Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Energetic and exergetic analysis of monocrystalline and polycrystalline photovoltaic modules

Suellen C.S. Costa, Janaína de O.C. Silva, Cristiana B. Maia, and Antonia Sonia A.C. Diniz

Pontifical Catholic University of Minas Gerais (PUCMinas)/Graduate Mechanical Engineering Program/Group of Energy Studies (GREEN-IPUC), Belo Horizonte (Brazil)

Abstract

In this paper, the concepts of energy and exergy are used to estimate and compare the performances of monocrystalline (m-Si) and polycrystalline (p-Si) silicon photovoltaics (PV) modules. The energetic efficiency is the ratio of the energy output of the module to the incident light energy (product of solar radiation and the area of incidence or area of the module). The exergetic efficiency is derived from the electrical parameters, the operating temperature of the modules, and the specific weather conditions. The electrical parameters of the modules were evaluated by adjusting module (nameplate) specifications to the climate variables obtained for the city of Belo Horizonte, Brazil. The m-Si module (190W) had energetic and exergetic efficiencies around 20% and 14%, respectively. In comparison, the p-Si module (210W) had an expected lower energetic efficiency of approximately 18% and exergetic efficiency about 13%. The modeling and analysis conditions are described in detail.

Keywords: *Photovoltaic modules, performance, energetic efficiency, exergetic efficiency.*

1. Introduction

Growing demand for electricity and the predicted depletion of fossil fuels are among the important factors to enhance research and financial incentives to facilitate use of renewable sources. According to Dincer et al. (2010), the decline in the supply of fossil energy in the world, associated with increased energy consumption and the continuing indications of global climate change, have driven research, innovation and market deployment for the realization of a global economy based on clean, renewable energy. Solar energy has to potential to provide a significant portion of the global energy demand—especially that associated with electrical power generation.

Renewable-electricity generation sources have capacity factors and availability factors less than optimum values (intermittent, dispatchable power). Semi-regular, periodic, and stochastic changes in resource availability affect the performance of systems using renewable energies throughout their livespans. One way to better address the impacts of changes or interuptions in resource availability is to use a *typical meteorological year* (TMY), which represents the behavior of weather variables generated from a data bank much longer than a year in duration. The TMY pattern is a set of experimental data that represents a typical year for a given location—and is used as baseline indicator for analysis and assessment giving annual averages that are consistent with the long-term averages for the location in question. The default year applies the knowledge of local weather procedures for evaluation, design, planning and operation of power plants from renewable sources. PV systems are among the energy conversion systems that have performances that are significantly influenced (controlled) through non-ideal conditions. The main factors contributing to the reduced PVmodule performance in operating conditions are the meteorological variables, mainly the ambient temperature and the solar radiation.

The performance of photovoltaic modules can be evaluated by processes applying the First and Second Laws of Thermodynamics, called energetic and exergetic analysis, respectively. According to Dincer (2002), the

Selection and/or peer review under responsibility of Scientific Committee
doi:10.18086/swc.2015.05.28 Available at http://proceedings.ises.org

exergy analysis is a tool for assessing the ensemble of environmental impacts on the use of any energy source. The exergy analysis technique provides pathways toward the operation of more efficient and higher performance energy sources. This methodology can provide a valuable tool in reducing the real encountered losses of existing energy systems. Pandey et al. (2013) recommend application of exergy analysis when a comprehensive analysis is required. The *energy efficiency* of photovoltaic modules is the ratio of the generated energy to the solar radiation energy, not including the direct influence of some factors, such as thermal properties (Sarhaddi et al. (2010)). The *exergetic efficiency* considers climatic parameters, geometric factors, and operation of the modules (including thermal properties) and provides more realistic insights into the energy conversion process for photovoltaic modules. Joshi et al. (2009) point out that the energy of a photovoltaic system has two primary components: electrical and thermal energy. The electrical exergy can is equal to the actual electricity generated by the photovoltaic system, since it is completely available to be converted into work. The thermal energy available from solar cells is not used to generate useful work (i.e., is not used by these devices to generate electricity) in operating PV systems, becoming heat lost into the environment.

The performance of a photovoltaic module depends on variables such as ambient temperature, solar radiation, incident angle, dirt accumulation, and the type or technology of the photovoltaic cell utilized. The temperature has an important influence on the efficiency of the modules and therefore the entire PV array. Sahin et al. (2007) investigated the thermodynamic characteristics of photovoltaic cells based on their energy and exergy efficiency. Results indicated that energy efficiency ranged between 7 and 12% during operation under available sunlight, while the exergetic efficiency varied between 2 and 8%. According Xydis (2013), exergy losses are related to the temperature correction factor due to the increase in module temperature, representing 1.3% losses in system performance. Colombo et al. (2014) presented a general thermoeconomic analysis to assess the economic and environmental effects of energy integration system, taking into account the life cycle and the effect of inefficiencies due to off-design operation of systems. The method was applied to a case study from a photovoltaic power plant and a standard commercial power plant gas turbine (without cogeneration) deriving the final cost of a kWh. The evaluation of the economic cost was accomplished through termoeconômicas techniques, while exergy costs were assessed using both Extended Exergy Accounting (EEA) and the Thermo-Ecological Cost (TEC) methods. The results showed that a purely monetary evaluation can lead to contrasting results, and that the EEA and TEC cost indicators can generate different rankings among the alternatives studied.

Many studies on the performance evaluation using the First and Second Law of Thermodynamics have been applied in photovoltaic/thermal (PV/T), where a single system generates electricity and heat. Ceylan and Gürel (2015) experimentally evaluated a new PV/T system design for cooling of the PV modules and using the extracted heat to warm water. This PV/T system is a forced circulation system without pump. The exergy analysis of PV/T system has accounts for thermal exergy of the PV module and the solar collector, as well as variations of electric exergy. The authors derived that for the temperature of 45°C that the exergetic efficiency was 17%, while at 55°C, the exergetic efficiency was 21%.

Yazdanpanahiet et al. (2015) used combined analytical and experimental analysis to evaluate the exergetic efficiency of a PV/T system. The operating parameters were obtained through the experimental setup, which recorded the intensity of solar radiation, wind speed, ambient temperature, temperature of photovoltaic cells, the flow and fluid input temperature, and fluid output temperature, open circuit voltage and short-circuit, and the voltage and current at the maximum power point. The numerical simulation used a three-dimensional model under a constant thermal load and a 4-parameter current-voltage model. The model was modified to account for the exergetic efficiency and exergy losses in the PV/T system components. The results of this numerical simulation were compared with their experimental measurements. Additionally, a comparison between the modified exergetic efficiency used in the study and one from the literature showed that the modified exergetic efficiency obtained in this approach avoids the shortcomings of exergetic efficiency from the literature, since it derives the loss of exergy in the system PV/T directly.

The First and Second Law of Thermodynamics can be used to determine and compare the efficiencies of different PV module technologies from a fundamental analysis approach, but this method has not been widely used. This approach has mainly been incorporated to evaluate PV/T technologies. This paper aims to analyze the performance of photovoltaic modules of monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si), applying the concepts of the First and Second Law of Thermodynamics. The energetic and exergetic efficiencies have been evaluated, expanding reported mathematical models to assess the influence of meteorological variables for the city of Belo Horizonte, Brazil. This analysis has provided direct evaluation and comparison of the two, most widely used commercial silicon PV technologies.

2. Methodology

Photovoltaic modules are composed of several solar cells connected in series and/or parallel configurations to provide the required voltage and current (power) for the given application. Currently there are several types of cell technologies, both in research and commercial stages. The most most prevalent in the market (about 90%) use silicon, because of cost and availability factors. Bulk silicon cells can be crystalline silicon, monocrystalline and polycrystalline, and these are the most common commercial technologies. Thin films, such as those using amorphous Si, are also used, but have a far lower manufacturing base and a much lower performance capability. According to Green et al (2015), the monocrystalline silicon modules have demonstrated manufacturing line efficiencies to 22.9%, due to the high degree of crystalline quality, low defect and impurity levels, and innovative device design. The polycrystalline silicon modules have comercial efficiencies to about 19%, while the amorphous silicon thin film approaches can achieve efficiencies in the 10%-12% range.

In the studies of this paper, we analyze the performances of the two major Si PV module technologies (m-Si and p-Si), through modeling and simulation of *energy and exergy efficiencies*. In this analysis, the estimated time meteorological data using models of Duffie and Beckman (2006) and Lorenzo (1994) are incorporated into the models. The weather conditions were for the city of Belo Horizonte, Brazil, with 19.93° S latitude and longitude 43.93° S. The inclination of the PV modules was set at 20°, the ground reflectivity index for the urban area (ρ) at 18%, and average monthly atmospheric transparency indices ($\overline{K_T}$) (as indicated in Table 1) were incorporated with minimum and daily maximum temperature data and wind speed at this location, provided by *Solar and Wind Energy Resource Assessment* project (SWERA). Weather conditions for Belo Horizonte were validated with data provided by the National Institute of Meteorology (INMET) and with the TMY information obtained through SWERA.

Tab. 1: Average monthly atmospheric transparency index

Month	$\overline{K_T}$	**Month**	$\overline{K_T}$
Jan.	0.46	**July**	0.64
Feb.	0.45	**Aug.**	0.53
Mar.	0.64	**Sept.**	0.48
Apr.	0.53	**Oct.**	0.50
May.	0.55	**Nov.**	0.45
June	0.60	**Dec.**	0.41

Guimarães (1995)

The simulations were performed using the Engineering Equation Solver (EES) software. The energetic and exergetic efficiencies were estimated hourly for the year studied and included the variation of meteorological parameters and operating parameters of the PV modules. To estimate electrical and thermal parameters of the PV modules for different operating conditions, the reference condition was chosen as the nameplate values of the operating parameters. The PV modules used were (1) monocrystalline Si: module of the 190Wp nameplate power output and (2) polycrystalline Si: module of the 210Wp. Table 2 presents the complete nameplate electrical specifications for each of these PV module technologies.

Tab. 2: Electrical characteristics of the PV modules

	Monocrystalline Module	Polycrystalline Module
Power	190 Wp	210 Wp
Open circuit voltage ($V_{oc,ref}$)	21.68 V	33.05 V
Short circuit current ($I_{sc,ref}$)	11.80 A	8.23 A
Voltage at maximum power point ($V_{m,ref}$)	18.07 V	27.54 V
Current at maximum power point ($I_{m,ref}$)	10.52 A	7.64 A
Temperature coefficient for short-circuit current (α)	0.05%/°C	0.05%/°C
Temperature coefficient for open circuit voltage (β)	-0.38%/°C	-0.38%/°C
Nominal operating temperature of the photovoltaic (NOCT)	47 °C	47 °C
Temperature in standard operating conditions (STC)	25 °C	25 °C
Width module	1.580 m	1.480 m
Module Length	0.808 m	0.990 m

3. Mathematical Model

The PV generator consists of a set of modules whose performance may be influenced by weather conditions (e.g., intensity of solar radiation, the ambient temperature, and wind speed). Performance can be evaluated by applying the First and Second Law of Thermodynamics for the assessment of the respective energy and exergetic efficiencies. Energy efficiency for the theoretical case is given by (Pandy et al., 2013):

$$\eta_{energy} = \frac{V_{oc} * I_{sc}}{G_T * A} \quad \text{(eq. 1)}$$

where A is the area of the photovoltaic module; G_T; the solar radiation; V_{oc} is the open-circuit voltage and I_{sc} is the short-circuit current. The open-circuit voltage and short-circuit current can be obtained by the model proposed by Chouder et al. (2012):

$$V_{oc} = V_{oc,ref} - \beta(T_{c,ref} - T_c) + A_f \ln\left(\frac{G_T}{G_{ref}}\right) \quad \text{(eq. 2)}$$

$$I_{sc} = I_{sc,ref}\left(\frac{G_T}{G_{ref}}\right) + \alpha(T_c - T_{c,ref}) \quad \text{(eq. 3)}$$

where T_c is the module temperature. Variables with subscribed ref indicate the parameters in reference (or namplate) condition. The parameters of reference used in this modeling were taken from the datasheet provided by the manufacturer of the PV modules evaluated, considering the standard test conditions (STC). The solar irradiance was set at 1000 W/m². The β and α are the temperature coefficients for the open-circuit voltage and short-circuit current, respectively. A_f is the modified ideality factor of the diode, defined by (Chouder et al., 2012.):

$$A_f = \frac{n\sigma T_c}{q} \quad \text{(eq. 4)}$$

where n is the diode ideality factor (and in this study was set n = 1), σ, the Boltzmann constant, and q is the electronic charge.

The module temperature (T_c) is defined from the data set to the nominal operating condition of the module, as proposed by Pandey et al. (2013):

$$T_c = T_a + \left(\frac{NOCT - 20\,°C}{800\ W/m^2}\right) G_T \quad \text{(eq. 5)}$$

where NOCT is the nominal operating temperature of the module and T_a is the ambient temperature. The ambient temperature (T_a) was estimated of according with the model proposed by Lorenzo (1994), which depends on the hour angle (ω) relating the displacement of the sun from noon and accounting for a displacement of 15 ° every hour, and the angle the sunset (ω_s), the completion of the sunlight period (Duffie and Beckman, 2006):

For $-\pi < \omega < \omega_s$, T_a is calculated by:

$$T_a = T_{aM}(i-1) - \frac{T_{aM}(i-1) - T_{am}(i)}{2}\left[1 + +cos\left(\left(\frac{\pi}{\left(\frac{\pi}{6} - \omega_s - 2\pi\right)}\ \omega\right) + \left(-\frac{\pi}{\left(\frac{\pi}{6} - \omega_s - 2\pi\right)}\omega_s\right)\right)\right] \quad \text{(eq. 6)}$$

In Eq. (6), T_{aM} and T_{am} are the maximum ambient temperature and minimum along a day, respectively, and i is the day of the year.

For $\omega_s < \omega < \frac{\pi}{6}$, T_a is calculated by:

$$T_a = T_{am}(i) + \frac{T_{aM}(i) - T_{am}(i)}{2} * \left[1 + \cos\left(\left(\frac{\pi}{\left(\omega_s - \frac{\pi}{6}\right)}\omega\right) + \left(-\frac{\frac{\pi}{\left(\omega_s - \frac{\pi}{6}\right)}\pi}{6}\right)\right)\right] \quad \text{(eq. 7)}$$

And for $\frac{\pi}{6} < \omega < \pi$, T_a is calculated by:

$$T_a = T_{aM}(i) - \frac{T_{aM}(i) - T_{am}(i+1)}{2}\left[1 + +cos\left(\left(\frac{\pi}{\left(2\pi + \omega_s - \frac{\pi}{6}\right)}\ \omega\right) + \left(-\left(\pi + \frac{\frac{\pi}{\left(2\pi + \omega_s - \frac{\pi}{6}\right)}\pi}{6}\right)\right)\right)\right] \quad \text{(eq. 8)}$$

To estimate the solar radiation on the inclined photovoltaic module(G_T), we used the isotropic sky model from Duffie and Beckman (2006) that considers the sum of direct components, the isotropic diffuse and diffuse solar radiation reflected by the ground:

$$G_T = G_b R_b + G_d \frac{(1 + cos\ \beta_{in})}{2} + G\ \rho \frac{(1 - cos\ \beta_{in})}{2} \quad \text{(eq. 9)}$$

In Eq. (9), G_b and G_d are the direct and diffuse solar radiation, respectively; G is the total incident solar radiation on a horizontal plane; R_b is the ratio between the total radiation incident on an inclined surface and a horizontal surface; ρ is the ground reflectivity, and β_{in} is the tilt angle of module.

The exergetic efficiency of photovoltaic modules is given by the ratio between output exergy and input exergy.

$$\varepsilon = \frac{\text{Output exergy}}{\text{Input exergy}} = \frac{\text{Ex}_{\text{elet}} - \text{Ex}_{\text{therm}}}{\text{Ex}_{\text{solar}}} \quad \text{(eq. 10)}$$

The input exergy is from the solar radiation:

$$\text{Ex}_{\text{solar}} = \left(1 - \frac{\text{T}_\text{a}}{\text{T}_{\text{sol}}}\right) \text{G}_\text{T} * \text{A} \quad \text{(eq. 11)}$$

The output exergy of the photovoltaic module is the difference between the electrical exergy and thermal exergy defined by Pandey et al. (2013):

$$\text{Ex}_{\text{elet}} = \text{V}_{\text{oc}}\text{I}_{\text{sc}} - (\text{V}_{\text{oc}}\text{I}_{\text{sc}} - \text{V}_\text{m}\text{I}_\text{m}) \quad \text{(eq. 12)}$$

$$\text{Ex}_{\text{term}} = \left(1 - \frac{\text{T}_\text{a}}{\text{T}_\text{c}}\right) \text{U} * \text{A}(\text{T}_\text{c} - \text{T}_\text{a}) \quad \text{(eq. 13)}$$

where V_m and I_m are the voltage and current at the maximum power point defined by (Chouder et al., 2012):

$$I_m = I_{m,ref}\left(\frac{G_T}{G_{ref}}\right) \qquad \text{(eq. 14)}$$

$$V_m = V_{m,ref} - \beta\left(T_{c,ref} - T_c\right) \qquad \text{(eq. 15)}$$

In Eq. (14) and (15), $I_{m,ref}$ and $V_{m,ref}$ are the voltage and current at the maximum power point for a reference condition. In Eq. (12), the variable U is the heat transfer coefficient:

$$U = 5.7 + 3.8 * v \qquad \text{(eq. 16)}$$

where v is the wind speed. Thus, the exergetic efficiency is the ratio between the difference of electrical and thermal exergy by solar exergy. The thermal exergy is subtracted from the electric exergy, because the heat generated in the process of conversion of solar radiation into electrical energy is rejected, and is not used as a useful product:

$$\varepsilon = \frac{\text{output exergy}}{\text{input exergy}} = \frac{V_m I_m - \left(1-\frac{T_a}{T_c}\right) U * A (T_c - T_a)}{\left(1-\frac{T_a}{T_{sol}}\right) G_T * A} \qquad \text{(eq. 17)}$$

4. Results

The monthly average estimated for the incident solar radiation on a horizontal surface were compared with experimental average monthly data for the years 2011-2013 for the city of Belo Horizonte/Brazil (provided by INMET as shown in Figure 1).

Fig. 1: Comparison of monthly averages of solar radiation to Belo Horizonte, Brazil

When comparing the values of the solar radiation estimated by the model with standard (TMY) year values, differences of up to 15% are possible. However, the overall performance and average annual are quite close. The standard (TMY) year is defined for a given location. There may occur substantial actual variations from one year to another, as seen in experimental curves obtained for the years 2011, 2012 and 2013 in Fig. 1.

The ambient temperature obtained by the model is shown in Figure 2, and it is compared with the standard year and with experimental data for the years 2011-2013. It is noted that experimental data varied significantly among the analyzed years. When comparing the data obtained by Lorenzo model (1994) and standard year, the data are very close, with maximum differences below 3%.

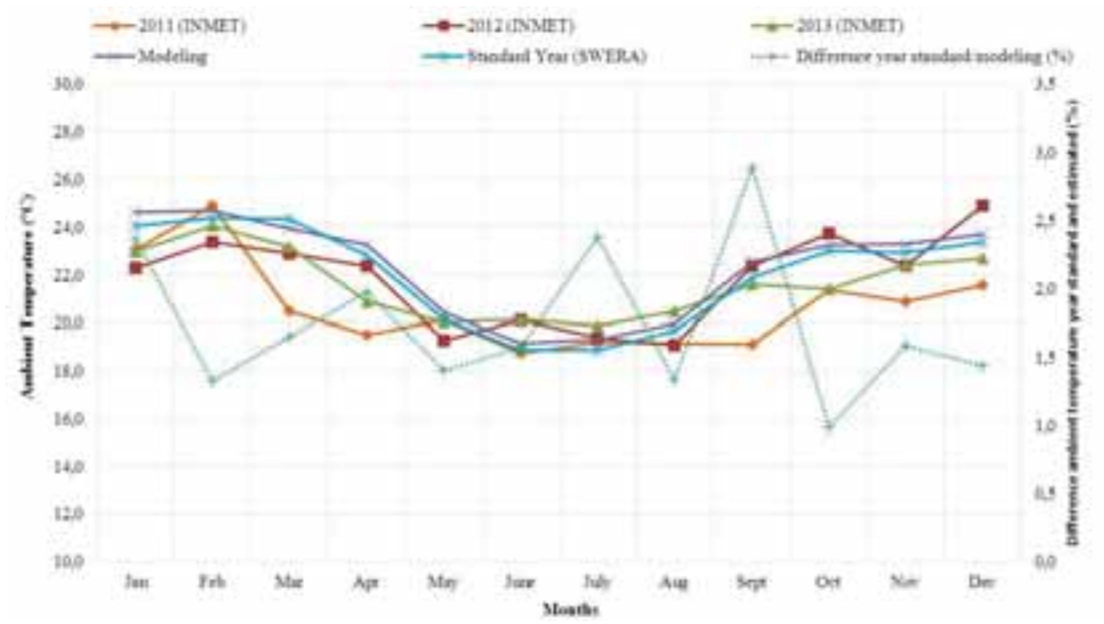

Fig. 2: Comparison of monthly averages of ambient temperature to Belo Horizonte, Brazil

Comparing the data obtained by this model with experimental data and data obtained by the TMY, it is concluded that the results are valid to estimate the performance of the solar radiation and ambient temperature for the city of Belo Horizonte, Brazil. Thus, these results were used as input data for estimating the radiation incident on the inclined photovoltaic modules (β_{in} =20°) and energy and exergy efficiency.

Figure 3 shows the monthly average values of ambient temperature and of solar radiation incident on the plane of the photovoltaic modules inclined (Belo Horizonte, Brazil).

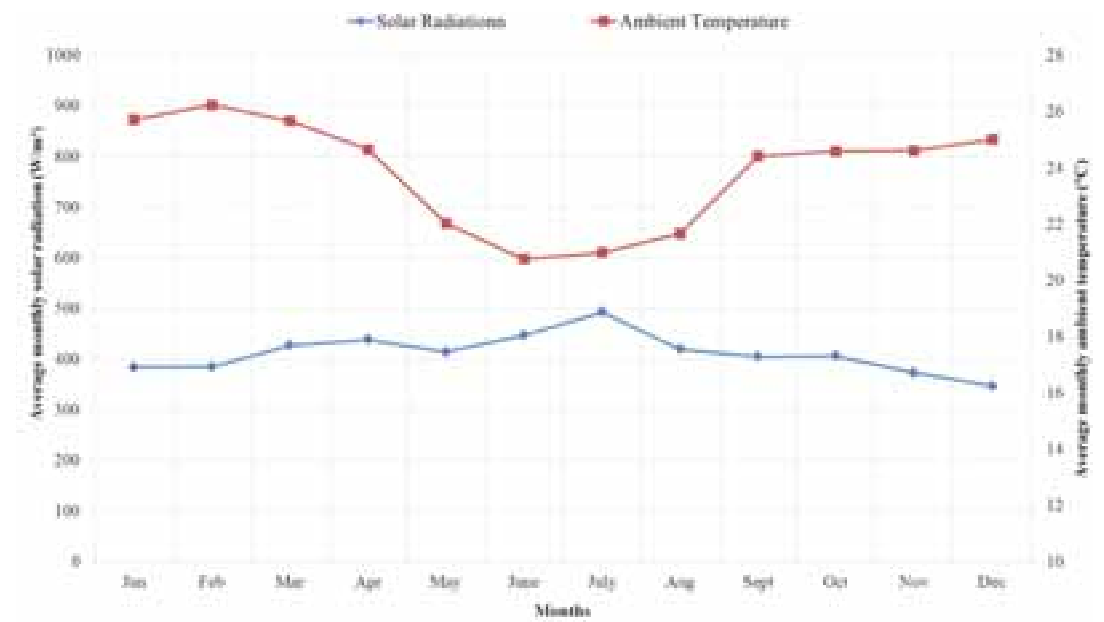

Fig. 3: Monthly average weather conditions for Belo Horizonte, Brazil

The months corresponding to winter in the southern hemisphere (June, July and August) have the lowest average monthly temperature indices—as expected. The months corresponding to summer in the southern hemisphere (December, January, February and March) have higher temperatures and lower values of solar radiation. This behavior can be attributed to both higher levels of atmospheric transparency that occurs in the winter and the inclination of the modules fixed at 20°. Duffie and Bekman (2006) affirm that for maximize incident of solar radiation in winter, the solar equipment must have inclination equal to the local latitude module.

Figure 4 presents and compares the exergy efficiency of the photovoltaic modules m-Si (190Wp) and p-Si (210 Wp). The exergy due to solar radiation is the maximum work that can be used by the photovoltaic module. When comparing the values obtained for the m-Si and p-Si modules on a particular date, it is clear that the p-Si module presents higher values. The exergy due to solar radiation depends on the environmental parameters (ambient temperature, sun temperature and solar radiation) and the module area. As environmental parameters are the same for both modules, the higher values obtained by the p-Si (210Wp) can be attributed to its larger area. For this module, the temporal variation of exergy depends only on weather conditions. The value of solar exergy depends only of solar radiation and ambient temperature; while the rates of electrical and thermal exergy depend on solar radiation, ambient temperature and wind speed. As the month of July has the highest values of solar radiation, exergies were higher this month compared to the months of December or January.

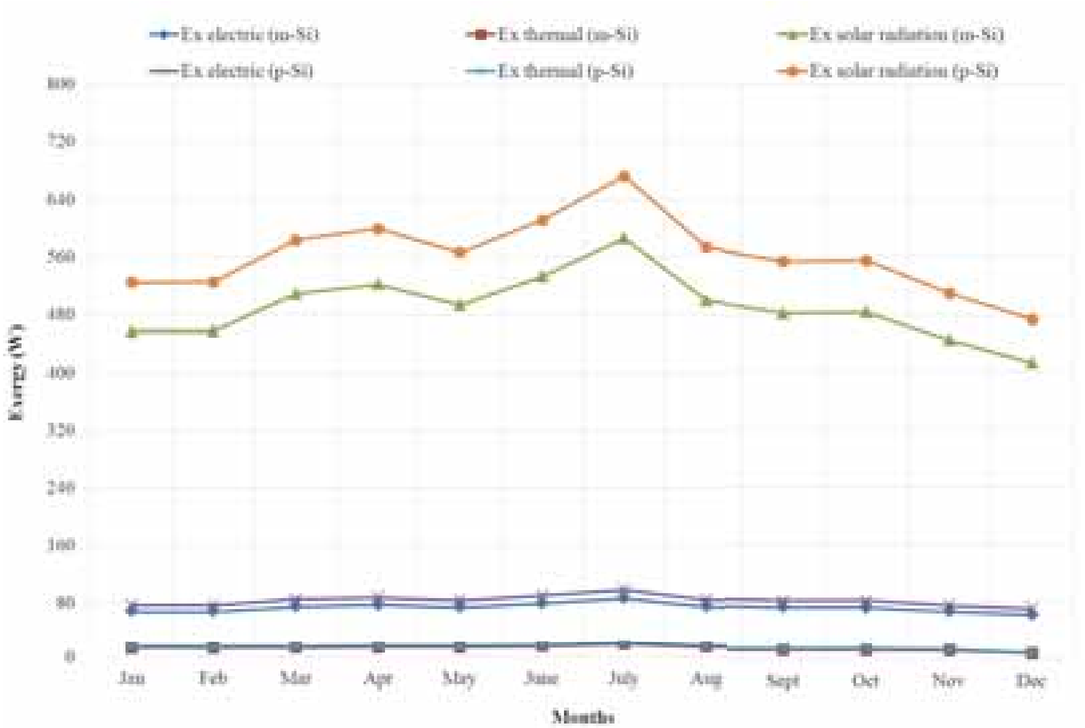

Fig. 4: Monthly averages of electrical and thermal exergias for m-Si and p-Si modules

The thermal exergy reduces the efficiency of the module. This loss can be reduced by minimizing two factors: the operating temperature of the cell and the heat transfer coefficient by convection. The electrical exergy depends on the electrical parameters of each cell and the particular technology. The electrical exergy of the PV modules can be maximized by reducing optical losses (e.g., using cells that absorb different portions oft he solar spectrum, and/or antireflection coatings to increase the photon absorption). Similarly, the value of solar exergy for the p-Si module (210Wp) were higher than m-Si module (190Wp), while the thermal exergy rates were approximately same for both technologies. In addition, the behavior throughout the year is similar for the three values of exergy, with highest values in July (Fig. 4).

The accumulation of dirt and dust are external environmental factors that can significantly affect the performance of photovoltaic modules. Piliougine et al (2013) evaluated the production of polycrystalline power modules with and without anti-soiling coatings. The authors report 12% loss in uncoated modules and 10% having the dust mitigting coating. According to the homogeneity of the distribution of the dust, these losses can be even greater (e.g., shading can occur). Appels et al (2013) developed an experimental work on photovoltaic modules, and observed losses between 3-4% due to deposition of dirt, even with rain in the review period. The coating modules with non-stick (udst preventing) films contributes to the reduction of accumulation of dirt and minimize losses due to reflection.

Figure 5 shows the monthly average energy and exergy efficiencies for the m-Si module and p-Si module. The monthly average of the energy efficiencies of the m-Si module or the order of 20.0% and for the p-Si module this variation was 18.3%-18.6%. The results of the analysis of the exergetic efficiencies showed an average of 13.0% to 13.8% for the monocrystalline photovoltaic module, and between 12.5 and 13.3% for polycrystalline photovoltaic module (approximately).

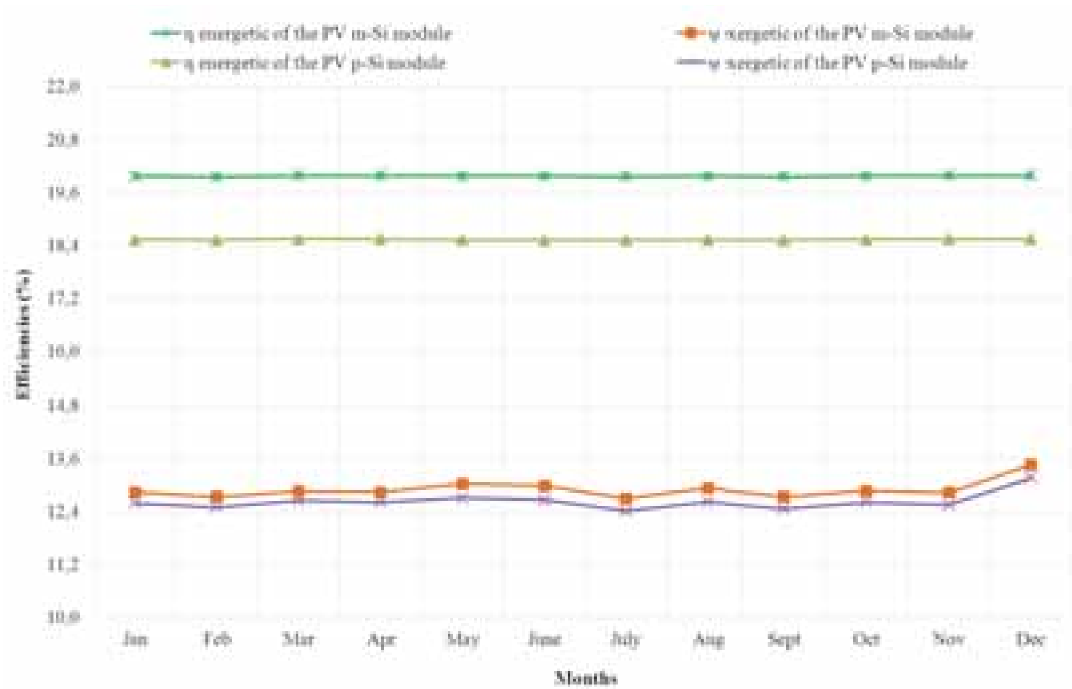

Fig. 5: Monthly averages of energetic and exergetic efficiencies for m-Si and p-Si modules

The polycrystalline module has higher measured power output compared with the monocrystalline module (Fig. 6). However, the area of p-Si module is larger, and has a lower energy efficiency values than the m-Si module. The behavior of the output power curves shown in Fig. 6, is a reflection of influence of the variation of the solar radiation on the output current of the modules These results show that although the input exergy and electrical exergy are higher in p-Si module compared to the m-Si, this is a consequence of the area and the nominal power (current and voltage) difference of the two types. Energy efficiencies and exergetic were higher for m-Si module. This is explained by inherent characteristics oft he m-Si technology that is characterized by less defective material and lower impurity levels than with the polycrystalline technologies. That is, a polycrystalline module would require greater area of the semiconductor for generate the equivalent power of a monocrystalline module because of its lower conversion capabilities.

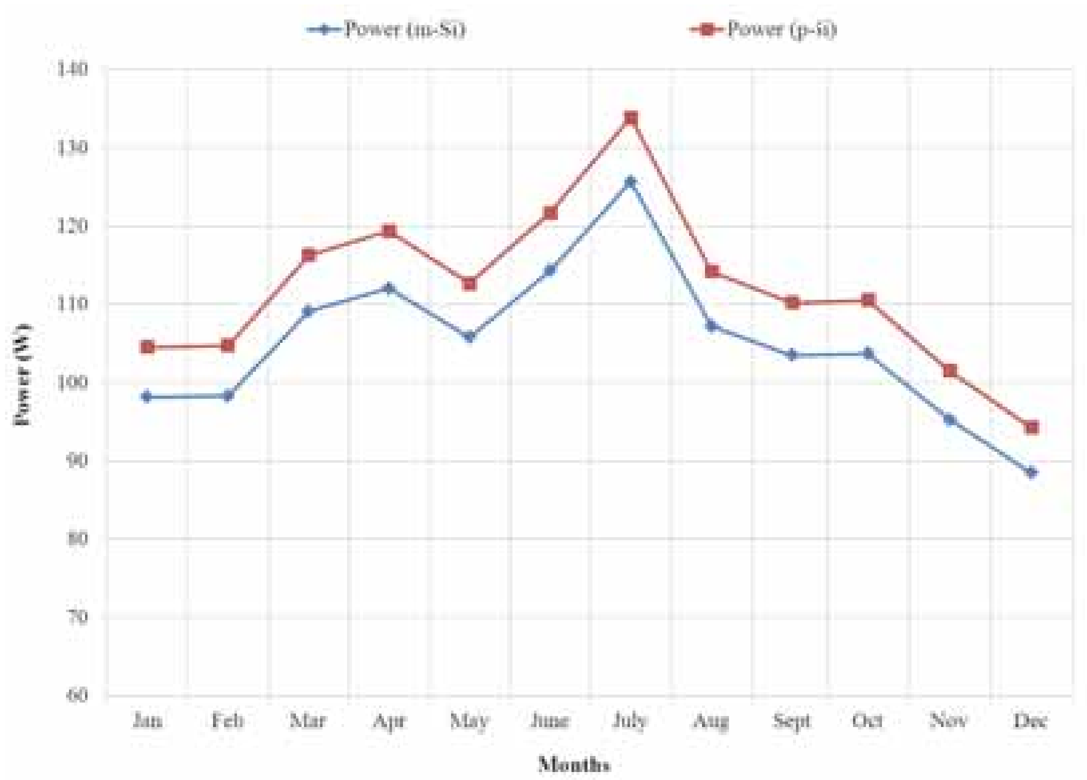

Fig. 6: Monthly average output power of the m-Si and p-Si modules

5. Conclusions

This study derives and uses a model incorporating TMY and PV module nameplate specifications to estimate and compare the energy and exergy efficiencies of photovoltaic of monocrystalline silicon and polycrystalline PV modules operating in the city of Belo Horizonte, Brazil. The module operating parameters were evaluated from mathematical models for solar radiation and temperature. The assessnent of efficiencies provides pathways to increase these values by reducing possible optical losses and the electrical conversion processes. The main losses related to photovoltaic technology are related to heat generation, which in this case is the heat rejected to the environment.

The m-Si module displayed higher values for average annual energy efficiency (19.9%) and exergy efficiency (13.3%). However, its exergy values were lower when compared to the p-Si module. These variations are explained by the energy and exergy differences in area between the module types and the inherent technology characteristics (i.e., the differences in crystalline quality and impurity levels).

Acknowledgments

The authors gratefully acknowledge the generous support of PUC Minas, FAPEMIG, CAPES and CNPq enabling us to perform this research. Also we thank L.L. Kazmerski, visiting research professor at PUC Minas, for his comments and suggestions for the analysis and presentation of this work.

6. References

1.Appels, R.; Lefevre, B.; Herteleer, B.; Goverde, H.; Beerten, A.; Paesen, R.; Medts, K.; Driesen, J.; Poortmans, J. Effect of soiling on photovoltaic modules. Solar Energy 2013; 96:283 – 291.

2. Ceylan, I.; Gürel, A.E. Exergetic Analysis of a New Design Photovoltaic and Thermal (PV/T) System. Published online 22 March 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/ep.12108

3. Chouder, A., et al. Modeling and simulation of a grid connected PV system based on the evaluation of main PV module parameters. Simulation Modeling Practice and Theory 2012; 20:46 – 58.

4. Colombo, E.; Rocco, M.V.; Toro, C.; Sciubba, E. An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: A case study at a regional level in Italy. Ecological Modelling 2014

5. Dincer, I..The role of exergy in energy policy making. Energy Policy 2002;30:137–149.

6. Dincer, I., et al. Global Warming: Engineering Solutions, Springer New York Dordrecht Heidelberg, London, 2010.

7. Duffie, J.A.; Beckman, W.A. Solar engineering of thermal processes. 3 ed. New York: John Wiley & Sons, 2006.

8. Green, M. A., et al. Solar cell efficiency tables (Version 45). Progress Photovoltaic: Research and applications 2015; 23:1 – 9.

9. Guimarães, A.P.C. Estudo solarimétrico com base na definição de mês padrão e sequência de radiação diária. 1995. Universidade Federal de Minas Gerais - Graduate Course in Mechanical Engineering.

10.Joshi, A. S., Dincer, I., Reddy, B. V.. Performance analysis of photovoltaic systems: A review. Renewable and Sustainable Energy 2009;13:1884-1897.

11. Lorenzo, E. Electricidad Sola: Ingenieria de los sistemas fotovoltaicos. 1 ed. Espanha: Progensa, 1994

12. Pandey, A. K.; Tyagi, V. V.; Tyagi, S. K. Exergetic analysis and parametric study of multi-crystalline solar photovoltaic system at a typical climatic zone. Clean Techn Environ Policy 2013; 15:333 – 342.

13. Piliougine, M.; Cañete, C.; Moreno, R.; Carretero, J.; Hirose, J.; Ogawa, S.; Sidrach-De-Cardona, M. Comparative analysis of energy produced by photovoltaic modules with anti-soiling coated surface in arid climates. Applied Energy 2013, 112:626 – 634.

14. Sahin, A.D., Dincer, I., Rosen, M.A..Thermodynamic analysis of solar photovoltaic cell systems. Solar Energy Materials&Solar Cells 2007; 91:153-159.

15. Sarhaddi, F., et al. Exergetic performance assessment of a solar photovoltaic thermal (PV/T) air collector. Energy and Buildings 2009;42:2184–2199.

16. Xydis G. On the exergetic capacity factor of a wind - solar power generation system, Journal of Cleaner Production 2013, 47:437-445.

17. Yazdanpanahi, J.; Sarhaddi, F.; Adeli, M.M. Experimental investigation of exergy efficiency of a solar photovoltaic thermal (PVT) water collector based on exergy losses. Solar Energy 2015, 118: 197–208