Evaluation of Photovoltaic Generation Systems for Residential Users in Santa Fe (Argentina)

Emmanuel Sangoi[1,2], Ulises Manassero[1], Jorge R. Vega[1,2]
[1] Control and Electrical Security Group (CySE)
[2] Institute of Technological Development for the Chemical Industry (INTEC)
Department of Electrical Engineering, Santa Fe Regional Faculty (FRSF)
National Technological University (UTN)
Santa Fe, Argentina
esangoi@frsf.utn.edu.ar; ulisesmanassero@hotmail.com; jrvega@frsf.utn.edu.ar

***Abstract*—The mathematical model of a single photovoltaic cell is used to built a numerical simulator of a residential solar generator. For the city of Santa Fe (Argentina), the following is analyzed: i) weather information on solar irradiances and ambient temperatures collected along the years 2008-2014; ii) the effect of the orientation assigned to the solar panels; and iii) the average household electricity consumption. It is proven that the annual energy uptake is maximized with an optimal panel inclination angle of 27°. Then, two solar generation systems suitable for residential users are proposed. The possibility of providing surplus electricity to the local distribution network under a net balance policy is analyzed. The results indicate that an installed capacity of 1,290 W (9 m^2 of panels) can cover around 60% of the household annual electricity consumption. Moreover, the total energy coverage is achieved with an installed power of 2,150 W (15 m^2 of panels).**

***Index Terms*—Distributed Power Generation, Photovoltaic Systems, Net Balance**

I. Introduction

In the last years, several research lines and technological solutions have been proposed with the aim of mitigating the current energy crisis worldwide. However, electricity generated from renewable energy sources is still small in comparison to that obtained from fossil fuels. For example, in Argentina, the total installed capacity for electricity generation reached 31,072 MW in 2013, with the following approximate distribution: 60% corresponds to thermal generation, 36% to hydroelectric plants, 3.2% to nuclear power plants, 0.53% to wind farms, and 0.26% to photovoltaic power plants [1]. Similarly, the electricity generated from fossil fuels has reached a share of 64% in the energy matrix, thus generating a high dependence on these fuels and consequently a significant environmental impact. By the end of 2013, the total energy generated from renewable sources in Argentina was only 1.23% [1], yet away from the target value of 8% that was established by the national government to be reached by the year 2016 [2].

In Argentina, the residential sectors currently consume around 40% of the total electricity demand [1]. In particular, the residential consumption in the city of Santa Fe (Argentina) reaches around 42%, while the commercial sector participates with approximately 15% [3].

A large imbalance between costs and selling prices of electricity is currently present in Argentina. This gap has emerged around a decade ago and was then confirmed by policies of relatively fix prices in the electricity tariffs perceived by the end users. In this regard, the reduction and / or removing of electricity subsidies are envisaged as inevitable in the short term, and therefore it is expected that users should have to implement strong energy saving strategies in the medium term [4].

Undoubtedly, power transmission and distribution grids are in a transition period across the world. The gradual integration of distributed energy resources into the existing power systems will move the electrical networks to take a more active role. In general, electrical power systems are progressively evolving towards more flexible networks, which involve new concepts such as renewable distributed generation, microgrids, and smart grids [5].

Since 2008, the state company ENARSA (Argentine Energy public limited company) has begun installing medium-scale distributed generation systems, with powers in the order of 5-40 MW [6], with a strong preponderance of diesel-based generation, and with a rather poor participation of renewable sources. Unfortunately, diesel engines have low efficiencies and contribute significantly to environmental pollution.

Several countries have already implemented low-scale photovoltaic (PV) distributed generation with net balance strategies [7, 8, 9]. The PV generation promotes the need for changes in consumption habits of users, promises a viable alternative to mitigate the energy crisis, boosts the integration of renewable energies in the generation matrix, and mitigates the environmental impact of electricity production [10, 11]. Previous research works have defined a solar atlas for Argentina [12], where the whole Santa Fe province appears to be well positioned to the potential use of the solar resource.

On the other hand, net balance strategies are not legally regulated in Argentina. In spite of that, some electricity distribution companies are making significant progress for determining new legal rules [13].

In this work, the mathematical model of a low-power PV cell is firstly implemented; and then, it is used to develop the model of a solar PV generator. Such model is used to predict the power generation capacity of a typical house in the city of Santa Fe (Argentina). Electric energy consumptions of some residential users are monitored to infer typical patterns of the electricity demand. Also, it is assumed that the simulated PV systems interact with the electrical network under a net balance policy. The technical feasibility of covering the home electricity demand with the proposed solar generator is investigated.

II. Photovoltaic Simulator

A. Basic Photovoltaic Model

The behavior of a polycrystalline solar cell is described on the basis of the "double diode model" [5] (Figure 1). This model considers the elementary PV cell as the parallel combination of an ideal current source, a shunt resistor, and two semiconductor diodes. In turn, these four elements are connected in series with a resistor.

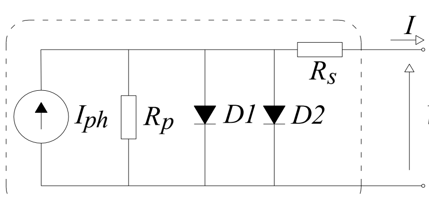

Figure 1. Equivalent electrical circuit of a polycrystalline solar cell: the "double diode model".

The relationship between the voltage V and current I in the cell terminals is given by:

$$I = I_{ph} - I_{s1}\left[e^{\frac{V+I R_s}{v_t}} - 1\right] - I_{s2}\left[e^{\frac{V+I R_s}{A v_t}}\right] - \frac{V + I R_s}{R_p} \quad (1)$$

where I_{ph} is the electric intensity generated by photoelectric effect in the cell, which in turn depends on the solar irradiance level; I_{s1} and I_{s2} are the saturation currents corresponding to diodes D1 and D2, respectively, which additionally depend on the cell temperatures; A is a diode parameter that is usually set to 2 [7]; v_t ($= k\,T/e$) is the equivalent thermal voltage of each diode, being k the Boltzmann' constant, T the absolute ambient temperature (in °K), and e the electronic charge. The resistor R_p simulates the leakage current of the cell, while the resistor R_s simulates the effect of the different internal contact resistances, which generate voltage drops that depend on the generated current.

The model parameters I_{ph}, I_{s1}, I_{s2}, R_s, and R_p can vary according to both the solar irradiance (E) and ambient temperature (T). Values for these parameters are calculated on the basis of empirical mathematical relationships, in turn obtained from experiments carried out with polycrystalline cells [5].

The mathematical model of a solar panel was developed on the basis of the previously-described single PV cell. To this effect, different series/parallel configurations of cells were associated to achieve a sought solar generator of predetermined nominal values of voltage and power.

The different characteristic curves of the panel can be simulated under E and T variations. To this effect, the values of the peak power and the voltage at the peak power (always referred to standard test conditions of 1,000 W/m^2 and 25 °C) were used. These curves were compared with those provided by the panel manufacturers. The mathematical model of the PV panel was then validated by comparing its results with those described in the technical reports of 20 polycrystalline panels available on the market, with electric power outputs that range from 135 Wp to 255 Wp.

The set of PV panels is assumed to be connected to the electric network through a dc/ac inverter. The effect of the inverter on the output of the panels was modeled according to the MPPT (Maximum Power Point Tracker) criterion. The performance variation of the inverter according to its charging status was also taken into account. Furthermore, the developed model considers: i) a unity power factor (as required by the technical regulation [13]), and ii) a full consumption of all the generated electricity (i.e, the generated electricity is either consumed by the user and/or injected into the network). The mathematical model was implemented in the Matlab (MathWorks, Inc.) software.

B. Meteorological Information

The Meteorological Information Center (CIM) belongs to the National University of the Litoral (Santa Fe, Argentina), and provided us with values of both *E* and *T* collected in the city of Santa Fe along 7 consecutive years (period 2008-2014). The *T* and *E* data were recorded each 60 minutes and 10 minutes, respectively. Particularly, the *E* values were measured on a horizontal plane.

First, both *E* and *T* data were statistically processed to analyze their average values and expected variability. More specifically, for a given hour of a given day, the averages $\{\overline{E}, \overline{T}\}$ and the standard deviations $\{\sigma_E, \sigma_T\}$ of *E* and *T*, respectively, were determined from their corresponding data collected along the 7 years. Then, a "base year" of *E* and *T* was built from (365 days × 24 hours/day =) 8,760 pairs of values $\{\overline{E}, \sigma_E\}$, plus 8,760 pairs of values $\{\overline{T}, \sigma_T\}$; with each pair corresponding to a given hour of a given day. Then, in all simulations of the PV generator, the information of the "base year" was used to produce a pair of random values {*E*, *T*} at each hour of a chosen day, which were used as the basic inputs to the simulator.

C. Influence of the panel orientation

All panels of the PV system were assumed to be placed at a common fixed orientation. The panel orientation was specified by two angles: the inclination angle (with respect to a horizontal plane) and the azimuth angle (with respect to the geographic north). Clearly, such orientation affects the energy uptake of the PV system. For every hour of a chosen day, the effective values of *E* (i.e., the irradiances perpendicularly received by the panels) were calculated according to the corresponding sun positions, which in turn depend on the geographical location of the solar panels. Thus, the *E* values of the "base year" were corrected according to the actual orientation of the panels (in practice, such orientation can be chosen by the user). These corrections were performed on the basis of the model presented in [14].

An optimum fixed inclination of the panels can be calculated. For example, in the present work the orientation was chosen to maximize the average solar energy collected along a year. Then, such orientation was used in all simulations. Alternatively, one might choose the panel orientation that maximizes the energy uptake during a given season. Moreover, along the time, a user could modify the panel orientation through a control strategy that maximizes the energy uptake along every hour of each day, or could alternatively prioritize the energy uptake for a given season [15]. However, these strategies were not considered in the present work.

D. Residential consumptions

Typical residential demands of electricity during some summer days were determined for Santa Fe city. To this effect, daily electricity consumptions were measured on three typical dwellings. Also, their annual electricity billings were analyzed to gain more information on their electric demand along a longer period (one year). The three analyzed dwellings have an average covered area of around 250 m^2, and all of them correspond to standard 5-member families.

Energy measurements were carried out along a few typical summer days; and the average consumption reached 20.8 kWh per day, which corresponds to an average power of around 867 W. In all cases, the peak demands were higher than 1.5 kW, and were detected between 4pm and 10pm. On the other hand, along 4 consecutive years, the average household electricity consumptions at each of the analyzed dwellings were 689.3 kWh, 611.9 kWh y 651.2 kWh each 2 months. Then, for further analyzes, the average household electricity consumption was adopted as 325.5 kWh per month.

E. The proposed photovoltaic systems

Precedents in residential PV installations as well as specifications established by the current regulations were taken into account for selecting the PV systems. According to the typical power consumption of residential users, the following single-phase PV systems were adopted: (i) a 1,290 W system (configured as 6 polycrystalline panels of 215 Wp each); and (ii) a 2,150 W system (configured as 10 polycrystalline panels of 215 Wp each). All panels were interconnected in series and then connected to a single phase inverter of 1,300 W or 2,100 W, respectively. The solar collector surfaces were 9 m^2 and 15 m^2, respectively.

III. RESULTS

The optimum inclination of the panels in the city of Santa Fe was determined on the basis of numerical simulations, with the aim of maximizing the average annual irradiation received by the panels. An azimuth angle of 0° was adopted (i.e., the panels were all oriented to true north). Figure 2 suggests an optimal tilt of 27°.

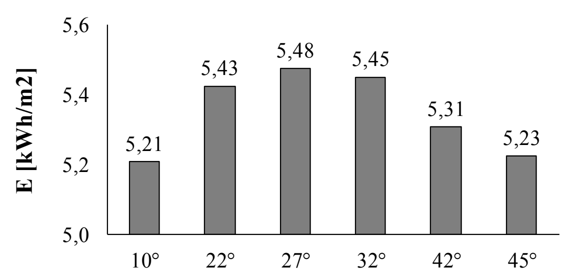

Figure 2. Average annual irradiation effectively collected by a 1 m^2 PV panel placed at different orientation angles (in Santa Fe, with azimuth = 0°).

Figure 3 shows the current-voltage characteristic curves of a panel of 240 Wp, which were obtained by numerical simulation of the model under different environmental conditions of E and T. Nominal values of the peak power and voltage are required as input data to the panel model (such data are typically reported in the technical datasheets).

The numerical simulations indicate that the 1,290 W system can provide an electrical energy of around 2,200 kWh a year (≈ 366 kWh bimonthly); while the 2,150 W system can provide around 3,700 kWh a year (≈ 616 kWh bimonthly). In this work, bimonthly analysis is adopted in accordance with the usual bimonthly billing for the electrical energy in Santa Fe.

For a hot summer day (January 22nd), Figure 4 compares the required and generated instantaneous active powers for one of the studied dwellings when using a PV generation system of 1,290 W. As it can be noticed, the chosen system could supply around 35.8% of the total energy consumption each day. An equivalent analysis with the PV system of 2,150 W indicates that it would be possible to cover up to 58% of the daily electricity demand.

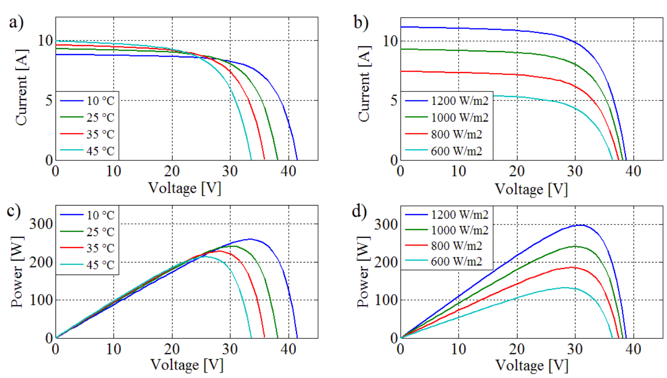

Figure 3. Characteristic curves for a polycristalline panel of 240 Wp according to the PV model at: (a, c) E = 1,000 W/m^2 and different ambient temperatures; (b, d) T = 25 °C and different irradiance levels.

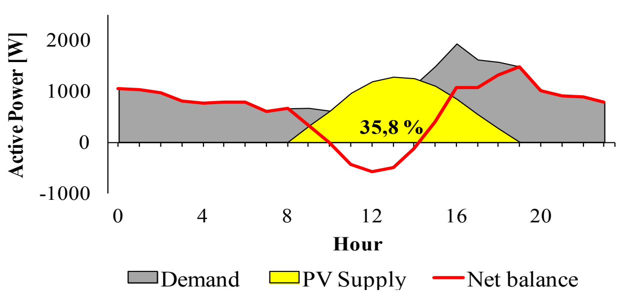

Figure 4. Comparison of required and produced instantaneous active powers for a typical dwelling when using a PV system of 1,290 W (results corresponding to January, 22nd.). The red curve represents the net balance.

The previously analyzed cases correspond to a particular day of high energy demand. Therefore, from the point of view of the energy balance, the situation could improve for other days, especially for winter days when the electricity demand is typically lower. In fact, the same analyzed home consumes around 3,670 kWh a year (≈ 612 kWh bimonthly). Then, the PV system of 1,290 W would be able to cover around 60% of the annual electricity consumption; and the net electric energy to buy to the external grid would be reduced from 3,670 kWh to 1,476 kWh. On the other hand, the PV system of 2,150 W would generate slightly over 100% of the annual consumption, and consequently a small amount of energy could additionally be exported to the external grid.

Figure 5 shows the bimonthly analysis for the same residential user. For example, the period November-December (months 11-12) provides the best energy ratio (79%) between the generated PV energy and the residential consumption. Months 5-6 belong to the winter season, and exhibit the lowest values of both electricity consumption and PV generation.

Figure 6 shows the estimated monthly energy that could be supplied to the network with a PV system of 1,290 W. The highest energy amount corresponds to March, while the lowest contribution occurs in June.

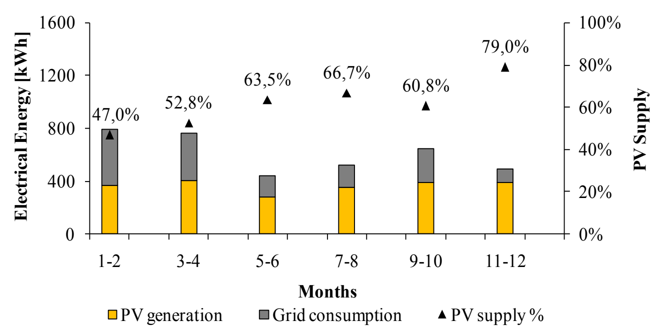

Figure 5. Energy balance for a residential user with an installed PV system of 1,290 W. (Triangles indicate the bimonthly fraction of the electric energy that could be covered with PV generation)

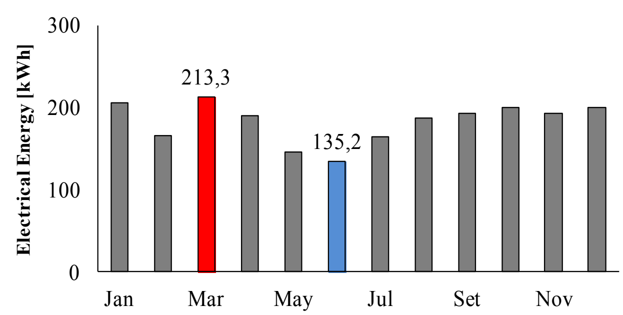

Figure 6. Electric energy that could be generated with a residential PV system of 1,290 W.

An average annual yield can be calculated as the ratio between the total generated energy and the total solar energy uptake. According to the present study, the average annual yield reaches 12.4% and 12.5% for the PV systems of 1,290 W and 2,150 W, respectively. These percentages are basically representative of the energetic efficiency of the PV panels.

IV. Conclusions

The present extension of the base model corresponding to a single photovoltaic cell was useful to describe the operation of a residential solar generator. The model parameters were adjusted to reproduce technical characteristics of solar panels available on the market. A wider generality of the present model was obtained by correcting the generated electric power according to the geographical location and inclination of the panels. The effective applicability of the model was achieved by using irradiance and temperature data specifically collected in Santa Fe city (Argentina) along 7 consecutive years.

From a technical point of view, the implementation of the proposed photovoltaic generation system under a net balance strategy is feasible for Santa Fe city, mainly in the positive context of its favorable meteorological conditions. While there is still no regulation governing the net balance, users are currently enabled by the local distributor of electricity to connect the photovoltaic system in parallel with the network, in order to either consume and/or supply electricity. It is recognized that the investment cost for a solar generation system is still high for a standard residential user, but in return its installation is simple and easily adaptable to particular housing conditions.

The comparison between total electricity consumption and generation capabilities suggests that a typical residential user, with a bimonthly consumption of about 600 kWh, could cover all his electricity demand by installing a PV system of 2,150 W. This will require an architectural integration of panels that could cover a surface of about 15 m^2 for an effective solar energy uptake. As additional positive aspects, a solar generator has almost negligible operation and maintenance costs, and an estimated 25-year useful life.

The proposed solar generator model can easily be extended to other geographic areas, but for achieving a reliable performance, appropriate records of solar irradiances and ambient temperatures are required. Also, this type of facilities would also be of possible interest for exploitation in malls or commercial centers, undoubtedly contributing to their energy savings. Finally, it should be stressed that any solar power system has the advantage of having virtually no negative environmental impact.

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