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DEVELOPMENT OF A SOFTWARE SIMULATION SYSTEMS: PHOTOVOLTAIC POWER GENERATION (PV), SOLAR HEATING (SAS)

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This paper aims at presenting an application developed in JAVA programming language as an extension of a previous program for optimizing solar water heating systems, in order to now encompass photovoltaic system design and optimization, based on the PV-f-chart method. The program focuses only stand alone photovoltaic systems, i.e., systems not connected to the electrical grid. The program uses solar radiation data from the Brazilian Solar Atlas, performance data of photovoltaic system components from standardized tests performed within the Brazilian Labeling Program, and appliance power consumption and other electrical load data inserted by the user. The program checks if the photovoltaic system is able for attaining the electrical load, and if not, it returns the monthly power fraction that will be supplied by the photovoltaic system. Both arrays in series and parallel of photovoltaic panels are allowed. The program also conducts economic analysis using classic parameters as net present value, discounted return and internal rate of return. The program was validated through examples from the book of Duffie & Beckman and also by comparison with the results generated by a commercial PV-f-Chart program, and obtained good agreement.
Keywords: *Solar Energy, Solar Heating, Thermal Simulation, Photovoltaic, Power Generation.*

1. INTRODUCTION

Solar energy participation in Brazil is so poor that it does not appear in the Brazilian Energy Balance. This is a consequence of the cheap and renewable hydropower responsible for more than 75% of electricity production, but nowadays the hydroelectric potential to be exploited is located in the Amazonian region, very far from the high consumption centers, with environmental constraints that delay or even block the licensing.

In the hottest summer days, the Brazilian electricity consumption peak has been displaced to between 2 pm and 3 pm due to the intense use of air conditioning systems. The solar energy is suitable for shaving this peak since both power generation and consumption are simultaneous.

The interest in photovoltaic systems has increased since the Aneel Resolution 482/2012 was promulgated, concerning to the distributed generation, allowing to interconnect solar energy to the electrical grid. A full panorama about the photovoltaic systems in Brazil can be viewed in Chiganer and Costa Filho (2013).

The lacking of an accurate economic analysis limits the photovoltaic penetration in Brazil, even where its results may be unfavorable, because any investor needs to know how much money would be added to complement the project, as solar energy is environmental friendly and may be used for marketing purposes. Additionally, public policies could be established for incentive to photovoltaic systems mainly due to the whole investment is private and distributed, against the traditional centralized power generation that requests huge governmental investments.

This paper aims at presenting an application developed in JAVA programming language as an extension of a program for optimizing solar water heating systems that has been treated in previous works (Souza, 2011; Barros et al., 2013; 2014), in order to now encompass photovoltaic system design and optimization.

2. MATERIALS AND METHODS

2.1 PV F-Chart

The PV F-Chart method is a tool for the design of photovoltaic systems. It uses monthly solar radiation and mean ambient temperature to predict the long-term annual performance of a photovoltaic array. The PV F-Chart was developed by Siegel et al. (1981) and Evans (1981), and extended by Clark et al. (1984). Several studies have been identified the accuracy PV F-Chart method, including Menicucci (1986) and Clark et al. (1984).

2.2 Solar Radiation

Solar radiation is split in beam and diffuses components. Sky models are mathematical representation of the diffuse radiation. The current software uses the isotropic diffuse sky model developed by Liu and Jordan (1962). The radiation on the tilted surface is considered to include three components: the beam radiation (I_b), the isotropic diffuse radiation from the sky (I_d), and solar radiation reflected diffusively from the ground ($I_{\rho g}$). One tilted surface with inclination β to the horizontal has a view factor to the sky Fc−s = (1 + cosβ)/2 and a view factor to the ground Fc−g = (1 – cosβ)/2. The total incident radiation can be written as: (Duffie, J. A and Beckman, 2006):

$$I_T = I_b . R_b + I_d . \left(\frac{1+\cos\beta}{2} \right) + I_{\rho g} . \left(\frac{1-\cos\beta}{2} \right) \qquad (1)$$

where R_b is the ratio of beam radiation on the tilted surface to that on a horizontal surface, defined as:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad (2)$$

where θ and θ_z are the incidence and the zenith angles, respectively.

The software employs an optimization routine to find the inclination angle (β) that maximizes the incident solar radiation on the collector surface taking into account all months, or optionally only the winter months, by maximizing R_b in Eqs. (3) or (4).

$$R_b = \frac{\left(\frac{\pi}{180}\right) . \omega_S' . sen\,(\phi+\beta) . sen\delta + sen\,\omega_S' . \cos\delta . \cos(\phi+\beta)}{\cos\phi . \cos\delta . sen\,\omega_S + \left(\frac{\pi}{180}\right) . \omega_S . sen\phi . sen\delta} \qquad (3)$$

where,

$$\omega_S' = \min \begin{bmatrix} \cos^{-1}(-\tan\phi \cdot \tan\delta) \\ \cos^{-1}(-\tan(\phi+\beta) \cdot \tan\delta) \end{bmatrix} \qquad (4)$$

δ, Ø and ω_s are the solar declination angle, the latitude and the sunset (or sunrise) hour angle, respectively.
However, for places in the northern hemisphere, $\gamma = 0^0$ instead of 180^0, and R_b is calculated by:

$$R_b = \frac{\left(\frac{\pi}{180}\right) . \omega_S' . sen\,(\phi-\beta) . sen\delta + sen\,\omega_S' . \cos\delta . \cos(\phi-\beta)}{\cos\phi . \cos\delta . sen\,\omega_S' + \left(\frac{\pi}{180}\right) . \omega_S' . sen\phi . sen\delta} \qquad (5)$$

The monthly average integrated daily extraterrestrial radiation $\bar{H}_o$ can be calculated by Eq. (6). For latitudes in the range of +60 to -60, $\bar{H}_o$ can be evaluated using n and δ for the mean day of the month, as proposed by Klein (1977). The mean day values presented in Table 1 are those that best represent the average for each month.

$$\bar{H}_o = \frac{24 \cdot 3600 \cdot G_{SC}}{\pi} \cdot \left(1 + 0{,}033 \cdot \cos\left(\frac{2.\pi.d}{365}\right)\right)(\cos\phi \cdot \cos\delta \cdot sen\omega_s + \omega_s \cdot sen\phi \cdot sen\delta) \qquad (6)$$

where:

G_{SC} is the solar constant and "d" is the day of the year, from 1 to 365 and ω_s is the hour angle of the sunset, in degrees.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day	17	16	16	15	15	11	17	16	15	15	14	10

Table 1: Mean day for each month (Klein, 1977).

The monthly average clearness index ($\bar{K}_T$) takes into account the atmospheric attenuation of the extraterrestrial solar radiation and is expressed as the ratio of monthly average daily solar radiation on a horizontal surface $\bar{H}$ to the monthly average daily extraterrestrial radiation. The software reads $\bar{K}_T$ values from the Brazilian Solar Atlas elaborated by Tiba (2000).

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \tag{7}$$

The software requires monthly average integrated daily radiation on the tilted surface $\bar{H}_t$, that are calculated by "Eq. (8)" through a similar sum procedure of "Eq. (1)", where the subscripts ρg and d refer to diffuse and ground reflected components, respectively.

$$\bar{H}_T = \bar{H}\left(1 - \frac{\bar{H}_d}{\bar{H}}\right)R_B + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{H}_{\rho g}\left(\frac{1-\cos\beta}{2}\right) \tag{8}$$

The diffuse component is related to the total radiation, as proposed by Collares-Pereira and Rabl (1979) (Duffie and Beckman, 2006):

$$\frac{\bar{H}_d}{\bar{H}} = 0{,}775 + 0{,}00606 \cdot (\omega_s - 90) - [0{,}505 + 0{,}00455 \cdot (\omega_s - 90)] \cdot \cos\left(115\bar{K}_T - 103\right) \tag{9}$$

All above mentioned procedures and equations are shared with thermal and photovoltaic designs.

The estimation of hourly radiation from daily data is performed as proposed by Collares-Pereira and Rabl (1979 a):

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}} \tag{10}$$

r_t = the ratio of hourly total radiation.

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \tag{11}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \tag{12}$$

In these equations ω is the hour angle in degrees at the midpoint for the time in question and ω_s is the sunset hour angle.

The monthly average hourly radiation on the inclined surface $\bar{I}_T$ can be calculated through "Eq. (13)":

$$\bar{I}_T = \bar{K}_T\bar{H}_0\left[\left(r_t - \frac{\bar{H}_d}{H}\,r_d\right)R_b + \frac{\bar{H}_d}{H}\,r_d\left(\frac{1+\cos\beta}{2}\right) + \rho_g r_t\left(\frac{1-\cos\beta}{2}\right)\right] \tag{13}$$

where

$\bar{H}_d$ = monthly-average daily diffuse solar radiation (MJ / m^2),
$\bar{H}$ = monthly-average daily solar radiation (MJ / m^2),
r_d = ration of diffuse radiation in na hour to diffuse in a day (%),
ρ_g = Ground reflectance (%).

2.3 Photovoltaic Generator Models

For system design purposes, the modeling of photovoltaic systems is performed through the voltage-current relationship of solar cells under various radiation levels and in different cell temperatures. The data on cells or modules necessary features to use the model should be available from the manufacturer. For this purpose, detailed models do not seem to be necessary, and simple models work well. Rauschenbach (1980), Townsend (1989), Eckstein (1990) and Schroder (1998) reviewed several models and their utility for system design purposes.

"Figure 1" shows an equivalent circuit that can be used either for a cell or a module that consists of multiple cells or an array consisting of several modules. This circuit requires five parameters: the light current I_L, the reverse diode saturation current I_D, the series resistance R_s, the shunt resistance R_{sh} and a curve fitting parameter α. At a fixed temperature and solar radiation, the voltage-current characteristic of this model is given by "Eq. (14)". (Duffie and Beckman, 2006):

$$I = I_L - I_D - I_{sh} = I_L - I_0\{\exp[(V + IR_s)I_a] - 1\} - \frac{V + IR_s}{R_{sh}} \tag{14}$$

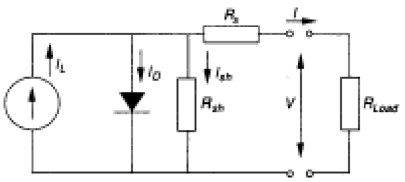

Figure 1.The equivalent circuit for a photovoltaic generator. (Duffie and Beckman, 2006).

The power is given by:

$$P = IV \tag{15}$$

Current-voltage (I-V) characteristics of a PV module are shown in Fig. (2). The current axis (where V = 0) is the short circuit current I_{sc} and the intersection with the voltage axis (in which I = 0) is the open circuit voltage V_{oc}. For this module the current is almost constant up to about 15V, at which point the diode current becomes increasingly important. At open circuit conditions around 20V, all generated light current pass through the diode and the shunt resistance.

The power output as a function of voltage is also shown in Fig. (2). The maximum power that can be obtained corresponds to the maximum rectangle area under the curve I-V. At the maximum power point the power is P_{mp}, the current is I_{mp}, and the voltage is V_{mp}. Ideally, the cells would always operate at the maximum power point, but practically cells operate at a point that matches the curve IV characteristic of the load.

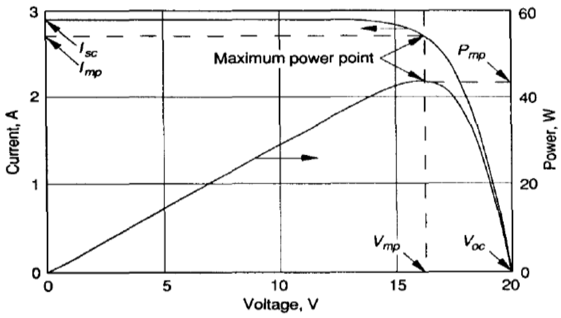

Figure 2. Typical curves I - V and Q - V of a photovoltaic module.(Duffie and Beckman, 2006).

The main factors that influence the electrical characteristics of a panel are the light intensity and the temperature of the cells. The current generated in the modules increases linearly with increasing light intensity. On the other hand, the temperature rise in the cell causes module efficiency drops, thus lowering the operating points for maximum power output.

Current-voltage curves are shown in "Fig. (3)" for a module operating at a fixed temperature and at several radiation levels. The maximum power points are also indicated. For this module, the short circuit current increases proportionally to the solar radiation, while the open circuit voltage increases logarithmically. For this module, up to nearby 15 V, the current is almost proportional to the incident radiation.

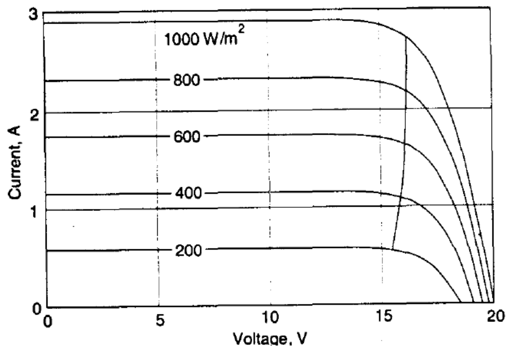

Figure 3. The I-V curves for a PV generator at several radiation levels. (Duffie and Beckman, 2006).

Due to the low voltage and current outputs from a photovoltaic cell, the cells are grouped into modules named solar panels. The individual modules may have cells connected in series and parallel to obtain the desired voltage and current. Arrays of solar panels are frequently arranged in series and parallel to match the suitable design condition. For identical modules or cells connected in series, voltages are additive, and when connected in parallel the currents are additive. If the cells or modules are not identical, a more complex analysis is required.

2.4 Photovoltaic system output prediction

The monthly average hourly array electricity output $\bar{E}_i$ for the hour i can be found using the "Eq. (16)":

$$\bar{E}_i = A_C \bar{I}_T \bar{\eta}_i \tag{16}$$

Where A_C is the photovoltaic array area and $\bar{\eta}_i$ is the monthly average array efficiency for the hour i, calculated by "Eq. (17)": (Haberl, 2004).

$$\eta\bar{\eta}_i = \bar{\eta}_{mp,ref}\, \bar{\eta}_e \left[1 + \frac{\mu_{mp}}{n_{mp,ref}}\left(\bar{T}_{a,i} - T_{ref}\right) + \frac{\mu_{mp}\, \bar{I}_T}{n_{mp,ref}}\, \frac{\tau\alpha}{U_L}\left(1 - n_{mp,ref}\right) Z_i\right] \tag{17}$$

where

$n_{mp,ref}$ = maximum power point efficiency from measurement at reference condition,
$\bar{\eta}_e$ = effciency of any power conditioning equipment,
μ_{mp} = temperature coefficient at the maximum power point efficiency measurement,
$\bar{T}_{a,i}$ = averange ambient temperature for the hour i (°F),
T_{ref} = temperature from measurement at reference condition (°F),
τ = transmittance,
α = absorptance,
U_L = collector overall heat loss coefficient, and
Z_i = $\frac{1}{N\bar{I}_T{}^2}\sum_{n=1}^{N} \bar{I}_{T,n}{}^2$ (where N = number of days), which can be expressed empirically as.

$$Z_i = \left(\frac{\bar{I}_0}{\bar{I}_T}\right)^2 (a_1 b_1 + a_2 b_2 + a_3 b_3) \tag{18}$$

where

$a_1 = R_b^2 + \rho(1 - \cos\beta)R_b + \rho^2(1 - \cos\beta)^2 / 4$
$a_2 = R_b(1 + \cos\beta - 2R_b) + \rho\,(1 + \cos\beta - 2R_b)\ (1 - \cos\beta) / 2$
$a_3 = [(1 - \cos\beta)/2 - R_b]^2$
$b_1 = -0{,}1551 + 0{,}9226\bar{k}_T$
$b_2 = -0{,}1456 + 0{,}0544 \ln \bar{k}_T$
$b_3 = -0{,}1551 + 0{,}9226\bar{k}_T$

Values for the commercial solar panel parameters of “Eq. (16)” are obtained from the official tests within the Brazilian Labeling Program, and when unavailable, from the product manual.

3. DEVELOPMENT SOFTWARE

“Figure 4” is shown the Entity-Relationship (ER) model for the proposed system. The ER model (Chen, 1976) provides a graphical abstraction for a relational database construction, which includes all major concepts (entities) of the solution modeled and how they are related with each other (relationships). This model is platform-independent since it considers system’s basics requisites before the effective implementation of the database and it is an important step in database development (Elmasri and Navathe, 2005).

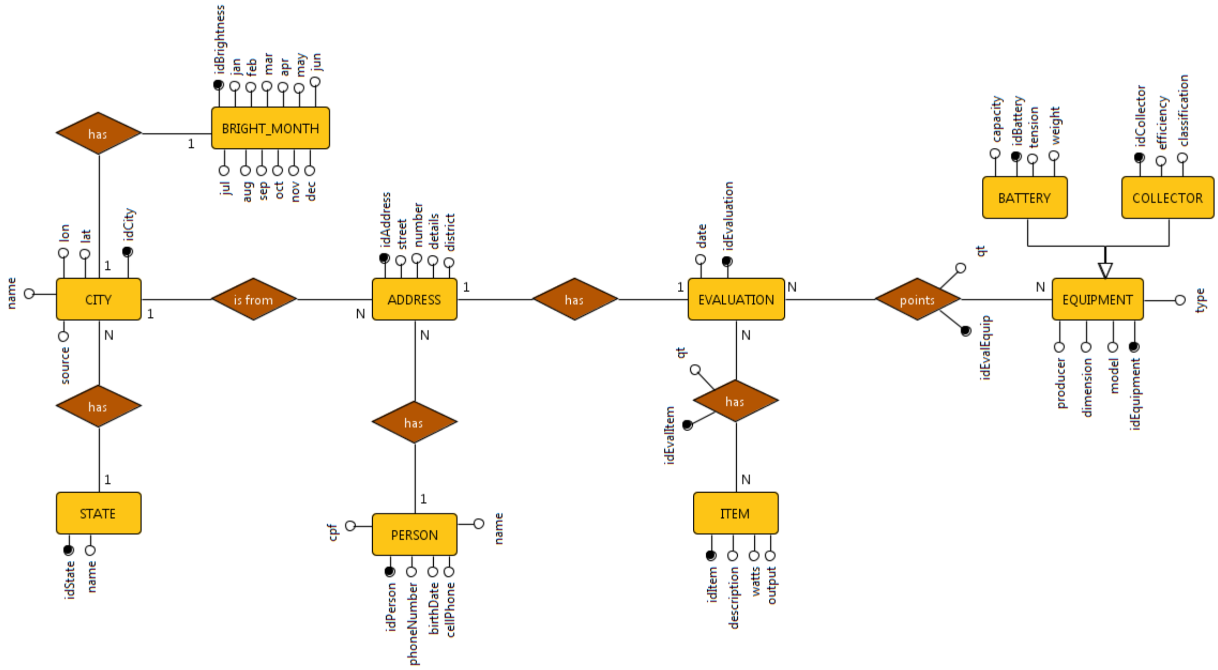

Figure 4. Entity-Relationship (ER) model.

In the model of the proposed system, a person can have one or more address registered in the system’s database and the address has an associated city with a brightness indicator for every month in a year. Therefore, for every address, it is possible to realize only one evaluation, which is composed of electronic and domestic appliances. These items are used to calculate the total potency of the evaluated household. So, the evaluation will point what kind of equipment should be used in the person’s residence based on the city location and brightness. The equipment could be of two types: battery, for the energy storage; and the collector for energy capitation.

After the database has been modeled it is possible to generate the database structure using a server side language named Structured Query Language (SQL), which is specific for database creation. It was used the GenDBM Tool (Guinelli et. al, 2015) for ER modeling and SQL code generation; and the MySQL Server as Database Management System.

In the evaluation screen showed the necessary information to implement the photovoltaic system and water heating as “Fig. (5)”. Starting the user's choice in a previous screen after this screen customers enter the location where the photovoltaic plant will be installed, the system queries the tables in the location database thus seeking their longitude and latitude and then calculates based on formulas quoted in the article items their variables for both heating water as solar power generation.

The program focuses only stand alone photovoltaic systems, i.e., systems not connected to the electrical grid, with appliance power consumption and other electrical load data inserted by the user. It checks if the photovoltaic system is able for attaining the electrical load, and if not, it returns the monthly power fraction that will be supplied by the photovoltaic system. The program also conducts economic analysis using classic parameters as net present value, discounted return and internal rate of return.

The program was validated through examples from the book of Duffie & Beckman (2006) and also by comparison with the results generated by a commercial PV-f-Chart program, and obtained good agreement.

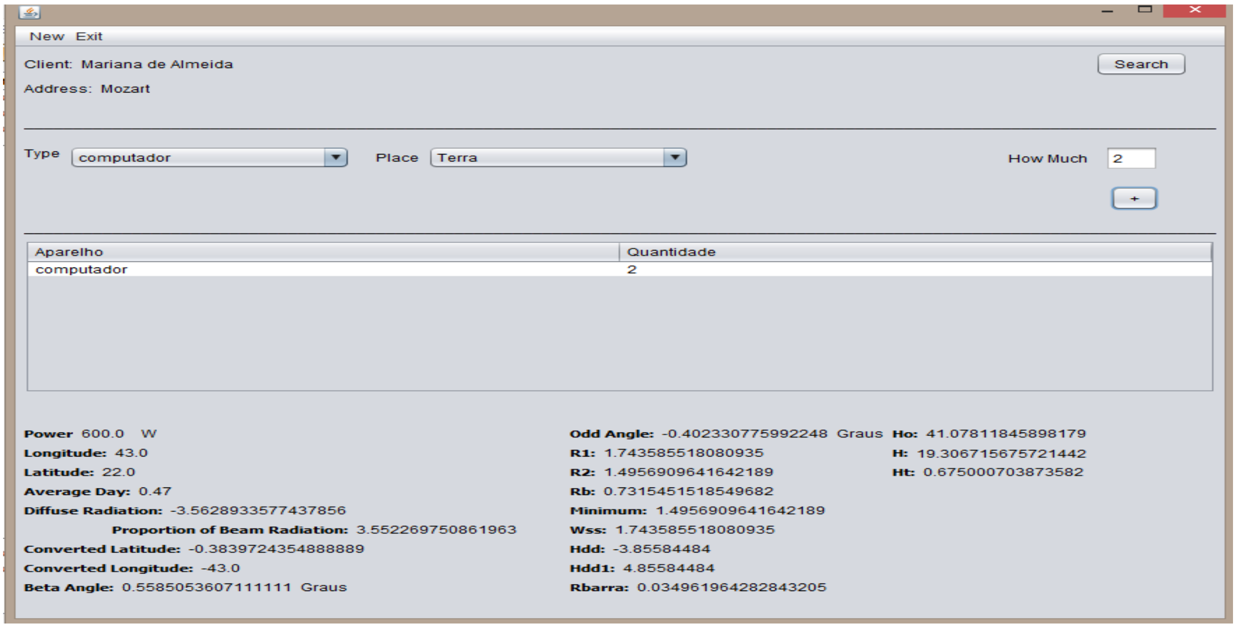

Figure 5. Calculation Screen.

4. CONCLUSION

Thermal and photovoltaic solar system designs face the same problem: investment costs dominate life cycle cost and overdesign must be avoided.

The software presented here is suitable for Brazilian designers because it uses meteorological data from the Brazilian Solar Atlas and performance data published by the Brazilian Labeling Program.

The authors expect that this software contributes directly for solar energy penetration and indirectly for the establishment of public policies for incentive to photovoltaic and thermal solar systems.

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