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Contribution for a Better Understanding of the Technological Sustainability in Electrical Energy Production through Photovoltaic Cells

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Abstract: The conversion of solar energy into electricity reveals a huge importance in the production of "clean" energy, mainly when applied to decentralized production systems (micro-generation). However, there is the need to develop and optimize these processes in order to turn it more sustainable in economic and technological scoops. The main purpose of this work is to study the solar energy conversion into electricity through photovoltaic cells, characterizing the process efficiencies. This study intends to evaluate the energetic and exergetic efficiencies defining them as indicators in the formulation of a sustainability index. All the procedures are in a theoretical scope with an illustrative example in the end of this work.

Key words: Sustainability index, energy, exergy, photovoltaic indicators.

Nomenclature

V_m Maximum voltage (V)
I_m Maximum current (A)
V_{oc} Open circuit voltage (V)
I_{sc} Short circuit current (A)
T_{amb} Ambient temperature (℃)
T_{cell} Solar cell temperature (℃)
A_{cell} Area of the cell (m^2)
h_{ca} Convective & radiative heat transfer coefficient from solar cell to ambient air ($W/m^2 \cdot K$)
S_T Solar irradiation (W/m^2)
ψ_{PV} Exergetic efficiency of photovoltaic system (%)
η_{PV} Energy conversion efficiency of PV system (%)
I Solar insolation (kWh/m^2/year)
PR Performance Ratio

1. Introduction

Searching for a sustainable future, in respect to energy consumption, one has been looking for alternative sources to fossil fuels in useful energy production.

Solar energy conversion through photovoltaic (PV) panels are one of those sources, which are rising in applications the last years.

Solar irradiation is an inexhaustible source of energy, but not permanently available during the day.

Electricity production through PV, besides being considered a clean energy conversion process, reveals low efficiencies putting some doubts in its sustainability. Due to these facts, the need to characterize this technology arises, being an index to define its sustainability formulated. For that, it is necessary to use indicators to describe the energy conversion process of the technology [1].

These indicators define the conversion efficiency, the costs associated and the environmental impact.

The exergetic efficiency of PV technology defines the strongest indicator for the energy conversion process. It gives a more realistic evaluation of how close the real process is following the ideal case. Besides that, its optimization can lead to its sustainability increase. Defined the indicators, the

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sustainability index can be obtained through a mathematical model given by K. Hanjalic, R. van de Krol, A. Lekic [2], as it will be explained in the section 3. Despite the theoretical knowledge of how important is the sustainability of an energy conversion process, there are some difficulties in measuring it to define how sustainable is the process. This work gives an approach to solve this issue by giving the most suitable technological indicators and by relating them through a mathematical expression. This mathematical expression allows the sustainability quantification of an energy process conversion, in this case, the electricity production through photovoltaic cells. This work also shows the importance of exergy analysis in the energy conversion and how valuable is to use it as indicator in measuring the process sustainability.

2. Sustainability Concept

Over the years there have been several definitions of sustainability and still there is not a worldwide acceptable common definition.

To define the sustainability of a process or system, it is necessary to assess the subsystems connected to it, namely environmental, economic, social and technological systems. So, to achieve sustainability, the subsystems balance must be checked within their limits. From a technological point of view, a sustainable development of energy conversion processes results in the consumption of resources that must be available in quantity and in time, avoiding its depletion and with the least negative impact on the environment [3]. Be sustainable determines the rational application of criteria of economic costs in energy conversion/transformation, necessary and adequate technology production to the process and especially in the useful energy acquisition by final consumer.

3. Sustainability Index

To assess the sustainability of a technological process it must be employed indicators that define and quantify the subsystems involved in the process. For the properties of the system that are not directly measurable, it should be used assessment tools in order to obtain their indicators. The exergetic analysis is an example of these tools, very useful in the evaluation of energy conversion processes, being a strong indicator of technology sustainability [4, 5].

Finally it is necessary to relate all indicators in order to express them in a single value that can quantify the technological process sustainability. This relationship is achieved through a sustainability index formulation using the mathematical expression defined by [2]. It is necessary to assign a membership function, $q(x_i)$ to each x_i indicator. For each indicator, we have to:

- choose a maximum and minimum values, respectively, max(i) and min(i);
- Indicate whether the function $q(x_i)$ increases or decreases with x_i, setting a value for the exponent λ in order to increase or decrease the $q(x_i)$ function x_i.

The relationship between the membership function and its indicator can be expressed as follows. If the membership function increases with the indicator them expression (1) must be used.

$$q(x_i)=\begin{cases} 0 & ,if\ \ x_i \le \min(i) \\ \left(\dfrac{x_i-\min(i)}{\max(i)-\min(i)}\right)^{\lambda} & ,if\ \ \min(i) < x_i \le \max(i) \\ 1 & ,if\ \ x_i > \max(i) \end{cases} \quad (1)$$

Expression (2) is applied when the membership function decreases the indicator value increase.

$$q(x_i)=\begin{cases} 1 & ,if\ \ x_i \le \min(i) \\ 1-\left(\dfrac{x_i-\min(i)}{\max(i)-\min(i)}\right)^{\lambda} & ,if\ \ \min(i) < x_i \le \max(i) \\ 0 & ,if\ \ x_i > \max(i) \end{cases} \quad (2)$$

If the exponent λ is negative, $q(x_i)$ becomes 1 for $x_i \le$ min(i) and 0 for $x_i \ge$ max(i).

The sustainability index (Q) is then given by the sum of the all considered indicators considering the weight (w_i) that each one has in the index mathematical expression formulation. The final mathematical expression is then given expression (3) and considering m indicators for the process characterization.

$$Q(q,w)=\sum_{i=1}^{m}\frac{dy}{dx}w_i\,q_i \quad (3)$$

4. Exergy

Exergy is defined as the amount of useful work that can be extracted from a system when brought into equilibrium with the environment through an energy conversion/transformation process. The energy analysis of a process, according to the 1st law of thermodynamics, is based on the energy quantities. The exergetic analysis of a process based on the 1st and 2nd laws of thermodynamics assesses not only the energy quantity but also its quality (or exergy level) on the thermodynamics interaction. It is important to take into account the energy quality, since this quality will be destroyed as the energy passes through conversion/transformation processes and due the irreversibility. The exergetic efficiency gives a more realistic evaluation of the energy conversion/transformation process performance, measuring how the actual process approaches or departs to/from the ideal case.

5. Exergy and Technological Sustainability

The exergetic analysis of an energy conversion/transformation process allows to identify its irreversibility characteristics. The exergy destruction, i.e. the energy that is useless due to its quality decline and the losses to environment in the form of other energy, is proportional to the process irreversibility. Therefore, identifying the irreversibility characteristics one allows to minimize them by reducing exergetic losses and increasing the process exergetic efficiency. Improved exergetic efficiency determines a lower consumption of resources for production of useful energy, leading to lower economic costs associated with the process and to the decreasing of the negative environmental impact. Thus, it can be concluded that the exergy plays an important role in the search for technological sustainability, being the exergetic analysis a rational process in the physical-mathematical formulation of a technological sustainability index.

6. Indicators for the Formulation of a PV Technology Index

To characterize the technological sustainability of electricity production through photovoltaic systems, according to a sustainability index, it is necessary to select the indicators that better describe the process. The index value allows us to do a comparative evaluation with other technologies in order to determine the most sustainable. Some indicators were used for the mathematical modulation of the sustainability index. These indicators characterize the electrical production process from a technological point of view, namely:

- Exergetic efficiency (1);
- Greenhouse Gas (GHG) Emissions (2);
- Electricity Generation Cost (EGC) (3);
- Electrical Production Efficiency (EPE) (4).

The numbers following the names of these indicators identify them in the index *i* of the membership function, q_i and indicator x_i. The exponent λ take the values 1 to turn the membership function linear.

6.1 Exergetic Efficiency

This indicator is based on the exergetic assessment of the PV cell at a thermodynamic level. The exergetic efficiency of a PV cell is given by [6]:

$$\psi_{PV} = \frac{V_m I_m - \left(1 - \frac{T_{amb}}{T_{cell}}\right)\left[h_{ca} A_{cell}\left(T_{cell} - T_{amb}\right)\right]}{\left(1 - \frac{T_{amb}}{T_{sun}}\right) S_T A_{cell}} \quad (4)$$

For a minimum value we will consider an exergetic efficiency of 1% assuming that values below that are no useful. For a maximum value we choose the exergetic efficiency for a reversible case. This one can be obtained by the ratio of electrical exergy (4) and solar irradiation (5). These last expressions are given by [6].

$$Ex_{electrical} = V_{oc} I_{sc} \quad (5)$$

$$Ex_{solar} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) S_T A_{cell} \quad (6)$$

$$\psi_{\max} = \frac{V_{oc} I_{sc}}{\left(1 - \frac{T_{amb}}{T_{sun}}\right) S_T A_{cell}} \tag{7}$$

The membership function q_i grows as the indicator increases, being this indicator expressed by the following parameters:

$x_1 = \psi_{PV}$;
min(1) = 0.01;
max(1) = $\psi_{\max}$;
$\lambda_1 = 1$.

6.2 Greenhouse Gas (GHG) Emissions

The greenhouse effect has increased due to excessive emissions of toxic gases from energy conversion/transformation and consumption [7-9]. For a technology to be sustainable, these emissions have to be minimal in order to preserve the environment. Emissions associated with PV cells are mainly due to fossil fuels used in their manufacture, as during its operation there are no GHG emissions. According to Refs. [10-12], a PV cell GHG emission is quantified by:

$$GHG(g_{CO2}/\text{kWh}) = \frac{\text{CO}_2 \text{ emissions through LCA}}{\text{S}_\text{T} \times \text{A}_\text{cell} \times \text{PR} \times \text{Lifetime(years)}} \tag{8}$$

The denominator expresses the electricity generated during the life cycle of the PV cell.

The minimum limit for this indicator will be for the ideal case, 0 g_{CO2}/kWh. This will be the theoretical situation. As a maximum we will consider 500 g_{CO2}/kWh, which is the value agreed and voted by the European Parliaments environment committee to all coal power plants built after 2015. Technologies with bigger emission values can be consider, at the moment not sustainable. The membership function will decrease when the indicator increase, so expression (2) will be applied.

For GHG emissions we suggest the following parameters:

$x_2 = GHG$;
min(2) = 0 (g_{CO2}/kWh);
max(2) = 500 (g_{CO2}/kWh);
$\lambda_2 = -1$.

6.3 Electricity Generation Cost (EGC)

PV cells have no costs for the primary energy consumption of electricity production, since this energy comes from solar radiation. However, as solar radiation is not always permanently available during the day, the maintenance costs of PV systems have a great influence on the price of the electricity generated [12]. The Electricity Generation Cost (EGC) is defined as the economic cost per unit of energy produced [13]. According to Ref. [9] this value can be estimated by expression (9). For this case, the maximum and minimum values depend on electricity market, and will not be considered here. Expression (2) is applied as membership function to this indicator.

$$EGC = \frac{\text{Annual expenses of the system (€/year)}}{\text{Annual electricity generation (kWh/year)}} \tag{9}$$

$x_3 = EGC$
$\lambda_3 = -1$

6.4 Electricity Production Efficiency (EPE)

The electricity production efficiency (EPE) according to Ref. [14] is calculated as the ratio of energy generated by the PV cell during its life cycle (E_{ger}) to the sum of different energy components used for the manufacture (E_{fab}), the installation (E_{ins}), the operation and maintenance ($E_{o\&m}$) during its life cycle and for recycling (E_{rec}). EPE is expressed by:

$$EPE = \frac{E_{ger}}{E_{fab} + E_{ins} + E_{o\&m} + E_{rec}} \tag{10}$$

This is an important indicator for PV technology in comparison with other technologies as it balances its assessment with the others. In order that a technology to be sustainable, the EPE value must be greater than 1. For a situation in which EPE is equal to unity, this means that the electricity produced during the life cycle covers the energy used to manufacture the PV cell. Any value below the unit makes the technology not sustainable. According to Ref. [14] due to the fact that lifespan of PV systems extends to 50 years resulting on a E.P.E. of 9.5, one considers this value as the maximum for this indicator. The following parameters can be suggested:

$x_4 = EPE$

min(4) = 1

max(4) = 9.5

$\lambda_4 = -1$

7. Formulation of a PV Technology Index

For the formulation of the sustainability index is necessary to assign a weight coefficient to each indicator. Despite all the above indicators being relevant in the PV technology sustainability, the exergetic efficiency will have the greatest weight coefficient. This is because higher exergetic efficiency influences the other indicators in a favourable direction for sustainability. The other indicators will be evaluated with equal weight coefficients. Therefore, the weight coefficient of each indicator varies between 0 and 1, and their sum equals unity. Thus, the sustainability index will always vary between 0 and 1, as expected. The membership function of each indicator is given by the functional relations (1) and (2), obtaining the values of q_1, q_2, q_3 and q_4. The sustainability index is then given by the following mathematical expression:

$$Q(q,w) = \sum_{i=1}^{4} w_i q_i = 0.55 q_1 + 0.15 q_2 + 0.15 q_3 + 0.15 q_4 \quad (11)$$

8. Illustrative Example

This section pretends to do an exemplification of the procedure to calculate the exergy efficiency indicator, assuming that its weight-coefficient value higher than the others (The weight-coefficient values for the selected indicators are shown in Table 1).

Three types of PV modules are evaluated with the aim to characterize their exergetic efficiency. The three types of PV modules are built with the following materials: mono-crystalline silicon (Si), poly-crystalline silicon (p-Si) and amorphous silicon (a-Si). The data provided is obtained from the SUNTECH Datasheets (Table 2). A Standard Temperature Condition (STC) is considered for the exergetic efficiency calculation (see Table 3). The radiative component of heat transfer coefficient was not considered. The convective component is calculated from an empirical expression given by Ref. [15] according to STC. The value obtained was 9.5 $W/m^2 \cdot K$. The exergetic efficiencies (Table 4) are determined with the expression (3). Using the maximum and minimum values established, the membership function of each cell is obtained and the values are expressed in Table 5.

Table 1 Weight-coefficient proposed values.

Weight	Value
w_1	0.55
w_2	0.15
w_3	0.15
w_4	0.15
Total	1

Table 2 PV cell data.

Parameter	Si STP185S-24/Ad	p-Si STP280-24/Ad	a-Si STPO90Ts-AA
Power (W)	185	270	86
V_m (V)	36.4	35.2	73.12
I_m (A)	1.23	7.95	1.23
V_{oc} (V)	45	44.8	93.8
I_{sc} (A)	5.4	35.2	1.5
A_{cell} (m^2)	1.27	1.94	1.43
NOCT (℃)	45	45	45
T_{cell} (℃)	56.25	56.25	56.25

Table 3 STC conditions.

Parameter	Value
Ambient temperature	25 ℃
Solar irradiation	1000 W/m^2
Wind speed	1 m/s

Table 4 Exergetic efficiency.

Exergetic efficiency	Si	p-Si	a-Si
ψ_{PV}	4.49	1.91	3.65

Table 5 Indicator parameters for exergy efficiency.

Parameter	Si	p-Si	a-Si
min	0.01	0.01	0.01
max	0.057	0.2028	0.1035
x	4.49	1.91	3.65
λ	1	1	1
q	0.7	0.04	0.2834

9. Discussions

The scope of this work is to demonstrate a mathematical procedure for a sustainability index formulation applied to electricity production through PV cells. It is explained the great role of exergy in technologic sustainability as indicator. Other indicators are suggested as important choices to the index construction. An exergetic efficiency characterization of PV cell is performed as an illustrative example. Although, this example do not correspond to reality, besides based on real data. In future, this procedure will be applied to a real PV micro-generation system in order to define its sustainability with the mathematical model described along this work.

10. Conclusions

In this work it was explained the concept of sustainability, exergy and how they are a related with each other. It was demonstrated how to quantify the sustainability of an energy conversion process through mathematical expressions and which indicators should be chosen to measure the electricity production by photovoltaic cells in a technological point of view. It is concluded that there exist some difficulties in obtaining values to some indicators, especially for GHG and EPE. In these indicators, the lifetime of PV, the CO_2 emissions through LCA and the energy for its fabrication, maintenance, installation and recycling are complex to define. These are parameters that are not usually accounted, due to difficult relationships between parameters and time needed to measured them, implying a lack of available data. Due to these conditions, the illustrative example was performed using just the exergetic efficiency for the formulation of the sustainability index for three different PV cells. It was also concluded that the approach to measure and quantify the sustainability of an energy conversion process is useful only to compare different processes or technologies, defining which is more sustainable, unless it is established a minimum value between 0 and 1 that states the sustainability of the process.

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