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THE RETSCREEN MODEL FOR ASSESSING POTENTIAL PV PROJECTS

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ABSTRACT

The RETScreen® software was developed to assist in the preliminary assessment of potential renewable energy projects. First released for on-grid applications, the RETScreen PV model was recently upgraded to cover off-grid applications. These include stand-alone, hybrid and water pumping systems. The program guides the users in the design of their systems, by providing initial estimates of array, battery, or pump size. By changing a few of the system's parameters, users are able to quickly screen the most effective technology and system size depending on load, climatic conditions, and season of use. This paper describes various models (radiation, array, battery, whole system) used to predict energy production from PV systems, given climatic variables and system parameters.

INTRODUCTION

RETScreen® International is an innovative and unique renewable energy awareness, decision-support and capacity-building tool developed by Natural Resources Canada's CEDRL with the contribution of 85 experts from industry, government and academia. Collaborating organizations include the United Nations Environment Programme (UNEP) and the National Aeronautics & Space Administration (NASA). RETScreen is provided free-of-charge to users around the world [1].

The core of the tool consists of a standardised and integrated renewable energy project analysis software that can be used worldwide to evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of renewable energy technologies (RETs), including photovoltaics. The software consists of easy-to-use Microsoft® Excel spreadsheets. In addition to the software, the tool includes: product, weather and cost databases; an online manual; a website; project case studies; and a training course. RETScreen provides a common platform for evaluating project proposals while significantly reducing the costs associated with preparing preliminary feasibility studies. In addition, the tool is ideal for educational and industry/market development purposes.

First released in 1998 for on-grid applications, the RETScreen PV model was recently upgraded to also cover off-grid PV applications. These include stand-alone, hybrid and water pumping systems. This paper details the various models used to calculate, on a month-by-month basis, the energy production of PV systems in RETScreen. They include a new model to compute solar radiation in the plane of the PV array, given monthly mean daily solar radiation on a horizontal surface; a model to calculate PV array efficiency given ambient temperature and available solar radiation; a simplified battery model taking into account variations of battery efficiency with temperature and rate of charge; and finally models making use of the concept of utilizability, as well as models developed from simulations, to evaluate the interaction of the various components of the system and predict how much energy (or water, in the case of a pumping system) can be expected from the system on an annual basis.

SOLAR RADIATION MODEL

The output of PV systems depends strongly on the average daily solar radiation incident upon the array, which in turn depends on its orientation and tilt. However, values of solar radiation are most often reported for horizontal surfaces (this is also true for the values provided by the on-line weather database of RETScreen), therefore converting monthly average horizontal radiation values to their plane-of-array equivalent is the first task faced by the program.

The problem is not new and has been treated by several authors (see [2]). However the situation is made more challenging in RETScreen due to the fact that both fixed and tracking configurations are considered. For that reason a new algorithm inspired by the work of Klein and Theilacker [2] was developed. The algorithm can be described as a succession of three basic steps:

1. Calculate hourly direct irradiance and diffuse irradiance on an horizontal surface for all hours of an 'average day' having the same daily global irradiance as the monthly average. This is achieved through the use of classical formulae first derived by Erbs, Collares-Pereira and Rabl, and Liu and Jordan (all described in [2]).

2. Calculate hourly values of global irradiance on the tilted (or tracking) surface for all hours of the day. This is done with a simple isotropic model. For tracking surfaces (one-

axis, two-axis or azimuth) the tracking angles are determined with the formulae of Braun and Mitchell [3].

3. Sum the above to obtain the average daily irradiance in the plane of the PV array (note that the sum is not calculated analytically, as was done in the original work of Klein and Theilacker, because this proves unpractical for tracking surfaces).

Despite its relative simplicity, the above algorithm works well when compared to full hourly simulations. Tests for various fixed and tracking surfaces and for sites ranging from the equator to the Canadian arctic revealed that the accuracy of the algorithm is below 4 % (in an RMS sense) for equator-facing surfaces tilted with an angle equal to the latitude, and below 7 % for tracking surfaces. For vertical east- and west-facing surfaces the RMS error may be as high as 9 %. Even then, the accuracy of the algorithm is considered to be sufficient for preliminary feasibility studies. Given that the model only requires the user to input 12 monthly data, as opposed to 8,760 for hourly simulations, the small reduction in accuracy is more than compensated for due to its ease-of-use and cost savings for the PV industry.

ARRAY MODEL

The PV array model is based on work by Evans [4] and is common to all types of PV systems represented in RETScreen. The array is characterized by its efficiency, η_p, which is a function of its nominal efficiency, η_r, measured at a reference temperature $T_r = 25\,\mathrm{C}$:

$$\eta_p = \eta_r \left[1 - \beta\left(T_c - T_r\right)\right] \tag{1}$$

where β is the temperature coefficient for module efficiency and T_c is the module temperature. T_c is related to the mean monthly ambient temperature T_a through Evans' formula [4]:

$$T_c - T_a = \left(219 + 832\,K_t\right)\frac{NOCT - 20}{800} \tag{2}$$

where K_t is the clearness index. $NOCT$ is the Nominal Operating Cell Temperature, which is characteristic of the type of module under consideration. Equation (2) is valid for optimally tilted arrays facing the equator. In other configurations a small correction is applied, depending on the actual tilt of the array, as described in [4]. The same correction is applied in the case of tracking surfaces, using the tilt angle at noon as the actual tilt angle.

The array efficiency calculated by Equ. 1 has to be reduced by two factors. The first one, λ_p, represents miscellaneous array losses such as losses due to dirt or snow covering the modules. The second, λ_c, represents various power conditioning losses such as those due to DC to DC converters or step-up transformers. The array power available to the load and the battery, E_A, is therefore:

$$E_A = H_t\,\eta_p\left(1 - \lambda_p\right)\left(1 - \lambda_c\right) \tag{3}$$

where H_t is the solar radiation incident upon the array.

MODEL FOR ON-GRID SYSTEMS

The grid-connected model is the simplest system model. The energy available to the grid is what is produced by the array, reduced by inverter losses:

$$E_{grid} = E_A\,\eta_{inv} \tag{4}$$

where η_{inv} is the inverter efficiency. Depending on the grid configuration not all this energy may be absorbed by the grid. The energy actually delivered E_{dlvd} is:

$$E_{dlvd} = E_{grid}\,\eta_{abs} \tag{5}$$

where η_{abs} is the PV energy absorption rate, equal to 1 for large grids, and ranging between 0.95 and 0.98 for small grids.

MODEL FOR OFF-GRID SYSTEMS

The off-grid model represents stand-alone systems with a battery backup, with or without an additional genset. The conceptual framework of the model is shown in Fig. 1. Energy from the PV array is either used directly by the load, or goes through the battery before being delivered to the load. The remainder of the load is provided by the genset if there is one, that is, stand-alone and hybrid systems differ only by the presence of a genset that supplies the part of the load not met directly or indirectly by photovoltaics.

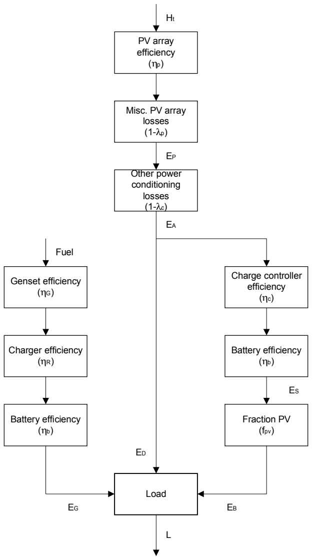

Fig. 1 – RETScreen model for off-grid systems

Load

The user specifies the total DC demand, D_{DC}, and the total AC demand, D_{AC}. This latter is converted to a DC equivalent by dividing it by the average inverter efficiency η_{inv}. Hence the total equivalent DC demand $D_{DC,equ}$ is:

$$D_{DC,equ} = D_{DC} + \frac{D_{AC}}{\eta_{inv}} \tag{6}$$

RETScreen pays great attention to the correlation between load and solar resource. The equivalent DC demand is broken down into:

$$D_{DC,equ} = D_{match} + D_{cont} + D_{bat} \tag{7}$$

where D_{match} is the part of the demand that is met directly by the PV modules only when there is enough energy produced (e.g. fan directly coupled to the PV module); D_{cont} is the part of the demand that is constant throughout the day (e.g. cathodic protection, monitoring system); and D_{bat} is the part of the demand that will be met primarily by the battery (e.g. night-time loads, or daytime intermittent loads such as a refrigerator).

Continuous and matched demand

The continuous demand D_{cont} is met either directly by the PV modules (during the day when there is enough sunshine) or through the battery (at night, or when there is not enough sunshine). The fraction of monthly radiation that falls above a certain level needed to meet the continuous load is called the *monthly average daily utilizability* $\bar{\phi}$. The concept of utilizability has been long used to estimate the performance of active solar systems, and $\bar{\phi}$ can readily be estimated from the monthly average clearness index and the continuous load (although the algorithm is too complicated to fit in the space allocated to this paper; see [2] for details). The energy delivered directly to the continuous load is simply:

$$E_{cont} = \left(1 - \bar{\phi}\right) E_A \tag{8}$$

while the energy delivered to the matched load is:

$$E_{match} = \min\left(D_{match}, E_A - E_{cont}\right) \tag{9}$$

The energy delivered directly to the load is therefore:

$$E_D = E_{cont} + E_{match} \tag{10}$$

and the energy delivered to the battery is:

$$E_A - E_D \tag{11}$$

Demand met primarily through the battery

The fraction of the load that a system with battery backup will provide depends on the size of the array and the battery, relative to the load. An estimate of this fraction was obtained from correlations derived from simulations. Using WATSUN-PV, an hourly simulation program for photovoltaic systems [5], a number of simulations were run for a dummy stand-alone system with night-only load, with weather data from six locations corresponding to a variety of climates (Toronto, Vancouver, Edmonton, Phoenix, Miami, Denver). Various array sizes were used and the battery capacity was varied from one to six days of storage.

Figure 2 shows in graphical form the output of the simulations providing, on a monthly basis, the fraction of the load met by the PV system, f_{PV}, given the storage/load ratio SLR and the array/load ratio ALR. ALR and SLR are defined as:

$$ALR = E'_A / L' \tag{12}$$

$$SLR = Q_U / L' \tag{13}$$

where L' is the part of the load *not* met directly by the PV system:

$$L' = L - E_D \tag{14}$$

and E'_A is the available array output reduced by the energy delivered directly to the load, and then by the charge controller efficiency η_c and battery efficiency η_b:

$$E'_A = \left(E_A - E_D\right)\eta_c \eta_b \tag{15}$$

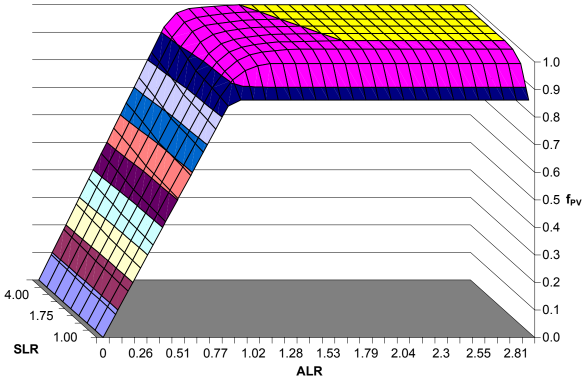

Fig. 2 – Fraction of load supplied by PV, given the array/load and storage/load ratios.

The usable battery capacity Q_U is related to the nominal capacity Q_B:

$$Q_U = f_B Q_B \tag{16}$$

where f_B is a factor dependent on battery temperature T_B and discharge rate r, as shown in Figure 3. Battery temperature is set by the user either to a fixed value or to ambient. The discharge rate is taken as $24n$ where n is the number of days of autonomy.

A tabulated version of the surface of Figure 2 is incorporated into RETScreen, and the demand met through the battery is given by:

$$E_B = f_{PV}\left(L - E_D\right) \tag{17}$$

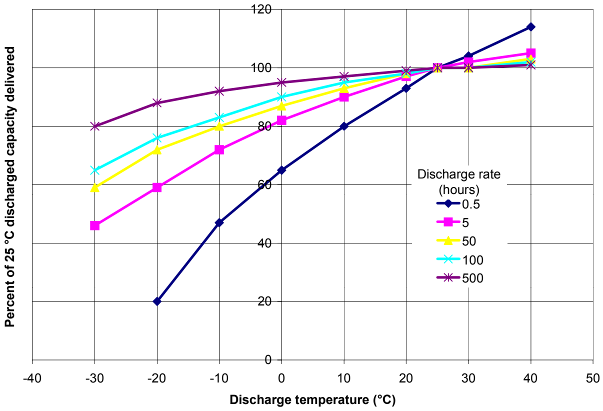

Fig. 3 – Usable battery capacity as a function of discharge rate and temperature (derived from [6]).

Demand met by the genset

The energy delivered by the genset, E_G, is simply the difference between the load and what can be provided by the PV array, either directly or through the battery:

$$E_G = L - E_D - E_B \tag{18}$$

Energy delivered

Energy delivered to the load is the sum of the demands met by the batteries, by the genset, and directly by the array:

$$E_{dlvd} = E_D + E_B + E_G \tag{19}$$

MODEL FOR WATER-PUMPING SYSTEMS

The water pumping model is based on simple equations found in [7]. Given a required daily volume of water Q (in m^3/d) that has to be lifted to a height h (in m), the daily hydraulic energy demand E_{hydr} (in J) is:

$$E_{hydr} = 86400\,\rho\, g\, Q\, h\left(1 + \eta_f\right) \tag{20}$$

where g is the acceleration of gravity (9.81 m s^{-2}), ρ the density of water (1000 kg m^{-3}), and η_f is a factor accounting for friction losses in the piping. Given the pump system efficiency η_{pump}, this hydraulic energy translates into an electrical energy requirement E_{pump}:

$$E_{pump} = \frac{E_{hydr}}{\eta_{pump}} \tag{21}$$

Energy delivered is simply:

$$E_{dlvd} = \eta_{pump} \min\left(E_{pump}, E_A\right) \tag{22}$$

where E_A is the energy available from the array.

CONCLUSION

The models described in this paper provide a set of equations that lend themselves well to an efficient spreadsheet implementation. The incorporation of these models into RETScreen makes it possible to compare quickly the benefits of solar photovoltaic systems to those of conventional energy sources. The models go into enough detail that meaningful physical phenomena are taken into account, while at the same time retaining enough simplicity to minimize data input requirements for users. The small reduction in accuracy due to the use of monthly data, rather than hourly data used in most other PV simulation models, is more than compensated for due to its ease-of-use and cost savings for the PV industry. The accuracy of the new RETScreen PV model is considered to be sufficient for preliminary feasibility studies.

REFERENCES

[1] Leng G et al., *RETScreen® Renewable Energy Project Analysis Software*. Available free-of-charge from NRCan/CEDRL at http://retscreen.gc.ca

[2] Duffie J and Beckman W, *Solar Engineering of Thermal Processes*, 2nd edition (1991). John Wiley & Sons.

[3] Braun JE and Mitchell JC, Solar Geometry for fixed and Tracking Surfaces. *Solar Energy* **31**,5 (1983) 439-444.

[4] Evans DL, Simplified method for predicting photovoltaic array output. *Solar Energy* **27**,6 (1981) 555-560.

[5] WATSUN-PV 6.1, Department of Systems Design Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1.

[6] CANMET (1991). *Photovoltaic systems design manual*. Natural Resources Canada, CANMET, 580 Booth Street, Ottawa, Ontario, Canada K1A 0E4.

[7] Royer J, Djiako T, Schiller E, and Sy BS, *Le pompage photovoltaïque: manuel de cours a l'intention des ingénieurs et des techniciens* (1998). Institut de l'Énergie des Pays ayant en commun l'usage du Français, 56, rue Saint-Pierre, 3^e étage, Québec, QC, Canada G1K 4A1.