Revista Nacional de
Gerenciamento de Cidades
ISSN eletrônico 2318-8472, volume 09, número 71, 2021

Perspectives of New Alternative Materials to Silicon for the Production of Photovoltaic Solar Cells: A Systematic Literature Review

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ABSTRACT
Much has been studied about solar energy as a renewable energy, as it can be transformed in electricity by means of solar panels. Innovation is very important when it comes to photovoltaic technologies, because the advantages of these technologies are low installation and maintenance costs and no environmental impact during operation. The market of photovoltaic products is dominated by the silicon technology, but new second- and third-generation cell technologies have been developed. This research shows that the Perovskite solar and the Multijunction solar cells have the potential to achieve maximum power conversion efficiency and minimum production costs in the near future. Dye-sensitized solar cells (DSSC), Organic photovoltaics (OPV), Quantum dot sensitized solar cells (QDSSC), Single-junction solar cells, and the Heterojunction solar cells will achieve such potential in a more distant future, because limitations imposed by efficiency and costs must be overcome. Having these parameters in mind, the overall objective of this research is to analyze the materials of strategic potential to compete with silicon in the composition of the photovoltaic solar cells. A Systematic Literature Review helped retrieve 112 papers that report the most researched materials from 2014 to 2018. It is concluded that despite good results have been obtained from many of such studies, some alternative materials to silicon are still not technologically acceptable in terms of efficiency. It is expected that the use of a better distributed and cheaper solar energy technology will be possible in the near future.

KEYWORDS: Photovoltaic Cells; Photovoltaic Solar Energy; Innovation; Silicon.

1 Introduction

The increasing energy consumption in the contemporary world calls for the necessity of constant research and development of new energy generation technologies that can, at the same time, supply the high energy demand and be less aggressive to the environment (MACHADO; MIRANDA, 2015). In this sense, solar energy is a good alternative of renewable energy generation; on the other hand, it still represents a small fraction of the total energy generated in the world. When compared to European countries, the incidence of solar radiation reaches good levels in Brazil, the average solar energy generation falling in the range of 1200 and 2400 kWh/m^2/year. In Germany, for example, such range is 900-1250 kWh/m^2/year (MACHADO; MIRANDA, 2015).

The development of the electronics industry has allowed a huge leap in the use of photovoltaics related to processes that involve silicon transformation, which is the essential raw material in the composition of photovoltaic cells. Silicon is purified, until high purity necessary for use in the photovoltaics industry is reached (DAVIES; FRISSO; BRANDAO, 2018).

It is not possible to disregard the materials used in the production of photovoltaic cells. Silicon is one of the basic raw materials most used in the production of photovoltaic solar cells and depending on the use costs and efficiency vary significantly. Three types of silicon are used in the photovoltaics industry: the polycrystalline, the monocrystalline, and the amorphous silicon. The monocrystalline silicon has a well-defined molecular structure: the higher purity, the higher efficiency – and higher is the cost. Contrarily, the polycrystalline silicon has a less homogeneous structure: lower is the efficiency and the cost. The structure of the amorphous silicon is undefined, implying low efficiency when used in the production of photovoltaic cells and panels.

Regarding environmental impacts, two aspects must be considered. The first is climate changes, once greenhouse gas emissions in the production of photovoltaic modules are in the range of 30-45 gCO_2/kWh (ALSEMA; DE WILD-SCHOLTEN, 2006), which is relatively low when compared to other sources. Chen et al. (2016) highlighted a greenhouse gas emission range from 30 to 110 gCO_2/kWh, considering life cycles from 20 to 30 years. These numbers show that from the point of view of climate changes, the advantage of photovoltaic energy is clear. On the other hand, the great concern is related to the environmental impacts of the silicon purification phase. Alternative materials such as perovskite/Si are potentially less toxic to humans (effects associated or not with cancer) and less ecotoxic to water, when considering a life cycle of 20 years (LUNARDI et al., 2017).

Additionally, the efficiency in transforming solar energy into electricity of most of the commercial photovoltaic modules is at maximum of the order of 20%. Teixeira (2019) identified several studies that show that alternative materials to silicon, such as polymers or multijunction materials, have potential for higher energy conversion efficiency (30 or 50 %), making the use of photovoltaic energy economically viable. Therefore, the reduction of the amount of material, energy and toxicity in production processes must be taken into account (DAVIES; FRISSO; BRANDAO, 2018).

Considering the necessity to research new technologies that cause less impact to the environment, the research question to be answered here is: “Which are the main alternative materials to silicon for the production of photovoltaic solar cells, based on academic-scientific production?.” The objective of this study is, by means of a Systematic Literature Review (SLR), to identify and classify the alternative materials to silicon for the production of photovoltaic solar cells, taking into account energy conversion efficiency, costs, and environmental issues.

2 Theoretical Reference

2.1 Photovoltaic technologies

Electric energy production using renewable sources has quickly grown and has called much attention thanks to its sustainability. The sun is an eternal source of renewable energy and it has been used in the production of electricity by means of photovoltaic devices, which has caused less impact to the environment (MITRA et al., 2018).

According to Pereira et al. (2017), the levels of global horizontal irradiance are good in Brazil, varying from region to region as a function of the climate. Thanks to the abundance of energy, the structure of the photovoltaic cells and the improvement of the energy conversion efficiency are the focus of continuous scientific studies of the solar energy transformation in electricity. The efficiency in energy conversion has successively increased and the next-generation photovoltaic cells are the solution to solar energy transformation (OPWIS et al., 2016). According to House et al. (2015), the research for the development of this technology has caused the reduction of costs and the expansion of the useful time of PV devices to more than 25 years. It is a viable solution to address global energy issues for a future based on sustainable energy.

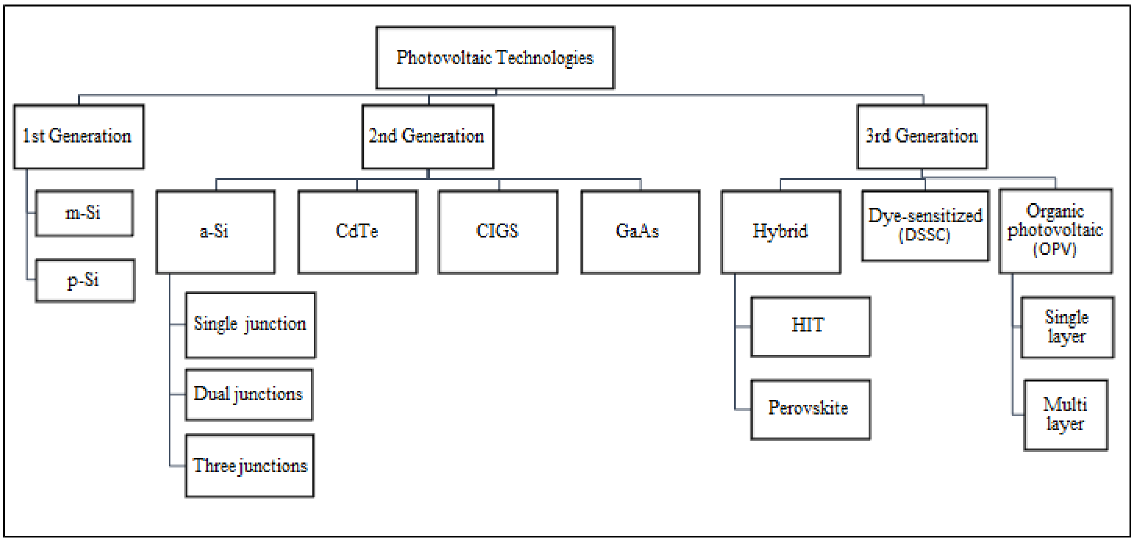
The photovoltaic effect was discovered by the French scientist Alexandre-Edmond Becquerel in 1839. However, a promising result of the solar energy/photovoltaic studies was obtained by the Bell Labs scientists in the 1950’s, who found out that silicon, when chemically treated from impurities, reacted to light and generated electric energy. This property was researched by Calvin Fuller, who demonstrated the first solar cell made of silicon, which later would become the major element for the production of computer chips (VALLÊRA; BRITO, 2006).

The silicon used in solar cells originated in the microelectronics industry. Silica (SiO_2) is the main material used to obtain high-purity silicon produced in electric ovens that, in turn, consume much energy (FERREIRA; FENATO, 2017).

2.2 The main materials

The photovoltaic technologies under development are basically divided in three types or “generations”, which can offer promising alternatives regarding cost, efficiency, and sustainability (BÜHLER; SANTOS; GABE, 2018). The variety of materials used in the production of photovoltaic cells is shown in Figure 1.

Figure 1 – The main photovoltaic cell technologies.



Source: Adapted from KUMAR; KUMAR (2017) and OGBOMO et al. (2017)

The main photovoltaic technologies for the production of solar cells existing in the photovoltaics market are presented below.

2.2.1 First-generation photovoltaic cells

The first-generation photovoltaic cells started to be developed in the 1950’s. To this day, the silicon technology has had the major share of the international market, thanks to low-cost production and efficiency in converting solar energy. The cells are basically 100 to 200 µm-thick silicon wafers cut from solar grade silicon boules (BÜHLER; SANTOS; GABE, 2018).

Depending on the manufacturing process, the photovoltaic cells are classified as: a) Monocrystalline Silicon (m-Si) – obtained from the growth of a single high-purity crystal; and b) Polycrystalline Silicon (p-Si) – produced from the solidification of a melted silicon block. In the latter process, the crystals are oriented along a fixed direction, resulting in melted Multi-Si square ingots, cut in blocks and then in wafers (KUMAR; KUMAR, 2017).

2.2.2 Second-generation photovoltaic cells

The second-generation photovoltaic cells are produced applying thin-film layers of photovoltaic material on a substrate, thus the term Thin-Film. The substrate can be glass, plastic, ceramics or metal. The thickness of the thin-film layers varies from nanometers (nm) to micrometers (µm), resulting in light and flexible cells. In the manufacturing process, little raw material is used, making the final product cheaper. Each layer can be sequentially deposited upon the previous one (OGBOMO et al., 2017).

2.2.3 Third-generation photovoltaic cells

The next-generation or third-generation photovoltaic cells are so called because they are still being researched in the laboratory and respond for a small market share. Several organic substances are being studied, including organic-metallic materials. The most commonly researched substances are: Dye-sensitized solar cells (DSSC), Organic photovoltaics (OPV), and Perovskite Solar Cells (OGBOMO et al., 2017).

a) The Dye-sensitized solar cell (DSSC) is based on a semiconducting material formed between a photo-sensitized anode, an electrolyte, and a photo-electrochemical cathode. DSSC combine organic and inorganic materials and are mechanically resistant. They are produced from low-cost raw materials and are easily processed. DSSC are light, can be produced on flexible substrates, and can be colored according to the dye used (O'REGAN; GRÄTZEL, 1991). The manufacturing process of the dye-sensitized solar cells is simple, of low cost, and their energy conversion efficiency ranges from 8 to 14%. The disadvantages are that they are sensitive to the climate, their useful life is 10 years, and they can be corrosive and toxic when lead is used in manufacturing (OGBOMO et al., 2017).

b) The Organic photovoltaics (OPV) are organic or plastic solar cells composed of organic materials such as polymers, pentacene, copper phthalocyanine, polyphenylene vinylene, and carbon fullerenes, known as small-molecule compounds (100 nm). Printing is used in the manufacturing process and the impact to the environment is small (KUMAR; KUMAR, 2017). Production is of low cost, OPV are flexible and cheap for photovoltaic applications. However, if not effectively protected, they undergo environmental degradation (OGBOMO et al., 2017).

The energy conversion efficiency expected for OPV cells are more than 11%, when heterojunctions are used, i.e., cells constituted of several layers of blends of conjugated polymers and soluble fullerene derivatives. These cells are sensitive to oxidation and humidity, and therefore their efficiency is reduced (KUMAR; KUMAR, 2017).

c) The Perovskite Solar Cell are hybrid perovskite-based solar cells that are suitable for the production of low-cost, efficient photovoltaic systems. The perovskite structure was discovered by Lev Aleksevich Von Perovski (1792–1856). It is a class of oxides, nitrides, halides and ternaries whose main physical properties are magnetism, superconductivity and magneto resistance (HERMES et al., 2015). Manufacturing involves chemical processes. Costs are low and the maximum efficiency already reported is 19.7% (BÜHLER; SANTOS; GABE, 2018).

Monocrystalline (m-Si) and Polycrystalline (p-Si) silicon photovoltaic cells dominate the PV market, although manufacturing processes are complex, expensive, and toxic. The production of thin-film solar cells involves physical vapor deposition or printing, resulting in thicknesses of a few microns and in the use of approximately 100 times less dying material than in the production of m-Si and p-Si. If sufficient efficiencies are achieved, not only significant reduction of costs, processes, and materials, but also a more extensive use of these materials will be attained, in particular in areas where more flexibility is required (HERMES et al., 2015).

3 Methodology

The Systematic Literature Review (SLR) method was applied to this research. It adopts transparent and reproducible procedures in the elucidation of the research objectives, in retrieving relevant research papers, assessing research findings, and presenting the results and contributions of such findings (COOPER; SCHINDLER, 2011).

The SCOPUS database was adopted in the search of papers written in English. The following search terms were investigated: “solar energy”, “sun power”, “photovoltaic solar energy” and “photovoltaic cells”, resulting in 112 papers published from 2014 to 2018. Figure 2 presents the research protocol.

Figure 2 - Results of the research using the SCOPUS Elsevier database.

Identification	Records obtained in the SCOPUS database using the filters "Articles or Review" and period from 2014 to 2018, (n=488) TITLE-ABS-KEY ((solar AND energy) AND (sun AND power) AND (photovoltaic AND solar AND energy) AND (photovoltaic AND cells)) AND DOCTYPE (ar OR re) AND PUBYEAR > 2013 AND PUBYEAR < 2019
Screening	Title reading, article summary and theme confirmation (n=138)
Eligibility	Detailed reading of the remaining articles that make up the research sample (n=112)
Included	Selected articles for qualitative analysis in the Systematic Literature Review (RSL) (n=112)

Source: Prepared by the authors (2020)

Information from the selected papers was exported to an Excel worksheet in the CSV format. Each paper was checked against the chosen theme, including title, abstract and final considerations. The information was systematized in tables, allowing the analysis and classification of the materials by chemical composition (classes).

4 Analysis of the results

The 112 selected documents were published in the 2014-2018 period, starting with 14 papers published in 2014 and an average of 18 publications per year until 2017. An increase of circa 140% was observed in 2018 in comparison to 2017, totalizing 38 papers.

The three journals that published more than five papers during the 5-year period and concentrated at least 20 of the 112 papers (63%) are: Solar Energy (SJR 1,59-2018) with eight papers, Energy and Environment Science (SJR 13,1-2018) with 7 papers, and Electrochimica Acta (SJR 1,37-2018) with 5 papers. The publications of papers and research reviews in these journals are concentrated in the following areas: a) Solar Energy – science and technology for solar energy applications; b) Energy and Environment Science –biochemistry, biophysics and chemistry engineering; and c) Electrochimica Acta –studies on electrochemical aspects.

Out of the ten countries that concentrate more than five publications during the 5-year period, the first three are: China (37 papers), United States (26 papers), and Switzerland (13 papers), representing more than 45% (76 papers) of the research published from 2014 to 2018.

The papers selected for analysis were divided in the following material categories: Dye-sensitized solar cell (DSSC), Graphene film, Heterojunction solar cell, Homojunction solar cell, Hybridized solar cell, Multijunction solar cell, Organic photovoltaic (OPV), Perovskite solar cell, Polymer solar cell (PSC), Quantum dot sensitized solar cell (QDSSC), and Single-junction solar cell.

4.1 Analysis of the material category Perovskite solar cell

Table 1 lists the papers retrieved for the material category Perovskite solar cell. Among the 10 papers with the highest number of citations related to this category, two were published in 2014; two in 2015; four in 2016; two in 2017, and none in 2018.

Table 1 – Material category Perovskite solar cell.

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Noel N.K. et al.	2014	Energy and Environmental Science	806	6,00	NA	NA	HIGH
Tan H. et al	2017	Science	595	20,10	NA	NA	NA
Qin P. et al.	2014	Nature Communications	471	12,40	NA	NA	NA
Shin S.S. et al.	2017	Science	414	21,20	NA	NA	NA
Anaraki E.H. et al.	2016	Energy and Environmental Science	252	20,70	NA	NA	NA
Kazim S. et al.	2015	Energy and Environmental Science	116	11,80	NA	NA	NA
Molina-Ontoria A. et	2016	Angewandte Chemie - International Edition	94	18,20	NA	NA	NA
Zarazua I. et al.	2016	Journal of Physical Chemistry Letters	93	7,69	NA	NA	NA
Rao H.-S. et al.	2015	Advanced Functional Materials	87	14,69	NA	NA	NA
Agresti A. et al.	2016	Advanced Functional Materials	85	11,14	NA	NA	NA

Source: Prepared by the authors (2020)

The retrieved papers present different types of study on the Perovskite Solar Cell. However, they do not mention cost and availability, but warn about the high environmental impact and concentrate in the development of: a) perovskite classes; b) materials with and without lead; and c) Hole Transporting Materials (HTM).

Each of the ten papers lists more than 50 citations, showing energy conversion efficiencies varying from 6% to 21.2%. The most cited paper (806 citations) is that authored by Noel et al. (2014), which was published in Energy and Environmental Science. This study focuses on the development of thin-film, lead-free halide solar cells. The efficiency reported in this study is 6%, well below 19.7% reported by Bülher et al. (2018) for this type of cell.

4.2 Analysis of the material category Dye-sensitized solar cell (DSSC)

Table 2 lists the papers retrieved for the material category Dye-sensitized solar cell (DSSC). Among the 10 papers with the highest number of citations related to DSSC, two were published in 2014; four in 2015; three in 2016; one in 2017, and none in 2018.

Table 2 - Material category Dye-sensitized solar cell (DSSC).

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Joly D. et al.	2015	Energy and Environmental Science	67	10,25	NA	NA	NA
Tang R. et al.	2015	Journal of Materials Chemistry A	27	4,70	NA	NA	NA
Liu T. et al.	2014	Journal of Physical Chemistry C	25	4,10	NA	NA	NA
Li C. et al.	2016	ACS Photonics	21	35,00	NA	NA	NA
Lee D.K. et al.	2015	Dyes and Pigments	16	5,20	NA	NA	NA
Zhang W. et al.	2017	Chemical Science	13	11,12	NA	NA	NA
Feng Y. et al.	2014	RSC Advances	13	8,62	NA	NA	NA
Vekariya R.L. et al.	2016	ACS Omega	8	2,40	LOW	HIGH	LOW
Zhu G. et al.	2015	Journal of Colloid and Interface Science	5	7,65	NA	NA	NA
Yuan H. et al.	2018	Solar Energy	5	5,00	NA	NA	NA

Source: Prepared by the authors (2020)

The papers present different studies on the Dye-sensitized solar cell (DSSC), but concentrate on the development of: a) organic materials to be applied on substrates(polymer solar cells); b) metal-free solar cells; and c) nanoparticles of inorganic-organic materials, indicating the interest in the development of new dyes to be applied to this type of cell.

Out of these studies on the Dye-sensitized solar cell (DSSC), only seven papers contain more than 10 citations, with energy conversion efficiencies varying between 4.1% and 35%. The most cited research (67 citations) was that of Joly et al. (2015), published in Energy and Environmental Science. The study focuses on the development of solar cells produced with thin films and metal-free organic dyes. The efficiency of these cells is 10.25%, which is within the 8-14% efficiency range reported by Ogbomo et al. (2017).

4.3 Analysis of the material category Quantum dot sensitized solar cell (QDSSC)

As shown in Table 3, 10 papers focusing of the material category Quantum dot sensitized solar cell (QDSSC) were retrieved. Two were published in 2014; four in 2015; three in 2016; one in 2017, and none in 2018.

Table 3 – Material category Quantum dot sensitized solar cell (QDSSC).

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Feng H.-L. et al.	2015	ACS Applied Materials and Interfaces	55	4,57	NA	NA	NA
Gopi C.V.V.M. et al.	2015	Dalton Transactions	37	2,85	NA	NA	NA
Firoozi N. et al.	2015	Journal of Power Sources	25	3,16	NA	NA	NA
Al-Hosiny N. et al.	2014	Materials Science in Semiconductor Processing	17	0,31	NA	NA	HIGH
Gopi C.V.V.M. et al.	2016	Dalton Transactions	15	3,11	NA	NA	NA
Yang S. et al.	2015	Journal of Materials Chemistry A	15	3,54	NA	NA	NA
Cao Y. et al.	2016	Electrochimica Acta	12	6,26	NA	NA	NA
Beattie N.S. et al.	2017	ACS Photonics	11	18,30	NA	NA	NA
Chang Y. et al.	2016	Journal of Power Sources	11	4,14	NA	LOW	NA
Sun H. et al.	2014	Journal of Colloid and Interface Science	11	1,22	NA	NA	NA

Source: Prepared by the authors (2020)

All the papers present more than 10 citations each and the approaches are varied: a) multiple architectures; and b) nonmetals, transition metals, and representative metals. These different materials indicate that the researchers and the reported studies tested materials of different electropositivity trends to improve the ECE and therefore take advantage of the multiple frequencies of the solar spectrum. Efficiencies reported in these studies vary from 0.31% to 18.30%, being the most cited research (55 citations) that of Feng et al. (2015).

4.4 Analysis of the material category Multijunction solar cell

Eleven papers on the Multijunction solar cell were retrieved: two in 2014; one in 2015; one in 2016; none in 2017, and six in 2018 (Table 4).

Among the papers containing more than 10 citations only the study of Kayes et al. (2014) stands out (39 citations). The papers focus on questions on multiple layers or multiple junctions or Tandem cells. Each individual junction produces electric current in different wavelengths of the electromagnetic spectrum. When using different semiconducting materials, absorption of a wider range of wavelengths is possible, improving the efficiency of electric energy conversion. The efficiencies reported by these studies vary from 4.50% to 53.90%, evidencing an interest in the development of new applications for this type of cell.

Table 4 - Material category Multijunction solar cell.

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Kayes B.M. et al.	2014	IEEE Journal of Photovoltaics	39	30,80	NA	NA	NA
Geisz J.F. et al.	2018	IEEE Journal of Photovoltaics	6	50,00	NA	NA	NA
Tiwari B. et al.	2016	Solar Energy	6	23,53	NA	NA	NA
Jain N. et al.	2018	Applied Physics Letters	4	34,00	NA	NA	NA
Zielony E. et al.	2014	Journal of Applied Physics	4	4,90	NA	NA	NA
Perl E.E. et al.	2018	IEEE Journal of Photovoltaics	3	16,40	NA	NA	NA
Huang Y. et al.	2015	Semiconductor Science and Technology	2	53,90	NA	NA	NA
Mitul A.F. et al.	2018	AIP Advances	1	4,50	NA	NA	NA
Routray S. et al.	2018	IEEE Transactions on Nanotechnology	0	9,82	LOW	NA	NA
Benlekhdim A. et al.	2018	Optik	0	18,55	NA	NA	NA

Source: Prepared by the authors (2020)

4.5 Analysis of the material category Organic photovoltaics (OPV)

Nine papers on Organic photovoltaics (OPV) were retrieved, as shown in Table 5. Three were published in 2014; none in 2015; two in 2016; one in 2017, and three in 2018.

Table 5 - Material category Organic photovoltaic (OPV).

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Mi D. et al.	2014	Journal of Nanoscience and Nanotechnology	37	6,22	LOW	NA	NA
Lechêne B.P. et al.	2016	Nano Energy	34	6,20	NA	NA	NA
Peng Y. et al.	2014	Applied Physics Letters	17	2,20	LOW	NA	NA
Cao W. et al.	2014	Renewable Energy	11	3,00	LOW	HIGH	LOW
Burlingame Q. et al.	2016	Advanced Energy Materials	9	6,60	NA	NA	NA
Chiu K.Y. et al.	2017	Journal of Electroanalytical Chemistry	6	0,28	NA	NA	NA
Min J. et al.	2018	Organic Electronics: physics, materials, applicat	2	6,19	NA	NA	NA
Cho K. et al.	2018	Macromolecular Rapid Communications	2	6,75	NA	NA	NA
Mitra K.Y. et al.	2018	Micromachines	0	0,18	LOW	HIGH	NA

Source: Prepared by the authors (2020)

The papers that present studies on the Organic photovoltaic solar cell (OPV) address the following: (a) the use of flexible substrates to manufacture organic cells; and (b) the production of inkjet-printed organic photovoltaic cells. The efficiencies reported by these studies vary from 0.18% to 6.75%. Only four papers contain more than 10 citations, highlighting Mi et al. (2014) with 37 citations.

4.6 Analysis of the material category Hybridized solar cell

Eight papers on the Hybridized solar cell were retrieved, as shown in Table 6. Three were published in 2014; one in 2015, 2016 and 2017, and two in 2018.

Table 6 - Material category Hybridized solar cell.

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Dutta P. et al.	2014	Polymer Chemistry	17	1,61	NA	NA	NA
Kim K. et al.	2014	Electrochimica Acta	12	1,63	NA	NA	NA
Duan J. et al.	2018	Journal of Energy Chemistry	3	6,51	NA	NA	NA
Wang Y. et al.	2017	Journal of Materials Chemistry A	3	9,50	NA	NA	NA
Mehrabian M. et al.	2015	Journal of Nanoelectronics and Optoelectronics	3	3,48	NA	NA	NA
Acciarri M. et al.	2018	Solar Energy	2	14,50	HIGH	LOW	NA
Sun J. et al.	2014	Macromolecular Chemistry and Physics	2	5,91	NA	NA	NA
Mehrabian M.	2016	Journal of Optical Technology	1	3,25	NA	NA	NA

Source: Prepared by the authors (2020)

The papers focus on: (a) the evaporation/spray coating method; (b) applications for solar energy, rain and use of nanocrystals; and (c) polymer synthesis and characterization. The efficiencies reported in these studies vary from 1.61% to 14.50%, and the most cited research is that of Dutta et al. (2014), with 17 citations.

4.7 Analysis of the material category Heterojunction solar cell

According to Table 7, six papers on Heterojunction solar cell were retrieved. No papers were published in 2014 and 2018, but two in 2015, three in 2016, and one in 2017.

Table 7 - Material category Heterojunction solar cell.

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Chiang T.et al.	2015	ACS Applied Materials and Interfaces	18	15,17	NA	NA	NA
Chou C.-L. et al.	2016	Journal of the Electrochemical Society	8	1,47	NA	NA	NA
Xu Y. et al.	2017	Journal of Materials Science	5	0,68	LOW	HIGH	LOW
Lan D. et al.	2016	Applied Physics Letters	5	0,44	NA	NA	NA
Dagher S. et al.	2016	Journal of Materials Science: Materials in Electr	4	5,04	NA	NA	NA
Balashangar K. et al.	2015	Journal of Nanoelectronics and Optoelectronics	4	14,50	NA	NA	NA

Source: Prepared by the authors (2020)

These papers address: (a) metal–organic molecular solutions; (b) the effect of the substrate roughness; and (c) semiconducting absorbent materials. The reported efficiencies vary from 0.44% to 15,17% and the most cited study is that of Chiang et al. (2015), with 18 citations.

4.8 Analysis of the material categories Single-junction solar cell, Polymer solar cell (PSC), Homojunction solar cell, and Graphene film

Only seven papers were retrieved on the following materials (Table 8): Single-junction solar cell (three papers published in 2018); Polymer solar cell (PSC – one paper published in 2016 and in 2018); Homojunction solar cell (one paper published in 2017), and Graphene films (one paper published in 2015).

Table 8 – Material categories Single-junction solar cell, Polymer solar cell (PSC), Homojunction solar cell and Graphene film.

Authors	Year	Journal	Citations	Energy Conversion Efficiency	Cost	Availability	Environmental impact
Shastry T.A. et al.	2016	ACS Energy Letters	7	5,81	LOW	NA	NA
Wu H. et al.	2015	ACS Applied Materials and Interfaces	7	3,56	NA	NA	NA
Russo J. et al.	2017	Applied Energy	5	29,00	NA	NA	NA
Xiao Y.-J. et al.	2018	Acta Polymerica Sinica	3	8,60	NA	NA	NA
Chen H. et al.	2018	ACS Photonics	1	13,40	NA	NA	NA
Rios-Ramirez B. et al	2018	Physica Status Solidi (A) Applications and Mat	0	5,93	LOW	HIGH	LOW
Ho W.-J. et al.	2018	Thin Solid Films	0	23,44	NA	NA	NA

Source: Prepared by the authors (2020)

The papers on the Single-junction solar cell focus on: (a) nanocrystals; (b) binary metallic chalcogenide semiconductors; and (c) the performance of GaAs cells. Regarding Polymer solar cells: (a) Hole transporting materials (HTM); and (b) carbon nanotubes. Regarding Homojunction solar cells: (a) a semiconductor composed of indium, gallium and phosphorus; and (b) the efficiency of the molybdenum oxide-modified graphene anode. The highest efficiency obtained in the 2014-2018 period for the Single-junction solar cells was 23.44%; for the Polymer solar cells (PSCs): 8.6%; for the Homojunction solar cells: 29%, and for the Graphene films: 3.56%.

5 Results

Analyzing the retrieved papers, it is observed that the majority did not indicate or focus on costs, availability, or environmental impact, but rather synthesis and manufacturing of photovoltaic cells.

The research on PV cells has aimed at the Perovskite solar cell because of the varied synthesis and manufacturing techniques involved; however, no mention regarding costs and availability was found in the studies, except for Noel et al. (2014), who reported high environmental impact.

Regarding the Dye-sensitized solar cells (DSSC), only Vekarya et al. (2016) mentioned low cost, high availability and low environmental impact, focusing on the development of environmentally-correct materials. Nevertheless, the research points to low energy conversion efficiency.

Quantum dots are used in Quantum dot sensitized solar cells (QDSSC) to improve the efficiency of the multijunction solar cells, making use of this property to capture varied ranges of the electromagnetic spectrum, by choosing the right material. Chang et al. (2016) mention the low availability and Al-Hosiny et al. (2014) analyzed the high environmental impact caused by the development of these materials. The other studies do not mention costs, availability and environmental impacts.

Multijunction solar cells use different semiconducting materials. By applying different materials, a better use of different wavelengths is possible, increasing the ECE. The use of multijunction solar cells is restricted to special projects, more specifically in the aerospace sector and in Concentrator photovoltaics (CPV) in photovoltaic plants. Only Routray et al. (2018) cited the low cost, but did not mention availability or environmental impacts.

The Organic photovoltaics (OPV) use conducting organic polymers for absorption and load transport in the production of electric energy using the PV effect. These cells are also called polymer solar cells. The organic solar cells are of low efficiency, of the order of 6%, when compared to crystalline silicon solar cells (c-Si) of energy conversion efficiencies in the range of 20 and 25%. Only Cao et al. (2014) reported the low-cost, high availability, and low environmental impact, thus being a possible environmentally-correct material.

The characteristics of the Hybridized solar cells are those of organic and inorganic semiconductors. These organic materials consist of polymers that absorb the light of the electromagnetic spectrum and are used as electron receptors and carriers in the structure. These hybrid solar cells yield low efficiencies, indicating that the research of this type of material must go on so that the industrial-scale manufacturing can start.

The Heterojunction solar cell produces electricity by means of semiconducting polymers based on organic macromolecules of petroleum derivatives, whose manufacturing processes spend much less energy than those used for cells based on mineral semiconductors. They are low cost, flexible, but their useful life is limited by the degradation of the polymers. The efficiency of these polymer cells must be improved in the laboratory to make their industrial-scale manufacturing possible. Only Xu et al. (2018) mentioned that these solar cells are of low cost. Adding the high availability and low environmental impact, the Heterojunction solar cells are expected to become environmentally-correct materials and of potential use.

Varied efficiencies were observed for material categories such as the Single-junction solar cells, Homojunction solar cells, Polymer solar cells and the Graphene films. It is not possible to determine their performance by comparing their efficiencies with those of the crystalline silicon solar cells, as only a few papers dealing with these materials are available.

6 Conclusion

The object of this study was to answer the following research question: “Which are the main alternative materials to silicon for the production of photovoltaic solar cells, according to environmental, efficiency and cost parameters and based on academic-scientific production?”. The systematic literature review from the classification of authors and respective study categories showed that several technologies have been researched to supply the electricity demand, making use of renewable energy sources that are more environmentally correct. This study focused mainly on studies of new materials that are being developed, in order to achieve better efficiency and lower costs, more availability and less toxicity.

The search for new, more efficient materials of longer useful time and ecologically better must be kept constant and permanent, thus contributing to the economic and environmental development. New materials for photovoltaic energy must be researched and produced internally in the country, in order to help develop the local industry, expanding production chains, with a positive impact on the economy, generating more financial input for federal, state and municipal governments, also contributing to expand scientific knowledge. Besides, the use of these materials in the production of solar cells and panels can increase efficiency and reduce costs.

The first, most significant group of third-generation cells is represented by the Perovskite solar and the Multijunction solar cells, once their potential of achieving higher efficiency and lower production costs can increase their share in the PV market and even replace silicon in the near future. The second representative group includes the Dye-sensitized solar (DSSC), Organic photovoltaic (OPV), and Quantum dot sensitized solar (QDSSC) cells. These third-generation cells yield similar, but low efficiencies. They can replace silicon cells in a slightly more distant future, as their energy conversion efficiencies must increase. The third representative group de cells includes the Single-junction solar and the Heterojunction solar cells, of higher, but still low, efficiency when compared to the second group.

A great number of new materials under development were retrieved in this systematic literature review and it is concluded that much research has been carried out with good results. Some alternatives are still not technologically acceptable in terms of efficiency, but it is expected that the use of a better distributed and cheaper PV cells will be possible in the near future. For further studies, the investigation of other databases is suggested, in order to retrieve more papers on Graphene, as it is an excellent semiconducting material but only a single paper was retrieved from SCOPUS database.

7 Acknowledgment

The present study was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES – Coordination for the Improvement of Higher Education Personnel) – Financing Code 001, and the UNINOVE Research Support Fund.

8 References

AL-HOSINY, N.; ABDALLAH, S.; BADAWI, Ali; EASAWI, K.; TALAAT, H. The photovoltaic performance of alloyed CdTexS1−x quantum dots sensitized solar cells. **Materials Science in Semiconductor Processing**, *[S. l.]*, v. 26, p. 238–243, 2014. DOI: 10.1016/j.mssp.2014.05.017.

ALSEMA, Erik A.; DE WILD-SCHOLTEN, Mariska J. Environmental Impacts of Crystalline Silicon Photovoltaic Module Production. **In 13th CIRP international conference on life cycle engineering**, *[S. l.]*, p. 6, 2006.

BÜHLER, Alexandre José; SANTOS, Fernando Hoefling Dos; GABE, Ivan Jorge. UMA REVISÃO SOBRE AS TECNOLOGIAS FOTOVOLTAICAS ATUAIS. **VII Congresso Brasileiro de Energia Solar - CBENS 2018**, *[S. l.]*, 2018. Disponível em: https://anaiscbens.emnuvens.com.br/cbens/article/view/267. Acesso em: 18 maio. 2021.

CAO, Weiran; LI, Zhifeng; YANG, Yixing; ZHENG, Ying; YU, Weijie; AFZAL, Rimza; XUE, Jiangeng. "Solar tree": Exploring new form factors of organic solar cells. **Renewable Energy**, *[S. l.]*, v. 72, p. 134–139, 2014. DOI: 10.1016/j.renene.2014.06.045.

CHANG, Yi-Cheng; SURIYAWONG, Nipapon; ARAGAW, Belete Asefa; SHI, Jen-Bin; CHEN, Peter; LEE, Ming-Way. Lead antimony sulfide (Pb5Sb8S17) solid-state quantum dot-sensitized solar cells with an efficiency of over 4%. **Journal of Power Sources**, *[S. l.]*, v. 312, p. 86–92, 2016. DOI: 10.1016/j.jpowsour.2016.02.051.

CHEN, Wei; HONG, Jinglan; YUAN, Xueliang; LIU, Jiurong. Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. **Journal of Cleaner Production**, *[S. l.]*, v. Part 1, n. 112, p. 1025–1032, 2016. DOI: 10.1016/j.jclepro.2015.08.024.

CHIANG, Tsung-Yu; FAN, Gang-Lun; JENG, Jun-Yuan; CHEN, Kuo-Cheng; Peter; WEN, Ten-Chin; GUO, Tzung-Fang; WONG, Ken-Tsung. Functional p-Type, Polymerized Organic Electrode Interlayer in CH3NH3PbI3 Perovskite/Fullerene Planar Heterojunction Hybrid Solar Cells | ACS Applied Materials & Interfaces. *[S. l.]*, v. 7, n. 44, p. 249732–24981, 2015. DOI: 10.1021/acsami.5b09012.

COOPER, Donald R.; SCHINDLER, Pamela S. Métodos de pesquisa em administração. **Revista de Administração Contemporânea**, *[S. l.]*, v. 7, n. 3, p. 225–225, 2011. DOI: 10.1590/S1415-65552003000300016.

DAVIES, Felipe Souza; FRISSO, Gustavo Luiz; BRANDAO, Matheus Vinicius. A UTILIZAÇÃO DO SILÍCIO NACIONAL PARA A FABRICAÇÃO DE PLACAS SOLARES: UMA REFLEXÃO DAS DIFICULDADES TECNOLÓGICA E FINANCEIRA. **VII Congresso Brasileiro de Energia Solar - CBENS 2018**, *[S. l.]*, 2018. Disponível em: https://anaiscbens.emnuvens.com.br/cbens/article/view/491. Acesso em: 18 maio. 2021.

DUTTA, Pranabesh; PARK, Hanok; LEE, Woo-Hyung; KANG, In Nam; LEE, Soo-Hyoung. Synthesis characterization and bulk-heterojunction photovoltaic applications of new naphtho[1,2-b:5,6-b']dithiophene–quinoxaline containing narrow band gap D–A conjugated polymers. **Polymer Chemistry**, *[S. l.]*, v. 5, n. 1, p. 132–143, 2014. DOI: 10.1039/C3PY00911D.

FENG, Hao-Lin; WU, Wu-Qiang; RAO, Hua-Shang; WAN, Quan; LI, Long-Bin; KUANG, Dai-Bin; SU, Cheng-Yong. Three-Dimensional TiO2/ZnO Hybrid Array as a Heterostructured Anode for Efficient Quantum-Dot-Sensitized Solar Cells. **ACS Applied Materials & Interfaces**, *[S. l.]*, v. 7, n. 9, p. 5199–5205, 2015. DOI: 10.1021/am507983y.

FERREIRA, André dos Santos; FENATO, Alexandre Junior. Potencial Impacto Ambiental Fotovoltaica. **Revista Científica Multidisciplinar Núcleo do Conhecimento**, *[S. l.]*, v. 01, n. 06, p. 228–242, 2017.

HERMES, Wilfried; WALDMANN, Daniel; AGARI, Michaela; SCHIERLE-ARNDT, Kerstin; ERK, Peter. Emerging Thin-Film Photovoltaic Technologies. **Chemie Ingenieur Technik**, *[S. l.]*, v. 87, n. 4, p. 376–389, 2015. DOI: https://doi.org/10.1002/cite.201400101.

HOUSE, Ralph L.; IHA, Neyde Yukie Murakami; COPPO, Rodolfo L.; ALIBABAEI, Leila; SHERMAN, Benjamin D.; KANG, Peng; BRENNAMAN, M. Kyle; HOERTZ, Paul G.; MEYER, Thomas J. Artificial photosynthesis: Where are we now? Where can we go? **Journal of Photochemistry and Photobiology C: Photochemistry Reviews**, *[S. l.]*, v. 25, p. 32–45, 2015. DOI: 10.1016/j.jphotochemrev.2015.08.002.

JOLY, D. et al. Metal-free organic sensitizers with narrow absorption in the visible for solar cells exceeding 10% efficiency. **Energy & Environmental Science**, *[S. l.]*, v. 8, n. 7, p. 2010–2018, 2015. DOI: 10.1039/C5EE00444F.

KAYES, Brendan M.; ZHANG, Ling; TWIST, Rose; DING, I.-Kang; HIGASHI, Gregg S. Flexible Thin-Film Tandem Solar Cells With >30% Efficiency. **IEEE Journal of Photovoltaics**, *[S. l.]*, v. 4, n. 2, p. 729–733, 2014. DOI: 10.1109/JPHOTOV.2014.2299395.

KUMAR, Manish; KUMAR, Arun. Performance assessment and degradation analysis of solar photovoltaic technologies: A review. **Renewable and Sustainable Energy Reviews**, *[S. l.]*, v. 78, p. 554–587, 2017. DOI: 10.1016/j.rser.2017.04.083.

LUNARDI, Marina Monteiro; HO-BAILLIE, Anita Wing Yi; ALVAREZ-GAITAN, Juan Pablo; MOORE, Stephen; CORKISH, Richard. A life cycle assessment of perovskite/silicon tandem solar cells. **Progress in Photovoltaics: Research and Applications**, *[S. l.]*, v. 25, n. 8, p. 679–695, 2017. DOI: https://doi.org/10.1002/pip.2877.

MACHADO, Carolina T.; MIRANDA, Fabio S. Energia Solar Fotovoltaica: Uma Breve Revisão. **Revista Virtual de Química**, *[S. l.]*, v. 7, n. 1, p. 126–143, 2015.

MI, Dongbo; KIM, Ji-Hoon; KIM, Hee Un; XU, Fei; HWANG, Do-Hoon. Fullerene derivatives as electron acceptors for organic photovoltaic cells. **Journal of Nanoscience and Nanotechnology**, *[S. l.]*, v. 14, n. 2, p. 1064–1084, 2014. DOI: 10.1166/jnn.2014.9007.

MITRA, Kalyan Yoti; ALALAWE, Abdelrahman; VOIGT, Stefanie; BOEFFEL, Christine; BAUMANN, Reinhard R. Manufacturing of All Inkjet-Printed Organic Photovoltaic Cell Arrays and Evaluating Their Suitability for Flexible Electronics. **Micromachines**, *[S. l.]*, v. 9, n. 12, 2018. DOI: 10.3390/mi9120642. Disponível em: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6316076/. Acesso em: 18 maio. 2021.

NOEL, Nakita K. et al. Lead-free organic–inorganic tin halide perovskites for photovoltaic applications. **Energy & Environmental Science**, *[S. l.]*, v. 7, n. 9, p. 3061–3068, 2014. DOI: 10.1039/C4EE01076K.

OGBOMO, Osarumen O.; AMALU, Emeka H.; EKERE, N. N.; OLAGBEGI, P. O. A review of photovoltaic module technologies for increased performance in tropical climate. **Renewable and Sustainable Energy Reviews**, *[S. l.]*, v. 75, p. 1225–1238, 2017. DOI: 10.1016/j.rser.2016.11.109.

OPWIS, Klaus; GUTMANN, Jochen Stefan; LAGUNAS ALONSO, Ana Rosa; RODRIGUEZ HENCHE, Maria Jesus; EZQUER MAYO, Mikel; BREUIL, Fanny; LEONARDI, Enrico; SORBELLO, Luca. Preparation of a Textile-Based Dye-Sensitized Solar Cell. **International Journal of Photoenergy**, *[S. l.]*, v. 2016, p. e3796074, 2016. DOI: 10.1155/2016/3796074.

O'REGAN, Brian; GRÄTZEL, Michael. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO 2 films. **Nature**, *[S. l.]*, v. 353, n. 6346, p. 737–740, 1991. DOI: 10.1038/353737a0.

PEREIRA, Enio Bueno et al. **Atlas Brasileiro de Energia Solar**. [s.l: s.n.]. Disponível em: http://labren.ccst.inpe.br/atlas_2017.html. Acesso em: 18 maio. 2021.

ROUTRAY, Soumyaranjan; LENKA, Trupti Ranjan. Polarization Charges in a High-Performance GaN/InGaN Core/Shell Multiple Quantum Well Nanowire for Solar Energy Harvesting. **IEEE Transactions on Nanotechnology**, *[S. l.]*, v. 17, n. 6, p. 1118–1124, 2018. DOI: 10.1109/TNANO.2018.2848287.

TEIXEIRA, Marco Antonio Casadei. **Perspectivas do potencial estratégico de novos materiais alternativos ao silício para a produção de células solares fotovoltaicas**. 2019. Disponível em: http://bibliotecatede.uninove.br/handle/tede/2149. Acesso em: 22 maio. 2021.

VALLÊRA, António M.; BRITO, Miguel Centeno. Meio século de História Fotovoltaica. **Gazeta de Física**, *[S. l.]*, v. 1, n. 2, p. 17, 2006.

VEKARIYA, Rohit L.; SONIGARA, Keval K.; FADABU, Kishan B.; VAGHASIYA, Jayraj V.; SONI, Saurabh S. Humic Acid as a Sensitizer in Highly Stable Dye Solar Cells: Energy from an Abundant Natural Polymer Soil Component | ACS Omega. **ACS Omega**, *[S. l.]*, v. 1, p. 14–18, 2016. DOI: 10.1021/acsomega.6b00010.

XU, Yafeng et al. Solution-processed CuSbS2 solar cells based on metal–organic molecular solution precursors. **Journal of Materials Science**, *[S. l.]*, v. 53, n. 3, p. 2016–2025, 2018. DOI: 10.1007/s10853-017-1663-8.