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Energy payback time and Greenhouse Gas emissions: Studying the international energy agency guidelines architecture

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ABSTRACT

The International Energy Agency (IEA) in collaboration with an international panel of experts has published three editions of the Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (2009, 2011 and 2016) with the growing purpose of making increasingly precise assessments. This reference implies the estimation of major environmental indicators reported in literature, such as Energy PayBack Time (EPBT) and Greenhouse Gas (GHG) emissions in order to determine their benefits in terms of energy compared to conventional alternatives. However, in most cases this framework provides simplified calculations at the expense of accuracy.

This study strengthens the monocrystalline (mono-Si) and polycrystalline (poly-Si) energy production estimation proposed by the IEA guidelines with formulas and calculation models of highest accuracy and contrast the resultant EPBT and GHG emissions in a case study. Likewise, a detailed analysis has been carried out to observe the range of orientations with the optimum performance while on the other hand; emphasis was placed on the need to compare the results directly with those corresponding to local energy sources, instead of regional or national ones.

Results indicated that EPBT was 17%–19% and GHG emissions were 14–16% lower with the proposed method compared to the IEA guidelines respectively. Moreover, a range of orientations with near-optimal performance is also detailed. Finally, despite having clear environmental benefits compared to the local electric mix, its benefit is lower than if compared to the national electric mix in the case studied. Therefore, conclusions expressed herein contribute to reliability consolidation of PV technologies

1. Introduction

At present, one of the most important international challenges is meeting the energy needs of the population. As a result, governments are tending to focus steadily on the diffusion of technologies that take advantage of different renewable sources of energy (Patkó et al., 2013).

Life Cycle Assessment (LCA) is an integrated and structured method of quantifying materials, energy flows and emissions associated with the life cycle of products and services. The regulations that describe the principles and structure, as well as the requirements and guidelines for the development of LCA are ISO 14040: 2006 and ISO 14044: 2006.

With the aim of unifying criteria, the guidelines for the elaboration of LCA of PV technologies within Task 12 group were published, as a substantial effort by the IEA Photovoltaic Power Systems Programme (PVPS) (Alsema et al., 2009). These guidelines -updated in 2011 (Frischknecht et al., 2016) and 2016 (Frischknecht et al., 2016)- have served to facilitate the comparison of results from different studies. The IEA guidelines actually allow the selection of different criteria, leading studies to gradually focus on assessments

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in terms of energy such as the EPBT and GHG emissions. The EPBT refers to the years that PV modules need to generate the electrical energy used for their manufacture. In contrast, the carbon footprint analyzes their impact on climate change. For this, a relation of kWh produced by them during their useful life cycle and the g of CO_2-eq. delivered by its manufacture needs to be done.

In the LCA of PV technologies, other environmental indicators have also been reported. However, these studies are characterized by evaluating PV devices on development phase, such as ceramic (Belussi et al., 2015), organic (Tsang et al., 2016), organic tandem (Hengevoss et al., 2016), perovskite (Celik et al., 2016), nanotechnology (Kim et al., 2016) or other polycrystalline silicon technologies such as aluminum surface field (AI-BSF), passive emitter and posterior cell (PERC) and PERC with frameless double glass structure (Luo et al., 2018)

In other cases, environmental indicators are analyzed when considering a particular type of installation; for example, the case of Building Integrated Photovoltaic (BIPV) as a shading device and with a tracking system (Jayathissa et al., 2016), in marine installations (Ling-Chin et al., 2016), or in photovoltaic/thermal systems (PVT) (Lamnatou and Chemisana, 2017). Likewise, the general environmental indicators have been estimated in evaluations that consider alternatives of general design (Nian, 2016), the general manufacturing process in China (Hong et al., 2016) or even in studies made by Yu, a metallurgical route was proposed for the manufacture of polycrystalline modules also in China (Yu et al., 2017).

In relation to methodological improvements, Li proposed a method to evaluate the sustainability on PV systems, where besides being based on LCA, aspects such as technical-economic viability, environmental indicators (EPBT, recyclability of materials and environmental emissions) and, social indicators (land use, impacts on the local community and fuel poverty) where addressed (Li et al., 2017). Other authors identified ideal countries for PV system allocation among 138 options for the manufacture and use of photovoltaic systems taking into consideration the 2012 market situation (Serrano-Luján et al., 2017). Finally, Sampaio and González highlighted the need to develop a higher number of research related to economic viability, supply chain coordination, analysis of barriers and incentives to photovoltaic solar energy and more in-depth studies on the factors that influence the market (Sampaio and González, 2017).

Energy parameters have also been the subject of discussion in the specialized literature (Wong et al., 2016), reviewed the LCA and embodied energy requirements of poly-Si and mono-Si PV systems. The study observed that the differences in the installation, as well as the orientation, direction and performance of those modules have remarkable effects in the GHG emissions. Subsequently Louwen analyzed the performance of different PV technologies from satellite radiation measurements in order to characterize their geospatial performance in most of Europe and across Africa and the Middle East. However, this information does not offer enough details to fully characterize the environmental profile of PV systems under different installation conditions especially for a specific orientation and inclination of the installation (Louwen et al., 2017).

Likewise (Woyte et al., 2013), highlighted that in the last 20 years, the Performance Ratio (PR) of photovoltaic installations has increased from 0.65 to 0.85; in addition, in the state-of-the-art prepared by Peng, it is pointed out that the formulas proposed by the IEA are simplified, so it is important to estimate through formulas of highest precision (Peng et al., 2013).

Thus, this study is intended to propose improvements on evaluation of energy parameters involved in PV systems. For this, the EPBT and GHG emissions of mono and Poly-Si systems obtained through the IEA methodology were compared with a proposed criteria of optimization considering their installation in Mexicali, the hottest city in Mexico and among the 10 hottest cities of the world. For environmental calculations, Ecoinvent® database v3.1 was employed via SimaPro® v8.1. The power photovoltaic production simulated in TRNSYS® v17 was made in compliance with Perez model for the estimation of radiation on tilted surfaces and the four parameters model for photovoltaic power calculation; using accurate weather data indexed in a Typical Meteorological Year (TMY) file built in METEONORM® v6.0.

In this paper, the *Antecedents* section is divided into four parts where: section 1) shows an overview of EBPT and GHG emissions result calculations from previous studies; 2) provides studies where the optimal orientation for PVs has been identified in different locations, demonstrating that this does not necessarily correspond to fixed configurations with azimuth angles due equator and latitude based inclinations; 3) reviews the literature related to radiation calculation modules on tilted surfaces, which offer higher precision than satellite data and 4) characterizes the electric mix of the state of Baja California and northwestern Mexico in order to set up a regional comparison of environmental benefits on PV systems. The *Method* section, on the other hand, describes the simulation process on photovoltaic production and calculation of the EPBT and the GHG emissions. Similarly, Results section shows different performance scenarios based on orientations and inclinations of photovoltaic arrays, as well as a comparison of the environmental benefits according to the national, regional and local electric mix. Finally, the *Conclusions* section highlights the significant results, their applicability and considerations for future research.

2. Antecedents

2.1. EPBT and GHG emissions of photovoltaic systems

Several reviews on energy profile of photovoltaic systems have been developed in recent years. Yue highlights that the LCA of photovoltaic systems are limited to Europe and North America (Yue et al., 2014).

Other studies underlined EPBTs estimated in 3.2–15.5 for mono-Si and 1.05–5.07 years for poly-Si systems. On the other hand, GHG emissions vary between 44-280 and 9.4–104 g CO_2-eq/kWh (Sherwani et al., 2010).

Have also been mentioned the importance of updating and reporting on the changes that photovoltaic technologies have experienced lately. Under average radiation conditions in the United States and southern Europe, the EPBT of mono-Si was about 2.7 and poly-Si technologies presented values over 2.2 years (Fthenakis and Kim, 2011).

Peng indicated that monocrystalline presented the worst performance having EPBT ranges between 1.7 and 2.7 years with GHG emission rates between 29 and 45 g CO_2-eq./kWh. The ranges for poly-Si was 1.5–2.6 years in terms of EPBT and 23–44 g CO_2-eq./kWh on GHG. This manuscript also pointed out the relevance of contemplating different solar calculation models on tilted surfaces (Peng et al., 2013).

In general, the LCAs from different PV technologies are most frequently carried out in southern Europe, where solar resource in this area is about 1700 kWh/m^2/year and the electric mix is made up of 50% from hydropower and 50% from coal. A number of studies have also been conducted for different Asian countries; however, it is important to note that data for developing countries in Latin America have not yet been reported.

Tables 1 and 2 summarize the results of EPBT and GHG emissions from both of these silicon technologies carried out since the year 2000.

Table 1
Summary of LCAs of Monocrystalline technology.

Location | kWh/m^2/year	Module efficiency (%)	Life time (years)	Performance Ratio	EPBT (years)	GHG g CO_2-eq/kWh	Author, year
Italy | 1700	13.0	30	0.75	3.2	60.0	(Alsema, 2000)
India | *	13.0	25	*	*	64.8	(Mathur et al., 2002)
Southern Europe | 1700	14.0	30	.	2.1	35.0	(de Wild-Scholten and Alsema, 2005)
Switzerland | 1117	14.8	30	0.75	3.6	110.0	(Jungbluth, 2005)
U.S.A. | 1700	14.8	30	0.75	2.7	45.0	(Fthenakis and Alsema, 2006)
Singapore | 1635	10.6	25	*	4.5	165.0	(Kannan et al., 2006)
Singapore | 1635	7.3–8.9	25	*	5.87	217.0	(Kannan et al., 2006)
Scotland | 800	11.5	30	0.75	8.0	44.0	(Muneer et al., 2006)
Southern Europe | 1700	10.6	30	0.75	1.75	165.0	(de Wild-Scholten et al., 2009)
China | 1.702	14.0	*	0.75	2.5	30.0	(Ito et al., 2010)
Several locations | 900-1000	*	30–20	0.75	2.8–4.9	8–47	(Laleman et al., 2011)
Europe |1700 (several)	*	20	0.75	3.81	37–73	(Bravi et al., 2011)
Spain | 1400-1900	14.0	30	0.75	7.1–9.6	*	(Sumper et al., 2011)
USA and Sourthern Europe | 1700	14.0	30	0.75	2.7	*	(Fthenakis and Kim, 2011)
Italy | 1383–1623	15.0	30	0.75	2.4–2.8	71–84	(Cucchiella and DAdamo, 2012)
Thailand |*	14.8	30	0.75	*	60.9	(Kittner et al., 2013)
Southern Europe| 1700	15.4	30	0.78	1.96	38.1	(de Wild-Scholten, 2013)
Malaysia | 1810	*	30	0.80	*	38.7	(Kim et al., 2014)
China | 1700	14.0	30	0.75	2.4	72.2	(Yue et al., 2014)
China | 772–2100	16.0	25	0.78	2.22–6.05	50.0	(Fu et al., 2015)

* Data not reported.

Table 2
Summary of LCAs of Polycrystalline technology.

Location | kWh/m^2/year	Module efficiency (%)	Life time (years)	PR	EPBT (years)	GHG g CO_2-eq/kWh	Author | year
Southern Europe | 1700	13.0	30	0.75	3.2	60.0	(Alsema, 2000)
China | 1675	12.8	30	0.78	1.7	12.0	(Ito et al., 2003)
Italy | 1530	10.7	20	0.80	3.3	26.4	(Battisti and Corrado, 2005)
Greece | *	*	20	*	2.9	104.0	(Tripanagnostopoulos et al., 2005)
USA | 1700	13.0	30	0.75	2.2	37.0	(Fthenakis and Alsema, 2006)
Southern Europe | 1700	13.2	30	0.75	1.9	32.0	(Alsema and de Wild-Scholten, 2005)
Swiss | 1117	13.2	30	0.75	2.9	*	(Jungbluth, 2005)
USA | 1359	12.9	20	*	2.1	72.4–54.6	(Pacca et al., 2007)
China | 2017	12.8	30	0.78	1.9	12.1	(Ito et al., 2008)
China | 2017	15.0	30	0.78	1.5	9.4	(Ito et al., 2008)
Southern Europe | 1700	14.0	20	0.75	2.4	72.0	(Raugei et al., 2007)
Italy | 1700	16.0	28	*	2.1	80.0	(Stoppato, 2008)
Southern Europe | 1700	13.2	30	0.75	1.75	29.0	(de Wild-Scholten et al., 2009)
China | 1702	*	*	0.75	2.0	43.0	(Ito et al., 2010)
Several locations | 900–1000	13.2	20–30	0.75	2.5–4.3	8–47	(Laleman et al., 2011)
Europe | 1700 (several)	*	20	0.75	3.47	32.64.1	(Bravi et al., 2011)
Spain | 1400–1900	*	30	0.75	3.67–4.94	*	(Sumper et al., 2011)
USA and Sourthern Europe | 1700	13.2	30	0.75	2.2	*	(Fthenakis and Kim, 2011)
Italy | *	14.4	25	0.80	4.17	*	(Desideri et al., 2013)
Italy | 1383–1623	13.2	30	0.75	2.5–2.9	72.0–84.0	(Cucchiella and DAdamo, 2012)
Southern Europe | 1700	14.1	30	0.78	1.24	27.2	(de Wild-Scholten, 2013)
Malaysia | 1810	13.5	30	0.80	*	36.2	(Kim et al., 2014)
China | 1700	13.2	30	0.75	2.3	69.2	(Yue et al., 2014)
China | 772–2100	*	25	0.78	2.22–6.05	50.0	(Fu et al., 2015)
China | 1654	14.08	30	0.796	3.06	*	(Yu et al., 2017)
China | 2017	17.5	30	0.835	2.3	*	(Wu et al., 2017a)
China | 2017	17.5	30	0.835	*	36.75	(Wu et al., 2017b)

* Data not reported.

2.2. Optimum orientation of photovoltaic technologies

In terms of LCA for photovoltaic systems, an array tilt angle equal to the specific location latitude (Φ) oriented due equator is assumed as the optimum orientation. However, revised literature indicates that it is preferable to evaluate each specific case. This section describes evaluations that determine the optimal orientation for the production of photovoltaic energy in cities with different latitudes

Benghanem developed an analysis in Medina, Saudi Arabia (Lat. 24.28° N). The optimum annual tilt angle was 23.5°. During winter months, the best inclination was 37° and 12° in the summer. He also noted that the annual optimum tilt angle is around 8% lower compared to the optimum one at each month (Benghanem, 2011).

Haller developed a model to analyze differences in optimal orientation of diverse PV technologies. Results obtained highlighted that the optimum orientation for different technologies (crystalline and thin film) is the same. Furthermore, in horizontal orientations, thin film modules achieve a higher energy output. However, this advantage is less than 1% regarding crystalline technologies (Haller et al., 2013). In this respect, Table 3 presents a summary of optimum orientations for these technologies without tracking axes.

Yan evaluated the performance of two arrays of poly-Si modules

Table 3
Summary of optimal orientations for photovoltaic technologies.

Location		Latitude (°)	Longitude (°)	Optimum Orientation (°)	Optimum tilt angle (°)	Technology *	Author, year
London, U.K.	51.50	00.13	S	30	m-Si	(Fordham, 1999)
Teheran, Iran.	35.71	51.41	NE	29	m-Si	(Asl-Soleimani et al., 2001)
Hamamatsu, Japan.	34.45	137.41	S	30	m-Si	(Nakamura et al., 2001)
Cairo, Egypt.	30.05	31.24	S	20–30	NR	(Hussein et al., 2004)
Medina, Saudi Arabia.	24.28	NR	S	24	NR	(Benghanem, 2011)
Brisbane, Australia	27.28	NR	N	26	NR	(Yan et al., 2013)

* m-Si, monocrystalline silicon; p-Si, Polycrystalline silicon; NR, Data not reported.

at the University of Queensland (Lat. 27.28° S). The array of 60 panels inclined at 2.5° due South, produced more energy in the long term. However, the array of 56 panels with a tilt angle of 5.5° due North is more efficient. The authors comment that the optimum theoretical inclination in Brisbane is 26° with a north orientation (Yan et al., 2013).

Bakirci developed an analysis to determine the optimum angle of inclination for solar energy applications for eight provinces of Turkey. It was observed that the optimum tilt angle reached a minimum of 0° in June and July and increased during winter months, reaching a maximum in December in all locations. The optimum tilt angles for a south-facing orientation of systems were 31.21°, 32.71°, 32.61°, 34.31°, 32.61°, 32.81° and 33.21° at Adana (Lat. 37.0° N), Ankara (Lat. 39.91 N), Diyarbakir (Lat. 37.9° N), Erzurum (Lat. 39.9° N), Istanbul (Lat. 41° N), Izmir (38° 24′), Samsun (Lat. 41.28° N) and Trabzon (Lat. 41° N) respectively (Bakirci, 2012).

Other research conducted an experimental study to determine polycrystalline systems production under different angles of inclination in Athens, Greece (Lat. 37.58° N). For this, the inclinations between 0°, 15°, 30°, 45°, 60° and 75° were different during 20 days in summer. The results showed that 15° tilt angle produced the greatest amount of electrical energy during most of the summer season (Kaldellis and Zafirakis, 2012).

This same author developed a theoretical and experimental study to determine the angle of inclination and optimum orientation to meet the need for electricity in remote locations in Greece. According to his results, the angle of inclination and optimal orientation to satisfy the local energy demand coincides with the angle that guarantees the maximum exploitation during the period of the lowest solar irradiation of the year. The authors pointed out that in order to satisfy a given energy consumption, the capacity of the system does not necessarily have to be increased, but angles of inclination and orientation must be adjusted to the annual consumption pattern of the particular case (Kaldellis et al., 2012).

In other studies, the optimal configuration has been evaluated from a financial perspective. For example, Hartner evaluated the economic situation of photovoltaic installations in 23 regions of Austria and Germany (Hartner et al., 2015). Their results showed that the configuration of optimal energy production is not necessarily better from the economic point of view. Likewise, they identified that the ideal economic configurations have an energy production even 1% lower than the optimal energy production configurations. In Mexico, latest studies showed that the optimal energy production configuration for photovoltaic installation does not necessarily correspond to fixed configurations with azimuth angles due equator and latitude based inclinations. Likewise, they define a broad range of configurations with a similar economic performance (variations to each degree in azimuth and inclination) for locations analyzed in three different climates (Armendariz-Lopez et al., 2016). Litjens, in particular identified that self-consumption can be increased 5.4% in residences and 2.7% in commercial buildings if the photovoltaic installations are configured in such a way that they focus on covering consumption demand and not in relation to greater annual energy production (Litjens et al., 2017).

2.3. Models for calculating radiation on tilted planes

Numerous studies have demonstrated that the selection of model for radiation calculation in inclined planes is fundamental to predict with more precision the best orientation for the photovoltaic installations (Michaelides and Eleftheriou, 2011). Some important statements conclude that the lack of radiation data is one of the main barriers to develop solar technologies at a local level. A short-term stepwise calculation of irradiation in inclined planes is required in order to predict the precise performance of solar systems, to improve their operating conditions and economic cost savings (Shaddel, et al., 2016).

A variety of models have been developed for calculating solar radiation on tilted surfaces from measured data of total, direct, diffuse and/or reflected radiation on horizontal surfaces. The importance of developing this kind of models lies on the fact that meteorological stations have unidirectional capacities to measure direct radiation in horizontal planes.

Models for calculating radiation in inclined planes can be classified as isotropic and anisotropic. The isotropic models assume that the intensity of diffuse radiation from the sky is uniform while anisotropic models are more accurate because they consider with complexity the sky diffuse radiation.

Demain observed calculated data from 14 radiation models for tilted surfaces contrasting them with measured data from 8 months that include diverse atmospheric conditions and solar altitude in the Real Meteorological Institute of Uccle, in Brussels, Belgium (Lat. 50.79° N). They concluded that any model performed equally under different sky conditions. Bugler, Pérez and Willmot models estimated properly the global radiation on south oriented tilted surfaces. The Bugler model had better performance in general conditions and partly cloudy and clear sky. The Willmot model obtained the best results under partly cloudy and cloudy sky. Meanwhile, Perez's model was the most accurate in totally cloudy sky (Demain et al., 2013).

Khalil studied 11 models from direct and diffuse total incident radiation data on a horizontal and tilted surfaces measured on a daily basis at hourly intervals between 1990 and 2010 in Cairo, Egypt (Lat. 30.15° N). The authors concluded that Hay (Ha), Skartveit-Olseth (SO) and Pérez et al. models are more accurate in south orientations; by contrast, Hay (Ha) and Pérez et al. models produced greater precision on the west (Khalil and Shaffie, 2013).

In turn, David studied the performance of the Skartveit-Olseth, Hay, Gueymard and Pérez 1990 models for diffuse radiation estimation on tilted panels in Reunion Island, France (Lat. 21.30° S). Results were compared with data measured on Saint-Pierre platform for 14 different surfaces (tilt angles of 20° and 40° and azimuths of 90°, 60°, 30°, 0°, −30°, −60° and −90°). In general, the Perez model had the best performance with a mean bias of −6.8 W/m^2 (David et al., 2013).

2.4. The electricity mix

2.4.1. The electricity mix in Mexico

In Mexico, power plants including diverse technologies are distributed all over the country; all related data is provided by the Energy Information System and the Electricity Sector Works and Investments Program (Subdirección general de la Comisión Federal de Electricidad, 2014, 2013, 2012). Thus, combined cycle plants in 2014 have a generation capacity of 146,256 GW-hours per year (GWh/year) and represents 57% nationwide. Thermoelectric and hydroelectric technology generated in 2014, 34,415.10 and 32,304,30 GWh/year respectively. In this regard, national percentages of electric generation by technology are shown in Fig. 1.

The generation of electrical energy produced by renewable energy sources accounted for 16.94% of the mexican electricity mix in 2014. The 12.59% came from hydroelectric power, 2.51% from geothermal energy, 1.84% from wind energy and the contribution of a PV solar energy pilot plant is practically non-existent.

2.4.2. The electricity mix in the north-western region

The Mexican electricity sector is divided in five zones: northwest, northeast, center-west, center and south-southeast. The northwest electrical mix includes the states of Baja California, Baja California Sur, Sonora and Sinaloa; this mix in 2014 reported production as: combined cycle technology (49.47%), conventional thermoelectric (23.64%), geothermal (11.67%), hydroelectric (7.71%) and internal combustion (6.09%) as seen in Fig. 2. The combined cycle technology has a generation of 16,853.6 GWh/year and is in itself 141.62% greater than the total sum of renewable energy sources (6975.3 GWh/year) used in the electric mix of the area (Secretaria de Energia, 2014).

2.4.3. The electricity mix in Baja California

In this region of Mexico, the percentage of users has increased at a rate of 3.50% per year during 2002–2013 period, while gross generation and domestic sales of electric power have only increased by an annual average of 2.66% and 1.93% respectively. Along with this, the state of Baja California has one of the most important wind and solar potential in the country; the Cerro Prieto power plant had 75% of the geothermal power installed nationwide in 2014.

In 2014, geothermal power contributed with 41.10% of Baja California's electricity generation, followed by turbogas (28.35%), combined cycle (23.46%) and conventional thermoelectric (7.09%) shown in Fig. 3.

3. Method

Several guidelines have been published by the IEA through the Task 12 project within the Photovoltaic Energy Program. This, with the intention of developing comparisons of LCAs of PV systems with higher quality, coherence and credibility. These documents are focused in three main areas related to technical characteristics; modeling approaches in life cycle inventory analysis and life cycle impact assessment; and lastly, to reporting and dissemination aspects.

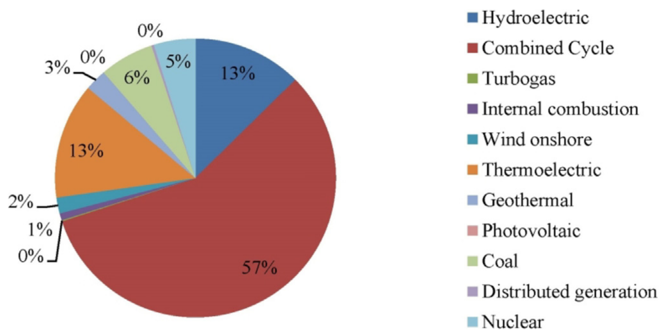


Fig. 1. National electricity generation by source.

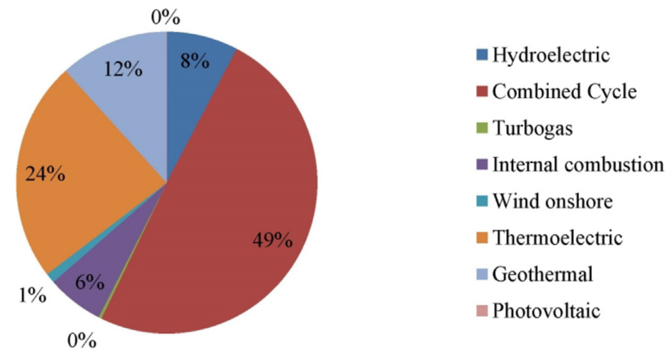


Fig. 2. Northwest region electricity generation by source.

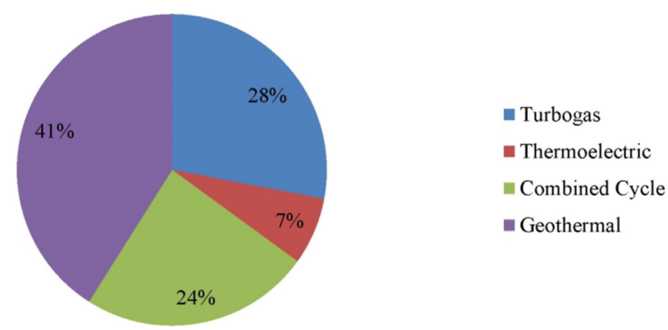


Fig. 3. Baja California electricity generation by source.

This work presents the LCA of mono and polycrystalline systems considering the global information in terms of operation for the city of Mexicali. The assumptions considered in this paper are detailed below, in compliance with Task 12 guidelines:

- Life expectancy: estimated a 30 years useful life period of PV modules and a 10 years term for inverters.
- Solar radiation: Optimum south orientation with 31° tilt angle, reaching an annual total value of 2200.15 kWh/m^2/year according to Mexicali weather data generated in METEONORM® v.6.0 and processed with the Perez radiation model in TRNSYS® v.17.
- Performance ratio: 75%.
- Generation of electricity during the useful life of PV system: Calculated according to the simplified Task 12 formula compared with four parameters model simulated in TRNSYS® using this iterative search routine largely developed by Townsend (1).

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{voc} = \frac{\gamma k}{q}\left[\ln\left(\frac{I_{sc,ref}}{I_{o,ref}}\right) + \frac{T_c \mu_{Isc}}{I_{sc,ref}} - \left(3 + \frac{q\varepsilon}{AkT_{c,ref}}\right)\right] \quad (1)$$

where:

$$A = \frac{\gamma}{N_S} \quad (2)$$

This equation where V_{oc}: Open-circuit voltage, T_c: Module temperature, μ_{voc}: Temperature coefficient of open-circuit voltage,

γ: Empirical PV curve-fitting parameter, k: Boltzman constant, q: electron charge constant, $I_{sc,ref}$: short circuit current at reference conditions, $I_{o,\ ref}$: diode reverse saturation current at reference conditions, μ_{Isc}: temperature coefficient of short-circuit current, ε: semiconductor bandgap, N_s: number of individual cells in module and $T_{c,ref}$: module temperature at reference conditions is derived by taking the analytical derivative of voltage with respect to temperature at the reference open-circuit condition (Kummert, 2007).

- Degradation: Assumes an initial efficiency of 18.5% and 16.3% for both silicon technologies respectively. In addition, data published in terms of PV technologies degradation throughout their useful life in the US, Europe, Japan and Australia during the last 40 years was used (Jordan and Kurtz, 2011). The average degradation of PV systems is about 0.23% for mono-Si and 0.59% for poly-Si systems; additionally, the degradation of 0.90% for both technologies is considered (Jordan et al., 2016).
- Storage systems: No storage device was contemplated due to its on-grid system characteristics.

For the energy impacts, the Cumulative Energy Demand (CED) methodologies is used to determine the EPBT, and the IPCC GWP100a methodology to estimate GHG emissions. The database used was EcoInvent® software v.3.1 in SimaPro® software v.8.1.1. The efficiency of Mexico's electricity grid is 12.0 MJ/kWh.

In addition, the orientations that present a similar performance to the optimum in relation to EPBT (+0.1 years) and GHG (+2.0 g CO_2− eq./kWh) were identified.

4. Results

The highest annual radiation is 2200.15 kWh/m^2/year and was found in south azimuth at a 31° tilt angle. In the analysis carried out, it was found that the azimuth −70° (Southeast) and azimuth 290° (Southwest) and angles between 5° and 50° achieved radiation magnitudes above 2000 kWh/m^2/year. Also, in Fig. 4 are shown radiation values that exceed 1750 kWh/m^2/year on inclinations lower than 10°.

For this case under review, the IEA guidelines estimate an annual energy output of 1650 kWh per kWp for both PV technologies. However, based on TRNSYS simulation, a production of 2008.40 kWh/year per kWp for mono-Si was taken into consideration, at the same time 1975.94 kWh/year per kWp was estimated for poly-Si systems.

Regarding degradation parameters reported by Jordan and Kurtz in 2011, and in terms of the IEA simplified formula vs TRNSYS simulation as contrast results, mono-Si technology had a 30-year energy production of 47,386.18 kWh vs 58,285.15 kWh; In turn, poly-Si technology had a 30-year energy production of 45,665.64 kWh vs 54,475.33 kWh estimated in TRNSYS.

At the same time, degradation reported by Jordan et al. in 2016 considering the same criterion mentioned, reported a mono-Si technology from 30-year energy production of 43,507.84 kWh and 53,011.36 kWh. On the other hand, poly-Si technology had a 30-year energy production of 43,729.08 kWh and 52,154.42 kWh.

From the IEA guidelines, an EPBT of 1.41 years was determined for mono-Si and 1.18 years for poly-Si systems. Thus, when electrical production was simulated, an EPBT of 1.16 and 0.99 years was estimated, representing a lower EPBT in 17.85% for mono-Si and 16.50% for poly-Si systems. This means that the difference in depreciation values noted in Jordan and Kurtz in 2011, and Jordan et al., 2016 had no influence on scenarios analyzed for the EPBT as shown in Fig. 5.

It is important to note that the range of orientations with an EBPT similar to the optimum (+0.1) for both technologies is considerable. With IEA, systems could be installed in orientations with a solar resource greater than 2050 kWh/m^2/year. In turn, methodological optimization proposed in this study – viaTRNSYS-allowed orientations with a solar resource superior to 2025 kWh/m^2/year See Table 4.

Considering the degradation reported by Jordan and Kurtz in 2011 and the variants for the estimation of energy production elaborated through the IEA simplified formula and the simulation processed in TRNSYS, the GHG emissions for mono-Si were 27.26 and 22.37 g CO_2-eq./kWh; its counterpart, poly-Si values reached 23.39 and 19.61 g CO_2eq./kWh as shown in Fig. 6. In this respect, degradation reported by Jordan et al. in 2016 resulted in GHG emissions for mono-Si technology about 29.97 and 24.59 g CO_2eq./kWh and 24.43 and 20.48 g CO_2eq./kWh for poly-Si components. In both cases, GHG emissions were 17.93% and 16.15% lower for mono-Si and poly-Si systems as described in Fig. 7.

According to detailed analysis shown in Tables 5 and 6, the range of orientations for installation technologies with GHG emissions similar to the optimum parameter (+2.0) is presented. In other words, where the solar resource is higher than 2050 kWh/m2/year; with the exception of Jordan et al. (2016) applied on IEA.

Finally, a graphic comparative of photovoltaic systems including the electric mix in relation to GHG emissions is detailed in Fig. 8.

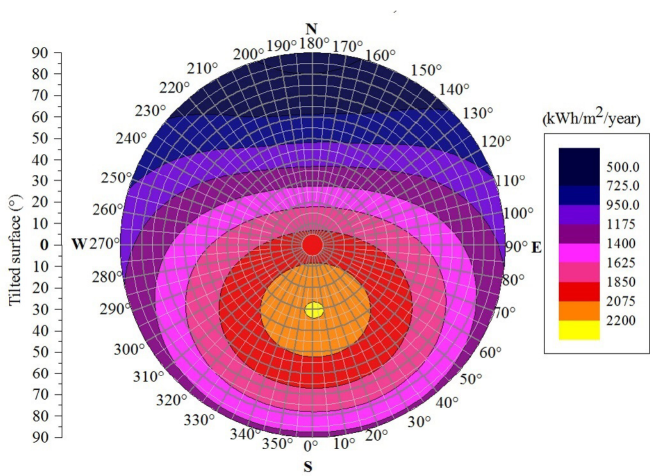
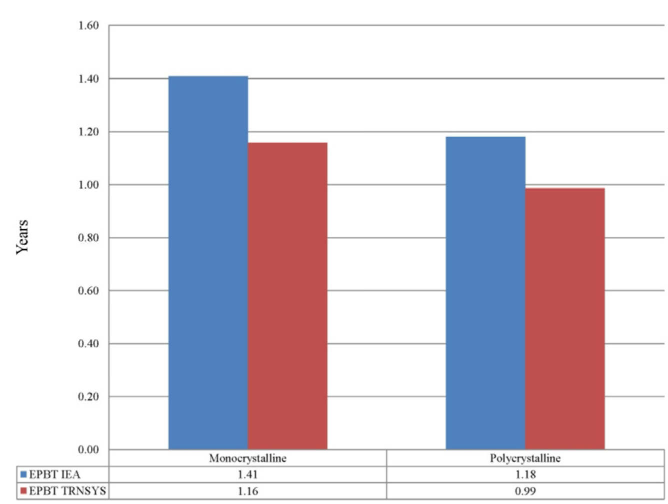


Fig. 4. Annual total solar radiation in Mexicali, B.C.



	Monocrystalline	Polycrystalline
EPBT IEA	1.41	1.18
EPBT TRNSYS	1.16	0.99

Fig. 5. Comparative Energy Pay Back Time of mono-Si and poly-Si systems.

Table 4
Range of orientations with near-optimal EPBT (+0.1).

Energy Pay Back Time (years)				
$kWh/m^2/year$	Monocrystalline		Polycrystalline	
	IEA	TRNSYS	IEA	TRNSYS
2200	**1.41**	**1.18**	**1.16**	**0.99**
2175	**1.43**	**1.19**	**1.18**	**1.00**
2150	**1.44**	**1.21**	**1.20**	**1.02**
2125	**1.46**	**1.22**	**1.21**	**1.03**
2100	**1.48**	**1.24**	**1.22**	**1.04**
2075	**1.49**	**1.25**	**1.23**	**1.05**
2050	**1.51**	**1.27**	**1.25**	**1.07**
2025	1.53	**1.28**	1.27	**1.09**
2000	1.55	1.30	1.28	1.10
1975	1.57	1.32	1.30	1.12
1950	1.59	1.33	1.32	1.13
1925	1.61	1.35	1.34	1.15
1900	1.63	1.37	1.36	1.16
1875	1.65	1.39	1.38	1.18
1850	1.68	1.40	1.40	1.19
1825	1.70	1.42	1.41	1.20
1800	1.72	1.44	1.42	1.21

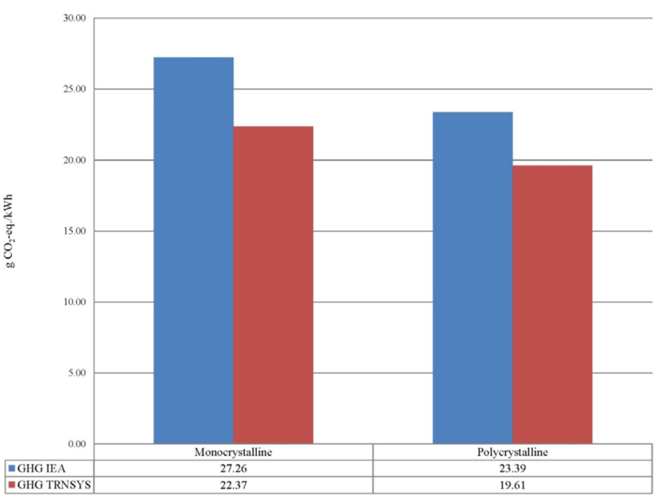


Fig. 6. Comparative GHG emissions of mono-Si and poly-Si systems with degradation rate reported by Jordan and Kurtz (2011).

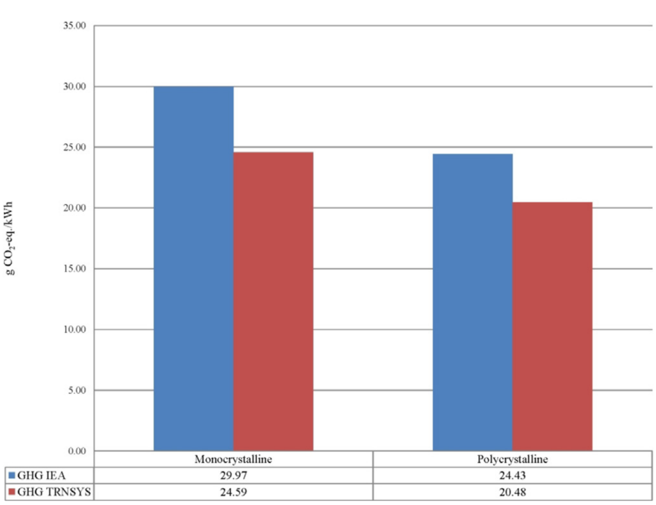


Fig. 7. Comparative GHG emissions of mono-Si and poly-Si systems with degradation rate reported by Jordan et al. (2016).

Table 5
Range of orientations with near-optimal GHG (+2.0) with degradation rate by Jordan and Kurtz (2011).

Green House Gas emissions (g CO2-eq/kWh)				
$kWh/m^2/year$	Monocrystalline		Polycrystalline	
	IEA	TRNSYS	IEA	TRNSYS
2200	**27.26**	**22.37**	**23.39**	**19.61**
2175	**27.57**	**22.48**	**23.65**	**19.67**
2150	**27.89**	**23.12**	**23.93**	**20.36**
2125	**28.22**	**23.41**	**24.21**	**20.52**
2100	**28.55**	**23.45**	**24.50**	**20.60**
2075	**28.90**	**23.64**	**24.79**	**20.78**
2050	**29.25**	**23.94**	**25.10**	**21.13**
2025	29.61	24.59	25.41	21.68
2000	29.98	24.82	25.72	21.84
1975	30.36	25.16	26.05	22.22
1950	30.75	25.39	26.38	22.33
1925	31.15	25.81	26.73	22.80
1900	31.56	26.21	27.08	23.12
1875	31.98	26.61	27.44	23.29
1850	32.41	26.98	27.81	23.57
1825	32.86	27.20	28.19	23.99
1800	33.31	27.41	28.58	24.13

Table 6
Range of orientations with near-optimal GHG (+2.0) with degradation rate by Jordan et al. (2016).

Green House Gas emissions (g CO2-eq/kWh)				
$kWh/m^2/year$	Monocrystalline		Polycrystalline	
	IEA	TRNSYS	IEA	TRNSYS
2200	**29.97**	**24.59**	**24.43**	**20.48**
2175	**30.31**	**24.72**	**24.71**	**20.55**
2150	**30.66**	**25.42**	**24.99**	**21.27**
2125	**31.02**	**25.74**	**25.29**	**21.43**
2100	**31.39**	**25.78**	**25.59**	**21.52**
2075	**31.77**	**25.99**	**25.90**	**21.70**
2050	32.16	**26.33**	**26.21**	**22.07**
2025	32.56	27.04	26.54	22.65
2000	32.96	27.29	26.87	22.81
1975	33.38	27.66	27.21	23.20
1950	33.81	27.92	27.56	23.33
1925	34.25	28.38	27.92	23.81
1900	34.70	28.82	28.28	24.15
1875	35.16	29.26	28.66	24.43
1850	35.64	29.67	29.05	24.61
1825	36.12	29.90	29.45	25.06
1800	36.63	30.14	29.85	25.21

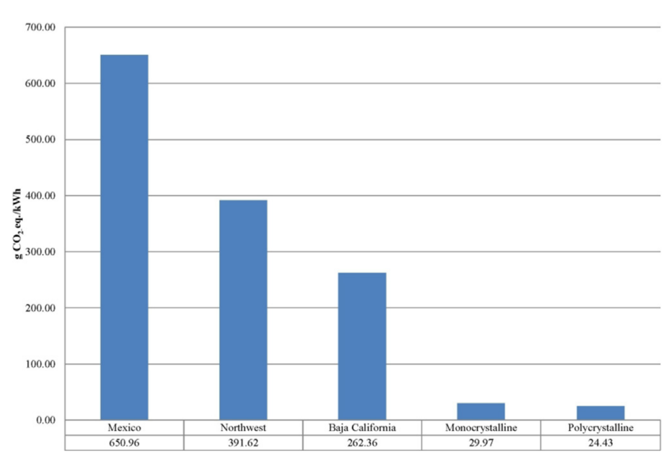


Fig. 8. Comparative of GHG emissions by electricity mix and PV systems.

With the objective of providing greater clarity in environmental impacts; the information of PV systems is contrasted with the one corresponding to national electrical mixes, north-west region and the state of Baja California.

GHG emissions from monocrystalline technology account for only 11.42%, 7.65% and 4.60%; Polycrystallyne technology 9.31%, 6.24% and 3.75% of the emissions, this in terms of the electric mixes in Baja California state, north-west region and nationwide level respectively.

5. Conclusions

A Life Cycle Analysis of Monocrystalline and Polycrystalline photovoltaic systems has been developed; in order to carry out these analyzes in detail, the following aspects were characterized:

- Solar resource values in different geometric configurations, as well as the estimation of PV electricity production with greater precision in relation to IEA simplified formulas.
- Based on the information provided by the Energy Information System (EIS) under the Secretariat of Energy administration in Mexico, the different energy sources that contribute to the national, regional (northwest) and the State of Baja California, the purpose of identifying the environmental advantages by the use of photovoltaic technologies.

The resultant EPBT using the IEA simplified formula was 1.41 and 1.18 years for monocrystalline and polycrystalline systems respectively, with a range of planes with 2050 kWh/m^2/year or higher both systems reach +0.1 years. In contrast, performed simulation produced EPBT of 1.16 and 0.99 years for mono and poly-Si systems reporting +0.1 years in this subject with configurations where radiation surpasses 2025 kWh/m^2/year.

In this regard and employing Jordan and Kurtz degradation rates (2011) resulted on Carbon footprint via simplified IEA formula of 27.26 and 23.19 g CO_2-eq./kWh for mono and polycrystalline. In turn, the analysis proposed as counterpart in this research, showed a carbon footprint of 22.37 and 19.61 g CO2-eq./kWh for each one.

However, employing Jordan's 2016 degradation rates resulted on Carbon footprint via simplified IEA formula of 29.97 and 24.43 g CO_2-eq./kWh for mono and polycrystalline. In turn, the analysis proposed as counterpart in this research, showed a carbon footprint of 24.59 and 20.48 g CO_2-eq./kWh for each one. In the same way that the EBPT, the range of geometric configurations for GHG emissions of up to +2.0 g CO_2-eq./kWh remain in 2050 kWh/m^2/year for both systems and methodologies.

Environmental impact caused by PV GHG emissions from national, to regional and local levels showed that the total amount of emissions of mono-Si systems represent 4.60%, 7.65% and 11.42% in the same order specified, while poly-Si represents for its part 3.75%, 6.24% and 9.31% under the same consideration.

For future research, the following should be taken into account:

- Relevant authors have mentioned the importance of reporting LCAs of PV technologies because of their constant improvement on efficiency, as well as the decreasing requirement of manufacture components.
- The degradation values that are reported over time.
- The environmental contrast between PV systems in different electrical mixes, especially in countries where electric power generation sources are diverse and have a fossil origin tendency.
- The future development of reliable models for the estimation of electric energy production for thin film photovoltaic technologies.

Thus, IEA methodology developed by important LCA experts has been demonstrated as perfectible in some aspects. According to the results presented, this research indicates that environmental impacts reported in literature overestimate the real ones for each photovoltaic technology; mainly due to the use of data that undervalue solar resource and at the same time calculation of photovoltaic electric energy production.

LCA indicators of interest in PV technologies reside in those of energy value, such as EPBT, GHG emissions, EROI, amongst other secondary aspects; this is due to the fact that in order to achieve the marketing consolidation, PV system virtues must be contrasted with conventional sources of energy dismissing —at the same time-the relevance of weighting a detailed environmental energy study that may enable precise diagnostics to model appropriate land-use policies regarding the specific potential of each geographic zone.

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