Technical and Economical Analysis of a Grape Irrigated Culture in the Northeast of Brazil Driven by A V-trough Photovoltaic Water Pumping System

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Abstract

The climate and soil of the Semi Arid Region of Brazil is perfectly propitious for a variety of crops of high economic value, grapes between them. The main problem faced by the regional agriculture is the availability of water. Traditionally, superficial water sources, frequently scarce and subject to high evaporation rates, has been used to meet the users demand. However during the last years, underground water, abundant in the region, has become the water source of largest interest. From the geological point of view, it is verified that 52% of the semiarid region is located in zones of sedimentary nature, favoring the occurrence of aquifers of good quality water. Several cultures, grapes between them, are produced in the Northeast of Brazil. Its largest fraction is concentrated in the Petrolina/Juazeiro complex, a pioneering area for grape cultivation in the semi-arid region. The main idea of this work is to consider the viability of expanding this area to other regions of the Northeast, by using the photovoltaic technology to produce water and energy. After a brief consideration of the problem of water supply, this paper analyses the technical and economical viability for implanting an irrigation system of a grape culture, driven by a photovoltaic generator. Taking advantage of some significant benefits provided by low concentration tracking devices we propose to use those systems to drive local irrigated crops. Among the large family of concentrators available, V-troughs are particularly adequate for photovoltaic applications due to its capacity to provide a perfectly uniform illumination in the region where the modules are located (absorber region). With that purpose, a drip irrigation system, located in the city of Petrolina, has been simulated and the maximum surface that can be irrigated by a V-trough photovoltaic pumping equipment was estimated. Calculations show that a V-trough photovoltaic generator of 1.3 kWp can irrigate an area of 2.11 ha. The economic viability of this proposal depends strongly on the market value of the crop. It was estimated the cost to implant a PV water pumping equipment coupled to four hectares of irrigated area. The profitability of the irrigated culture for sedimentary and crystalline regions is separately considered. Because of the large difference in market value, the analysis is made for grapes with and without seed. It is verified that the accumulated net income for grapes without seed becomes already positive in the second crop, both for sedimentary and crystalline geological regions.

Keywords: Hydrological potential, Photovoltaic Pumping System, Irrigation

1. Introduction

Brazil has one of the largest hydrological reserves in the world, with a concentration of about 12% of the available, superficial potable water of the planet. However, it presents a large contrast in its distribution. For example, the Northeast Region with 29% of the population, has 3% of the country's water. None of the Brazilian Regions have suffered, from the lack of water, more than the Northeast's Semi-Arid regions. Nowadays, the available hydrological capacity per capita of the region is insufficient for the 15 million inhabitants.

The solar radiation and the winds in the region account for an index of 30% of evaporation loss in the dams. As a result, smaller storage systems, such as cisterns or tanks, more adequate for the regional climatic conditions, are used, even though limited by the scarcity of rains and the water volume that can be accumulated. On the other hand, underground water, abundant in the region, can become the main source for human consumption and irrigation. In this way, the photovoltaic pumping systems can be considered as quite an attractive alternative.

The high irradiation levels in the region favor the use of this technology. However, when considering the operational characteristics of the system, it should be mentioned that one of the parameters from which the water volume, pumped by a photovoltaic pumping equipment, significantly depends is the critical irradiance (minimum irradiance level, (I_C), to start the operation of the system). Large critical irradiance levels reduce the daily operational time and consequently the water volume pumped along the day. For a pumping system operating with a given water head, ways available to overcome this problem are either to increase the nominal power of the PV generator that drives the pumping system or to use tracking devices to increase the average irradiance level ($\bar{I}_{coll}$) by the PV generator.

The increase of $\bar{I}_{coll}$ by solar trackers can be amplified by the use of solar radiation concentrators, as for example V-trough cavities. Photovoltaic generators coupled to V-trough cavities have been proposed in the past with the purpose of increasing the electrical energy output generated by those systems (Fraidenraich, 1998). Photovoltaic pumping systems, coupled to low concentration devices, constitutes another application able to obtain further benefits from those configurations, and to reduce, consequently, the final cost of the pumped water volume. Among the large family of concentrators available, V-troughs are particularly adequate for photovoltaic applications since, for certain combinations of the concentration ratio (C) and vertex angle (Ψ), the illumination they provide is perfectly uniform in the region where the modules are located (absorber region) (Fraidenraich, 1998).

Several cultures, grapes between them, are produced in the Northeast of Brazil. Its largest fraction is concentrated in the Petrolina/Juazeiro complex, a pioneering area for grape cultivation in the semi-arid region. The main idea of this work is to consider the viability of expanding this area to other regions of the Northeast, by using the photovoltaic technology to produce water and energy.

With that purpose, we present, in this study, an analysis of the availability of subterranean water in the Northeast regions of Brazil, followed by a simulation of the hydrological balance for grape cultivation in the state of Pernambuco, irrigated by a photovoltaic pumping system coupled to a V-trough concentrator. The work concludes with an analysis of cost and profitability. The long-term water volume pumped by the pumping systems is determined by the utilizability method using the relationship between instantaneous water flow and collected solar radiation (characteristic curve of the system).

2. Subterranean Water in the Northeast

The use of superficial water is some times difficult because of its distance from the place of consumption and the high rate of evaporation in regions such as the Northeast of Brazil. On the other hand, subterranean waters are more abundant and constitute a safer supply to meet rural populations demand and irrigation needs. Then, the answer for the lack of water in the Northeast of Brazil, seems to be in the subsoil and not on the surface. In spite of the predominant semi-arid climate in various parts of the region, there are subterranean reserves of water (aquifers) that are sufficient for solving a great deal of the water supply problems.
The underground water reserves are particularly large in sedimentary rock regions. These very porous rocks have a large capacity for rain water absorption and storage. Others areas, formed by crystalline rocks, are, on the contrary, extremely impermeable, forcing the water to run to other places and leaving the air and soil drier.
The Northeast geological formation has 48% of crystalline and 52% of sedimentary rock. The latter is concentrated in the states of Maranhão, Piaui, part of Bahia and the coastal area. Crystalline rocks are predominant in the interior of most of the states, where the climate is more arid. But there are various places with sedimentary rocks in the middle of crystalline rocks, which could be explored and used in irrigation systems.

3. Hydrological Potential for Irrigation

Taking, as reference, the sedimentary basins of the state of Pernambuco, whose static level varies between 7 and 100 meters, we find representative values of permanent and exploitable reserves (Table 1).

Table 1 – Characteristics of sedimentary Basins in the State of Pernambuco

Sedimentary Basin	**Principle Aquifers**	**Area in (km^2)**	**Permanent Reserves in Millions of (m^3)**	**Exploitable Reserves in Millions of m^3 per year**	**Production capacity (m^3/h) per well**
Jatobá	São Sebastião	1.550	46.500	93	5-30
	Inajá	2.700	70.000	142,2	5-250
Fátima	Tacarutu	270	500	2,0	20-70
Mirandiba	Tacarutu	70	55	0,2	5-70
Betânia	Tacarutu	175	140	0,5	5-70
Belmonte	Tacarutu	700	580	2,3	5-70
Cedro	Mauriti	275	320	0,5	15
Araripe	Missão Velha	2500	2.500	10,0	5-150

Source: CPRM (2002) – Serviço Geológico do Brasil, e-mail: http://www.cprm.gov.br

Fraidenraich and Costa (1988), verified that the mean daily water consumption required for grape cultivation in the region of São Francisco River, is around 20 m^3 per hectare per day. Observing the column of the production capacity of the wells in Table 1, and considering that a photovoltaic pumping system works 6 hours a day, we verify that the smallest production capacity (5 m^3/h/well), can still meet a demand of water of that order (20 m^3/ha/day).

4. Selection of Culture

In horticulture, one option is grape cultivation, because it presents elevated rates of profitability per hectare cultivated. Grape cultivation is very demanding in treatment, during the whole cycle of production, and consequently, has an elevated rate of labor demand, reaching up to 6 people per hectare.

Among other cultures, grapes are being produced in the Northeast of Brazil. The largest fraction of that production is concentrated in the Petrolina/Juazeiro complex, a pioneering area for grape cultivation in the semi-arid region. The total area cultivated in this complex is around 4,000 hectares of planted grape vines.

5. Water Volume Pumped by the PV V- Trough System

The selection of a PVP system, capable to meet the water demand for irrigation, requires implementing a design procedure. Determining, first of all, the hydraulic load of the irrigation system, one could select different sets of inverter/converter-motor-pump able to meet that load. With the manufacturer curves of water flow vs. electric power ($\dot{V}_B$ vs. P_{DC}) for the specific water head, and simulating P_{DC} values for the local climate (using as input collected irradiance (I_{coll}), ambient temperature and electrical and thermal characteristics of the PV modules), we can obtain the characteristic curve of the PVP systems ($\dot{V}_B$ vs. Icoll) for different array sizes (Vilela et. al, 2001).

The pumped water volume V_B is then determined by the utilizability method, for each month (Fraidenraich and Vilela, 2000).

The collected irradiance of the V-trough system (Fig. 1) has been calculated considering the relationship between the effective concentration (C_{eff}) and the fraction of diffuse irradiance on the aperture of the concentrating device $\left(\frac{I_{dA}}{I_A}\right)$

$$\text{Ceff} = \frac{I_a}{I_A} = C_o \eta_b \left[1 - \frac{I_{dA}}{I_A} \frac{\eta_b - E_{Aa}}{\eta_b}\right] \quad (1)$$

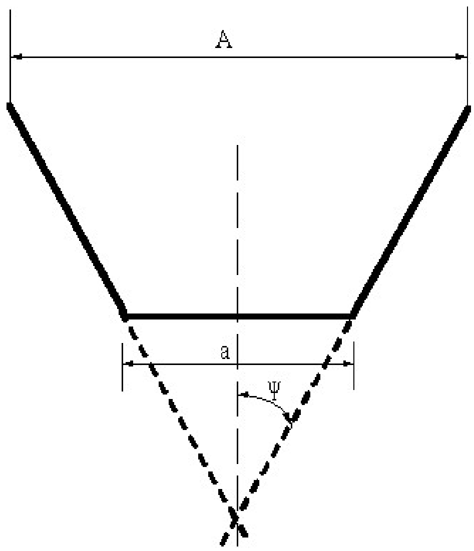

Figure 1 Cross section of a V-trough cavity

where I_a and I_A are the irradiance collected at the absorber and aperture plan, respectively, I_{dA} the diffuse irradiance at the aperture, (E_{Aa}) denotes the fraction of diffuse radiation transferred from aperture to absorber (radiative exchange factor), (η_b), the beam optical efficiency, and (C_o) the concentration ratio of the cavity (A/a).

We use in this work the geometric and optical characteristics of a V-trough cavity tested in our laboratory. The PV-V-trough generator is mounted on a east-west tracker with the north-south axis tilted at a fixed angle. The cavity is composed of commercial back silvered mirrors, with 3 mm thick. The concentration ratio (C_o) and vertex angle (Ψ) are 2.2 and 30^o, respectively. Light rays with normal incidence at the aperture reach the mirror walls at 60 degrees. The reflectivity at that incidence angle, is equal to 0.80, yielding a beam optical efficiency (η_b) of 0.82 (Fraidenraich, 1995).

The interchange factor between aperture and absorber (E_{Aa}), considering reflection losses in the mirror walls, is equal to 0.43 (Fraidenraich, 1995). The irradiance components have been obtained using the isotropic model proposed by Collares-Pereira and Rabl (1979).

6. Hydrological Balance

The hydrological balance of the irrigated crop takes into account: a) The water demand, determined by the evapotranspiration of the crop; b) The availability of water, given by the rainfall and the pumped water volume for the PVP system; c) The water stored in the soil.
Using the irrigated surface (A) as a variable, in the simulation model, it is possible to find the maximum area that can be irrigated by a given photovoltaic pumping system. It has been adopted the criterion that the deficit of water should be equal to zero. The simulations have been done for the city of Petrolina (PE-Brazil; latitude (-9^o)). The input data for the climate has been obtained from the database of EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária). To irrigate the grape crop we propose the drip system, which allows a crop coefficient C of the order of 0.5, with the advantage of smaller water consumption, reduced costs, smaller incidence of fungus in the foliate and flexibility in the use of fertirrigation.
The PV generator used in the simulation is a C-Si array with 1.3 kW of peak power driving an AC three-phases motor coupled to a centrifugal pump with 10 stages. The total pumping head is 40m. Two kinds of PV pumping systems have been simulated for the same inverter-motor-pump set, one no moving set (fixed), without concentration, and a V-trough tracker system. The tilt angle of the generator has been chosen in such a way as to minimize the relationship between supply and demand of water, resulting equal to (–10^o).
For the fixed system, without concentration, the maximum area that can be irrigated without deficit is equal to 1.2 ha. For the V-trough system the area is around 2.11 ha (Fig. 2). The water stored in the soil contributes with an increase of 33% to the irrigated area, as compared to the case where that contribution is not considered.

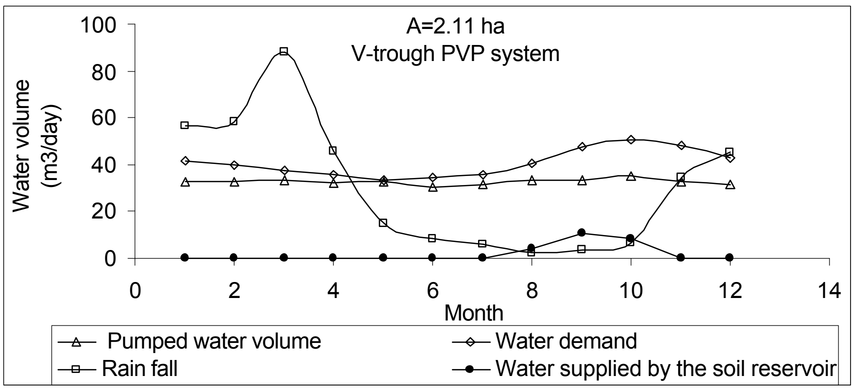

Figure 2 – Hydrological Balance

7. Analysis of Cost and Profitability

Based on the sheets produced by Lásló Dorgai (Embrapa Frupex Magazine, ref. 1413-375x) and data collected with enterprises specialized in irrigation systems and semi-artesian wells, we have elaborated Table 2, adapted for a four hectares irrigation system, where the cost and profitability for a sedimentary and a crystalline region are separately calculated.

Table 2 – Production costs and profitability for an irrigated area of four hectares

Cost (US$)			First Year		Second Year	
			1º Crop	2º Crop	1º Crop	2º Crop
Irrigation system and accessories			6.230,21			
Handling of the crop			20.000,00	20.000,00	20.000,00	20.000,00
Equipments and Installations			49.023,95			
PV pumping system			28.353,60			
Water well in sedimentary area			26.666,66			
Water well in crystalline area			5.333,34			
Total Cost	Sedimentary area		130.273,84			
	Crystalline area		108.940,52			
Production Value	Grape with seed (ws)		23.001,00	46.002,00	46.002,00	46.002,00
	Grape with no seed (ns)		75.000,00	150.000,00	150.000,00	150.000,00
Profitability (US$)						
Sedimentary area	*ws	Net Profit	-130.273,84	-107.272,84	-81.270,84	-55.268,84
		Accumulated Net Profit	-107.272,84	-81.270,84	-55.268,84	-29.266,84
	*ns	Net Profit	-130.273,84	-55.273,84	74.726,16	204.726,16
		Accumulated Net Profit	-55.273,84	74.726,16	204.726,16	334.726,16
Crystalline area	*ws	Net Profit	-108.940,52	-85.939,52	-59.937,52	-33.935,52
		Accumulated Net Profit	-85.939,52	-59.937,52	-33.935,52	-7.933,52
	*ns	Net Profit	-108.940,52	-33.940,52	96.059,48	226.059,48
		Accumulated Net Profit	-33.940,52	96.059,48	226.059,48	356.059,48

*ws and ns refer to grapes with seed and with no seed, respectively

Using a photovoltaic pumping systems of 2.6 kWp, to meet the demand of a four hectares irrigation system (as shown, 2.11 ha can be irrigated with a 1.3 kWp V-trough generator) we consider the cost of the PV generator, as around US$7/Wp, adding the price of the tracking structure of about US$ 2,400.00, the price of the concentrator mirrors and fitting structure of around US$50/m^2, having a total mirror area of 63.4 m^2, and the price of the subsystem (inverter/motor pump) equal to US$ 2,400.00. This set of equipment represents 10% of the cost of implantation of the four hectares irrigation system.

It is verified that the accumulated net income becomes positive, for grapes with no seed, in the first two years, presenting a larger profit return in crystalline areas. However, it is very likely that the water, extracted in those areas, presents high salinity levels. On the other hand, sedimentary area also shows a good profit return and its water is more adequate for use in irrigation systems. Accomplishing the same study for grape with seed, the accumulated net income becomes positive in three years (not shown in Table 2).

8. Final Comments

It is shown that he use of V-trough cavities for PV pumping system increased the maximum irrigated area in 76%, as compared with fixed systems.
Regarding the main idea behind this work, it is shown that there are important areas in the semi-arid region of the Northeast where the use of photovoltaic pumping technology, to drive irrigation systems, is economically viable. We verify that the return time of the investment is around two years for grape without seed and three years for grape with seed.

Important benefits for local farmers, in terms of income, can be expected, with due consideration still for their socio-cultural traditions.

References

1. Collares-Pereira M. and Rabl A., 1979. The average distribution of solar radiation. Correlations between diffuse and hemispherical and between hourly and insolations values, In: Solar Energy, vol. 22, pp. 115.
2. Fraidenraich N., 1995. Analytic solutions for the optical and radiative properties of nonaccepted light radiation of V-trough concentrators. In: Applied Optics, vol. 34, pp. 4800-4811.
3. Fraidenraich N., 1998. Design Procedure of V-trough cavities for photovoltaic systems. In: Progress in Photovoltaics, Research and Applications, vol 6, pp. 43-54.
4. Fraidenraich, N. and Costa, H. S., 1988. Procedure for the determination of the maximum surface which can be irrigated by a photovoltaic pumping system. In: Solar and Wind Technology, vol. 5, nº 2, pp. 121-126.
5. Fraidenraich N. and Vilela O. C., 2000. Performance of solar systems with non linear behavior calculated by the utilizability method. In: Solar Energy, vol. 69, pp. 131-137.
6. Vilela O.C., Fraidenraich N., Galdino M. A., 2001. Performance of photovoltaic pumping systems driven by tracking collectors. In: 17^{th} European Photovoltaic Solar Energy Conference, Munich, Germany, vol. 3, pp. 2766-2770.
7. Embrapa Frupex Magazine, 1996. Série uva para exportação, código 61010, ref. 1413-375x). In: Empresa Brasileira de Pesquisa Agropecuária – Embrapa, Brasil.

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