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Hydrogen vector for using PV energy obtained at Esperanza Base, Antarctica

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ABSTRACT

The use of solar photovoltaic (PV) is universally considered valuable for its renewable and clean nature; solar energy is especially important in regions far from urban centers and power distribution networks. It is known that the loss due to the latitude and the atmospheric layer is partially offset in very different annual distribution (i.e., by the long summer days) and in sparsely populated areas, because of the clearer atmosphere. Even with these assumptions, low temperatures (snow often combined with strong winds) and the effects of seasonality are difficult obstacles for the proper use of solar PV energy at high latitudes.

In this work, both analytical and experimental data of the solar resource at Esperanza Base, Antarctica, are presented. The PV modules were installed in a vertical configuration and NW–NE orientation, which not only maximizes performance but also mitigates the adverse effects due to the latitude. In order to overcome the very asymmetric annual irradiance distribution, the use of a system of hydrogen production and accumulation, is proposed for effective energy storage.

The results of two years of evaluation of PV potential at Esperanza Base show that duplicating the PV capture area in Esperanza allows to obtain the same total annual energy than the maximum acquired in Buenos Aires (PV module facing north with optimum tilt for solar capture).

To effectively overcome discontinuity of solar energy and its sharp drop in four of the twelve months of the year an appropriate hydrogen vector system is proposed and analyzed.

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Introduction

Autonomous power generation is a strategic matter for Argentina and other large and sparsely populated countries, where solar PV and wind energy associated to the hydrogen vector could play an important role for the country's development [1–4].

The use of solar photovoltaic (PV) energy is universally considered valuable for its renewable and clean nature [5], mainly in tropical and subtropical scenarios [4,6]; solar energy is especially important in regions far from urban centers and power distribution networks [7,8]. It is known that the loss due to the latitude and the atmospheric layer is partially offset in very different annual distribution (i.e., by the long summer days) and in sparsely populated areas, because of the clearer atmosphere [9–11]. Even with these assumptions, low temperatures (snow often combined with strong winds) and the effects of seasonality are difficult obstacles for the proper use of solar PV energy in some Antarctica bases and other high latitude locations such as south Patagonia [12,13].

Argentina has over 100 years of continuous presence in Antarctica. As a signatory to the Antarctic Treaty, our country is firmly committed to the advancement of scientific research and environmental preservation in the white continent [14]. In that sense, the use of large amounts of fossil fuel is not only a factor of contamination but is also associated with economic and safety factors associated with its transfer from the mainland [15].

Recent works try to integrate the use of cleaner forms of energy with fossil fuels, tending to their complete elimination [16,17]. Many works have been devoted to this goal for high latitudes; among them, Tin et al. conducted a thorough study of energy efficiency and use of renewable energy in the "coldest, darkest and remote continent of the world" [15]. Recently, Malavazi de Christo et al. published the design and analysis of a hybrid energy system for a Brazilian Antarctic Station [18].

It is a fact that one of the most important problems in the photovoltaic capture at high latitudes is the accumulation of snow or ice: a part of the solar energy must first be used to melt the barrier; after that, only a small fraction of the energy is captured and used. Thus, the discontinuities in the direct sun and frequent snowfalls – even in summer – suggest that it may be interesting to have a facility that prevents the formation of this barrier [19].

The use of vertical installations is supported by the fact that the higher is the latitude, the lower is the solar altitude; in many cases an extra gain due to albedo can be obtained [20]. In addition, the sun path covers a much wider angle between spring and autumn, so any static installation loses access to much of the available resource. Considering the low temperatures and strong Antarctic winds, photovoltaic systems installed directly on housing, laboratories or autonomous stations have practically solved the problem of installation and anchoring [21].

Taking advantage of the orientation of the houses in Esperanza, in this paper we use vertical wall installations with two directions: northeast (NE) and northwest (NW). Thus, not only the crucial problem of accumulation of snow and ice is resolved, but also the largest solar energy available is captured and, perhaps more importantly, the time of year of use of the resource is extended.

On the other hand, hydrogen appears to be the vector suitable for storage and use of clean forms of energy [22,23]. Negrou et al. [24] published an interesting work on the evaluation and development of hydrogen production from solar photovoltaic energy in Algeria. In reference to the application of PV-hydrogen in high latitudes, Ghosh et al. [25] have published a work with the results of ten years of operation of a system that uses solar energy and hydrogen fuel cells in Jülich (Germany). Ulleberg et al. [26] evaluated a wind-hydrogen energy system at Utsira (Norway): wind energy is used to produce hydrogen from a PEM-electrolyzer; the pressurized hydrogen is then used in engines as well as in fuel cells.

Since 2007 our research group is testing at Esperanza Base (Antarctica, 63°24′S 56°59′W) a fuel cell stack manufactured with Argentine technology. This allowed us to gain experience on its performance under extreme climate conditions and on its operation by inexperienced personnel working in this permanent Antarctic Argentine Station (60–90 people live annually, distributed in fifteen houses, the command, dormitories, two labs, restaurant, museum and maintenance buildings).

Recently, Aprea [27] relates a two year experience of obtaining hydrogen also at Esperanza Base, which is an interesting starting point for the use of hydrogen to medium power scale in Antarctica.

In this work, both analytical and experimental data of the solar resource at Esperanza Base are presented. The PV modules were installed in such a vertical NE–NW configuration that maximizes performance while mitigates the adverse effects due to the latitude. The use of a hydrogen vector system in order to overcome the disadvantages in the accumulation of energy at low temperature is also proposed and analyzed in one of several possible scenarios according to the annual operative campaigns at Esperanza Base.

Calculation section

Daily maximum energy obtainable for different orientations is calculated by integration of the corresponding irradiances, for a series of characteristic days (the 21st day of each month) was chosen for the purpose of being in the environment of the equinoxes (March, September) and solstices (July, December).

The suitable orientations for the PV modules were chosen based on the possible location of solar panels in a typical house at Esperanza Base: Northeast wall (NEW, 90°), Northwest wall (NWW, 90°). Both were compared to typical orientations: surface perpendicular to Sun's rays (PSR), and horizontal (H). A third possible installation, northeast roof (NER, 25°) was included for evaluating the possible extra gain in summer.

The solar position at every moment was calculated following the method proposed by Meeus [28]. To calculate the influence of the atmospheric mass above ground-level irradiance, formulas used by Gueymard, Young and Gansler were applied [9,11,29]. The angle of incidence was determined by the scalar product of the unit vectors, which determine the

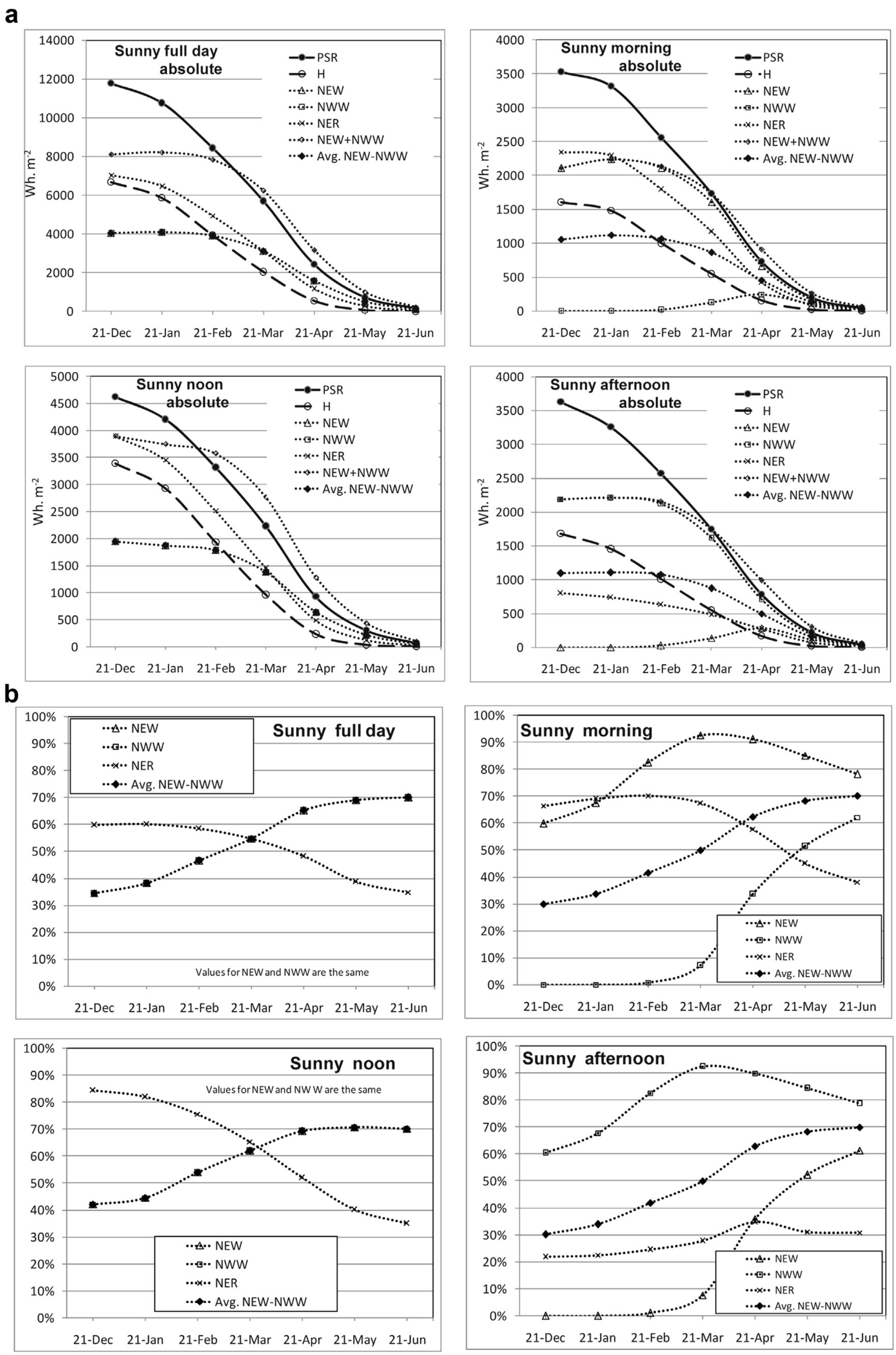

Fig. 1 — Daily energies in Esperanza calculated for the proposed orientations, in connection with the incident energy on PSR and H surface. a. Total solar energy calculated for characteristic days and orientations at Esperanza Base. b. Energy for the proposed orientations as a percentage of the total theoretically available.

direction of the radiation at each moment and the normal to each surface [30]. From these data, the normal irradiance on the Earth's surface is evaluated; then effective irradiance on each surface orientation is calculated. The ideal total energy obtainable in typical days for each orientation was then calculated. A segmentation of the day was also held in three equal periods of time (morning, noon and afternoon) to get and approximation of the effect of clouds on the affordable energy (Fig. 1). For clarity, the period Dec-21/Jun-21 is only displayed. Naturally, there is correspondence between the calculated values for the 21st day of the months January and November, February and October, March and September, April and August, May and July.

The total energy obtained by integrating the incident power on the proposed configurations and days is shown in Fig. 1a. The total solar energy incident on a PSR and H surfaces are included for reference; the average energy obtained for NEW and NWW is also shown.

It is observed that the average energy between both surfaces NEW and NWW for the full day – coinciding with each orientation – remains well below the NER orientation during December and January/November; the energy values get closer around February/October; and the energy values are equal by March/September; the average energy for NEW and NWW exceeds that of the NER orientation in the following months. Similar results were obtained for the “sunny noon”. The advantage observed in favor of NER installation on the average of the NEW + NWW system during the “sunny morning” is offset by the gain of the “average system” that it is much higher during the afternoon. All this indicates that the use of both orientations (NEW + NWW) presents an interesting gain in daily and seasonal unfavorable conditions.

It is noted (Fig. 1a) that in the latitude of Esperanza Base, the energy obtained with the configuration NEW + NWW exceeds that obtained with NER in all seasons (actually, the energy for the NEW + NWW system is more than twice the NER in three of them from March/September). Even more interesting is the comparison of what happens in cases of high energy (December, January/November and February/October): even when the normal total energy decreases markedly and the incident on NER follows it, the incident energy on the NEW + NWW configuration remains constant, even increasing in some particular case. In the following months, when the total energy incident declines sharply, the NEW + NWW configuration still maintains its gain, persisting in the worst months. As an additional comment is appropriate to note that although the total energy from April 21 is not significant compared with the summer values, it can be considered “latent energy” or for the extension of operation in stand-alone installations; for this reason it is very important to gain power even under the most unfavorable conditions.

In Fig. 1b energies as percentages of the total energy incident (PSR) on a normal surface are represented: the relative evolution of plant performance is clearly observed. While the reference orientation PSR adds its percentage drop to the natural annual evolution, the NEW + NWW installation continuously and significantly improves its percentage yield throughout the period, delivering: energy equivalent to NER energy on December 21; near to the total normal energy by February/October; doubling the energy of NER on the representative day of March. The rest of the year, the percentage of energy increases for the vertical configuration. It is important to point out that the months where the vertical installation is more efficient, are those that most influence the shield of snow or ice in non-vertical installations.

The above calculations show that the NEW + NWW vertical installation not only solves the effect of snow or ice deposits on the solar modules but solve other serious problems presented by other tilt angle installations in Antarctica.

In short, the NEW + NWW installation on the walls is a better choice than a roof installation, improving the weaknesses of any photovoltaic installation in Antarctica, namely:

- Daily variation. The NEW + NWW configuration captures solar energy available at any time of day. In addition, the NEW and NWW orientations allow capturing the maximum daily irradiances.
- Seasonal variation. The NEW + NWW installation captures and maintains constant energy available during the spring and summer. This configuration outstrips any other static installation in the other months of the year with solar energy available.
- Energy losses by snow or ice. The NEW + NWW installation prevents energy loss by melting ice and snow deposits, which are inevitable in tilted installations with low maintenance [19,31].

Experimental

Materials and methods

Three commercial KS-3T 12 V Solartec polycrystalline silicon photovoltaic cell panels having a rated power of 3 W were used (panel dimensions are 243 mm × 176 mm; standard reference parameters corresponding to a solar radiation intensity of 1 kW m^{-2} and 25 °C are: rated voltage: 12 V; short-circuit current: 0.21 A; open-circuit voltage: 21 V). Two Fluke 189 True RMS Multimeters were used for voltage and current measurements. The automatic data collection was performed using a Lascar Electronics EL-USB-3 0–30 V USB voltage data

Fig. 2 – View of Esperanza Base. The location of NE and NW modules on a building are shown.

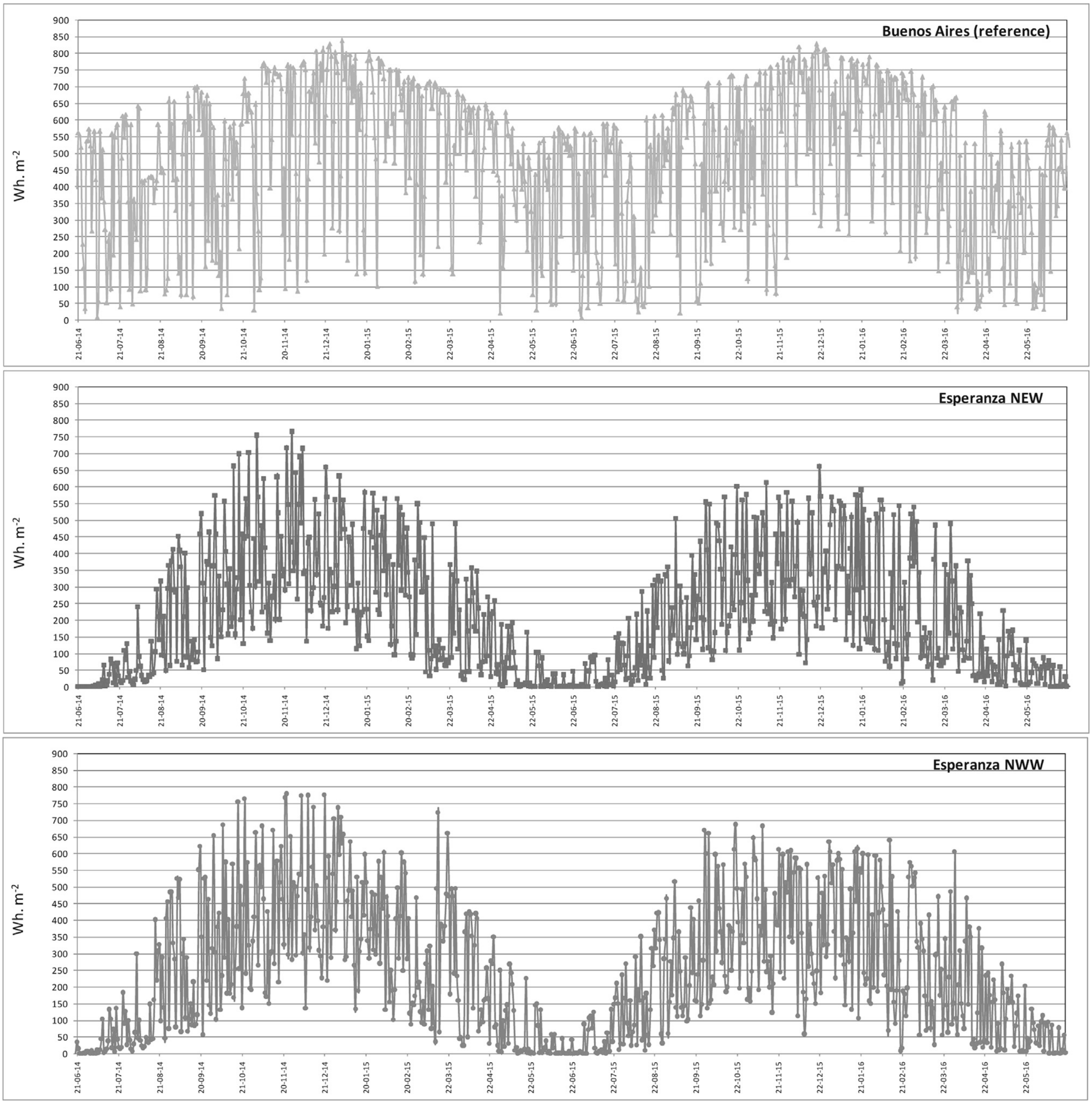

Fig. 3 – Daily energy captured for measurement systems at Buenos Aires (top) and Esperanza (middle: NEW; bottom: NWW).

logger 0–30 V. A resistor load bank constructed in our laboratory was used to obtain the characterization of the PV panels. A resistance of 47 Ohms was selected to evaluate the power delivered by the photovoltaic panel over time. The potential drop on this resistance was recorded by the dataloggers with a frequency of 1 min^{-1} [7]. Data were downloaded by Esperanza Base personnel every two weeks and were sent to our laboratory at Buenos Aires.

PV installation

The measuring system is composed by two vertical photovoltaic modules (facing NE and NW) placed on the walls of a house at Esperanza (Fig. 2). The measured variable was the electrical power delivered. The measurement period was two years, between June 21, 2014 and June 20, 2016. As reference, a similar device was installed in Buenos Aires, facing north with optimum tilt for solar capture (plane of the capture surface perpendicular to the solar rays ±5°).

Results

Fig. 3 shows the daily energy measurements for the two years of evaluation. It is noted that seasonality in Esperanza is more marked than in Buenos Aires. Another notable difference is that the daily power in Esperanza is more variable and there are longer periods of low irradiance than in Buenos Aires.

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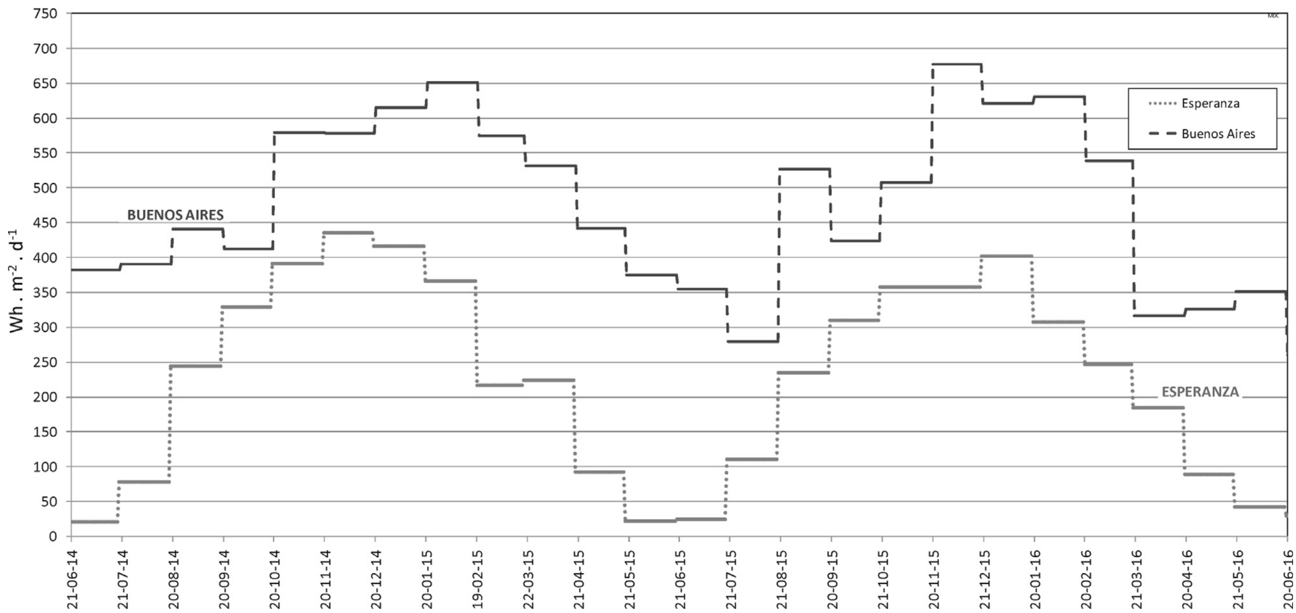

Fig. 4 – Monthly average energy at Esperanza base and Buenos Aires (June 2014–June 2016).

Double installation (NEW + NWW) helps to alleviate differences throughout the day, but it is not useful against several days of permanent cloudiness. These factors suggest the need for a method that allows greater energy storage for a long time. The hydrogen vector meets this condition.

Experimental results agree well with theoretical calculations: the use of vertical PV modules in housing and school at Esperanza not only maximizes resource but also extends the annual season for harnessing solar energy.

Fig. 4 shows the mean energy obtained in periods of 30 days (the energy calculated by averaging fewer days is strongly dependent on weather conditions). By this representation it is easy to estimate the available energy that depends only on seasonality. This is one of the important reasons to consider storing energy as hydrogen.

Another important problem to be solved is the strong influence of seasonality on the available energy. Table 1 and Fig. 4 shows the dramatic fall in the availability of solar resource from April to August. This is another important factor to consider for choosing the hydrogen vector.

Table 1 – Total annual and seasonal energy measured at Esperanza and Buenos Aires (June 2014–June 2016).

	Esperanza (kWh m^{-2})	Buenos Aires (kWh m^{-2})	%
Total annual 2014–2015	86.30	181.25	47.6%
Total annual 2015–2016	81.32	169.20	48.1%
Two years average	83.81	175.22	47.8%
Winter 2014–2015	10.61	36.98	28.7%
Winter 2015–2016	11.40	35.59	32.0%
Spring 2014–2015	35.04	47.64	73.6%
Spring 2015–2016	31.10	48.75	63.8%
Summer 2014–2015	30.29	55.31	54.8%
Summer 2015–2016	29.13	54.40	53.5%
Autumn 2014–2015	10.35	41.32	25.1%
Autumn 2015–2016	9.69	30.46	31.8%

For identical systems installed as proposed, average solar PV usable at Esperanza is 74–64% and 29–32% (see Table 1) of the maximum obtainable in Buenos Aires for spring and winter, respectively. The use of vertical panels at Esperanza prevents of the shielding caused by accumulation of snow or ice; the NE + NW orientation reduces the negative effect of cloudiness.

The results in Table 1 show that it is possible to obtain in Esperanza – with the proposed installation – a very important amount of energy: about 48% of the maximum energy obtainable in Buenos Aires under the conditions described, for both periods.

The average consumption of electricity (excluding heating) for a typical house in Esperanza was estimated in 11 kWh day^{-1}; this value corresponds to an annual energy consumption of 4015 kWh.

Taking into account the area available on the walls of the houses in Esperanza, and from the data in Table 1 and Fig. 4, can be calculated that the energy for the electricity consumption of a house in Esperanza can be obtained from PV modules of 50 square meters: 2 panels of 25 square meters each placed on the walls of the house in NE and NW directions, provide 4190 kWh per year. This value shows that the energy obtained would be sufficient to supply the electricity needs of a house, if it could be used directly; but assuming losses of 10% in the conditioning and distribution of electrical energy, 94% of all the electrical energy (3772 kWh) could be supplied by the proposed solar panel configuration: this is equivalent to saving 1000 L of Antarctic fossil fuel per year, per house (see next section). Solar panels on the roof could provide additional energy in spring and summer. This result has greater importance when considering that the PV system used only guarantees a conversion of 15%, limit of actual

Table 2 – Three possible scenarios for the use of electricity in Esperanza. Total annual consumption per house: 4015 kWh; PV power from vertical panels: 4190 kWh.

Scenario	Direct use or energy storage	Annual electric energy (kWh) from		% of the total energy	Fossil fuel saved per year[c]
	Contributions	PV (direct)[a]	Hydrogen[b]		
1	100% electric energy from PV	3771	0	94	1020
2	100% electric energy from H_2	0	1676	42	453
3	50% from PV, 50% converted to H_2	1885	838	68	713

[a] Conversion efficiency: 90%.
[b] Conversion efficiency: 40%.
[c] Electric energy obtained from fossil fuel: 3.7 kWh/L.

technology of massive production in the market (some manufacturers offer today new modules with yields of up to 20%).

As said, discontinuity of solar energy and its sharp drop in four of the twelve months of the year is a strong disadvantage to be solved [32,33].

The hydrogen connection

As mentioned above, Argentina has gained experience with the production of hydrogen, fuel cell testing and use of renewable energies in Antarctic bases [7,27]. We propose here a modular system consisting of an alkaline electrolyzer powered by photovoltaic energy for the production of hydrogen and oxygen; reservoirs for pressured gas storage at 15 bar [26,27] and a PEM fuel cell stack [2,26,34], based on our own experience at Esperanza Base [35].

As previously observed, the maximum power deliverable by the system depends on the capacity of the PEM fuel cell, while the total energy supply and continuity of service is determined through appropriate dimensioning of the components and by the characteristics of radiant solar energy. On the other hand, the efficiency of alkaline electrolyzers and fuel cells can be easily measured [4,34,36,37]. It is accepted that electrolysis efficiencies are between 50 and 60% [34,37]. Fuel cell stacks have efficiencies between 50 and 70%, depending on the energy consumption from peripheral devices [36]. In this sense, the development of new technologies is continually helping to reduce this energy consumption [38]. In addition, cogeneration can prevent heat loss in fuel cells close to 18% [39]. For our purposes, we will consider a net utilization of 40% of the energy coming from the PV.

Let's consider the Antarctic fossil fuel consumption for electricity production in a house at Esperanza: based on our own experience there, an electric generator provides 3.7 kWh per liter of Antarctic fossil fuel. This means that a house in Esperanza annually consumes 1085 L of fossil fuel for the generation of electricity. As stated above, 94% of this energy can be provided by the solar panels in NE–NW configuration (scenario 1, Table 2).

Two additional scenarios can now be analyzed:

Scenario 2: Assuming the standard operation of systems using hydrogen vector, we consider an overall efficiency of 40% on the total electrical energy produced by the vertical PV modules proposed above: 1676 kWh per year could be supplied by high latitude solar hydrogen through fuel cell stacks; this value corresponds to the same percent of the electricity consumed annually by a house in Esperanza. According to the estimation of fossil fuel consumption at Esperanza, this represents a significant saving of ca. 450 L per year and per house.

Scenario 3: Assuming that 50% of the PV energy is used directly and 50% through the hydrogen vector, more than 700 L of fossil fuel could be saved per house in Esperanza.

Table 2 shows the results for all these situations; the calculations are based on the most unfavorable conditions.

Conclusions

The configuration of vertical solar panels in NE + NW directions is an efficient way to capture solar energy at Esperanza Base.

The use of vertical PV modules in housing and school at Esperanza not only maximizes resource but also extends the annual season for harnessing solar energy.

The available PV energy at Esperanza is very high, but strongly dependent on seasonality, so hydrogen vector is proposed for energy storage.

The use of alkaline electrolysis, hydrogen storage at 15 bar and fuel cell stacks can provide at least 40% of the total electric energy consumed by a house at Esperanza Base without considering the direct electric consumption.

At least 450 L of Antarctic fossil fuel could be saved per year and per house by using the hydrogen vector through fuel cells.

Fossil fuel savings can be increased by properly combining the use of direct PV energy with the hydrogen vector.

The whole installation is particularly suitable for Antarctica because it uses static components (resistant to low temperatures), and, specially, it is environmental friendly.

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