991).

Currently, the PCE using DSSCs is around 9%. Although DSSCs are simple and inexpensive to produce, efficiency is still a challenge. So, different studies and modifications are carried out. In a recent study, An et al. (An et al. 2020) reported obtaining a device with PCE of 10.8% for DSSC. The authors have used carbazole derivative dyes containing triphenylamine fractions combined with a Cu(I/II) redox couple as electrolytes. Three different devices were obtained and evaluated as a function of the presence and position of the triple bond, which influenced the efficiency of the devices, which ranged from 9.2 to 10.8%. In another work, the authors combined two sensitizers to collect incident light in the entire visible spectrum range in the copper electrolyte. The device's efficiency was 11.3% for solar energy conversion, while for indoor lighting, the device achieved a PCE value of 28.9% (Freitag et al. 2017).

The fabrication and operation principles of a DSSC are illustrated in Fig. 7a. Traditional DSSC has five compartments: (i) glass substrate that behaves like the anode; (ii) TiO_2 film, which is deposited on the anode to make it conductive; (iii) sensitized dye bound to the TiO_2 surface to increase light absorption; (iv) electrolyte containing a redox mediator that acts on dye regeneration; and (v) counter electrode (CE), usually containing catalyst agent. In a DSSC, dye molecules absorb sunlight, and electrons are excited in the conduction band of the TiO_2 network. In this step, the dye is oxidized. Next, electrons are transported through the circuit to the CE and transferred to the electrolyte solution. The oxidized dye receives electrons from the redox mediator to flow through the circuit, generating electrical current (Freitag et al. 2017; Roslan et al. 2018).

To improve the efficiency of DSSCs, studies focus on the materials that will be used in each compartment. For example, at the anode, indium-doped tin oxide (ITO) or fluorine-doped tin oxide (FTO) are employed as glass substrates. FTO has stood out for its conduction properties, stability, and overall efficiency of 9.4%. Alternative plastic and metal substrates are also used, but their application is limited because the plastic is unstable, and the metal is opaque. The most used semiconductor is TiO_2 due to its porosity, stability, high surface area, cost, and ease of obtaining. But other oxides are used, such as zinc oxide (ZnO), tin oxide (SnO_2), aluminum oxide (Al_2O_3), and magnesium oxide (MgO) (Roslan et al. 2018).

Recent studies reported using a mixture of oxides in the photoanode for DSSC, as in the work by Bakr et al. (2018). The authors obtained nanofibers (NFs) from SnO_2 combined with TiO_2 by electrospinning. The NFs were supported in FTO, and the energy conversion efficiency of DSSC was 8%, higher than the results in which the authors used the isolated oxides (Bakr et al. 2018). Another important component of the DSSC is the dye, responsible for the absorption of solar radiation. A large number of dye molecules have been synthesized since the first DSSC, and some examples are N719 (Nazeeruddin et al. 1999), Y123 (Liu et al. 2017), and Z907 (Xie et al. 2010).

To be used in DSSC, the dye must meet specific criteria, such as being luminescent, compatible with the solar spectrum, having long-term operational stability, and having high redox potential for regeneration through a redox mediator. In this context, the function of the electrolyte is to renew the oxidized dye and allow for the quick and efficient diffusion of charges. The redox couple of iodide and triiodide ($I^-/I^-{}_3$) is the most used. However, other redox mediators have been used as Br^-/Br_2, SCN^-/SCN_2, Co(II/III), and Cu(I/II) (Sharma et al. 2018).

Finally, at the cathode, electrons are moved to the electrolyte, and, therefore, the catalysts used in the electrode need to have high electrical conductivity and high catalytic activity. Usually, the catalyst used is platinum (Pt). Still, to improve the efficiency and reduce the costs of DSSCs, recent works have been done replacing Pt with alternative catalysts such as carbon-based materials, metallic alloys, conductive polymers, and metallic oxides.

Although the efficiency of DSSCs is still smaller than other SCs, characteristics such as the ability to act in different lighting conditions, substrate flexibility, and low-cost production increase the potential for the commercialization of these devices. In studies carried out by Kalowekamo and Baker (2009), the cost of a DSSC was estimated between 0.5$/W and 1$/W (Kalowekamo and Baker 2009). This calculation is based on the cost of materials and the efficiency of the SC. The efficiency of the SC is a determining factor, as the higher the efficiency, the more kilowatt-hours (KW/h) of energy will be produced.

In current years, the price of silicon SCs has come down. According to Mozaffari et al. (2017), for a DSSC, currently, presents price compatible with silicon SCs (around 0.66 US$/W), the efficiency should be 13.6–17.6%, results not yet reached (Mozaffari et al. 2017). Because of this, researchers in the different stages have focused on searching alternative materials for DSSC to increase efficiency and reduce the cost of the device.

In terms of sustainability, the recycling capacity of the DSSC can be highlighted. Rabaia et al. (2021) highlighted recycling as one of the advantages of DSSCs when compared with other third-generation SCs, such as perovskite SCs and QDs SCs (Rabaia et al. 2021). However, the materials used in SCs and their combinations affect the recycling of DSSCs. Conventional DSSCs create harmful waste without an economically favorable form of recycling. Some newer DSSC devices use materials such as ruthenium and platinum to increase efficiency. However, these materials are toxic and scarce and make recycling DSSCs difficult (Schoden et al. 2021).

On the other hand, Miettunen and Santasalo-Aarnio (2021) highlight the use of alternative materials such as flexible thin substrates that can support Ag recovery or replacement of iodine electrolyte with cobalt or copper electrolytes that eliminate toxic gas issues. The initial purpose of using these materials was the efficiency of the devices, but they significantly contribute to improving the recycling of DSSCs (Miettunen and Santasalo-Aarnio 2021).

OSC

Another class of third-generation SCs that has been widely studied is the organic solar cell (OSC), also known as organic photovoltaic cells (OPV). This type of SCs uses polymeric materials as a light-absorbing layer. In inorganic semiconductors, the incident light absorption produces excitons, which are strongly bonded and electrically neutral electron-hole pairs. The valence and conduction bands are replaced by the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), with positive and negative charge carriers. Then, there is the dissociation of excitons in free carriers, transported and collected in the electrodes (Hösel et al. 2013).

The working principle of a conventional OSC is based on four compartments: (i) a substrate to absorb solar radiation; (ii) an anode; (iii) a photosensitive layer of active material (polymer); and (iv) a cathode. The interest in OSC is due to advantages such as lightness, high efficiency, flexibility, and the possibility of generating energy on various surfaces.

The substrate used in OSC is usually glass or a flexible and transparent polymer, illuminated using solar radiation. The material used to coat the glass substrate in OSC is ITO. In addition, the ITO substrate can act as an anode to capture solar energy. A protective layer of PEDOT:PSS material is deposited on the substrate to prevent the device's degradation (Khalil et al. 2016).

In sequence, there is an active layer of organic material. Basically, OSCs can be single-layer or multi-layer (heterojunction), as shown in Fig. 7b. Single-layer OSC is formed by only one active organic material, which is often a limitation in device's efficiency due to the length and rate of decay in the diffusion of excitons demanding high energy. In this context, OSCs with mass heterojunction layer (BJH) emerged to overcome this limitation. In heterojunction, the active layer is composed of the donor (low LUMO) and acceptor (high HOMO) layers, as first proposed by Tang in 1986 (Tang 1986). Finally, the last compartment in an OSC is the cathode, usually made from silver, aluminum, or copper.

Recently, the Japanese company Toyobo Co., Ltd., in partnership with the French Government Institute CEA, developed an OSC with a high PCE value (of around 25%). The SC was created using glass substrate, poly (ethylene terephthalate) (PET) film substrate, solvent optimization, and coating technique. Toyobo plans to use the material as a wireless power source in temperature-humidity and motion sensors, with a perspective for 2023. Although research is ongoing, the efficiency shown is superior to PSC, bringing high expectations (Toyobo Co. 2020).

In 2009, Kalowekamo and Baker estimated the OSC cost and compared it with DSSC ones. According to the authors, the cost for OSC unity with 5% efficiency would be between $1.0 and $2.83/Wp, higher than the estimated cost for DSSC unity in the same period (Kalowekamo and Baker 2009). Recently, Lee et al. (2020) estimated the cost of transparent OSC integrated into buildings based on solution processing in a roll-to-roll (R2R) manufacturing line. For an OPV unity with 10%

conversion efficiency, the estimated manufacturing cost per module is \$1.6 Wp. The authors expect the cost drops in the near future to around \$0.47 per Wp due to the synthesis of new materials (Lee et al. 2020).

As OSC are recent and developing devices, there are no works that discuss the recycling of the related materials. However, alternatives such as those presented by McDowell and Bazan (2017) in using green solvents can be satisfactory alternatives in future processes for recycling OSCs (McDowell and Bazan 2017). Although the third-generation SCs stand out in research, they are up to now limited by the stability and useful life of the devices (Mozaffari et al. 2017).

PSC

Perovskite is a class of crystallite that presents a composition of ABX_3. Generally, A is a large cation as methylammonium (represented by MA), ethyl ammonium, formamidinium (FA), or inorganic cesium (Cs^+); B represents a metal cation that can be Sn^{2+}, Pb^{2+}, and Ge^{2+}; and X is a halide anion Cl^-, I^-, or Br^- (Llanos et al. 2020). SC-based perovskite has shown great attention due to high PCE, low cost of fabrication, and simple solution processing (Gholipour and Saliba 2018). This material was used for the first time in a PV cell in 2009 by Kojima et al. (Kojima et al. 2009). In such research, the perovskite was formed by ammonium and lead ions, and iodide or brome as halogen ion. The material was supported on TiO_2 conductive mesoporous glass and presented conversion efficiency of about 3.8%. As the PSCs have been developing, the researchers of the field look for better features and efficiency to change the composition and structure of the mineral or parts of PSCs.

The conventional PSC is composed of several layers, Fig. 7c. One layer contains compact TiO_2, which is responsible in avoiding the direct electrical contact between the hole transporting material and transparent conductive oxide (TCO). TCO is a layer usually composed of fluorine-doped tin oxide (FTO) that actuates as conducting electrodes, the same works as a metallic layer (another layer in the PSC). The HTL layer acts as hole-transporting material. Another layer is composed of TiO_2 mesoporous or alumina Al_2O_3, which works as the electron-transporting layers (ETLs). The deposition of perovskite precursor solution conventionally forms the perovskite layer upon TiO_2 mesoporous, responsible for light absorption. The PSC arrangement may be in a planar layout. The glass-TCO-ETL-Perovskite-HTL-metal, determined as conservative conformation (n-i-p), may present an inverted conformation (p-i-n) glass-TCO-HTL-Perovskite-ETL-metal (Ansari et al. 2018).

The perovskite films are deposited on the substrate by different methods such as solution process (spin-coating), vapor deposition, and hybrid vapor-solution. The solution process is more accessible and cheaper technique than other processes. Because of this, it is a widely used method for PSC production (Ansari et al. 2018). The preparation of perovskites films can be divided into two methods: one-step and two-step deposition. The main difference is that the precursor solution is prepared before the coating surface in a single-step deposition. Already, in two-step (sequential) deposition, there is generating of a first layer with PbX_2 species ($X = I, Br, Cl$) on the substrate. Then the solution with CH_3NH_3X ($X = I, Br, Cl$) in a specific solvent is further deposited. Both (one- and two-stepped) methods need drying and annealing process to finalizing the synthesis (Ansari et al. 2018).

Although the low cost and simplicity of the solution process, this method presents some disadvantages, such as incomplete coverage of the surface, which decreases the performance. Therefore, vapor deposition under vacuum can be used to produce a perovskite layer. In this method, the crucible precursor solutions are co-evaporated to their respective sublimation temperature. The perovskite layer is formed on the substrate that is fixed above the crucibles. Liu et al. (Liu et al. 2013), for instance, reported the synthesis of the perovskite layer using vapor deposition, and the device shows efficiency of 15.4%. This method offers some advantages, such as films with high-purity composition. The film can be formed on various substrates because the wettability issues are not verified in this procedure (Ansari et al. 2018).

Currently, the PSCs can have layers of different materials that increase efficiency, stability, and lifetime once the degradation and device stability are key issues for obtaining high PCE and application of PSCs in scale large as well. Furthermore, it can decrease the production cost of the PSC. Materials such as carbon, aluminum oxide (Al_2O_3), and polymers can be used as substitute layer and improve PSC properties. PSC produced in the laboratory can be reached above 20% of conversion efficiency, and this evolution was obtained in a short time (Niu et al. 2015; Ono et al. 2016; Petrus et al. 2017).

Up to now, perovskite is the only third-generation PV in the market. With 25.5% of efficiency, the perovskite cell based on $CH_3NH_3PbI_3$ perovskite layer sandwiched between two thin organic charge-transporting layers [arylamine-containing polymer (polyTPD) and [6,6]-phenyl C61-butyric acid methyl ester (PCBM)] was recently employed in commercial IoT applications. In 2021, Saule Technologies was the first to begin industrial production of this type of cell, representing an important landmark in the evolution of photovoltaic systems (Saule Technologies 2021).

Although the potential use of perovskite is being an absorbed agent in SCs, it is necessary to pay attention to the environmental impact of these devices, since in most of the composition of PSC there is Pb, which is hazard to human health and the environment. To solve the problem, the Pb can be replaced by another element, such as Sn and Bi. Sn exhibits some composition with a bandgap near perovskites based on Pb.

The PSC also can be reused by an economically attractive process without loss of performance, and once every layer can be removed separately. Binek et al. (Binek et al. 2016) reported the process of recycling $MAPbI_3$ perovskite for the first time. In this process, they separated the $MAPbI_3$ into MAI and PbI_2, and then it was possible to reuse the toxic lead iodide in the same device. The performance of the recycled PSC showed efficiency above 16%. Besides recycling own devices, new devices can be constructed using raw recycled materials. Chen et al. (Chen et al. 2014) show PSC fabrication with an efficiency of 9.37% using lead from recycled car batteries.

QDsSC

Quantum dots (QDs) are semiconductor nanoparticles that exhibit ultrasmall size (Yang et al. 2019). Their optoelectronics properties are mainly dependent on the size and the composition. This material shows quantum mechanical behavior due to the specific size of the energy bandgap. Because of these features, the QD is currently used in various electronic devices, such as SCs (Hong 2019). The first report about QD desorption on TiO_2 electrodes was made by Vogel et al. (1990). They evaluated the performance and found about 6% efficiency, and various authors reported the use of QD on mesoporous TiO_2 thenceforth (Sahu et al. 2020).

The configuration of QDs sensitized SCs (QDSCs) is like the DSSC. This similarity is due to the replacement of dye by QD in this configuration, looking for a more efficient device. QDSCs have photoanode based on mesoporous metal oxide film (TiO_2), an electrolyte, generally the polysulfide, and CE (Chebrolu and Kim 2019; Du et al. 2019). The operation of QDSCs occurs following two steps, as shown in Fig. 7d. Firstly**,** the light is absorbed for QD and produces electrons-hole pairs, resulting in photosensitizer oxidation. After, the electrons in the conduction band (CB) are injected into the TiO_2 layer, and the holes migrate to the electrolyte and are responsible for oxidizing it. The electrolyte donates electrons to QD that is regenerated.

One of the main advantages of QD in SCs is multiple exciton generation (MEG). The number of excitons produced by only one photon is restricted by energy conversion (Smith and Binks 2013). The process of MEG occurs in the QDSCs when the absorbed photon has once, twice, or three times the value of the energy bandgap. The excitons will correspond, respectively, to the one, two, and three electron-hole pairs. This process avoids energy loss and improves conversion efficiency (Du et al. 2019).

In the last years, the main component of the QDs used in SCs is chalcogenide semiconductors such as CdS, CdSe, and PbS. Like those related to the PSC, these elements are considered toxic and can cause environmental problems due to their nanoscale nature. One of the possibilities to solve this problem is to employ the QDs green synthesis with high efficiencies such as InAs, Sb_2S_3, Ag_2S, Cu_2S, and others. These new materials already show good efficiency (Du et al. 2019).

The QDSCs show less environmental impact than other SC devices. Şengül and Theis (Şengül and Theis 2011) compared QDSCs with other SC, like silicon SC and thin films SC. They show that QDSC exhibit fewer SO_x and CO_x gases emission than other SC devices and carbon-based energy sources. However, the QDSC demonstrated higher heavy metal emissions than other devices due to the incineration process of the hazardous waste disposable produced during the size-selective precipitation steps of QD and the coating of QD layer. This issue can be resolved by recovery of solvent, for example.

Finally, most third-generation SCs are still under development, and some perovskite SCs were recently commercially employed. So, recycling methods are still being studied; as they are the materials used for manufacturing SCs, it is expected to make the recycling process economically favorable.

SCs: Reuse or Recycle?

The solar panel's EOL is around 20~30 years, depending on its generation. There is an increase in solar panels production, and consequently, over the next few years, it will result in an exponential growth in waste. According to the International Renewable Energy Agency (IRENA) (Augustine et al. 2019), it is estimated that the cumulative photovoltaic waste by early loss scenario would reach 78 million tons by 2050.

Due to the importance of the subject, the European Union (EU), for example, already has an established directive to deal with the subjugate, 2012/19/EU, applicable to the management of domestic and industrial photovoltaic waste (Parliament et al. 2020). The adopted policy values the recycling and reuse of materials and encourages research to develop processes that meet the purposes. Japan and the USA also invest in policies and research to recycle solar modules. Developing countries are already discussing the issue of implementing specific policies for the sector (Majewski et al. 2021).

The impact created by waste solar panels can be mitigated through reuse or recycling. During the life cycle, infiltration repairs, replacement of electrical components, and external junction boxes located outside the main body of the solar panel can help with the potential output and reuse of old equipment without the need for cell separation or treatment. Recycling demands an intensive energy process when compared to reuse. The normal recycling process includes the complete crushing of the EOL panels into small pieces. It focuses on recovering and recycling the essential parts, mainly Si panels, and recovering contaminating or higher-cost metals, as shown in Fig. 8.

The process employed for the first- and second-generation panels is different due to the structure of the modules. Mechanical and chemical treatments are commercially used in the recovery and recycling of the solar panels, but other methods are under investigation.

For first-generation panels, the focus is on recycling glass, polymer, Si cells module, and other metals. One of the fundamental points in recycling is removing the anti-reflective coating layer of colorless ethylene-vinyl acetate copolymer, (EVA), used to recover the crystalline silicon, which involves the application of organic solvents, such as trichloroethylene, O-dichlorobenzene, benzene, and toluene, or nitric acid, following the temperature (Chowdhury et al. 2020a).

Second-generation panels represent a small portion of the panels sold. In this case, there are concerns with the recovery of toxic metals that can result in environmental problems. Ongoing research demonstrates conducted Cd and Te separation by using various ion-exchange resins on the metals in sulfuric acid solution over different periods, obtaining high yields. For copper indium gallium(di) selenide (CIGS), wet-chemical extraction of metals is the evaluated method. The wet-chemical extraction method is dependent on desalinizing composites, recovering the Cu, and separating other metals such as In and Ga (Chowdhury et al. 2020b). The evaluated processes, however, demand high cost, waste generation, dangerous emissions in some cases, and high energy demand.

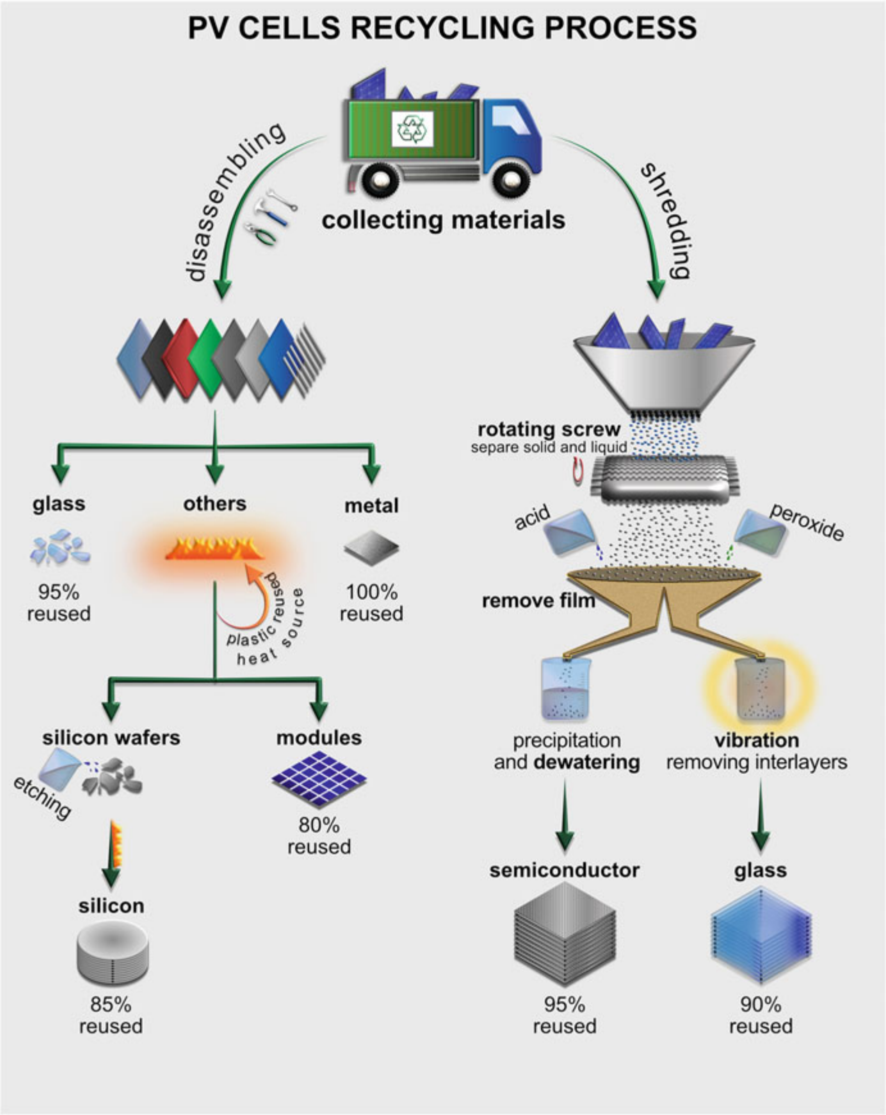


Fig. 8 Recycling and reuse process for SCs

The main component in third-generation cells is ITO, very expensive due to the limited supply of indium and the geopolitical state of its main reserves (Lokanc et al. 2015). It can correspond to more than 50% of the cost of the SCs (Augustine et al. 2019). Ongoing researches demonstrate that ITO recovery can be made by applying non-volatile alkaline solvents, maintaining the ITO properties that can be returned to the production line for reuse. However, methodologies are still under study. It is expected that for this generation PV technologies, such as perovskite devices, significant EOL waste products are more likely because of its technology limitation.

Considering current technologies, the cost for recycling is higher than the number of valuable materials existing in PV, making recycling economically unfavorable. The implementation of reverse logistics programs can expand and facilitate the recycling of solar panels, improving the involved costs. However, in the coming decades, the amount of material recovered will make the process viable with the increase of EOL plates. In addition, it can guarantee the sustainability of the supply chain in the long term, benefiting the whole chain by reducing costs and gas emissions.

Another favorable point for recycling is that this will be a global problem. It will require an entire organization of several sectors, including governments, producers, and so forth, in terms of a circular economy that brings benefits and cost reduction for the entire chain.

Advantages and Challenges in Sustainability in SCs

The first installations of solar panels took place in the 1990s. From the year 2000 onwards, PV energy generation has grown at an accelerated pace, mainly encouraged by the accessibility of domestic and industrial consumers. Greater accessibility to PV technology and awareness of the use of renewable energy boost the popularization of this system (Ahmad et al. 2021).

Most of the installed equipment, ~80%, are the first-generation type, based on monocrystalline or polycrystalline Si. Silicon is preferred due to its semiconductor property and lower cost when compared to more efficient materials. The efficiency of this PV-type SCs varies with the installation location, temperature, and time of direct incidence of solar radiation (Righini and Enrichi 2020).

The installed second-generation systems are easier to manufacture and have lower production cost due to the smaller amount of material needed in their manufacture. These systems perform better at high temperatures but have shorter lifespan and slightly lower efficiency than traditional cells. In expansion, the research and development of the third generation that explores new materials and manufacturing methods are ongoing at strides, seeking to combine high efficiency and very cheap production (Fthenakis 2009).

The great challenge for these systems is the supply of some materials, making any small increase in demand for their components result in high acquisition costs. For example, currently, Te is quoted >\$400/kg, Se > \$150/kg, and ITO powder >\$300/kg, values much higher than those observed over previous years (SMM 2022). However, using these systems has several advantages, such as exploring a renewable and inexhaustible source of energy available for free, being eco-friendly because no harmful byproducts are released, or pollutants released. Furthermore, PV requires low maintenance costs and thus reduces the final cost of electricity, the produced noise pollution. So, this technology certainly leads to the solution of nowadays energy crises.

Another general challenge observed for spreading uses of SCs is the initial cost of installation. In addition, SCs are not that very steady because they are not able to generate or save energy when there is no solar radiation, low efficiency compared to its size, and need for a larger area for installation and processing.

The integration of PV installation on the roof-top in urbanized environments generates insignificant effects on the ecosystem. However, the creation of solar plants with high capacity (> 1 MW) that cover large areas should be considered mostly in regions with a low impact on biodiversity, besides combining the objectives of generating renewable energy and maintaining conservation areas, for example (Chowdhury et al. 2020b). This factor should be noted as the installation is generally far from the center of consumption and demand for large areas, fragmenting the landscape and creating barriers for the movement of species, for example. In addition, another point of attention is with the maintenance of utility-scale solar energy (USSE), which requires dust suppressants, water consumption in panel cleaning, anti-rust, and herbicides, which, when used without control, can cause environmental damage. The USSE association with degraded areas or co-location with agriculture is an interesting combination as long as they are safe and do not pose food risks (Righini and Enrichi 2020).

Respect for environmental aspects in terms of installation and handling and correct subsequent destination for solar panels guarantee sustainability for the application of the system at competitive costs compared to other energy sources. Nowadays, silicon SCs (first-generation) are probable to decrease the price and could be installed in huge numbers in industrial, commercial, and residential sectors. These improvements will be possible by cumulative bulk manufacturing and innovative technologies that allow the SCs being much more efficient and cheaper. Government subsidies are expected to stimulate rapid expansion in residential and small commercial consumers, who will then receive significant returns on their investments in SC systems.

The universal PV growth will be driven by the emerging market in developing countries with low share of SCs in their energy matrix. Also, by considering how best to meet their future energy and development clean and sustainable, the falling costs of key clean energy technologies offer significant opportunities to chart new, lower emissions path to growth centered on clean energy.

General Conclusions and Future Perspectives

Although global fossil fuel resources are not completely exhausted, the negative impacts in the social, health, and environmental segments due to current unsustainable energy-use patterns are strongly evident. Renewable and non-polluting sources have become important already in the past decades and will become still more important in the next ones. Therefore, as an alternative to fossil fuels, solar energy is increasingly advancing on the whole planet.

The solar energy system is environmentally clean, free, inexhaustible, and surprisingly available in adequate quantities in almost all habitable parts. This system has already left the trend level and started to become popular as a renewable energy-source generation. Although solar energy is sustainable, some disadvantages thwart its entire sustainability, such as high cost, hazardous materials employment, and CO_2 footprint emission through the manufacturing development. As mentioned in this chapter, three levels of development must be traced to solar cells (SCs) to reach high degree of sustainability, economic, environmental, and social impacts. In this context, here it was presented the main technologies studied to improve efficiency, reduce the cost, replace hazardous materials, and develop the manufacturing development. Among these technologies, the third generation is the maximum promising SCs, including the DSSC, perovskite, organic, and QDs SCs. Perovskite is an emerging photovoltaic (PV) technology with high potential to dominate the market since it can hit impressive 25.5% efficiency besides being the first of the commercially available third-generation SCs.

Nevertheless, from now there is a long path to cross. The global energy demand is continuous and growing, the higher the advanced country, the greater its energy dependence. Despite great effort to diversify energy sources, today, modern society still has non-renewable sources as universal energy matrix, such as gas, coal, and oil which result in high costs to the planet due to the constant emission of high amounts of greenhouse gases. The decrease in the alarming levels of emission of these gases will only be achieved with the influence of all countries, in a mutual effort to change the energy matrix gradually.

Among the available sources, SCs today have relevant importance in producing energy from a renewable, clean, cheap source, with the capacity to supply world parts that enjoy high insolation. To date, investments made in research have already resulted in the SCs growth which combines the attractively cost-efficiency factor.

New research continues an increasing scale in improving and developing new systems. Still, above all, in the progress of reuse and recycling methodologies, that will drive growing waste generation with the end-of-life (EOL) of old systems in the next years. Adding to these factors, the awareness of companies, consumers, and governments, among the financial subsidy for the implementation of large solar parks, will play a fundamental role in the extension of photovoltaic energy generation, always maintaining its harmonious coexistence with the environment and energy security for all.

Acknowledgments The authors acknowledge Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (Grant #150866/2020-8, 165734/2020-5, 423818/2018-0, 573636/2008-7, 435975/2018-8, 309711/2019-3, 421648/2018-0 and 307429/2018-0) for the financial support and for the concession of a scholarship and the São Paulo Research Foundation (Grant 2018/12871-0, 2012/07067-0, 2013/23572-0, 2016/019405, and 2013/07296). Special thanks to Serrapilheira Institute (grant number Serra-2018-4357) for the technical support and to CEPID (2013/07296-2), INCTMN (2008/57872-1). This study was financed in part by the Coordination for the Improvement of Higher Education Personnel (CAPES – Brazil) – Finance Code 001, CAPES-EPIDEMIAS (Programa Estratégico Emergencial de Prevenção e Combate a Surtos, Endemias, Epidemias e Pandemias Número do Processo: 88887.513223/2020-00).

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