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Photovoltaic Solar Energy: Is It Applicable in Brazil? – A Review Applied to Brazilian Case

Fotovoltaična sončna energija: ali je uporabna v Brazliji? – Pregled, uporaben za primer Brazilije

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Abstract

The photovoltaic technologies have been developed year by year in different countries; however, there are some countries where this kind of energy is being born, such as the Brazilian case. In this paper, some important parameters are analysed and applied to different solar cell materials, identifying that if the fossil fuels were substituted by solar cells, it would reduce the CO_2 emissions by 93.2%. In addition, it is shown that the efficiency of solar cells is not as farther as it could be thought from coal thermoelectrical plants in Brazil and the cost of energy using solar cells could be as good as these thermoelectrical plants. Finally, the potentiality of Brazilian territory to implant this technology is presented, identifying that with the use of 0.2% of the territory, the energy demand could be supplied.

Key words: Solar cells, CO_2 Emissions, Fossil fuels, Brazil, Thermoelectrical plants

Povzetek

Fotovoltaične tehnologije se iz leta v leto razvijajo v različnih državah. Obstajajo nekatere države, kot na primer Brazilija, kjer ta vrsta energije igra pomembno vlogo. Zaradi tega smo v članku analizirali nekatere pomembne parametre, ki se nanašajo na različne material sončnih celic. Ugotovili smo, da bi se v primeru zamenjave fosilnih goriv s sončnimi celicami izpusti CO_2 lahko zmanjšali v najboljšem primeru za 93.2%. Prav tako smo pokazali, da učinkovitost sončnih celic in cena z njimi pridobljene energije ne zaostaja za termoelektrarnami v Braziliji. Na koncu je predstavljen potencial ozemlja Brazilije, kjer bi lahko z uporabo 0.2% ozemlja pokrili energetske potrebe.

Ključne besede: sončne celice, emisije CO_2, fosilna goriva, Brazilija, termoelektrarne

Introduction

Both economic and population growth have an effect on energy demand, having as principal consequence an accumulative increase in the use of fossil fuels, a way to supply this demand, increasing the average greenhouse gases concentration, being the CO_2 the principal gas among them [1]; therefore, the biggest challenge is to reduce the CO_2 emissions to the atmosphere by means of using diverse green energy sources, such as natural gas, ethanol, nuclear, wind and solar energy [2]. In this order of ideas, the concern in these alternative energies has been bigger in conformity of the growing global warming and air pollution [3].

Some countries have implemented the use of renewable energy in order to solve the environmental problems, solar photovoltaic systems being one of them [4] and is also placed as one of the most promising energies because of its potential to reduce greenhouse gases (GHG) emissions [5] and how not considering as it, when along its operational time it does not emit CO_2? [6] [7]. Also, an important parameter has been studied and it is its pricing by Wp (Watts Peak), being reported 1.60 US$/Wp in 2011, 0.34 US$/Wp in 2017 and reduced to 0.244 US$/Wp in January 2019 [8].

On the other hand, placing the focus on Brazil, its grid is composed by 67.9% of hydroelectrical sources; however, the photovoltaic energy occupies a low 0.7% [9]. Also even when the hydroelectrical source is considered clean, its application is restricted due to environmental impact, such as flooding in large areas, methane emissions from anaerobic degradation of organic material, dependence on local hydrological stability [10]. In addition, because of the climate change, more frequent, intense and prolonged droughts in Brazil are expected, which would affect dramatically the hydroelectrical source [11].

Hence, due to all the above mentioned environmental impact, this work tries to show a review focused on some specific parameters such as the GHG emission, energy payback time (EPBT), energy return on energy invested (ERoEI), efficiency, cost and irradiance potentiality and focused on different materials to know how green this energy (no matter about the solar cell material) can be and how it can be applied in Brazil, trying to illustrate how the country could be helped, due to its enormous capability [12] [13].

Cell Technologies

In brief, solar cells transform the solar power to electrical power. This photovoltaic cell is created by a semiconductor material which is exposed to the photons emerging from sunlight. This semiconductor has an absorption capacity, depending on its specific band gap energy that will absorb photons with the same energy (the band gap energy) and, if the energy is higher, these photons will release the surplus energy in heat form and, in that way, retaining the specific band gap energy of the material [14]. Having in consideration the different kinds of materials, the global share is illustrated in Figure 1.

Monocrystalline photovoltaic cells are made using a single and continuous crystal of silicon, having almost no impurities, obtaining a blue solid colour [15], sharing around 30% of

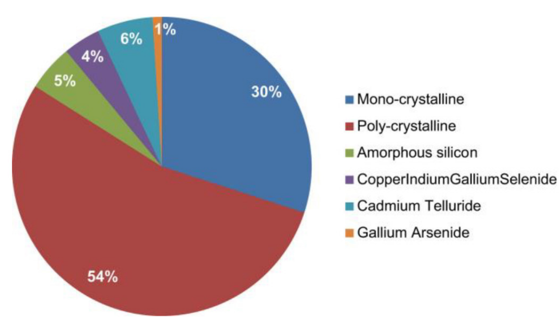

Figure 1: *Global market share of photovoltaic cells [14].*

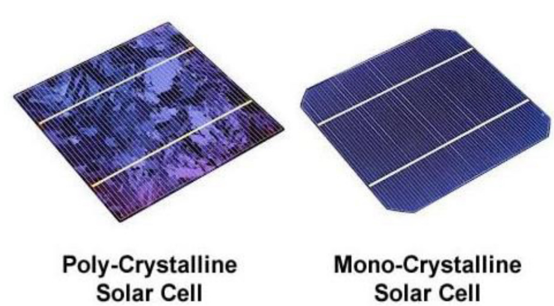

Figure *2: Silicon solar cells [19].*

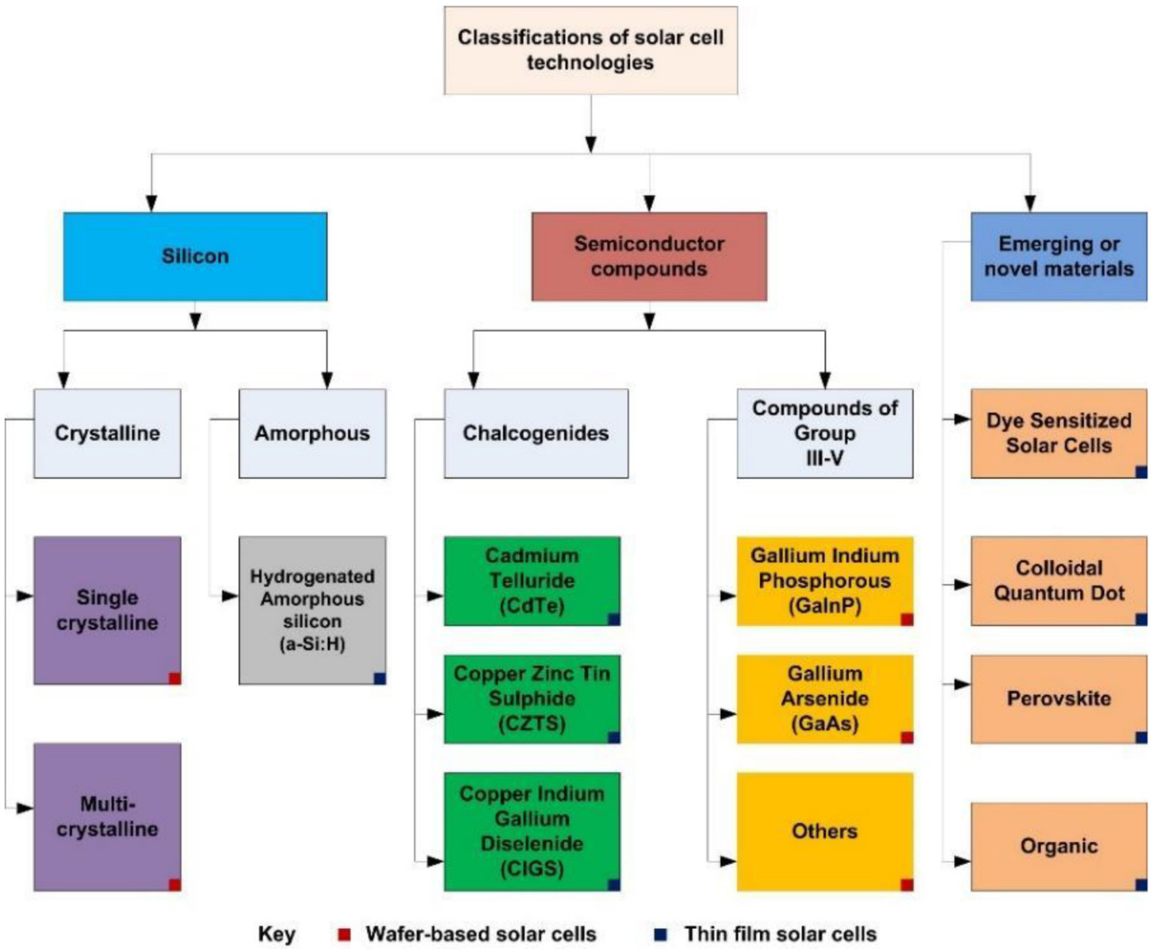

Figure 3: *Solar cell technologies classification [26].*

the market (Figure 1). The manufacturing of these cells is more expensive due to processing of high purity crystal and also guaranteeing a higher efficiency compared with polycrystalline cells [16] [17]. On the other hand, polycrystalline photovoltaic cells occupied most of the market share (more than 50%) (Figure 2). They are produced using several different monocrystalline silicon grains which are melted and consequently solidified slowly by cooling down [18].

Another kind of photovoltaic cells are thin films which are known as second generation of photovoltaic cells, having a range of thickness varying between 10 nm to 10 μm [20]. Also, it has been reported that in comparison with silicon solar cells (amorphous, polycrystalline and monocrystalline), the EPBT and the price of thin films have been lower, although the efficiency is not as high as silicon solar cells [21]. Nevertheless, in attempting to be a better contender in front of silicon photovoltaics, some materials have been performed. Copper indium gallium selenide (CIGS) is one of the best absorber materials in thin films, because it possesses a chalcopyrite crystal structure and can modify the band gap energy values changing indium by gallium and obtaining $CuInSe_2$ and $CuGaSe_2$ with 1.02 and 1.67 eV [22]. Another material is cadmium telluride (CdTe) with a band gap energy of 1.5 eV which gives it a theoretical efficiency of around 30% (see section 4.4) and the most attractive characteristic of this material is its chemical simplicity so that it could be applied to space applications [21]. Also, gallium arsenide (GaAs) is used in thin films and by the year 2014, this material had been shown the best efficiency by a single junction (27.6%) [23]. In addition, GaAs uses a band gap between 1.43 and 1.7 eV [14].

The next generation of solar cells is covered by organic solar cells (OSCs) or organic photovoltaics (OPV). These cells are based on photosynthesis process in order to absorbing light which is done by the dye that substitutes the silicon, compared with conventional cells; however, they have been demonstrated with low efficiency of around 3–5% [24] and they are still a promising alternative because of their low cost and relative ease of chemical synthesis [25]. Even though only some materials have been presented, there are a huge variety of solar cells materials. Figure 3 shows the three biggest blocks of these materials.

Applied Review Methodology

This methodology is based on a comprehensive method to evaluate and analyse, along the whole product lifetime, the environmental performance and energy consumption, covering the whole processes [27] having a life cycle assessment as principal analogy. Therefore, it has been proposed and standardised by ISO 14040 and ISO 14044 [28] [29] using some fundamental stages: first is goal and scope; second is life cycle inventory; third impacts assessment and fourth is the interpretation of the results [30]. Hence, taking the impact into consideration in this study, the following points were analysed: diverse aspects of GHG emissions, EPBT, ERoEI, the efficiency, how suitable it could be with respect to the potentiality of the territory and how much it could be, in order to demonstrate that this alternative can be a substitute of fossil fuels, being applied specifically to Brazil.

Results and Discussion

Efficiency

Efficiency of Solar Cells

The first essential point to be evaluated, which has been studied along the years, is the efficiency that most of the green parameters depend on the efficiency to be better, such as recovering the invested energy, trying to get shorter time and producing even more energy. Also, low equivalent CO_2 emissions are expected by energy produced along the lifetime, without affecting the efficiency. For this reason, the results from 39 different materials and studies are gathered and represented in Table 1. All these data are analysed by means of two graphs, first to com-

Table 1: *Efficiency by materials.*

Material	Efficiency (%)	Reference	Year
GaAs	23.5	[31]	2011
CZTS	7.3	[32]	2012
Poly-Si	20.3	[33]	2012
CZTS	8.9	[34]	2012
CIGS	15.5	[35]	2012
DSC	11.4	[36]	2012
OPV	8.4	[37]	2012
InGa/GaAs	26.6	[38]	2013
CZTS	12.6	[39]	2013
DSC	9.4	[40]	2013
CdTe	12.3	[41]	2013
CIGS	20.4	[42]	2013
CIGS	15.2	[43]	2013
CZTS	8.4	[44]	2013
OPV-triple junction	11.55	[45]	2014
CZTS	11.6	[46]	2014
Perovskite	11.13	[47]	2014
Poly-Si	18.45	[48]	2014
Mono-Si	25.6	[49]	2014
Perovskite	16.6	[50]	2014
Perovskite	15.07	[51]	2014
OPV	10.31	[52]	2014
Perovskite	17.6	[53]	2015
Mono-Si	20.6	[54]	2015
Mono-Si	22.5	[55]	2015
Perovskite	17.7	[56]	2015
Perovskite	18.3	[57]	2015
CIGS	21.7	[58]	2015
OPV	9.94	[59]	2015
GaAs	28	[60]	2015
CdTe	21	[60]	2015
OPV	11.25	[61]	2016
GaAs	15.3	[62]	2016
Poly-Si	21.25	[63]	2016
Mono-Si	19.42	[64]	2016
Poly-Si	16.7	[64]	2016
CdTe	17	[65]	2016
Poly-Si	18.62	[66]	2017
OPV	13.1	[67]	2017
Perovskite-silicon	26.4	[68]	2017

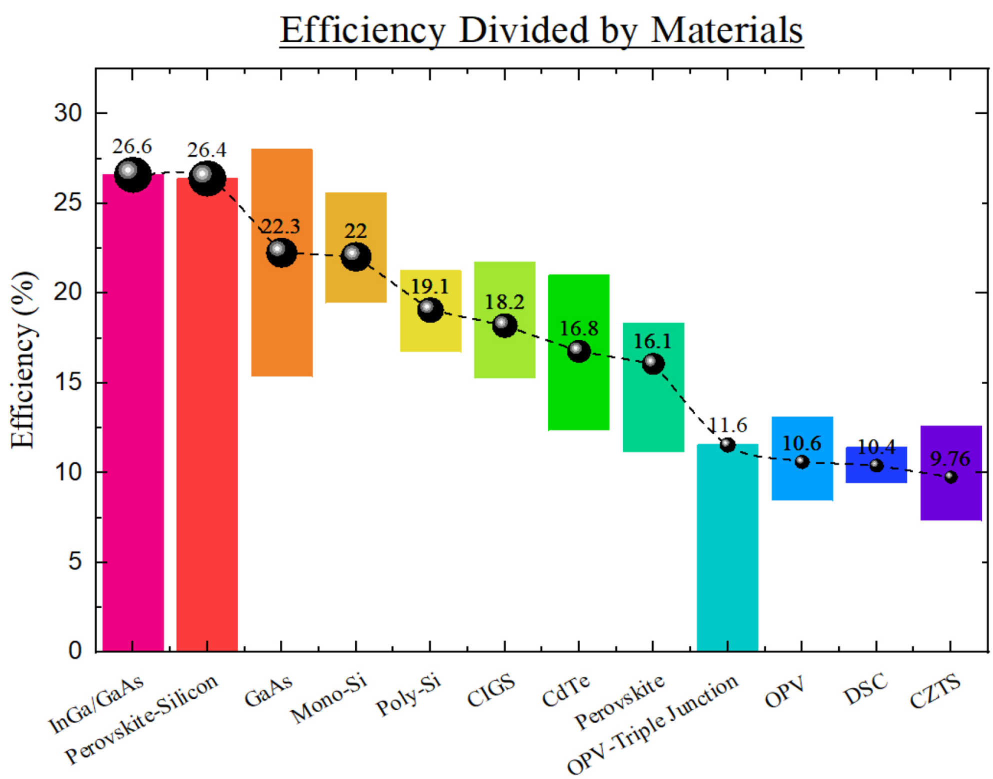

Figure *4: Efficiency divided by materials.*

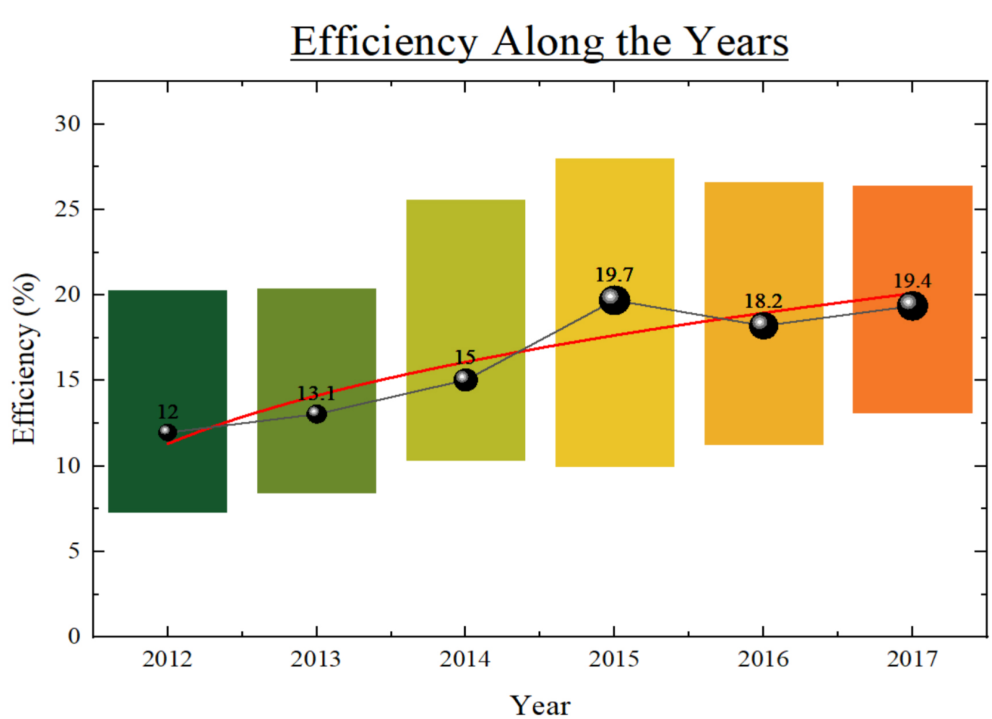

Figure 5: *Efficiency along the time.*

pare the efficiencies by materials (Figure 4), and the other, along the last years, to average the different studies (Figure 5).

When the materials are seen, it is possible noticing a top around 26% of efficiency; also, the first three materials correspond to newer technologies like tandem (InGa/GaAs and perovskite/silicon) and thin films (GaAs). However, monocrystalline and polycrystalline silicons (which are the most commonly used) are ubicated later with the efficiencies of approximately 19% and 18%. On the other hand, in recent years, the average efficiency of solar cells has been increasing.

Efficiency of solar cells in front of thermoelectrical plants

If the efficiency was compared with the thermoelectrical power plants, there would be still a gap between them, with a global average efficiency around 35% [69] [70], which represents almost the double if compared with silicon solar cells (1.85 times). Also, if it is considered on account of the Brazilian case, there are some carbon power plants which have a varied efficiency, being 20.5% in Charqueadas power plant, 25%, 29,4%, 36.1% and 35.8% corresponding to Jorge Lacerda A1, A2, B and C, the most 36.5% belonging to Candiota III [71], but this corresponds only to 1.88% of the total produced energy in Brazil and 8.51% of thermoelectrical plants [72]. Besides, the biggest part is taken by thermoelectrical gas plant (7.75% of total grid and 35.07% of thermoelectrical energy) which was reported a 42% of efficiency [71], obtaining a 5.14% of total energy grid by oil (23.25% of thermoelectrical energy) with 34% of efficiency [73]. The rest is corresponded to biomass (8.58% of total energy grid and 38.84% of thermoelectrical plants) having an efficiency around 23.05% in Brazil [72].

It could resemble that there is nothing to do against the efficiency of thermoelectrical power plants; however, observing the efficiency along the years, there has been a constant increase in efficiency which could then help developing better solar cells. Also, even when the carbon thermoelectrical efficiency is bigger than silicon solar cells, the CO_2 emission is 20 times higher and when it is used as natural gas, the emissions are 10 times higher and 16 times higher for oil thermoelectrical plants [74] (this point will be analysed later). Hence, it is possible asking, is it fear, right or correct using thermoelectrical plants just because of increasing efficiency? It does not look like.

Greenhouse Gases Emissions (Equivalent CO_2 Emissions)

CO_2 emissions by energy produced in solar cells

When evaluating the GHG emissions, the principal gas on which this parameter is based is CO_2, assessing it along the whole life of the studied material and expressing its value in CO_2 g/kWh. For that reason, in this section a total of 24 ref-

Table 2: *CO_2 emissions.*

Material	CO_2 emission (g/KWh)	Reference	Year	Average CO_2 emission (g/kWh)
Mono-Si	131	[75]	2009	131.00
CdTe	17	[76]	2010	36.00
CIGS	33	[76]	2010	
CIGS	44	[77]	2010	
CdTe	50	[77]	2010	
OPV	37.77	[78]	2011	47.21
OPV	56.65	[78]	2011	
Poly-Si	88.74	[79]	2012	63.01
DSSC	22.29	[80]	2012	
CdTe	48	[80]	2012	
CIGS	95	[80]	2012	
Mono-Si	61	[81]	2012	

Table 2: *CO_2 emissions (continue).*

Material	CO_2 emission (g/KWh)	Reference	Year	Average CO_2 emission (g/kWh)
CdTe	15.83	[82]	2013	35.61
CdTe	20.11	[82]	2013	
CIGS	21.44	[82]	2013	
Poly-Si	27.2	[82]	2013	
CIGS	27.64	[82]	2013	
Mono-Si	38.06	[82]	2013	
Poly-Si	49.7	[82]	2013	
Mono-Si	81.2	[82]	2013	
Mono-Si	47.9	[83]	2013	
GaInP/ GaInAs/Ge	27	[84]	2013	
CdTe	20	[85]	2014	36.73
CIGS	22	[85]	2014	
OPV-Multi J.	48.18	[86]	2014	
CdTe	15.1	[87]	2014	
Poly-Si	31.5	[87]	2014	
Mono-Si	41.8	[87]	2014	
DSSC	28.1	[88]	2014	
CdTe	68	[88]	2014	
CIGS	70	[88]	2014	
Poly-Si	12.28	[89]	2014	
Poly-Si	13.04	[89]	2014	
Poly-Si	18.11	[89]	2014	
Poly-Si	19.49	[89]	2014	
Poly-Si	51.68	[89]	2014	
Poly-Si	54.82	[89]	2014	
Poly-Si	55.89	[89]	2014	
Poly-Si	58.81	[89]	2014	
Poly-Si	31.8	[90]	2014	
Mono-Si	37.3	[90]	2014	
Poly-Si	50.9	[91]	2015	64.50
Perovskite	60.1	[92]	2015	
Perovskite	82.5	[92]	2015	
Mono-Si	5.6	[93]	2016	46.50
Mono-Si	12.07	[93]	2016	
OPV	14.7	[94]	2016	
Poly-Si	60.1	[95]	2016	
Mono-Si	65.2	[95]	2016	
Poly-Si	80.5	[95]	2016	
Mono-Si	87.3	[95]	2016	

Table 2: *CO_2 emissions (continue).*

Material	CO_2 emission (g/KWh)	Reference	Year	Average CO_2 emission (g/kWh)
CdTe	35	[14]	2017	40.50
CIGS	46	[14]	2017	
AZTS/Si	19.8	[96]	2018	24.72
CZTS/Si	20.4	[96]	2018	
CIGS/Si	27.8	[96]	2018	
Poly-Si	20.9	[97]	2018	
Poly-Si	29.2	[97]	2018	
Poly-Si	30.2	[97]	2018	

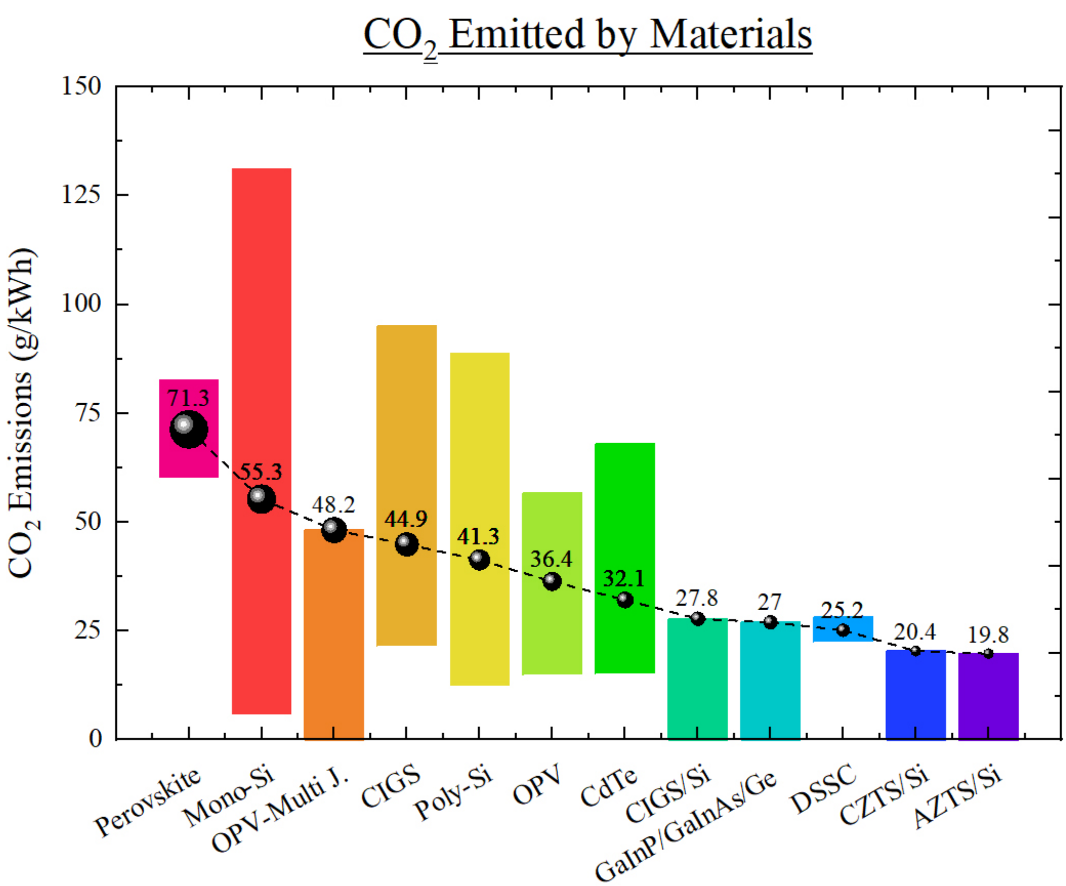

Figure 6: *CO_2 emission by different materials.*

erences, from 2009 to 2019 (Table 2), was gathered, obtaining a graph (Figure 6) where the highest value is 131 CO_2 g/kWh, and the values correspond to the oldest data (2009). However, the average values by materials vary in a range of ~20 to ~70 g/kWh which shows an improved, although, relatively low value when compared with fossil fuel emissions. This will be discussed in the next subsection.

CO_2 emission compared with fossil fuels

If all the data are averaged from Figure 6, it will be 42.15 CO_2 g/kWh. Also, using the data from International Energy Agency that pub-

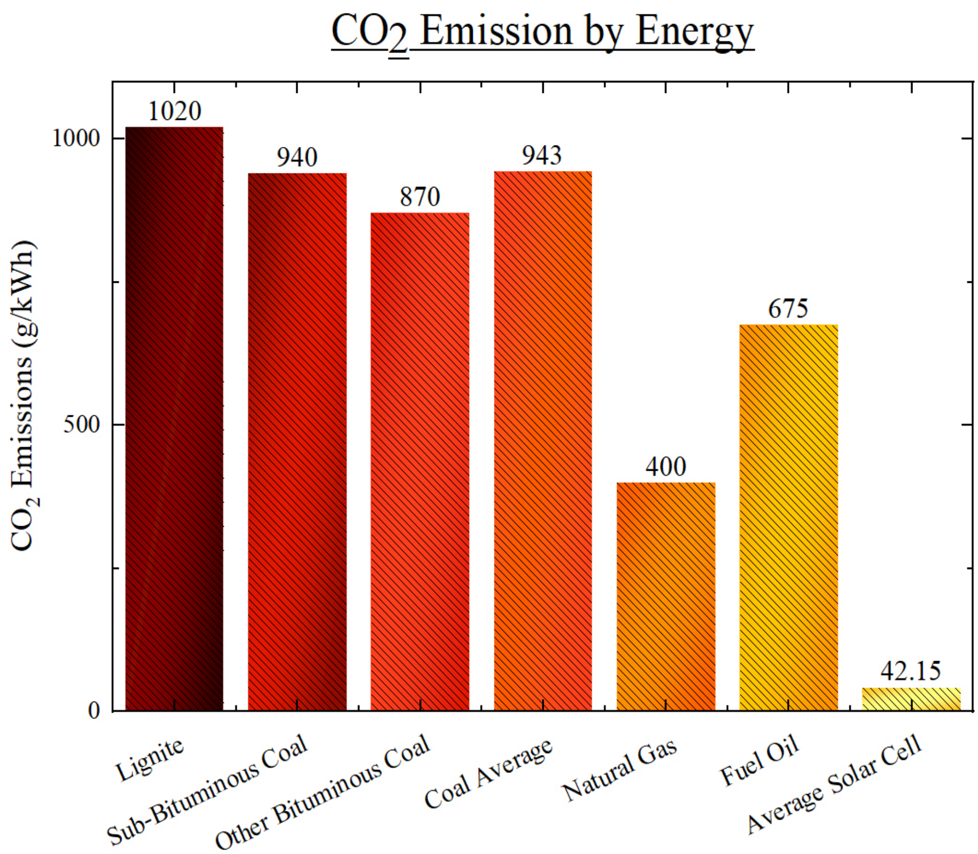

Figure 7: *CO_2 emission by energies.*

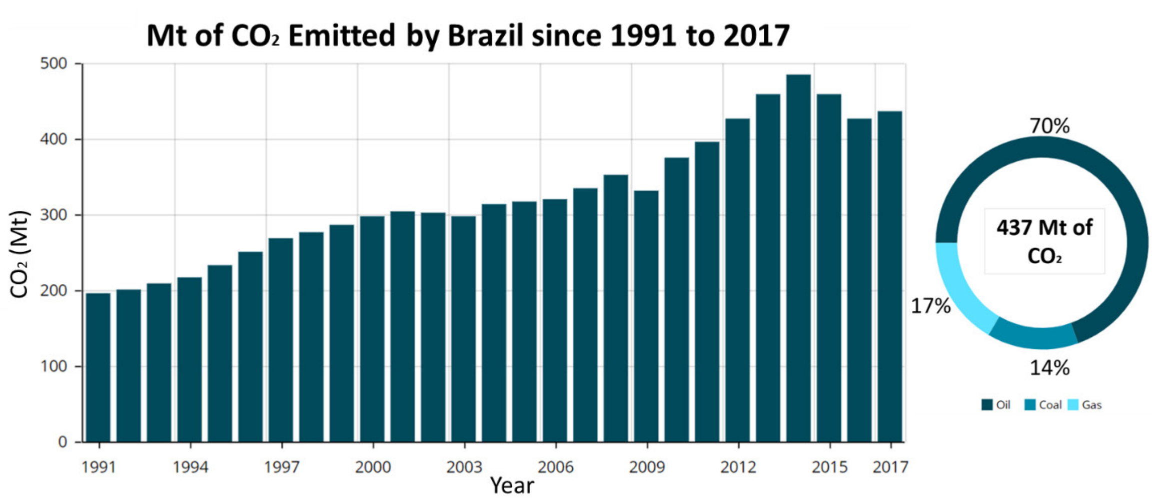

Figure 8: *CO_2 emitted by Brazil in 2017 [98].*

lished its report about CO_2 emissions from fuel combustion [74], a graph (Figure 7) is drawn to represent the big difference between them and a solar cell system; for this reason, the energy emitted by coal (average), natural gas and fuel oil contains approximately 22.37, 9.49 and 16.01 times more CO_2 than an average photovoltaic panel. This leads to analyse the case of Brazil, which is shown in Figure 8, with a focus on the year 2017 (the last obtained data), and

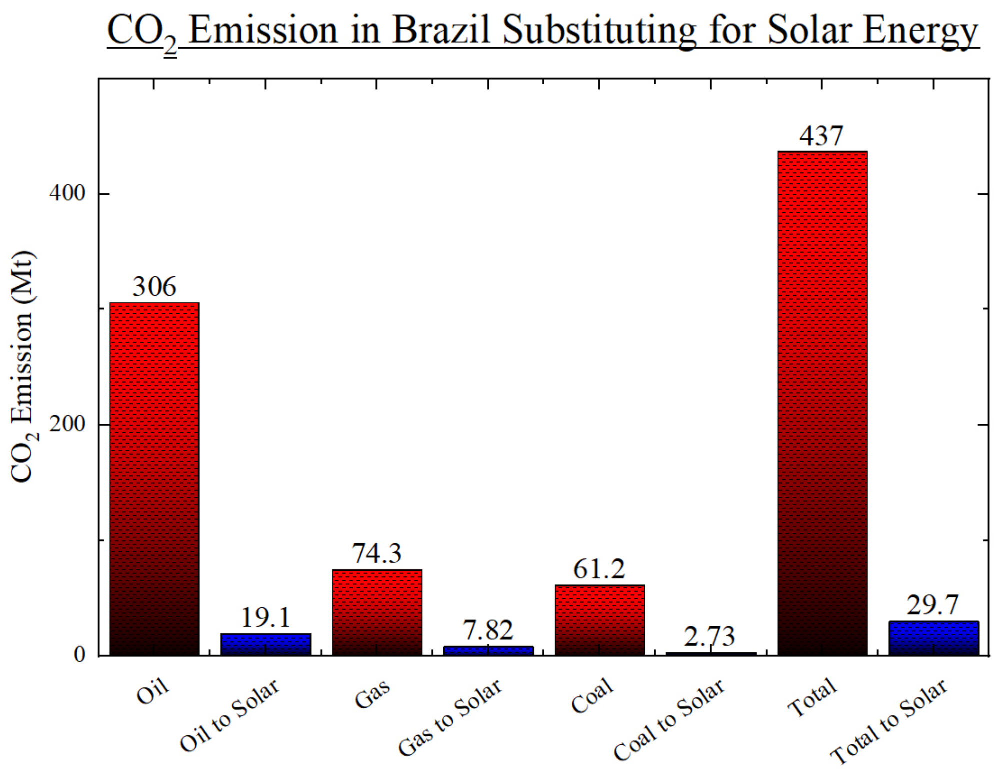

Figure 9: *Emissions of CO_2 if the fossil fuels are substituted by solar energy.*

the data is divided by the emission by the fossil fuels the emissions of CO_2 is calculated if they are substituted by solar panels (Figure 9), reducing from 437 to 29.7 Mt, being only 6.8% of the CO_2 emitted nowadays.

Energy Payback Time

This parameter refers to the required time that the system takes to recover all the used energy from its cradle to grave [84]; for this reason, even when a system has low CO_2 emission, it needs to recover its used energy as fast as possible, as a way to be sustainable. In this order of ideas, some studies have been gathered to analyse how these values have been developed (Table 3) by materials (Figure 10) and along the years (Figure 11).

Observing the graphs, it is notorious how the EPBT is decreasing with the years, varying with materials, getting even lower values than the average by year, nevertheless, there are no data in 2008, 2010 and also in 2009 but there was a data with a really high value. On the other hand, the evolution of EPBT could be defined in a range between 1 and 2.5 years, in average, to recover the used energy. However, it is valid asking if the obtained EPBT values are framing inside the lifetime of solar cells.

To answer the lifetime framework, an analytical review based on degradation rates of photovoltaics made by Jordan and Kurtz [106], the authors concluded that even when the companies warranty a lifetime of 25 years, moreover the reported report some panels with 40 years of duration. Also, they obtained degradation rates of 0.8% by year in average; in fact, 78% of their study reflected a degradation rate less than 1% by year, concluding that a range of 1 to 2.5 years to recover the energy is an excellent parameter. Additionally, in the Brazilian case, by the year of 2011, an EPBT was reported which varied between 3.1 and 4.1 years [107] (Figure 12), compared with the analysis in this review in the same year which was 3.9 years in average. Brazil fits good, besides, the tendency was from 3.9 years in 2011 to 1.26 years in 2018 for EPBT; for this reason, an interval could be proposed for Brazil (following the same tendency until 2018) from 1.085 to 1.435 years.

Table 3: *Energy payback time.*

Material	EPBT (year)	Reference	Year	EPBT average (year)
GaAs	5	[99]	2007	4.60
GaInP/GaAs	4.6	[99]	2007	
Poly-Si	4.2	[99]	2007	
Mono-Si	9.08	[75]	2009	9.08
OPV	2.02	[78]	2011	3.90
OPV	1.35	[78]	2011	
Mono-Si	8.04	[100]	2011	
Poly-Si	4.18	[100]	2011	
Poly-Si	4.17	[79]	2012	2.77
CIGS	2.8	[80]	2012	
DSSC	1.58	[80]	2012	
CdTe	1.5	[80]	2012	
Mono-Si	3.8	[81]	2012	
Mono-Si	2.34	[82]	2013	1.68
Mono-Si	1.96	[82]	2013	
Poly-Si	1.45	[82]	2013	
Poly-Si	1.24	[82]	2013	
CIGS	1.02	[82]	2013	
CIGS	1.01	[82]	2013	
CdTe	0.68	[82]	2013	
CdTe	0.68	[82]	2013	
Mono-Si	5.5	[83]	2013	
GaInP/GaInAs/Ge	0.9	[84]	2013	
OPV-Multi J.	0.24	[86]	2014	1.74
Mono-Si	3.11	[87]	2014	
Poly-Si	2.97	[87]	2014	
CdTe	0.94	[87]	2014	
CIGS	1.98	[88]	2014	
CdTe	1.95	[88]	2014	
DSSC	0.95	[88]	2014	
Mono-Si	1.9	[90]	2014	
Poly-Si	1.6	[90]	2014	
Mono-Si	4.1	[101]	2015	1.85
Poly-Si	3.5	[101]	2015	
CIGS	1.7	[101]	2015	
CdTe	1	[101]	2015	
Poly-Si	2.2	[91]	2015	
Perovskite	0.266	[92]	2015	
Perovskite	0.193	[92]	2015	
Mono-Si	0.91	[93]	2016	1.34
Mono-Si	0.42	[93]	2016	
OPV	0.34	[94]	2016	
Poly-Si	2.1	[95]	2016	
Mono-Si	2.06	[95]	2016	
Mono-Si	1.95	[95]	2016	

Table 3: *Energy payback time (continue).*

Material	EPBT (year)	Reference	Year	EPBT average (year)
Poly-Si	1.6	[95]	2016	1.34
Perovskite-Si	1.1	[102]	2017	0.92
Perovskite-CIGS	0.625	[102]	2017	
Perovskite-CZTS	0.21	[102]	2017	
Perovskite-perovskite	0.11	[102]	2017	
GaAs	1.67	[14]	2017	
CIGS	1	[14]	2017	
CdTe	0.75	[14]	2017	
Perovskite	0.5	[14]	2017	
Poly-Si	2.3	[103]	2017	
Perovskite-Si	0.88	[104]	2018	1.26
Perovskite-CIGS	0.5	[104]	2018	
Perovskite-CZTS	0.45	[104]	2018	
CIGS/Si	1.4	[96]	2018	
CZTS/Si	1.3	[96]	2018	
AZTS/Si	1.3	[96]	2018	
Poly-Si	1.11	[97]	2018	
Poly-Si	1.08	[97]	2018	
Poly-Si	1.01	[97]	2018	
CdTe	3.6	[105]	2018	

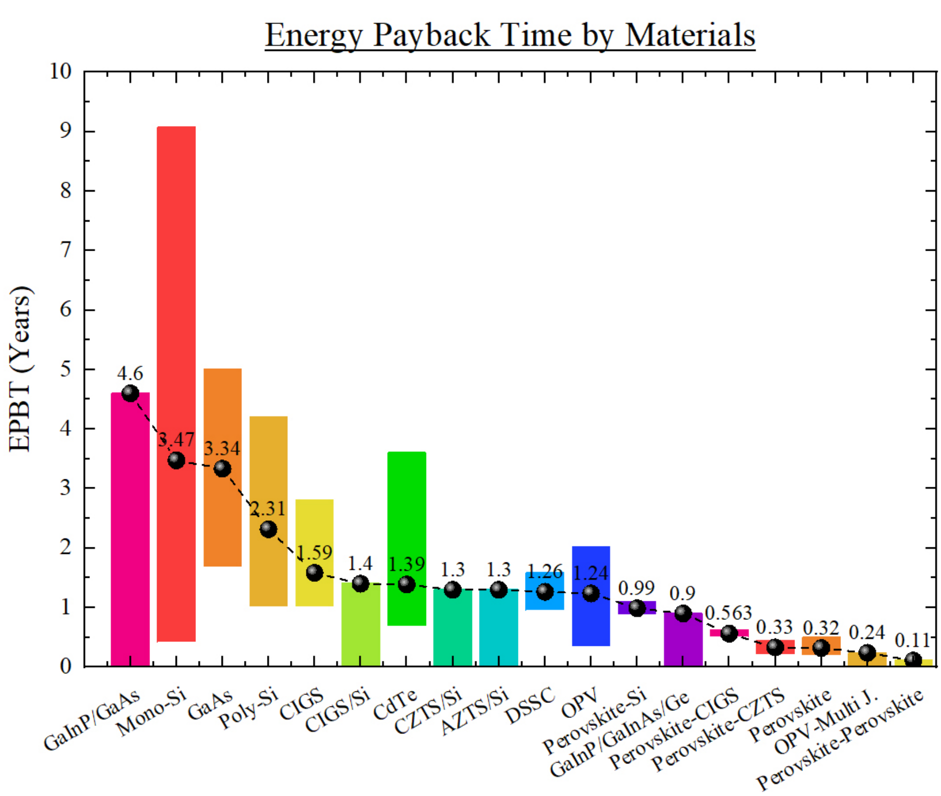

Figure 10: *EPBT corresponding to each material.*

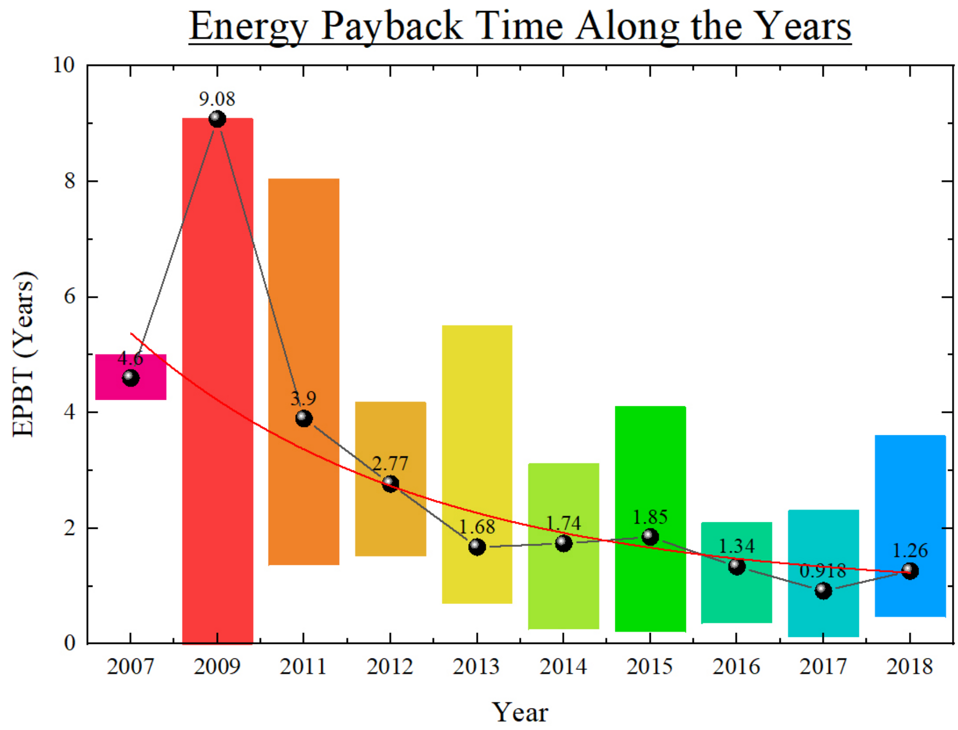

Figure 11: *EPBT along the years with its corresponding average values and tendency.*

Figure 12: *EPBT in Brazil using a low-cost solar system [107].*

Energy Return on Energy Invested

ERoEI in solar cells

Another important parameter to be assessed is the ERoEI, which refers to the ratio between the energy generated and given to commercial usage and the input system energy along its lifetime, since cradle to its final dead use which can be recycled [108]. Having this data into consideration, the results from 19 different materials from 2012 to 2018 are considered (Table 4) and this parameter is graphed with respect to different materials (Figure 13), obtaining that the ERoEI varies from 5.2 to 16.9; however, as it is known that silicon panels are the most common, it can be taken in a range between 8.5 and 10.4 which are the average values for monocrystalline and polycrystalline silicon panels.

Table 4: *ERoEI studies.*

Material	ERoEI	Reference	Year
Poly-Si	4.83	[79]	2012
CdTe	13.33	[80]	2012
CIGS	7.14	[80]	2012
DSSC	12.67	[80]	2012
Mono-Si	6	[109]	2012
Poly-Si	6	[109]	2013
CdTe	12	[109]	2014
Mono-Si	16.1	[90]	2014
Poly-Si	19.1	[90]	2014
CdTe	34.2	[101]	2015
CIGS	19.9	[101]	2015
Mono-Si	8.7	[101]	2015
Poly-Si	11.6	[101]	2015
CdTe	8	[110]	2016
Mono-Si	3.3	[110]	2017
Mono-Si	8.45	[111]	2017
Perovskite-CIGS	9.2	[104]	2018
Perovskite-CZTS	8.1	[104]	2018
Perovskite-Si	5.2	[104]	2018

ERoEI of solar cells in front of Brazilian grid

The range of solar cells obtained earlier has to be compared with those values corresponding to other energies, especially non-renewable energies, and some studies are shown in Table 5 and graphed (Figure 14) together with solar cells data, which were divided into two, only silicon solar cells (Solar-Si) and the average between solar cell materials (Solar-System).

If the Brazilian energy grid was analysed, it could be possible to notice that only 22.10% of the total energy is produced by thermoelectrical source, which is the most common pollutant (Figure 15). Also, as shown in Figure 14, the ERoEI could be reduced from a range between 18.3 and 13.1 (thermoelectrical plants from fossil fuels) to 9.45, which has to be re-

Table 5: *Different energies and their ERoEI.*

Energy	ERoEI	Reference	Year
Oil and gas	5.02	[113]	2007
Oil and gas	10.65	[113]	2007
Oil and gas	16	[114]	2008
Oil and gas	13	[114]	2008
Oil and gas	20	[114]	2009
Gas	20	[114]	2009
Coal	12	[108]	2010
Coal	16	[108]	2010
Oil	5.9	[108]	2010
Oil	5	[108]	2010
Gas	4.8	[108]	2010
Gas	8.2	[108]	2010
Oil and gas	10	[115]	2010
Coal	27	[115]	2010
Coal	28	[116]	2012
Oil and gas	17	[116]	2012
Hydroelectric	84	[116]	2012
Coal	30	[117]	2013
Gas	28	[117]	2013
Hydroelectric	35	[117]	2013
Coal	12	[108]	2015
Gas	11	[110]	2016
Coal	3	[110]	2016
Oil	1.7	[110]	2016
Hydroelectric	58	[110]	2016

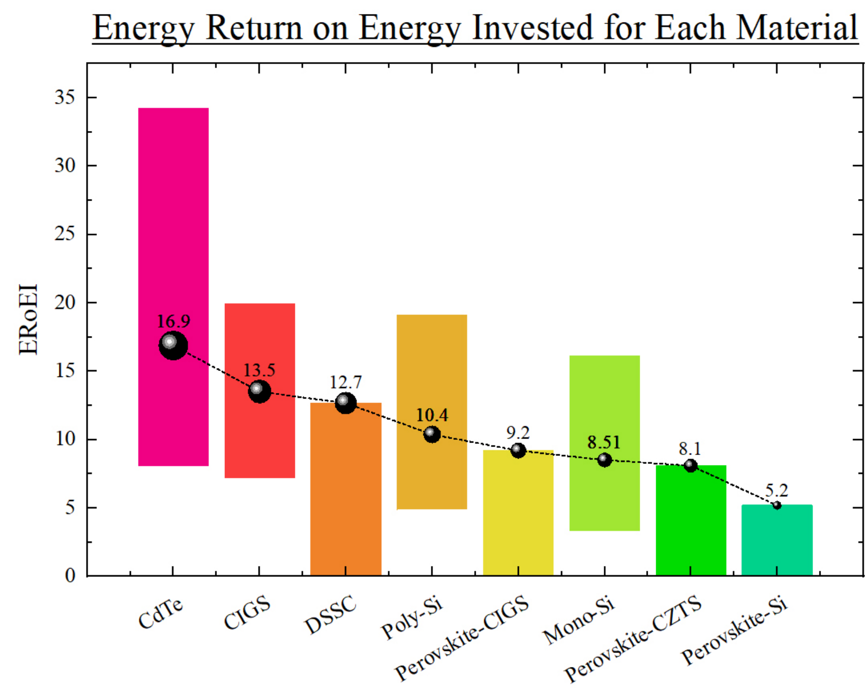

Figure 13: *ERoEI corresponding to different materials and their average.*

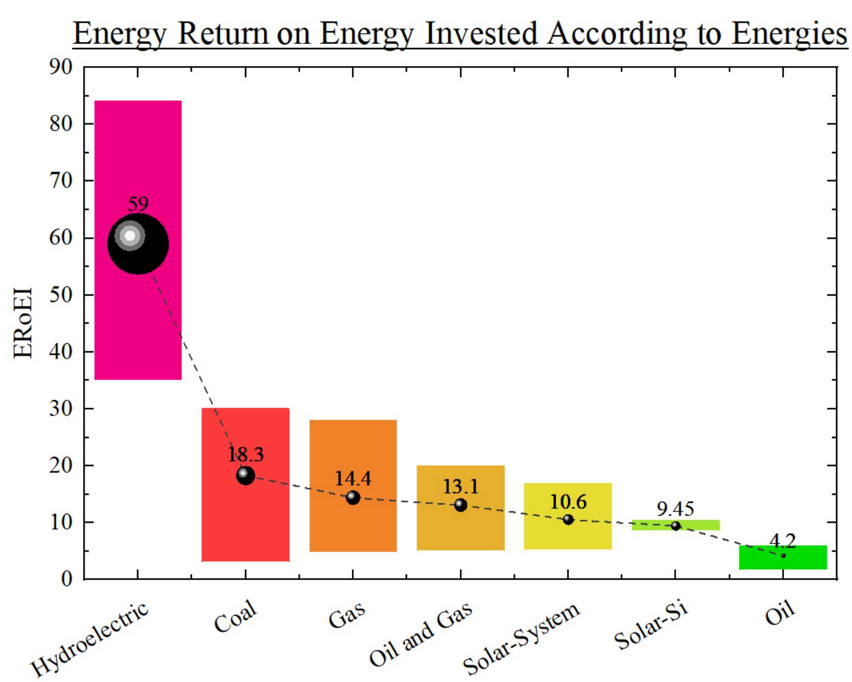

Figure *14: Different energies and their ERoEI.*

duced further. However, analysing the total energy capacity in Brazil which is 156.4 GW [9], getting its maximum peak in the same month (70.66 GW) [112] and having thermoelectrical potential energy as 34.56 GW, then without this energy, the total capacity in Brazil would be 121.84 GW. Therefore, even when the ERoEI of solar cells is lower than the thermoelectrical

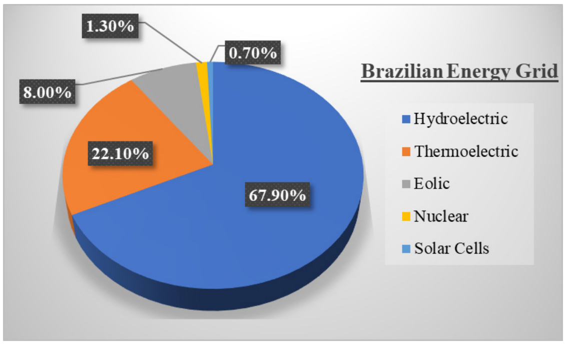

Figure *15: Brazilian energy grid (March 2018).*

plants, the country would be stable if thermoelectrical plants were substituted by solar cells.

The Brazilian Scenario

Potentiality of the territory

The four important parameters to be evaluated in the performance of a green energy have been analysed; however, the economical aspect and application potentiality of the region have to be investigated. First, the irradiance is analysed (Figure 16) where Brazil is compared with Europe, obtaining similar, and even better, values, compared with other countries, such as Portugal, Spain and Germany, where the solar energy has been applied [118]. Also, the potential system that could exist in Brazil is 5153 Wh/m^2 [119], and knowing they are of the country (8.52 × 1012 m^2) the potential energy is 43.96 PWh (4.396 × 1016 Wh). Compared with the maximum energy demand (≈85,000 GW) [120], it is 0.085 PW and 0.193% of the potentiality of solar cells energy; therefore, this result might be translated as 0.193% of the Brazilian territory could supply the energy demand.

Economic aspect

Another point is the economic aspect. It was analysed how could cost the energy by MWh, obtaining the levelised cost of energy (LCOE), in 2019, with the corresponding value of solar energy 45.7 US$/MWh, compared with 39.1 US$/MWh in hydroelectrical industry, 104.3 US$/MWh for thermoelectrical plant using coal and 46.3 US$/MWh when the thermoelectrical plant is used for natural gas [121].

On the other hand, in 2015, the cost in Brazil for solar energy was studied, getting around 175 US$/MWh [10], but using the tendency from 2015 to 2019 it could be reduced from around 0.6 to 0.244 US$/Wp [8], the value being 40.67% compared with the value 4 years ago. Therefore, it could be thought that in Brazil, nowadays, the projected value for solar

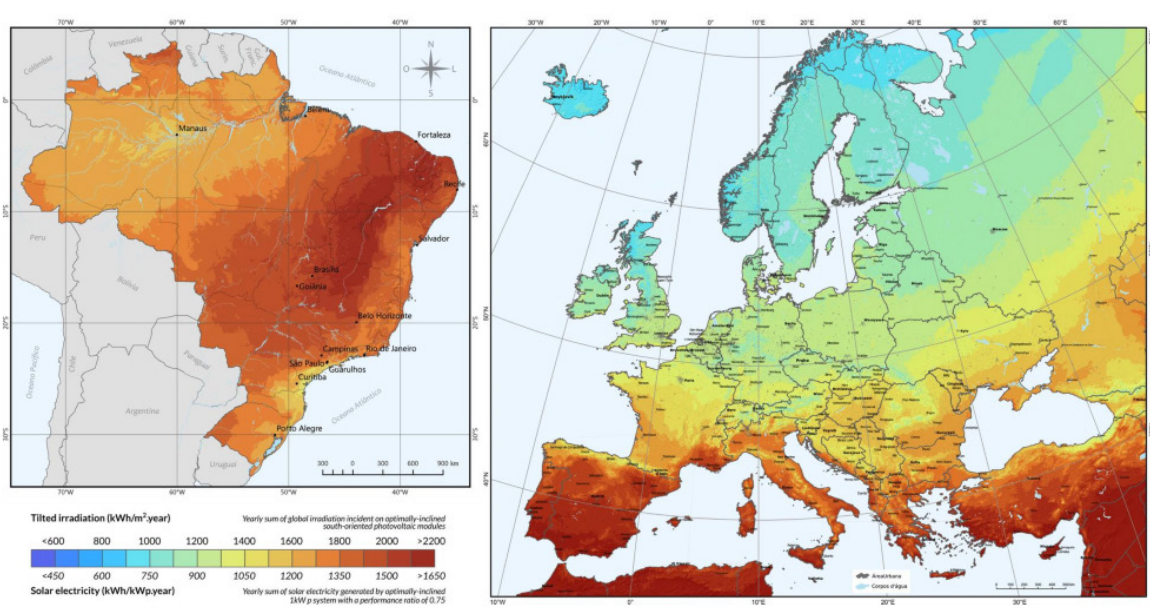

Figure 16: *Solar irradiance in Brazil (left) and in Europe (right) [118].*

energy could cost 71.17 US$/MWh which is more competitive. Also, another studied value for Brazil is the price of carbon thermal plant- with a value between 70.9 and 100.6 US$/MWh [71], being better using the solar energy.

Conclusions

In addition to all those mentioned and explained earlier, five critical points were analysed, observing the behaviour of solar cells and how they could act in the Brazilian scenario, and they are summarised below.

CO_2 emissions: In this point, the emission generated by different solar panels along their lifetime was obtained, from the factory to the grave getting values from 19.8 to 71.3 CO_2 g/kWh and being much lower than the energy from coal (943 CO_2 g/kWh). For this reason, if Brazil substitutes its fossil fuels to solar energy, the emissions could be reduced from 437 to 29.7 Mt of CO_2 by year, which is 6.8% of the actual emissions.

EPBT: Here, the time to recover all the used energy by solar panels varies from 0.11 to 4.6 years and in Brazil the value is around 3 to 4 years. There are improvements every year, having in consequence a reduction of this value. Also, they are good values that some companies offer a warranty of 25 years.

ERoEI: One of the most remarkable points was that photovoltaic panels can be compared with fossil fuels, showing better values than oil.

Efficiency: The efficiency has been a point with a constant increase every year, reaching 20% of efficiency easily, being rival to Brazilian thermoelectrical plants.

Cost and irradiance: Analysing the Brazilian case directly, the photovoltaic panels are more expensive than in Europe; nonetheless, they show a cheaper price than energy from coal. Also, the irradiance in Brazil is thus big that it is needed 0.2% of their territory to supply the national energy demand.

Finally, the solar energy presents low CO_2 emissions, a fast payback time, good efficiency and lower prices every year showing how green it could be, and in the Brazilian case it is perfectly suitable because of all those points mentioned earlier, and the Brazilian territory presents a wonderful irradiance potential.

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