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CALCULATION OF ECONOMIC VIABILITY AND ENVIRONMENTAL COSTS OF PHOTOVOLTAIC SOLAR ENERGY FOR THE BRAZILIAN NORTHEAST REGION

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ABSTRACT

The availability of energy resources is a central point to economic development. The energy matrix of most countries is based on the consumption of fossil fuels, which adds annually over 5 billion tons of carbon into the atmosphere. The energy consumption in developing countries has quadrupled since the 60s further aggravating global environmental conditions. The need to implement alternative energy sources to the energy matrix was proved. In addition, Brazil has a large number of people without access to electricity, which affects the quality of life of these populations. In this context, it is necessary to think in economic development way, and then the sustainable and alternative sources appear as an option for its features and its availability in Brazil. The solar energy captured by photovoltaic cells can be highlighted in the Brazilian scenario because of its wide availability, especially in the Northeast. The aim of this paper is to estimate the economic feasibility of insertion of solar systems in small communities in the Brazilian Northeast, considering environmental costs involved in electricity generation. The methodology is based on economic concepts and economic valuation of environmental resources. The results shows that solar power is becoming increasingly competitive due to reduced costs of components and due to the environmental costs reduced when compared with fossil fuels.

1. INTRODUCTION

There is a very close and direct relationship between economic activities and the environment [1]. All decisions made by the economy agents will affect in some way and with some degree, the environment and society.

The energy model of most countries is based on the consumption of fossil fuels, which account for 90% of energy consumption in the world. The combustion of these fuels for energy production is responsible for the annual addition of more than 5 billion tons of carbon into the atmosphere [1].

Energy consumption predictions suggest an increase in CO_2 emissions of 7.4 billion tons per year in 1997 to 26 billion tons in 2100 [2]. The increased demand and energy consumption arising from technological advancement and human development are factors identified as most significant in accelerating climate change and environmental changes, as power consumption has tripled since the Industrial Revolution. Trends indicate that in developing countries will exceed consumption in developed countries even in the second decade of the 21st century [3].

It is necessary to think of a sustainable economy, based on three pillars: social, environmental and economic. According to Hinrichs and Kleinbach [1] the sustainable growth will only be possible with the efficient use of energy resources, technology development and use of alternative energy sources, particularly in developing countries. Growth needs to be defined according to the carrying capacity of ecosystems, within the limits of the environment [4].

The reduced supply of conventional fuels combined with the increased demand for energy and increasing concern about the environment, boost the scientific community to seek alternative energy sources that are less polluting, renewable and low environmental impact [3] and the alternative sources of energy seems to be an option.

Environmental costs and externalities are being increasingly debated by society and according to Mankiw [5] externalities arise "when a person engages in an action that causes an impact on the welfare of a third party that does not participate in this action, without pay or receive any compensation for this impact". If the generated impact is adverse, it is a negative externality and it is beneficial if it is a positive externality. Those externalities need to be identified and valued so these costs or benefits can be internalized in the final price of the good.

In Brazil, since 1992, with the Eco 92, the subject took a breath and went on to be a recurring theme. But the concern with externalities may be seen in the early twentieth century through major works of great economists like Pigou [6] and Coase [7], who have tried to appraise the costs imposed on society by externalities.

So, the aim of this work is to calculate the environmental cost during electricity generation to supply solar photovoltaic and estimate the economic viability of this source in small communities in northeastern of Brazil. To achieve the proposed objective will be developed equations to estimate feasibility source and application of the methodology of the Economic Valuation of Environmental Resources (VERA), in which will be obtained the environmental cost of photovoltaic energy for the generation phase.

2. SOLAR PHOTOVOLTAIC ENERGY

The generation of photovoltaics (PV) is the direct conversion of sunlight into electricity. In many remote areas of the autonomous PV systems are the only forms of electricity generation feasible. Solar cells have little or no pollution associated with its use and have fast assembly (1-2 years) [1].

The majority of cells used today are made from monocrystal silicon. Individual solar cells are electrically connected to the plates and flat plates these arrangements provide 47W at 12V under full sunlight. On smaller scales individual cells can be connected in series or in parallel. The output is direct current (DC) and their storage can be done by means of batteries requiring a stabilizer to prevent overcharging and to demands for alternating current (AC) inverter is required [1]. A simplified schematic of a photovoltaic system can be seen in Figure 1.

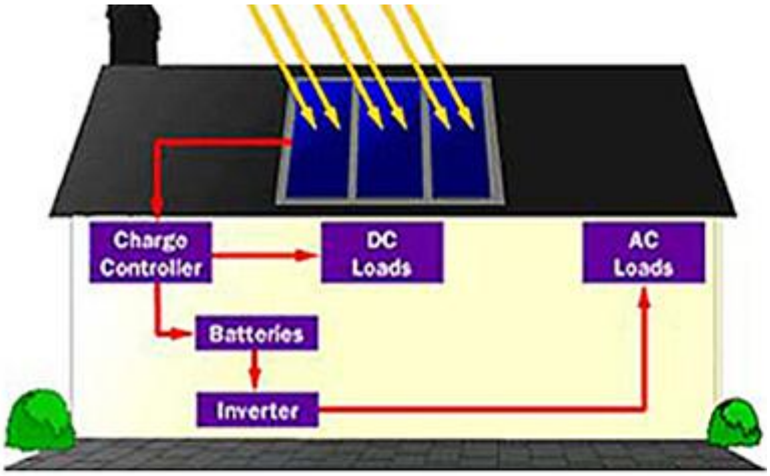

Figure 1: Residential photovoltaic system [8].

The use of solar energy, according to Pereira et al. [3], in the long term, would bring several benefits. It enables the development of remote regions of the country where the cost of a conventional network would be too high; regulates the energy supply in dry periods and reduces dependence on fossil fuels that contribute to reducing the emission of pollutants coming generation energy.

The use of solar energy ranges from small isolated systems up to large power concentrated autonomous, but this source also has a small share in the energy mix of the country and its largest use today is as a source for solar thermal water heating [3].

3. THE NORTHEAST REGION

The electricity supply model in Brazil is based on the generation of large amounts of connected power distribution, an uneconomical model to regions of low population density, as is the case in some parts of the Northeast. Because of this, the electrification in these regions is based on isolated systems with diesel generators, inefficient, high-cost and high environmental cost. Diesel fuel is the primary energy source used in the non-electrified communities [9], which is why this will be the source to be considered as a basis of comparison for the analysis of environmental costs.

The lack of access to electricity directly reflects the living conditions of the populations. The Human Development Index (HDI) of the Brazilian Northeast in 2005 was 0,720, the lowest among the Brazilian regions. The nine states that comprise the region are in the last placements in the national rankings, the worst being Alagoas state in number of HDI in the country [10]. Access to electricity is a way to provide improvements in the quality of life of these isolated populations; it would allow these individuals the possibility of productive activities associated with power generation [9].

To change this situation and bring electricity to excluded populations, it is necessary to insert alternative sources of energy in these remote regions. To Coelho et al. [9], we need to embed fonts available locally.

For this work it was developed a database with all the municipalities in the Northeast region of the country, with a population between 1,000 and 10,000 inhabitants analyzing the number of inhabitants, population density, land area, Municipal Human Development Index (IDHM) from 2000 and estimated the number of households with an average of 5 people in the county. The table was developed from data obtained from the IBGE [11] and the United Nations Program for Development [12]. Are shown the results obtained for the Alagoas state that has the lowest HDI of the country where they were found 29 cities with populations between 1,000 and 10,000 inhabitants.

4. METHODOLOGIES FOR THE CALCULATION OF ENVIRONMENTAL COSTS

4.1. VERA Methodology

To have a better allocation of environmental resources, it is important to make a proper economic evaluation of environmental goods and services. The monetized allows comparison of gains / losses with other environmental monetary benefits of the alternative use of resources. So the best option is the one that brings the best net benefit [13]. The internalization of environmental costs is intended to control the use of natural resources and services, leading to more efficient control of pollution and the use of these resources. Thus the consumer would pay the actual cost of what is consuming. The importance of environmental valuation methods is beyond the scaling of environmental impacts and their internalization: shows the costs and benefits of the expansion of human activities on the environment [4].

The economic value of environmental resources is sourced all his attributes that may or may not be associated with its use. Thus one can say that the VERA is determined by use-value (VU); composed of direct use value (VUD), indirect use value (VUI) and option value (VO) and non-use value (VNU) representing the value of existence of good (VE) [14].

So Motta [14] defines the VERA according to equation (1):

$$VERA = (VUD + VUI + VO) + VE \tag{1}$$

In cases where the environmental effects are localized or specific it is possible to measure their impacts directly [4].

This work is an analysis of the avoided costs to the environment by replacing electricity generators run on diesel by solar photovoltaic energy. Initially it describes the gas emissions in the environment originated by diesel generators to produce electricity and these values are converted to monetary values and compared with the values obtained for the studied source. The environmental cost obtained for the analyzed source is subtracted from the value found for the environmental cost of diesel. If the generated value is negative the impact of this alternative source is beneficial, positive externality. If the impact is adverse, negative externalities it is. From the input values of these externalities in the equations will be calculate the economic viability of the source studied.

4.2. Analysis of Emissions of Greenhouse Gases (GHG)

Alvim et al. [15] evaluated the emissions of Greenhouse Gases (GHG) emissions in tones of CO_2 equivalent per unit of electricity (MWh) of various energy sources in order to compare them. For this work it will be considered only emissions from generation phase. Emissions of CO_2 (carbon dioxide), CH_4 (methane), NMVOCs (volatile organic compounds except methane), CO (carbon) and N_2O (nitrous oxide) are converted into CO_2 equivalent following the criteria adopted by the Global Warming Potential (GWP). The criterion considers the conversion of a pulse emission of 1 kg of some compound to 1 kg of the reference gas, the CO_2 in the case of GWP [16].

In Table 1 there are presented in gCO_2eq/kWh_{el} emissions, equivalent to tCO_2eq/GWh_{el} stage to final electricity generation estimated for some sources of energy.

Table 1: Emissions related to electricity generation phase [15]

Energy Source	Total emissions from the generation phase (gCO_2eq/kWh_{El})
Diesel Oil	755
Fuel Oil	725
Coal	1262
Natural Gas	465
Nuclear	0,8
Wind	5,4
Photovoltaic	0

4.2.1. The Clean Development Mechanism (CDM) and its contribution to the analyze of environmental costs

The Clean Development Mechanism (CDM) allows the collection of international resources to projects that can contribute to the reduction of environmental impacts caused by the greenhouse effect. It consists in the certification of projects to reduce emissions and carbon sequestration in developing countries and the sale of these certificates for developed countries in order to ascertain their emissions reduction targets. Developing countries that implements the CDM will generate Certificates of Emission Reduction (CER) and these will be used by developed countries to meet their targets for reducing emissions of greenhouse gases, agreed in the Kyoto Protocol [2]. CDM projects are considered if anthropogenic GHG emissions are lower than emissions in the case of absence of the CDM project inserted or if carbon sequestration with the implementation of the project is greater than without it [17].

Then, for each metric unit of carbon is reduced through the project inserted in the CDM will be credited a carbon credit (CER) to be marketed [17]. The carbon unit will be calculated according to the methodology described above has GWP.

According to IPEA [17], the range of prices for emission reductions is very high. This range for the price of carbon in the CDM market, through the CERs is between US$ 3.00 and US$ 7.00. Due to this variation in prices for this work will be adopted the mean value between the minimum and maximum practiced in the market, or US$ 5.00 per tonne of CO_2 equivalent.

It can be observed, then, that the marketing of CERs can contribute positively in the feasibility studies of these sources, and considered as credits in the calculation of externalities source referenced in this work. So for feasibility studies presented here will be considered for the evaluation of externalities and environmental costs, the possibility of the sale of carbon credits.

As demonstrated previously, photovoltaic cells do not emit any greenhouse gases into the atmosphere in power generation. From this information, it will be calculated VERA air polluted by GHG emissions from diesel and thus obtained will be the cost avoided by replacing this source for solar photovoltaic cells.

5. RESULTS

Initially it is important to distinguish the concepts of financial assessment and economic evaluation, which are very different in economic science. The financial assessment, developed under the private point of view, comparing direct private benefits of a project with their direct monetary costs, using financial instruments, summarizing revenues and expected costs for the greater possible returns. In economic evaluation, there is a vision for the formulation of public policies in the national interest, taking into account in analyzing the indirect effects and externalities. So, in economic analysis the positive externalities are incorporated to the benefits and negatives to their costs [18]. From these concepts, are discussed the methodologies adopted for obtaining the environmental costs of the analyzed source.

The calculus of the costs of photovoltaic cells energy were made considering the life of the system generating electricity for 30 years due to the lifespan of photovoltaic panels taking into account the initial value of the equipment and their replacements at the end of life, which is incorporated into the corresponding equation as Shayani et al. [19].

The system specifications and calculations were performed by clarification obtained from Dr. Roberto Zilles and according to the current literature. Photovoltaic systems will be considered in mini-grids and isolated systems. All calculations will be done for the two configurations, but will be demonstrated here the equations of mini-networks because this is considered more appropriate to the proposed project.

The free energy provided by the government is a maximum of 80 kWh/month per household. In the case of mini-grids, the system should not exceed 200 kWh month. So for this study, the energy that is generated through mini-grids will supply four residences with 50 kWh/month. The amount of energy to be supplied to each family (five people), seeks to meet the provisions of the legislation on the subject, ANEEL 83/2004 SIGFI for individual systems [20] and ANEEL 493/2012 MIGDI [21] to mini-grids.

For the design of the system it was used the energy available in a given period of a year in the studied area. The solar irradiation is given in kWh/m^2 and to calculus it was converted into Hours Sun Full (HSP), which, according to Barreto [22], is given by the number of hours of sunshine per day on average with an intensity of 1000 W/m^2, equivalent to the total daily incident on the surface of the generator in kWh/m^2. So, considering that the maximum solar irradiation on Earth's surface is 1.000 W/m^2, 1 HSP is the energy received with this irradiance for 1 hour. The amount of HSP in a day is calculated by dividing the energy received kWh/m^2 in the level of peak irradiance of 1000 W/m^2 is [22].

According to the Brazilian Atlas of Solar Energy [3] the potential average annual solar energy to the Brazilian Northeast region is 5.9 kWh/m^2, or 5.9 HSP, so this region has the highest energy availability for deployment projects based on photovoltaic systems. In addition, the region is the one with the lowest variation of daily total global solar irradiation on the surface. This value is between 5.7 and 6.1 kWh/m^2.

For calculations in the system it was adopted the Safety Factor of 1.25, the total system performance (PR) of 0.75 which takes into account all system losses, the HSP and the nominal power (PN) of the photovoltaic system. Mini-grids used has the power peak of 2160 Wp (PN = 2.16 kWp). The main equations used for the calculations come next.

5.1. Equations and calculus to the mini-grids

The energy generation through the photovoltaic system to one day is given by the equation (2):

$$E_{FV1day} = P_N \times HSP \times PR \quad . \qquad (2)$$

Where the E_{FV1d} is the energy of the solar photovoltaic system for 1 day (kWh), P_N is the nominal power (W or kW), *HSP* is the number of hours of full sun (h) and *PR* is the total system performance. So $E_{FV1d(mr)} = 9{,}6kWh$. In 30 years E_{FV30} is 105,120 kWh.

The cost of the photovoltaic cell system in mini-grids is given by equation (3) considering the necessary number of components required for all of the lifespan on the project.

$$V_{TSS(mr)} = 1\times V_{MF} + 6\times V_B + 3\times V_C + 3\times V_I + 1\times V_{EF} + 1\times V_{AB} + 1\times V_{KI} \times 1xV_{SI} \qquad (3)$$

Where $V_{TSS(mr)}$ is the total value of the components of the solar system in mini-network in 30 years, V_{MF} is the value of photovoltaic modules, V_B is the value of the batteries, V_C is the value of controlling loads, V_I is the value of power inverters, V_{EF} is the value of the attachment structure; V_{AB} is the value of the cabinet for batteries, V_{KI} is the value of the installation kit and V_{SI} is the value of the service installation. The cost of one system in mini-network in 30 years is R$ 158,800.00.

For these calculations, the data for this system are shown in table 2. The quotations were made in December 2012 together with Kyocera Solar [23] and are not considered in the calculations the distribution network, such as poles, meters and extensions input.

Table 2: Prices of the components of a solar photovoltaic system (mini-grid) of 200 kWh/month (MIGDI) for the Brazilian Northeast [23]

Discrimination	Quantidade	Preço unitário com impostos (R$)	Preço total com impostos (R$)
PV module KD240 (240Wp)	9	1.222,22	11.000,00
Fixing Structure	1	1.500,00	1.500,00
Charge controller MPPT 60/150	1	7.000,00	7.000,00
Stationary battery 150Ah	9	1.000,00	9.000,00
Inverter/Charger 6048	1	15.000,00	15.000,00
Cabinet for batteries	1	3.000,00	3.000,00
Installation kit	1	9.300,00	9.300,00
Serviço de instalação	1	14.000,00	14.000,00
Total price of 1 system with taxes (R$)			69.800,00

The number of systems required - $n_{SS(mr)}$ - to serve the population through mini-grids - is obtained by dividing the number of families with 5 people estimated by the municipality for 4, which is the number of families served by each mini-network.

From these data it is then possible to obtain the equation for the energy calculation considering the Nominal Power (E_{PN}) and Effective Power (E_{PE}) system. The energy that is considered effective is the effectively delivered energy to the final consumer. To calculate the energy for mini-grids in 30 years using the equations (4) and (5), for the nominal and the effective potential, is respectively.

$$E_{PN} = E_{FV30} \times n_{SS} \tag{4}$$

$$E_{PE} = n_{SS} \times E_{FV1mEF} \times n_m \times n_a \tag{5}$$

The value of the environmental cost to be inserted in calculations of viability will be assessed from the avoided cost, which is the difference between the environmental cost (VERA) and the environmental cost of diesel supply in question. The VERA diesel and solar photovoltaic cells can be calculated using equation (6):

$$VERA = E_{30} \times V_{CER} \times EmC_{eq} \tag{6}$$

Where $VERA$ is the economic value of the environmental resource polluted air source analyzed, E_{30} the energy in 30 years, V_{CER} the value of carbon credits and EmC_{eq} is the carbon equivalent. Then, the avoided cost to the environment by using solar photovoltaic cells (CE_{FV}) is given by equation (7):

$$CE_{FV} = VERA_{solar} - VERA_{diesel} \quad (7)$$

Thus, the total cost of the development of solar energy in 30 years (CTE_{FV}), is given by equation (8). In this equation is inserted the obtained value from external power source in question.

$$CTE_{FV} = n_{SS} \times V_{TSS} + CE_{FV} \quad (8)$$

The amount of power per kWh (R$ / kWh) over 30 years for mini networks ($V_{kWh(FVmr)}$) is 1.5 R$/kWh generated when considering the rated power output. But when you consider the energy actually delivered to the final consumer that value rises to 2.19 R$/kWh due to the efficiency of the system. The efficiency of the systems was obtained from the energy considering the effective power and nominal power systems which is 0.68 for mini-grids.

In table 3 are shown the values obtained for the state of Alagoas. In the table you can see the impact of externalities on the total cost of the project beyond the total costs avoided by the substitution of the diesel system fueled by solar systems..

Although the value in R$/kWh for isolated systems is less than the mini-grids (1.50 R$/kWh for mini-grids and 1.34 R$/kWh for isolated systems) when considering the nominal power systems it is important to note that the isolate will supply a family with only 80 kWh/month, while the mini-networks will supply four families with 50 kWh/month each. It is worth to remember that for the calculations it was not considered the costs of distribution networks. Furthermore, it is observed that the yield of mini networks are larger than the isolated system, making them more competitive and efficient, which confirms the indication given by expert Dr. Zilles, who suggested the use of mini-rids . The efficiency of the isolated systems calculated was 0.54 while the 0.68 mini-grids. Then the value of the mini-networks becomes more attractive when considering the energy actually delivered to the final consumer, as is R$ 2.19/kWh for mini-grids for isolated systems while this value is 2.50 R$/kWh.

Table 3: data and calculus about Alagoas state in mini-grids

Município	Nº de habitantes projetados (2012)	nº de mini-redes	Energia Potência efetiva	Energia Potência nominal	Custo evitado (R$)	Custo do empreendimento (R$)	Custo do empreendimento considerando a externalidade (R$)
Barra de São Miguel	7.755	388	27.918.000	40.760.280	307.740,11	61.574.700,00	61.266.959,89
Belém	4.635	232	16.686.000	24.361.560	183.929,78	36.801.900,00	36.617.970,22
Belo Monte	6.499	325	23.396.400	34.158.744	257.898,52	51.602.060,00	51.344.161,48
Campestre	6.655	333	23.958.000	34.978.680	264.089,03	52.840.700,00	52.576.610,97
Campo Grande	9.273	464	33.382.800	48.738.888	367.978,60	73.627.620,00	73.259.641,40
Carneiros	8.548	427	30.772.800	44.928.288	339.208,57	67.871.120,00	67.531.911,43
Chã Preta	7.146	357	25.725.600	37.559.376	283.573,29	56.739.240,00	56.455.666,71
Coqueiro Seco	5.586	279	20.109.600	29.360.016	221.668,12	44.352.840,00	44.131.171,88
Feliz Deserto	4.482	224	16.135.200	23.557.392	177.858,31	35.587.080,00	35.409.221,69
Jacaré dos Homens	5.352	268	19.267.200	28.130.112	212.382,35	42.494.880,00	42.282.497,65
Jacuípe	6.950	348	25.020.000	36.529.200	275.795,46	55.183.000,00	54.907.204,54
Japaratinga	7.888	394	28.396.800	41.459.328	313.017,93	62.630.720,00	62.317.702,07
Jaramataia	5.524	276	19.886.400	29.034.144	219.207,79	43.860.560,00	43.641.352,21
Jundiá	4.142	207	14.911.200	21.770.352	164.366,16	32.887.480,00	32.723.113,84
Mar Vermelho	3.588	179	12.916.800	18.858.528	142.381,89	28.488.720,00	28.346.338,11
Maravilha	9.981	499	35.931.600	52.460.136	396.074,03	79.249.140,00	78.853.065,97
Minador do Negrão	5.251	263	18.903.600	27.599.256	208.374,38	41.692.940,00	41.484.565,62
Monteirópolis	6.952	348	25.027.200	36.539.712	275.874,83	55.198.880,00	54.923.005,17
Olho d`Água do Casado	8.708	435	31.348.800	45.769.248	345.557,82	69.141.520,00	68.795.962,18
Olho d`Água Grande	4.967	248	17.881.200	26.106.552	197.104,47	39.437.980,00	39.240.875,53
Palestina	5.201	260	18.723.600	27.336.456	206.390,24	41.295.940,00	41.089.549,76
Paulo Jacinto	7.412	371	26.683.200	38.957.472	294.128,91	58.851.280,00	58.557.151,09
Pindoba	2.857	143	10.285.200	15.016.392	113.373,76	22.684.580,00	22.571.206,24
Porto de Pedras	8.156	408	29.361.600	42.867.936	323.652,92	64.758.640,00	64.434.987,08
Roteiro	6.607	330	23.785.200	34.726.392	262.184,26	52.459.580,00	52.197.395,74
Santa Luzia do Norte	6.967	348	25.081.200	36.618.552	276.470,07	55.317.980,00	55.041.509,93
São Brás	6.744	337	24.278.400	35.446.464	267.620,80	53.547.360,00	53.279.739,20
São Miguel dos Milagres	7.360	368	26.496.000	38.684.160	292.065,41	58.438.400,00	58.146.334,59
Tanque d`Arca	6.172	309	22.219.200	32.440.032	244.922,24	49.005.680,00	48.760.757,76

3. CONCLUSIONS

These findings emphasize the evolution of prices of the components and the final cost of solar power generation over time. Currently, solar power, even still with relatively high costs, can already be considered viable. It is observed that the mini-networks systems are more economically viable, as evidenced by the calculations, confirming the appointment of the expert to the project.

Avoided costs from the use of solar photovoltaic alternative source to replace systems that use diesel fuel as a power source enables the insertion of this type of project in the CDM. In this case the avoided costs generated a positive externality that can be transformed into CER's and sold on the international market, enabling the creation of a revenue to be reinvested in the project. This fact shows to the society and decision makers of energy policies how much the use of fossil fuels are harmful to the entire society and its replacement by alternative sources, such as solar, will only bring benefits not only economic and environmental.

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