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PERFORMANCE ANALYSIS AND ECONOMICS OF A 2.2 KW_P GRID CONNECTED PV SYSTEM IN THE STATE OF CEARÁ - BRAZIL

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Abstract. *In the present study, we show the performance and economic analysis of a 2.2 kWp PV system located in Ceará State, Brazil. The performance parameters will be based on the IEC 61724 Standard and will be calculated the return on investment of the PV system and the value of PV generation cost and the cost of the life cycle. The total annual energy output delivered to grid was found to be 3,708.21 kWh and the annual average daily final yield was 4.62 kWh/kWp.*

Keywords: *PV System, Grid Connected, Performance Analysis*

1. INTRODUCTION

Due to decrease in global fossil fuel reserves worldwide and emissions to the environment (during the extraction processes, production and use of these fuels) many countries are reviewing their energy policies aimed at reducing carbon emissions and developing alternative energy (Adaramola and Vågnes, 2015). With the current energy consumption rates in the world and the increasing world population fossil fuels will be exhausted in a few decades. To meet future global energy demand, the development of new technologies that make possible alternatives to the global energy sector is necessary (Omer, 2008).

Brazil stands out on the world stage with a significant development of alternative energy sources. The use of renewable energy in the Brazilian energy matrix remained among the highest in the world in 2013. The Brazilian Electricity Regulatory Agency (ANEEL) approved in 2012 rules for the tax incentive and reduction of tariff barriers for small power generation throughout the country, the goal is to encourage small producers (ANEEL, 2012). The result of the increased use of alternative sources for electricity generation is low CO_2 emission rates to the atmosphere. To generate 1 TWh, the Brazilian energy matrix emits seven times less than the European and nine times less than the USA (EPE, 2014).

Solar energy is the primary source for all other energy sources, the solar potential available in the world is thousands of times larger than the worldwide energy demand (FUNCEME, 2010). Among the alternative ways to power generation, photovoltaic technology stands out for presenting distinct advantages such as not degrading the environment through emissions of pollutants, oil spills and toxic by-products (Omer, 2008). The Brazil, however, does not present a great contribution to the generation of electricity from solar energy. Currently power generation from hydropower represents 70% of the Brazilian energy matrix (EPE, 2014). Photovoltaic technology is considered one of the most promising types of power generation for several countries (Al-Otaibi *et al*., 2015).

It is notable considering that Brazil is a major producer of electricity from water power, however, considering the country's northeast region such power generation model becomes unfeasible due to topographical features and hydrography. Located in regions of low latitudes northeastern Brazil is characterized by having considerable potential for generating electricity from solar radiation. Brazil has an excellent level of solar radiation mainly in the northeast region. In its semi-arid region, there is the best insolation, with typical values of 200 to 250 W/m^2 of continuous power which is equivalent the falling solar radiation from 1,752 to 2,190 kWh/m^2/year, it has comparable radiation to the best regions of the world as the city of Dongola, Sudan desert (ANEEL, 2008).

The state of Ceará located in northeastern Brazil has a land area of about 148,825 km^2, corresponding to 1.74% of the territory of Brazil (Sacramento *et al.*, 2008). The state of Ceará has invested in the development of technologies in alternative energy, primarily by investing in wind power, now well established, currently focusing on the development of solar energy, seeking fiscal incentives for development to happen. In the state of Ceará the months of September, October and November have the greatest incidence for the generation of photovoltaic energy (FUNCEME, 2010). It is estimated that in those months, the state of Ceará presents a radiation variation potential of 250-270 W/m^2 (FUNCEME, 2010).

The purpose of this paper is to show the performance analysis and economics of a grid connected photovoltaic system of 2.2 kWp installed in the city of Fortaleza, state of Ceará, Brazil and demonstrate the potential of photovoltaic solar power generation in the state of Ceará.

2. THE GRID CONNECTED PV SYSTEM

The study was developed on the premises of the academic Master Program on Applied Physics, located at the State University of Ceará – UECE, with geographical location defined by the coordinates 3°40′39,7″ south latitude e 38°33′29,8″ west longitude and about 31m above the sea level. The system has 18 panels of the Canadian Solar brand, CS6P-245P polycrystalline silicon model with nominal power of 245W_p, supplying power to one inverter of the brand SMA model Sunny Boy SB 2500HF-30. The PV system consists of 18 modules covering a total area of 29 m^2 with an installed capacity of 4.4 kW_p. For the present study only 9 modules were used because of limitation on the number of available inverters. By this way the used system consists of 9 modules covering an area of 14.5 m^2(A_M) with an installed capacity of 2.2 kW_p ($P_{PV,rated}$). The PV system is shown in fig.1.

Figure 1. Photograph of the PV System

The inverter is connected to a data logger Sunny WebBox model that is responsible for the acquisition and storage of data. They were also used equipment for the collecting and storage of solar irradiance data, they are: one pyranometer, a signal amplifier, a capture card and a computer.

The panels were installed directed to the geographic north (azimuth 0°), as is recommended for facilities located south of the equator, and with an inclination of 8.2°. The recommendation for the maximum output throughout the year is that the panels are installed with the slope equal to the latitude of the location. The tilt angle is often chosen because of other different factors of maximum annual production. The manufacturers of these devices impose minimum angles of installation (usually close to 10°) to avoid accumulation of water and dirt that could cause damage to them. On roofs are usually installed next to those taking the same angle. You can also install the panels at an angle to increase production at a certain time of year. In the system under study it was determined angle to reduce accumulation of water and dirt that could damage the panels and cause production losses.

It is worth noting that often the annual losses caused by a different angle of the local latitude are very small and can even be offset by increased production at a time of year that it wanted a higher production due to increased seasonal consumption.

3. PERFORMANCE PARAMETERS

The performance of a grid connected PV system usually is evaluated taking as reference the IEC 61724 Standard (1998). Evaluated parameters are: power output of the inverter (E_{AC}), power output array (E_{DC}), reference yield (Y_R), array yield (Y_A), final yield (Y_F), array losses (L_A), system losses (L_S), array efficiency (η_A), system efficiency (η_{sys}), inverter efficiency (η_{inv}), performance ratio(PR), capacity factor (CF), in-plane solar radiation (H_T) and reference radiation (H_R), as the equations below (de Lima *et al.*, 2017; Adaramola and Vågnes, 2015; Ayompe *et al.*, 2011; Decker, 1997):

$$E_{AC,h} = \sum_{t=1}^{60} E_{AC,t} \tag{1}$$

$$Y_R = \frac{H_T}{H_R} \tag{2}$$

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \tag{3}$$

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} \tag{4}$$

$$L_A = Y_R - Y_A \tag{5}$$

$$L_S = Y_A - Y_F \tag{6}$$

$$\eta_A = \frac{100 \times E_{DC}}{H_T \times A_M} \tag{7}$$

$$\eta_{sys} = \frac{100 \times E_{AC}}{H_T \times A_M} \tag{8}$$

$$\eta_{inv} = \frac{100 \times E_{AC}}{E_{DC}} \tag{9}$$

$$PR = \frac{100 \times Y_F}{Y_R} \tag{10}$$

$$CF = \frac{E_{AC}}{P_{PV,rated} \times 8,760} \tag{11}$$

4. PERFORMANCE ANALYSIS RESULTS

4.1 Performance parameters

The figure 2 shows the performance of the hourly average power generated by the array (DC Power) at the time average of solar radiation. The graphical display allows the correlation of the magnitudes.

In November, December and January, there was a visible anomaly in the expected profile of DC power (causing a subtle reduction in the value of DC power while the irradiance follows the sinusoidal profile), beginning with the 14h and extending to practically the end of the day. After observations made on site, it was confirmed that a pole located near the array was causing a partial shading.

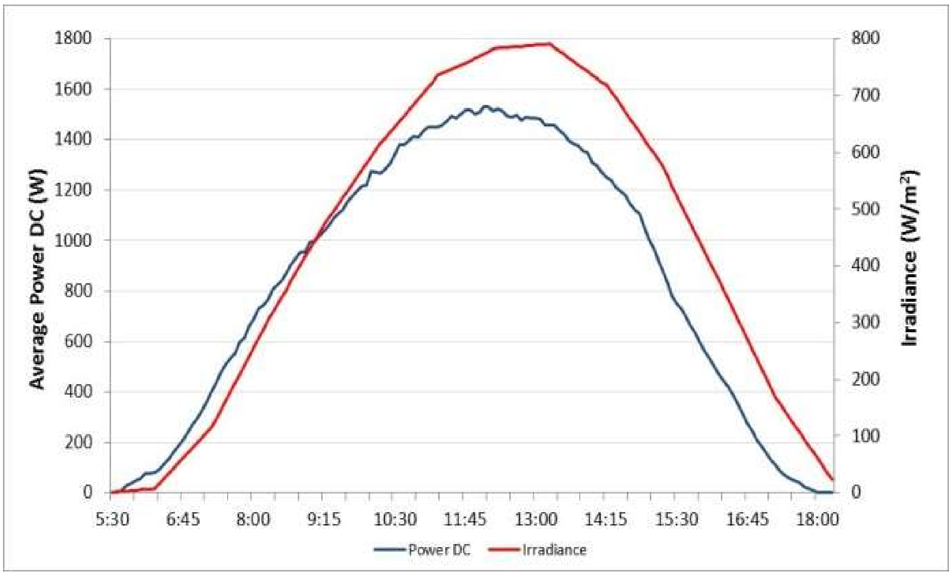

Figure 2. Hourly average generated power by the array and the hourly average solar irradiation at the system for the period June 2013 to May 2014

Through the power generated by the panels data and power supplied to the grid, it was possible to prepare the inverter efficiency graph of the irradiance shown in fig. 3. Above 230 W, the inverter will display a 90% efficiency, and from 570 W, the efficiency exceeds 95% to approximately 97%.

At lower powers to approximately 320 W, the graph presented a separation lines. The top line represents the efficiency in the morning, and the bottom line, in the afternoon.

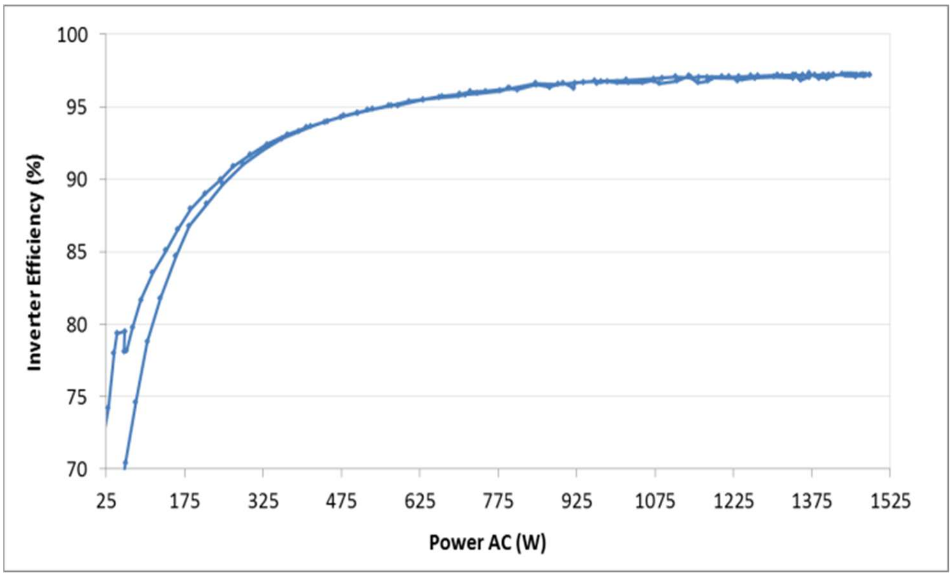

Figure 3. Inverter efficiency versus Power CA

The figure 4 shows the graph of the total energy produced per month and the solar measure irradiance, where we have the variation of 244.94 kWh in April/2014, with the lowest energy produced and in October/2013 the largest value produced AC electrical power equal to 373.96 kWh. The total energy produced in the 12-month period was 3,708.21 kWh, and the arithmetic mean of energy produced in the twelve months equal to 309.02 kWh/month. The final energy over the period of a year divided by the total system capacity ($P_{PV,rated}$) is equal to 1,685.55 kWh/kW_p.

The irradiance varied between the values of 135.90 kWh/m^2 in April/2014 and 200.57 kWh/m^2 in October/2013. The minimum amount of solar radiation was observed in the rainy season and the maximum value was comprised within the dry season (summer).

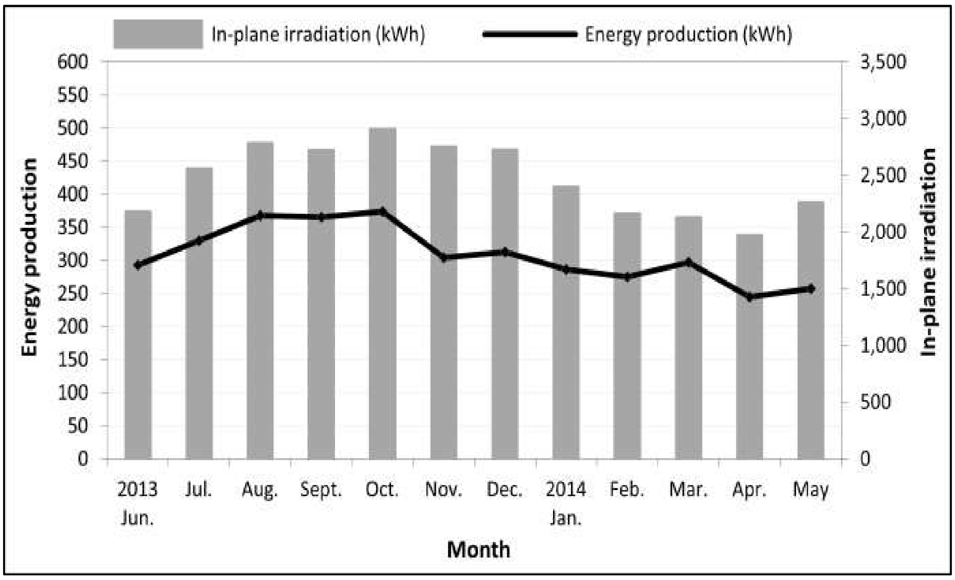

Figure 4. Energy production versus in-plane irradiation

The performance ratio quantifies the overall losses in the system due to the inverter inefficiency, losses in wiring, losses in protection components, heat dissipation in modules, incorrect installation panel, dirt, shading, possible shutdowns and losses associated with errors following the maximum power point (Marion *et al*., 2005).

This index of merit is the real system's ability to convert solar energy available in the plane of the panels into electricity; it is the ratio of the energy delivered by the system and the energy that was available in the relevant plan (Marion *et al*., 2005). It allows you to compare systems regardless of geographic location, positioning of the PV generator and rated power, because normalizes productivity in relation to irradiation, and shows the total effect of losses and system failures (Almeida, 2012).

In figure 5 the annual average system capacity factor was 19.23%, ranging from a minimum of 15.46% value in April and the maximum value of 23.7% in September. Whereas the capacity factor is the index that shows the amount of time in percentage, the production of the photovoltaic system operated at full capacity, so the system produced at full capacity in about 70.18 days or 1,684.55 hours.

The annual average performance ratio of 87.62%, with the minimum value in November 77.48% and the maximum value in March 97.65%.

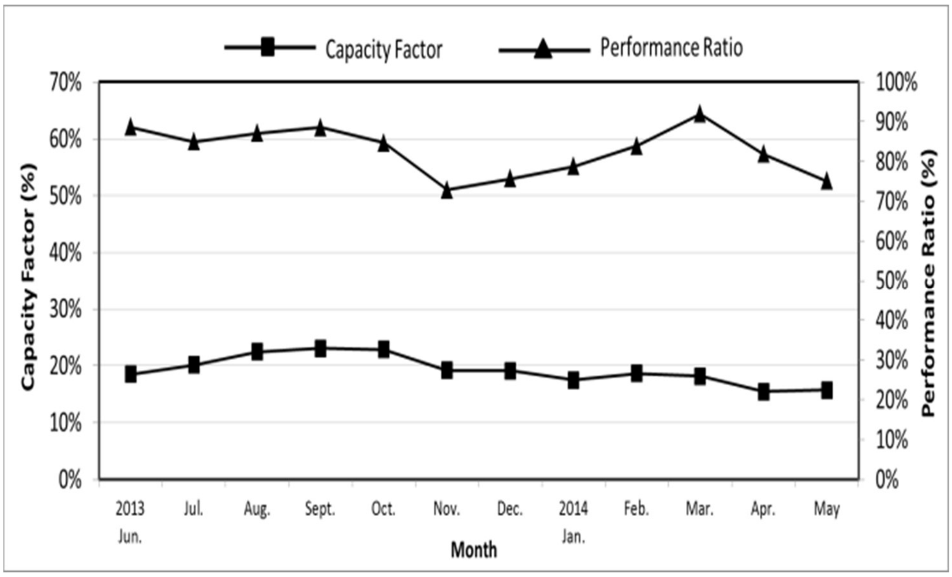

Figure 5. Capacity Factor and Performance Ratio

The average values of efficiency in the array, system and inverter had the values of 13.29%, 12.57% and 94.56% respectively. The maximum efficiency of the array, and inverter system were 14.80% (in March), 13.90% (in March) and 95.3% (in July), respectively (de Lima *et al*., 2017).

The average annual value of the final yield of our study was 4.62 kWh/kW_p, as shown fig. 6.

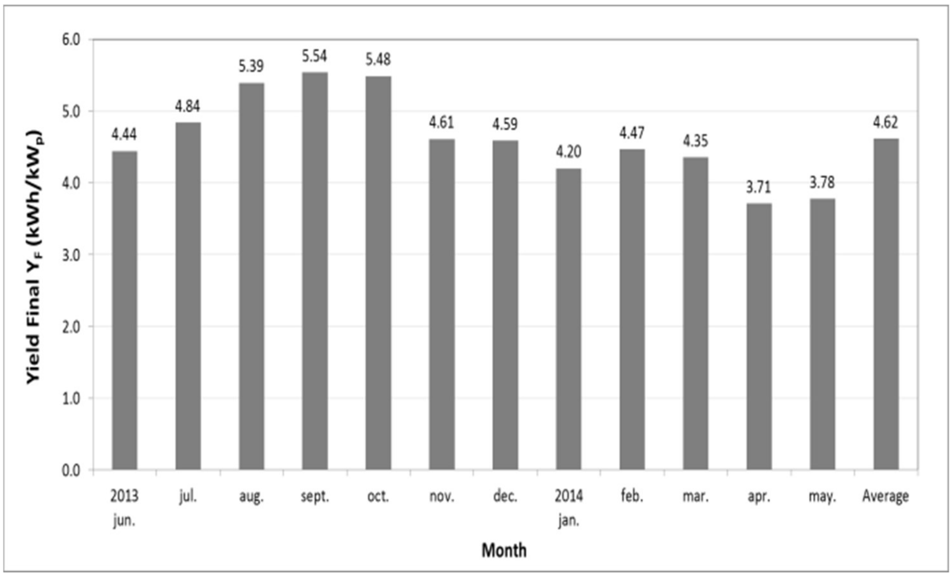

Figure 6. The average daily final yield

4.2 Economic Viability

To determine the cost of energy generated and payback time on investment some economic assumptions have to be determined. The first is the discount rate, which should adequately represent the opportunity cost to the investor.

It was stipulated the amount of 9% (per year) corresponding to the average annual income of debt title public (based on the interest rate) discounting inflation and taxes. Few investment options in the financial market without risk outweigh this rate of return for a long-term period (Benedito, 2009).

The value of the adopted inflation rate is 6% (per year), as measured by the National Consumer Price Index – IPCA (IBGE, 2014) corresponding to the twelve months to October 2014.

The average value of W_p installed sold in the Brazilian market ranges from US$ 3.22 to US$ 4.20 for 1 kW_p to 3 kW_p systems. For over 5 kW_p systems, the value ranges between US$ 2.56 and US$ 2.88. For systems over 1 MW_P, the value is approximately US$ 1.92 per W_P. Whereas the system under study is small and was on the ground, the adopted value was US$ 3.22/W_P. Considering the amount of US$ 3.22 for 1 W_P installed, as already mentioned, the investment amount for the installation of a 2.2 kW_p system is US$ 7,084.00 (in the year 2014). Based on the equation of the simple payback period (SPP) (Santos and Sauer, 1998):

$$SPP = \frac{Initial\ investiment}{Economics\ by\ year} \tag{12}$$

Calculating the simple payback period (SPP) will have the following result:

$$SPP = \frac{7,084}{3,708.21 \times 0.17} = 11.23\ years$$

It was adopted value of US$ 0.17 for electricity tariff, corresponding to the rate at the end of 2014. The simple payback period only considers the current rate of energy without taking into account future increases.

To calculate the Discounted Payback Period – DPP (Kolhe *et al*., 2002) is required to determine the useful life of the photovoltaic system. Three different scenarios were chosen: the first considers the service life of 20 years, the second 25 and the last 30 years. Considering the SPP equal to 11.23 years and the discount rate (d) of 9%, we have:

$$DPP = n \times CRF(d,n) \times SPP \tag{13}$$

$$DPP_{20} = 24.60 \ years$$
$$DPP_{25} = 28.58 \ years$$
$$DPP_{30} = 32.79 \ years$$

The capital recovery factor (CRF) is another economic figure of merit used for the analysis of energy alternatives, which annual the value of a particular investment made at present considering a certain discount rate (d) and a period of n years (Santos and Sauer, 1998). Where capital recovery factor (CRF), equals:

$$CRF(d,n) = \frac{d \times (1+d)^n}{(1+d)^n - 1} \quad (14)$$

The higher the discount rate d, the greater the payback period deducted from capital and the longer the recovery period of the investment.

At first sight, the results seem contradictory, considering that the system has the highest life also has the largest discounted payback period. But the explanation is simple: this economic indicator determines the time that the investment in question is financially equated to an investment with the same initial value, with a particular interest rate and for a determined period. The longer the investment value was applied in these rates, the higher would be the interest generated and the longer the photovoltaic system would need to work to make such interest that could be earned on other investment.

To calculate the cost of photovoltaic generation (represented by C), considering the amortization of capital, operating and maintenance costs and the relative discount to the opportunity cost (Kolhe *et al.*, 2002).

The three periods were considered useful life longer used, 20, 25 and 30 years.

$$C_{20} = US\$ \ 0.50 / kWh$$
$$C_{25} = US\$ \ 0.46 / kWh$$
$$C_{30} = US\$ \ 0.45 / kWh$$

Cost of the life cycle (CLC) and cost of energy saved (CES). For a period of 25 years the LCC and EEC were:

$$CLC_{25} = US\$ \ 26{,}956.25$$
$$CES_{25} = US\$ \ 0.31 / kWh$$

The CES indicates the amount that will be spent to save one 1 kWh of energy consumed (Kolhe *et al.*, 2002).

Now, we will update the economic data with the year 2017, where the investment amount for the installation of a 2.2 kW_p system is US$ 5,490.00 and value of US$ 0.23 for electricity tariff, corresponding to the rate at the April 2017. We will calculate the simple payback period (SPP):

$$SPP = \frac{5{,}490}{3{,}708.21 \times 0.23} = 6.43 \ years$$

With this new scenario, we must update the values of the new discounted payback period (DPP) and cost of photovoltaic generation (C), considering the same values for the discount rate (d) of 9%:

$$DPP_{20} = 14.09 \ years$$
$$DPP_{25} = 16.37 \ years$$
$$DPP_{30} = 18.78 \ years$$

$$C_{20} = US\$ \ 0.39 / kWh$$
$$C_{25} = US\$ \ 0.36 / kWh$$
$$C_{30} = US\$ \ 0.34 / kWh$$

And the actually cost of the life cycle (CLC) and cost of energy saved (CES). For a period of 25 years the CLC and CES were:

$$CLC_{25} = US\$\ 21{,}025.88$$
$$CES_{25} = US\$\ 0.37\,/\,kWh$$

The values of these indicators for 20 and 30 years were close, so the calculation for 25 years was made, which is the most plausible period of operation of a system.

5. CONCLUSION

The performance analysis and economics of a $2.2kW_p$ PV system installed is presented. The total annual output energy was 3,708.21 kWh, presenting an equal system efficiency of 12.67% and average annual capacity factor was 19,23%. The annual final yield value of 4.62 kWh/kW_p was determined for the system. The simple payback period (SPP) was 6,43 years and cost of photovoltaic generation (C) for a period of 25 years was equal US$ 0,36/kWh. The difference between the cost of photovoltaic generation and the current electric tariff is US$ 0,13/kWh.

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8. RESPONSIBILITY NOTICE