A CONCEPT OF BOUNDARIES OF PERFORMANCE FOR ANALYSIS OF HYBRID SYSTEMS BASED ON COMPLEMENTARY ENERGY RESOURCES

ALEXANDRE BELUCO

[albeluco@iph.ufrgs.br]

Instituto de Pesquisas Hidráulicas (IPH), Universidade Federal do Rio Grande do Sul (UFRGS)

Porto Alegre, Rio Grande do Sul, Brazil

KEYWORDS: hybrid energy systems, complementary energy resources, energetic complementarity, complementarity index, boundaries of performance, method of analysis, feasibility study.

1. INTRODUCTION

Hybrid systems have been studied for decades as a way of enabling the use of renewable resources. The use of different forms of energy together improves the specific cost of energy, even with higher initial costs. The characteristics of different forms of energy allows meet times of drought in a way that the use of one of them alone would require very high costs. Complementarity between energy resources used to generate energy, when available, would contribute significantly to the feasibility of the systems in which it can be harnessed.

This chapter introduces a concept of boundaries of performance and discusses some of its features and limitations. The introduced concept seeking to adapt the modeling of availability of energy resources for analysis of hybrid systems based on complementary resources. It is necessary to filter effects of meteorological and climatological phenomena to deal only with the combination of the available energy of different forms of energy harnessed. This theme is not finished and it is a current research topic.

The next two sections recall some important ideas for the development of this chapter. The next two chapters discuss the modeling proposed for the availability of energy resources and the quantification of complementarity between energy resources. The section on boundaries of performance is dedicated to the central concept of this chapter. Finally, an application example illustrates what has been discussed throughout the chapter. Throughout the text, several topics for further research and for the continuation of this work are presented.

2. HYBRID ENERGY SYSTEMS

Generation systems based on renewable resources alone, usually for small and isolated power grids, face many difficulties for acceptance. Difficulties associated mainly with high installation costs and low financial income. Currently these difficulties are decreasing because of concerns about climate change, with emissions of greenhouse gases, with the reduction in oil inventories and with oil costs, among others.

Among the available renewables, some show a certain economic and financial maturity, such as hydropower, wind energy, some forms of solar energy and biomass energy. In recent years, several projects around the world try to also advance with other forms of energy such as marine energy, geothermal energy, ocean thermal energy, among others.

In the last decades, and especially in recent years, rising oil costs encouraged the use of renewable resources through schemes in which two or more sources of energy are used to meet consumer loads. These hybrid systems have high initial costs, but may result in lower energy costs when compared to equivalent systems based on only one source of energy.

Several systems constituted with those renewables who have reached technical and economic maturity exhibit competitiveness with conventional generating devices. [1] The feasibility of these systems can be more easily proven when analyzes take into account longer periods and include comparisons of greenhouse gas emissions or other environmental impacts.

The key to the feasibility of projects involving renewable energy resources necessarily requires planning for decentralized use of energy and the creation of a specific market for use of renewable energy on a small scale. [1] Even in regions where there are vascularized interconnected systems, the implementation of hybrid systems based on renewables can contribute to social and economic development.

Government incentives, a greater number of manufacturers, the availability of tools for design and analysis of hybrid systems, among others, contribute to encourage decisions in favor of solutions for energy supply related to the use of renewables. The current situation indicates the urgent need to reduce dependence on oil [2], but the changes are still distant, institutions and companies always have much conservativeness and the challenges are enormous. [3]

Homer [4] and other similar software are important tools [5]-[6] in modeling, simulation-and optimization of hybrid systems based on renewable resources. Himri et al. [7] study the minimum values of wind speed and maximum price of diesel to make feasible a diesel wind hybrid system at a site in southwestern Algeria. Givler and Lilienthal [8] evaluate the insertion of diesel gen sets at various photovoltaic systems in Sri Lanka. Weis and Ilinca [9] consider the inclusion of devices for energy storage to improve the economic feasibility of wind diesel hybrid systems in remote communities in Canada.

In the next sections, the complementarity between energy resources and its impact on the performance of hybrid systems are discussed. The focus of this chapter is the performance analysis of hybrid systems based on complementary resources and, in the following sections, a concept for modeling of these systems will be proposed and discussed. An application example shows how the proposed method can lead to important results in the analysis of systems based on complementary energy resources.

3. COMPLEMENTARY ENERGY RESOURCES

The complementarity between energy resources is the ability of these resources to complement each other. When one faces a period of low availability, the other has higher availability. At another time, when the first has high availability, compensates the reduced availability of the second. Considering the combined use of these energy resources, consumers receive a sufficient average availability to meet their demand.

Complementarity is a way to compensate the difficulties associated with obtaining supplies of energy from renewables, which are unpredictable and intermittent, contributing both to reduce effects of drought as to reduce effects of intermittency of renewables. The complementarity can exist naturally between renewables, but can also be enhanced with the proper design of generation systems and can be encouraged by economic mechanisms.

Hoicka and Rowlands [10] propose the assessment of complementarity with a dimensionless index to compare the smoothness of the energy obtained using only a power source or using two energy sources and in this case, even considering only one location or considering two locations. Their work has been focused on solar and wind power, intending to extend its use for the integrated power supply in Ontario, Canada. The work shows that there is an increase in the smoothness of the energy obtained with the integrated use of these resources.

Denault et al. [11] studied the complementarity between hydro and wind energy in Quebec, Canada, to evaluate the impact of the complementarity of these energy resources on the risk profile of the power supply obtained from the grid. They compared the security of energy supplies obtained from an all hydro energy system with supplies obtained from a wind hydro hybrid system. The scenarios studied indicated that wind penetration up to 30% contribute to reduce the risk profile compared to all hydro system.

On the typical intermittency of renewables, Sovacool [12] led a very interesting work which questions the true impact of this intermittency on the interconnected systems. The study is based on interviews with professionals in the electricity sector. He proposes that the intermittency of resources such as solar or wind power can be predicted, managed and mitigated and further asserts that the difficulties associated with intermittency of renewables is mainly due to the characteristics of the electricity sector.

The intermittency and unpredictability of wind regimes impose many difficulties in harnessing wind energy. Angarita and Usaola [13]-[14] studied a mechanism to compensate for these difficulties, suggesting the inclusion of wind power in the energy market associated with hydroelectric plants. These plants would be managed so as to compensate, within certain limits, the difficulties encountered with wind power. Obviously, a parameter that is important is the existence of accumulation capacity, limiting the use of run-of-the-river plants to this solution.

Combining wind power with hydropower with storage capacity or pumped storage plants have been widely studied. Benitez et al. [15] conducted a study in Alberta, Canada, which stated among other things that the inclusion of pumped storage would reduce the need for additional power plants to meet peak demand. Anagnostopoulos and Papantonis [16] relate dimensions of pumped storage with increases in wind turbine capacity factor.

Beluco studies the influence of complementarity between renewable resources on the performance of energy systems. Beluco et al. [17] proposed a dimensionless index to assess complementarity then employed [18]-[19] to distinguish the effects of energy resources with different degrees of complementarity over the performance of hybrid systems. The next steps will be directed towards linking information related to complementarity with design parameters.

The work of Beluco is based on the study of hydro PV hybrid systems. It is a combination that may initially seem hardly feasible [20], but that comes calling increasing attention of researchers. Bekele and Tadesse [21], for example, assess the feasibility of a hydro PV wind hybrid system for off grid rural electrification in Ethiopia. Nfah and Ngundam [22] evaluated also with Homer the feasibility of pico hydro and PV hybrid systems for remote communities in Cameroon. Kruangpradit and Tayati [23] compare different systems with PV modules, micro-hydro power, diesel gen sets and batteries for rural electrification in Thailand.

The description of the complementarity between energy resources and the study of their effects on the performance of hybrid systems requires adequate description of the spatial and-or temporal availability of energy resources. The next sections discusses the modeling of energy availability in the light of the concepts presented in the following sections. An analysis method which identifies the effects of complementarity on the performance of hybrid systems is necessary, although climatological and meteorological effects.

Complementarity is a parameter that can hardly be useful for optimization for a given site, as it depends almost directly on the physical characteristics of the energy resource. However, knowing the complementarity over a region, the managers who decide on where to prioritize the implementation of new generating plants, may choose those with better complementarity and hence with better cost of energy and better performance. Complementarity is therefore a management tool rather than a way to improve the performance of a given hybrid system.

4. EVALUATING ENERGETIC COMPLEMENTARITY

The proposition of an index to quantify the complementarity between energy resources does not constitute a mathematical problem with a single solution. In fact, different indices can be proposed, depending on the purposes to be met. The idea is to compare energy resources in pairs and assign a number according these resources approach or move away from the situation of perfect complementarity.

Beluco et al. [17] proposed an expression for the index of complementarity in time for the case of hydro and PV energy. This paper presents a generalization of this index, considering the availability of any two sources of energy. The chapter with an application example, below, is based on the complementarity between hydroelectric and photovoltaic energy.

The index of complementarity in time, κ, consists of a value that expresses the degree of complementarity between the availability of two energy resources. It is defined according to equation (1) and includes the evaluation of the lag in time between the minimum and maximum values, the relationship between the means and the relationship between the amplitudes.

(1) $\kappa = \kappa_t \ \kappa_e \ \kappa_a$

In this equation, κ_t is the partial index of complementarity in time, κ_e is the partial index of complementarity between the mean values of availability and κ_a is the partial index of complementarity between the ranges of variation of the available energy. All these indices are dimensionless and range always between 0 and 1.

The overall index, as well as the partial indexes, can be quantified by different mathematical expressions of these are described here. The total index could be described, e.g., by an expression involving the square root of the partial indices squared, giving a character more "curved" to situations which deviate from perfect complementarity.

The partial index of complementarity in time, κ_t, is defined according to equation (2) and evaluates the time interval between the minimum values of availability (or possibly the maximum values) of the two power sources. If this interval corresponds to half of the period, the index will result in the unit. If match zero, that is, if minimum values coincide in time, the index will result null. Intermediate values show a linear relationship between them.

$$(2) \qquad \kappa_t = \frac{|d_1 - d_2|}{\sqrt{|D_1 - d_1||D_2 - d_2|}} = \frac{|d_1 - d_2|}{180}$$

In this index, D_1 is the day corresponding to the maximum value and d_1 is the day corresponding to the minimum value of availability of the first energy source, D_2 is the day corresponding to the maximum value and d_2 is the day corresponding to the minimum value of availability of the second energy source. This expression can be rewritten, assuming that the differences (D-d) is always equal to half a year.

This index can be described by a mathematical expression that establishes a quadratic relation for the gap between maximum and minimum availability. The index could be defined as the square root of D or d squared. Such a relationship would provide a better distinction to the situations near full complementarity in time.

The partial index of complementary of energy, κ_e, is defined according to equation (3) and evaluates the ratio between the mean values of the availability of the two power sources. If the mean values are equal, the index should result in the unit. If they are not equal, the index should move away from the unit, tending to zero. Intermediate values also hold a linear relationship between them.

$$(3) \qquad \kappa_e = 1 - \left(\frac{E_1 - E_2}{E_1 + E_2} \right)$$

In this index, E_1 is the total annual energy provided by the first generator and E_2 is the total annual energy provided by the second generator. The index κ_e must associate the value 1 to the situation in which the annual total energies of the two sources are equal. Complementarity will be as small as total annual energy are different.

This index can also be described by a quadratic function, defined simply adding an exponent to the brackets in equation (3) or by a manipulation involving the square root of the total annual energies squared. Such a relationship would also provide a better distinction to the situations near full complementarity of energy.

The partial index of complementarity between amplitudes, the κ_a, is defined by equation (5) and evaluate the relationship between the ratios of the maximum and minimum values of the two functions of availability. If the differences are equal, the index will result in the unit, and be different as the index moves away from this value, tending to zero.

$$(5) \qquad \kappa_a = \begin{cases} \left[1 - \dfrac{(\delta_1 - \delta_2)^2}{(1-\delta_2)^2}\right] & \text{se } \delta_1 \leq \delta_2 \\ \left[\dfrac{(1-\delta_2)^2}{(1-\delta_2)^2 + (\delta_1 - \delta_2)^2}\right] & \text{se } \delta_1 \geq \delta_2 \end{cases}$$

In this index, δ_1 and δ_2, respectively defined in (6) and (7), corresponding to a manipulation with the differences between the maximum and minimum values respectively of daily energy provided by generators associated with each energy source.

$$(6) \qquad \delta_1 = 1 + \frac{E_{d\,1\,\max} - E_{d\,1\,\min}}{E_{d\,c}}$$

$$(7) \qquad \delta_2 = 1 + \frac{E_{d\,2\,\max} - E_{d\,2\,\min}}{E_{d\,c}}$$

In these equations, $E_{d\,1\,\max}$ and $E_{d\,1\,\min}$ correspond to the energy provided by the first generator respectively on days of higher and lower availability of energy, $E_{d\,2\,\max}$ and $E_{d\,2\,\min}$ correspond to the energy provided by the second generator respectively on days of higher and lower availability of energy, and $E_{d\,c}$ corresponds to the daily energy consumed by the loads, considered constant over all days of the year.

The values of the differences in (6) and (7) can vary greatly, depending on availability of energy resources and the capacity of the generators, but hardly assume much larger values than 5. Furthermore, the way they were defined, they will never be less than one, corresponding to a situation in which the generators produce power constant over time.

One difference δ calculated e.g. for photovoltaics, whose availability may be well known and is perfectly predictable for a vast territory, it becomes relatively easier. These differences can take a single value for very large areas, with variations mainly to different latitudes. Beluco et al. [17] shows the value of δ for the territory of the State of Rio Grande do Sul, in southern Brazil.

The index of complementarity between the ranges of variation in available energy is defined to include the difference between the maximum and minimum values of energy resources in the evaluation of complementarity. Where one of the sources do not show differences in availability over the period considered, or have small differences, it is impossible to consider it for purposes of complementarity, resulting in a null index. If the two sources present availability with the same difference between the respective maximum and minimum values may be considered as complementary, with the maximum value of the index.

This proposition can be improved and other proposals may be presented to characterize and quantify the complementarity between energy resources. Possibly the best approach to assess complementarity, as discussed in this work, should be constructed from the convolution of the curves of average annual availability of renewable energy resources. Importantly, the calculation method explored in this work is focused on the performance analysis of hybrid systems.

5. BOUNDARIES OF PERFORMANCE

The proposed model for studying the effects of complementarity is based on the idealization of the availability of energy resources considered in the analysis. This type of model has been proposed precisely to allow the study of the effects of complementarity and has no meaning as a way to describe natural phenomena.

Real data show a reasonable variability, which complicates the study of complementarity in hybrid systems. This variability is due to meteorological effects that may result from cycles of change with seasonal, annual and multi-annual frequencies. This variability can hide effects associated with complementarity.

Ideal data obviously allow to study the effects of the combination of two or more energy resources excluding weather effects. This idealization of real data allows the behavior of generation and consumer equipment due solely to variations in energy availability can be analyzed with greater clarity.

This proposed modeling then allows the hybrid system under study could be simulated and the effects of complementarity on the operation of the system are known. The results thus obtained do not show a real system behavior, but would showing a boundary of performance. Something like a border that would be achieved as the weather effects were weakest.

The next chapter discusses the complementarity between energy resources and the approach of the annual energy availability curves with the use of idealized curves. Some data sets are presented and their modeling is exploited to clarify the proposed method. In the next chapter, results with real data and idealized data are compared in a case study.

6. MODELING THE AVAILABILITY OF ENERGY RESOURCES

The starting point is a hybrid system based on complementary energy resources. Figure 1 shows availability of two power sources. This figure is completely illustrative and shows a situation of full complementarity. Clearly, the maximum and minimum values of both complement each other. Furthermore, the mean values for each source and their ranges of variation are identical.

In this figure, two pop charts showing monthly total energy availability of two energy resources. These charts are very similar to the graphs of monthly rainfall totals over a year. May also represent monthly totals of other energy sources. Here will be considered only as fictitious examples for discussing complementarity.

These data are illustrative and away from real data, but allow to study effects of complementarity. These data can be approximated by sinusoidal functions and applied in computational simulations to study the effects of complementarity on the performance of hybrid systems. Beluco et al. [18]-[19] present some results on this subject.

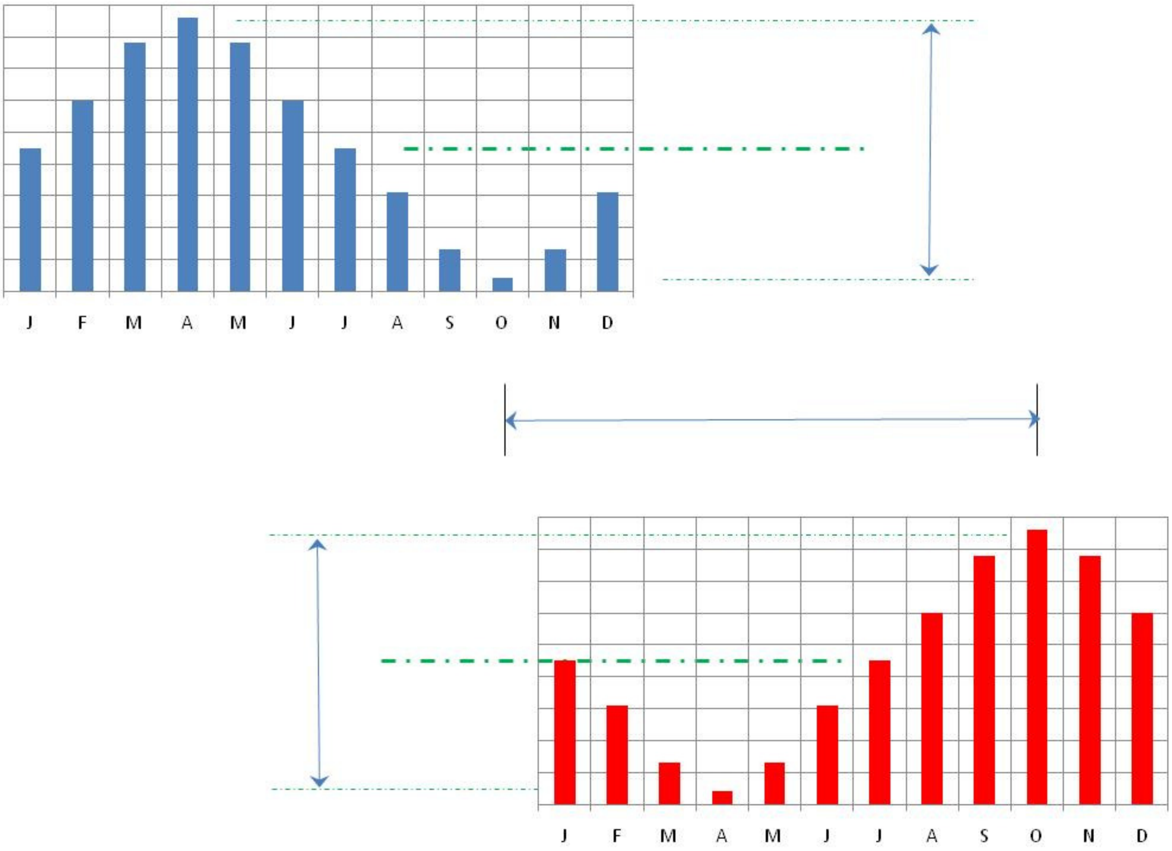


Figure 1. Availability of energy resources with full complementarity.

In this figure, the minimum values of energy availability (October in blue and April in red) occur exactly six month lag. The maximum values (in April and October) also occur with six month lag. Additionally, the minimum and maximum values keep the same gap between them. Dot and dash lines indicate the mean values are identical. There are also indications that the amplitudes of variation between the minimum and maximum values of each energy resource are also identical. Obviously it will be very difficult to find a situation like that in real conditions.

Figure 2 shows a first set of sample data, with characteristics closer to reality. Data in red are harmonious, while the data in blue require a more careful interpretation. Data “in blue" have an obvious minimum but a maximum of hard location. Data "in red" are more similar to the data in Figure 1, with minimum and maximum easy to locate.

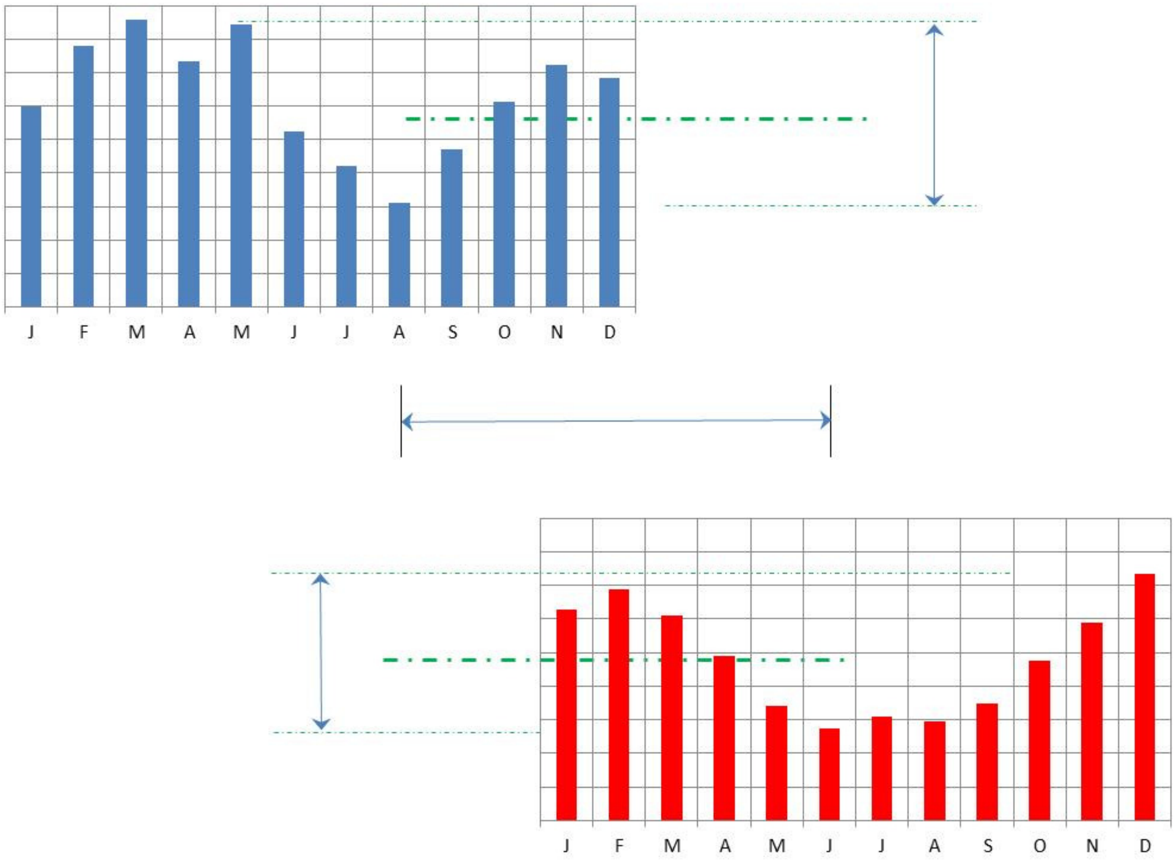


Figure 2. First set of sample data.

The assessment of complementarity should be done with the comparison of the curves rather than identifying features in one and then in the other. The minimum in blue, in August, is located slightly below the minimum in red, which could be in June, July or August, and the closeness of the minimum established in this case virtually no complementarity. Between the maximum values also happens almost the same lag.

Figure 3 shows a second set of sample data. In this case, the two sets of annual data provides very difficult to be interpreted in the light of energetic complementarity. The data corresponding to two energy resources in this case show great variability throughout the year, making it difficult to identify minimum and maximum values.

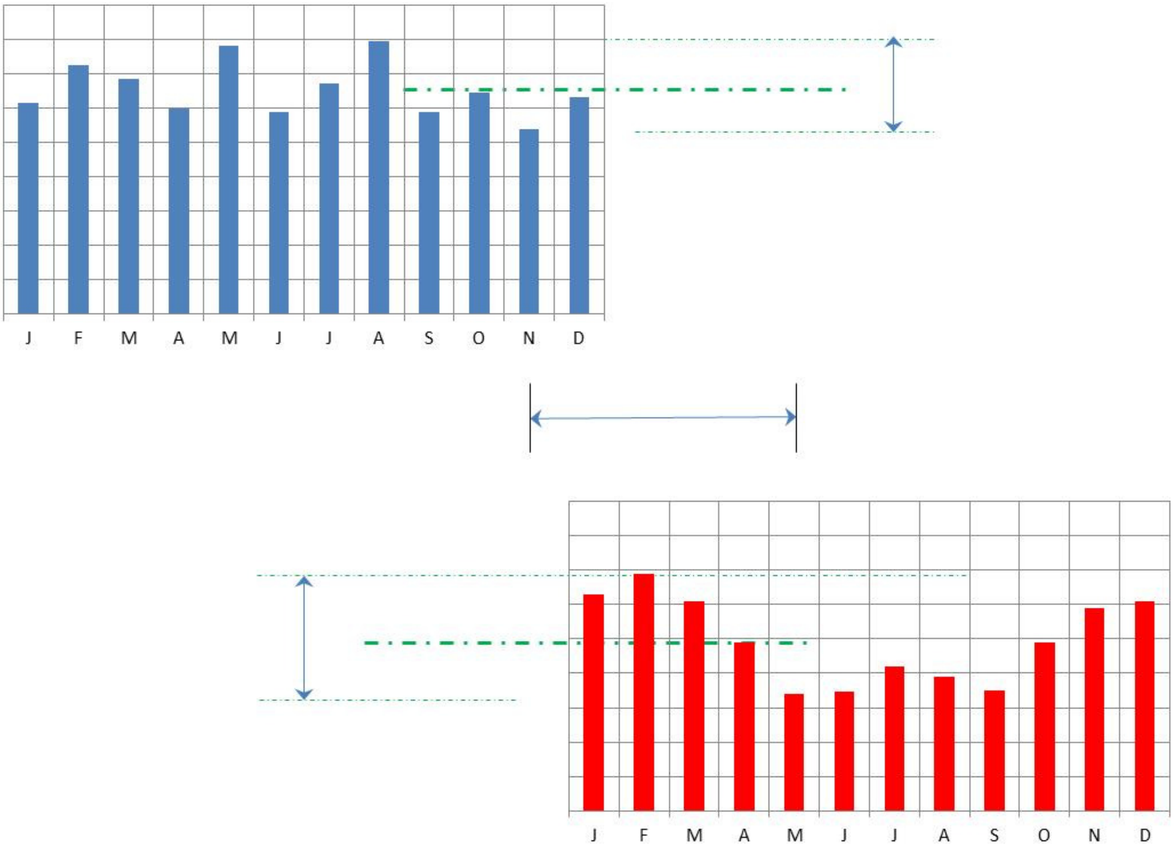


Figure 3. Second set of sample data.

The overall look of this dataset seems unreasonably obstruct any analysis. However, the maximum values of the data in blue, located in May and August, occurs at the same month of the minimum value of the data in red, which occurs in May and June, complementing each other. Thus, even if the gap is not an ideal gap, there is a partial complementarity.

The process of data analysis should be performed with attention and sensitivity. The analysis of complementarity on actual data can be facilitated if the data are normalized to the range between 0 and 1. Moreover, aiming simulations, real data can be approximated by polynomials with higher degree, to better simulate the oscillations availability over a year.

7. A METHOD OF ANALYSIS

Hybrid systems are usually analyzed from an energy balance conducted for a period of one year. Or analysis is performed for longer periods, such as 20 or 25 years, to take into account costs of replacing components, with the results presented on an annual basis. Such an analysis, based on real data obviously shows the actual operation of the system, particularly in times of drought.

The use of mathematical functions to the idealization of the availability of energy resources allow a study focused on the determination of generic performance characteristics of hybrid systems based on partial or full complementary energy resources. Thus, it is possible to characterize more clearly the effect of complementarity between the energy sources employed.

The method consist of a few simple steps. First, the hybrid system and the range of values of complementarity to be studied should be established. Second step, the most appropriate mathematical functions for the representation of the available energy should be established. Third step, the simulations themselves, resulting in a total time of failure to meet demands of consumers. Fourth step, the analysis of the results.

The performance of a system can be measured in several ways. The annual failure time in meeting the demands of consumers can be used to compare hybrid systems simulated on an annual basis. When there is no failure, this parameter can be complemented by the annual time in which the available energy exceeds the energy consumed.

The study of a specific system through simulation should consider the specific information of energy resources to be employed. The simulation of hybrid systems with idealized functions for description of energy resources allows complementarity effects are studied. The actual data, however, may present days with extreme values that need to be taken into account for proper sizing of generators and energy storage devices.

8. AN APPLICATION EXAMPLE

This section presents an application of the concept of boundaries of performance on the simulation of a hybrid system based on complementary energy resources. By the characteristics of their availability over time, hydroelectric photovoltaic hybrid systems are very suitable for this type of research work. The site chosen for the study is close to the city of Santa Cruz do Sul[1], State of Rio Grande do Sul, southern Brazil.

Flow data and data of solar radiation incident on a horizontal plane were used. The flow data consist of daily data between February 1, 1979 and January 31, 1989, extracted from a series of data obtained with the Agricultural Research Foundation of the State of Rio Grande do Sul [24]. Data from incident solar radiation on horizontal plane consist of a series of ten years of hourly data, generated with the software Radiasol [25] for the city of Cachoeira do Sul[2], near where flow data were collected.

Figure 4 shows the monthly mean values for the flow rate and Figure 5 shows the monthly average maximum values of incident solar radiation on a horizontal plane. Figure 6 shows the complete sequence of the data used in computational simulations.

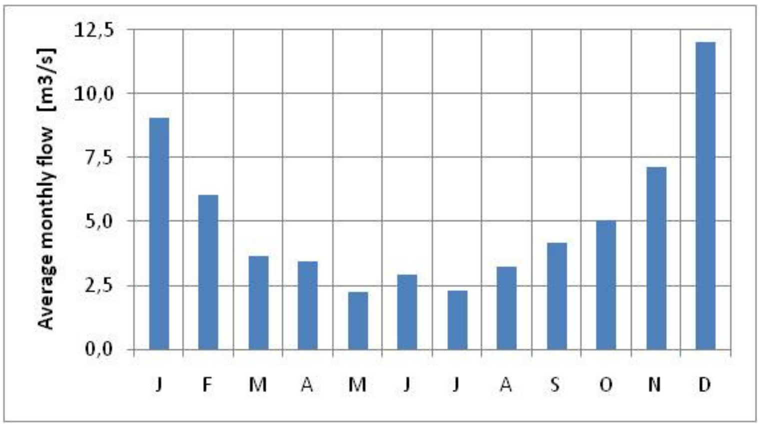


Figure 4. Monthly mean values for the flow rate.

---

[1] The site can be located on Google Maps: goo.gl/maps/A8O5L.

[2] The site can be located on Google Maps: goo.gl/maps/oMnWC.

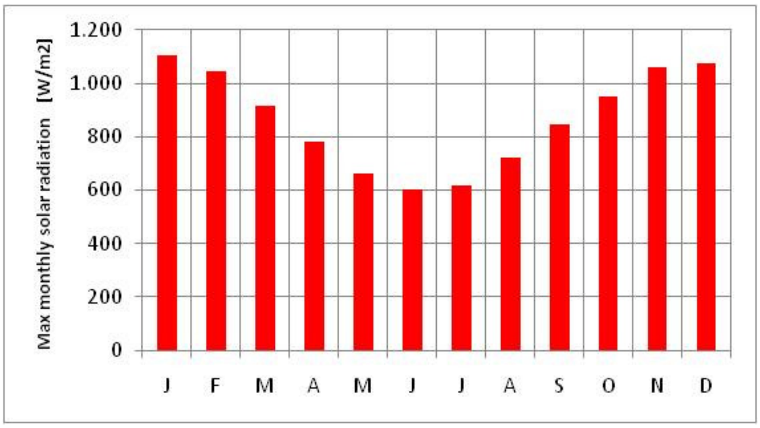


Figure 5. Monthly average maximum values of synthetic incident solar radiation on a horizontal plane.

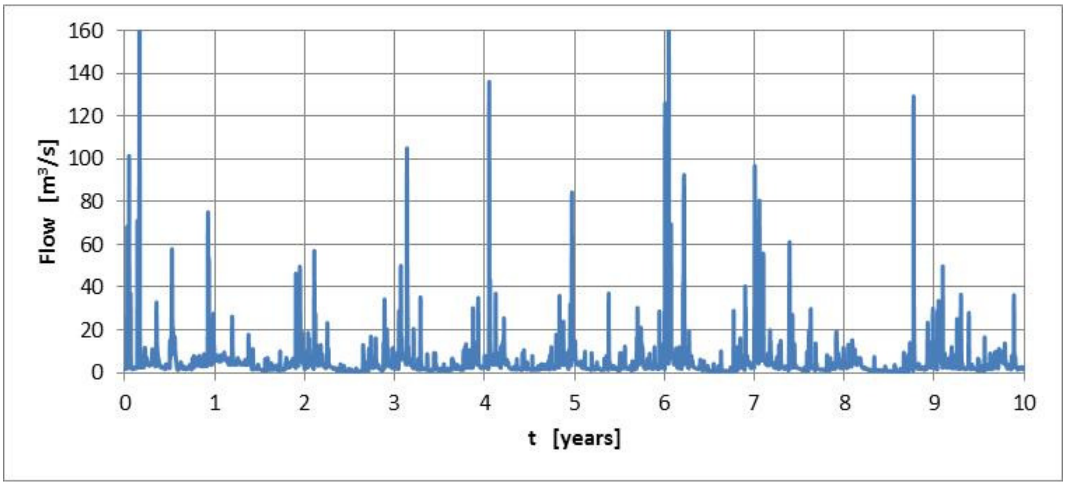
Graphics of energy availability for the two resources in this case are simple enough to be adapted for the simulations. A visual evaluation of the data already shows that there is no complementarity. The values of minimum availability occur at the same time of year. The minimum in Figure 4 occur between May and June and the minimum in Figure 5 occurs in June.

These data were used as input to a simulation that makes the energy balance of a hydroelectric photovoltaic hybrid system. The total load to be served sum 70 kW. The hydroelectric power plant was sized to 10 meters drop and a flow rate of 1 m^3/s. The system also has a battery bank with a capacity for two days of consumption.

The simulation was performed with Matlab software and was designed with the application of pu system for units. The simulation was performed for the period of ten years of data and results from year to year are shown in Figure 7 to Figure 16. The performance in each simulation can be evaluated by the total time of failure to meet demands.

The demand profile considered in the simulations is constant. The discharging of the batteries was limited to 40% of maximum load. The maximum hydroelectric power available was considered equal to the maximum load power. In this configuration, the load will always be met by hydropower, whenever there is availability for this energy.

(a)



(b)

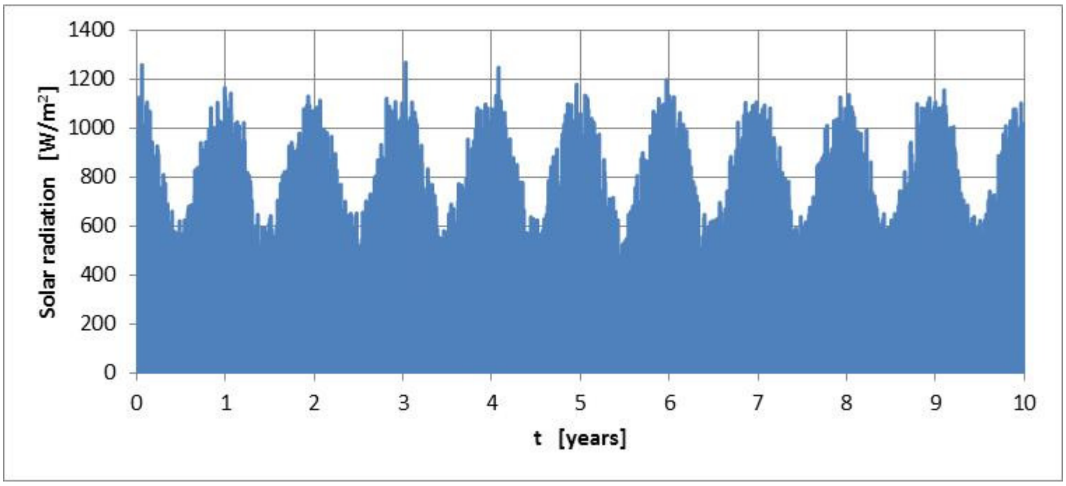


Figure 6. (a) Flow data. (b) Synthetic dataset of incident solar radiation on a horizontal plane.

Figure 7 shows the results obtained for the first year. As is reported in the legend, the red line indicates the state of charge of batteries. The green line indicates consumer demand, the blue line indicates the power provided by hydroelectric power plant and the black line indicates the maximum daily power provided by PV modules.

The power consumed by the loads, the power provided by hydro power plant and power of PV modules are indicated as vertical axis to the left. The state of charge of batteries is indicated as the right axis. The hatched areas in blue and green correspond to periods in which the hydro power plant is disconnected, for excess energy, or consumers are not served, by power outages.

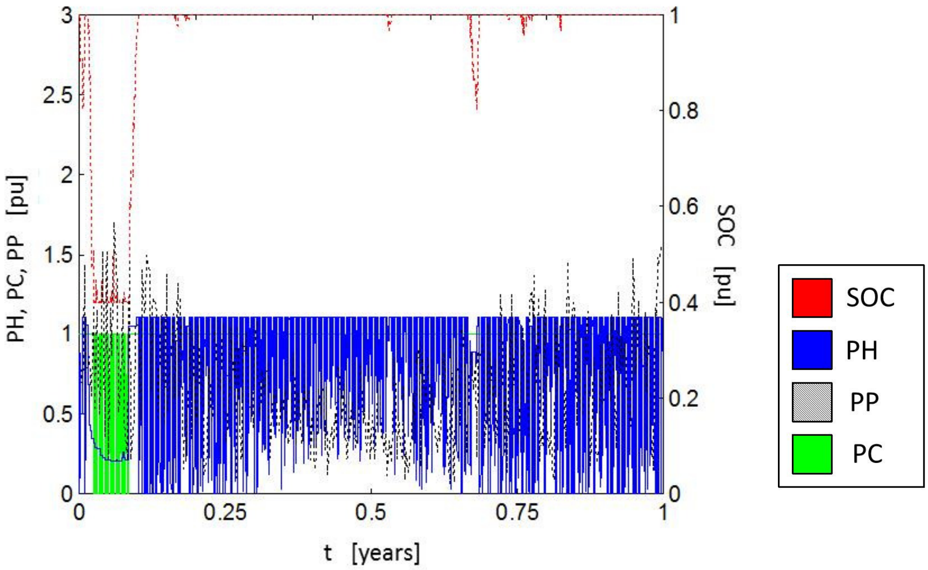


Figure 7. Simulation results for the first year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

In this figure, the system fails to meet demands of consumers in 10.89 days, corresponding to 2.89% of the total period of one year. It is important to note that failures occur at the beginning of the year, when energy is plentiful, probably due to weather effects. During the period in which the two energy resources cross by droughts, no failures occur!

Figure 8 shows the results obtained for the second year. In this figure, the system fails during 4.36 days, corresponding to 1.20% of the total period of one year. In this case, there is energy left over in the first half of the year and lack of energy in the second half, when the two energy resources experience droughts.

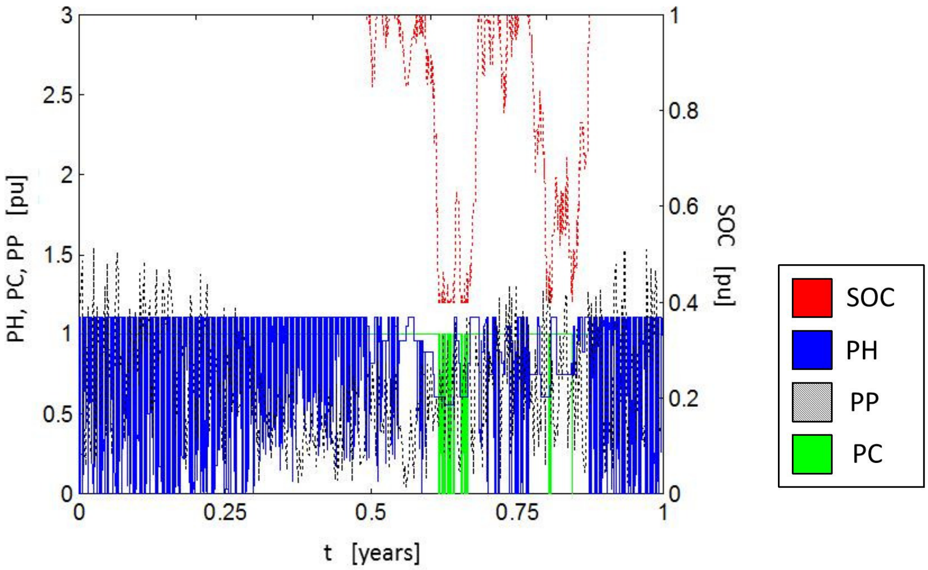


Figure 8. Simulation results for the second year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Figure 9 shows the results obtained for the third year, where the system fails to meet demands of consumers in 36.42 days, corresponding to 9.98% of the total period of one year. The results of this figure repeat the most likely outcomes, with failures concentrated in the second semester, in which periods of minimum energy availability of the two energy resources occur.

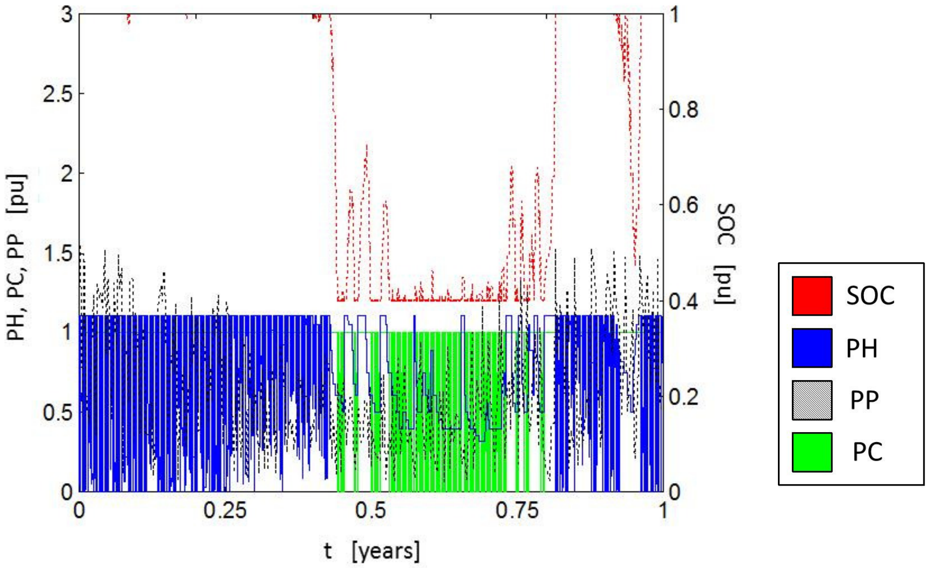


Figure 9. Simulation results for the third year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Figure 10 shows the results obtained for the fourth year. In this figure, the system fails to meet consumers during 13.52 days, corresponding to 3.70% of the total period. Again, failures concentrated in the second semester. The total time of failure can vary, but it is expected to happen in periods of low energy availability.

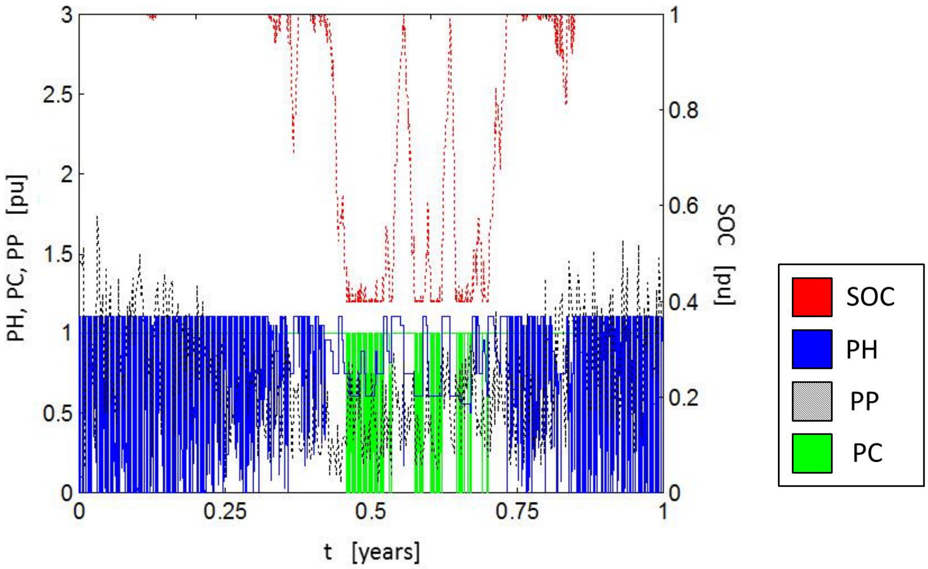


Figure 10. Simulation results for the fourth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Figure 11 shows the results obtained for the fifth year. In this figure, there are failures in 0.75 days, corresponding to 0.20% of the total period. Figure 12 shows the results obtained for the sixth year, where the system fails in 3.71 days, corresponding to 1.02% of the year. These two years had small amount of failures, probably by a higher total energy availability.

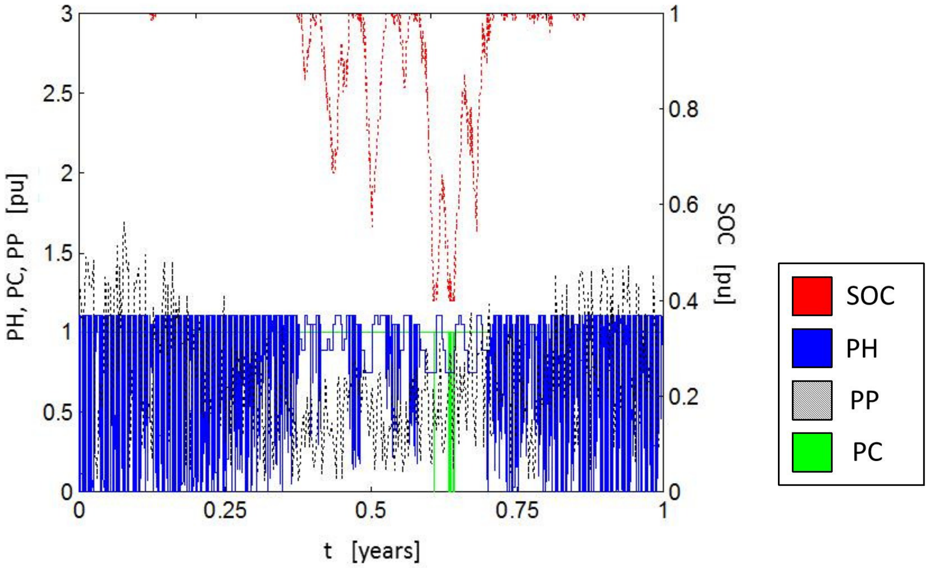


Figure 11. Simulation results for the fifth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Interestingly, in the sixth year, some failures concentrated in the middle of the year before the most critical period occurred. Such a situation can be resolved with a small increase in the capacity of the battery bank capable of supplying the energy required at the moment of failure.

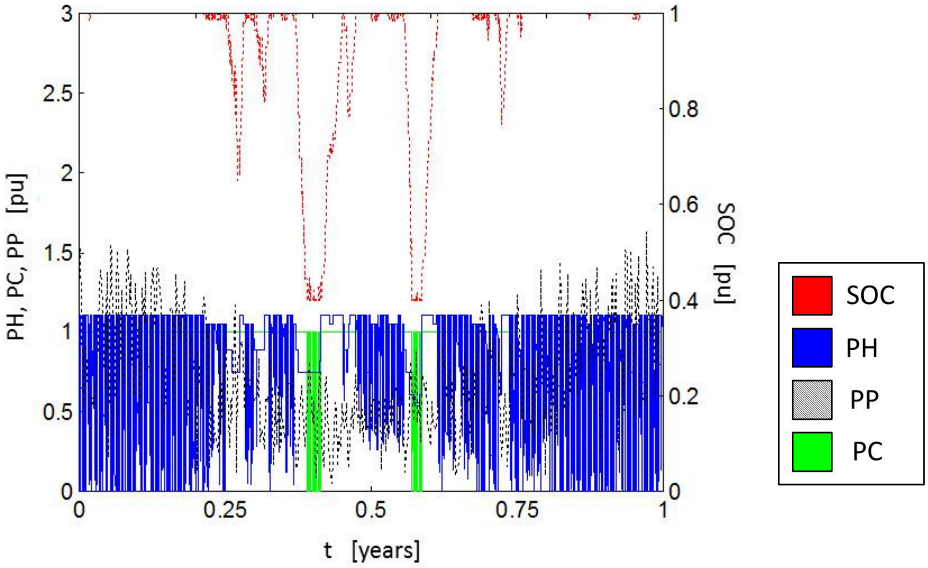


Figure 12. Simulation results for the sixth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

The years with fewer failures also have excess energy in other periods. This result indicates that it would be possible to reduce the installed power and raise the accumulation capacity of the battery bank. Such a change obviously depends on local costs of these components.

Figure 13 shows the results obtained for the seventh year. In this figure, failures occur in 27.58 days, 7.56% of the year. A typical year for a system without complementarity, as well as the third and fourth years, as shown, and the ninth year, shown below.

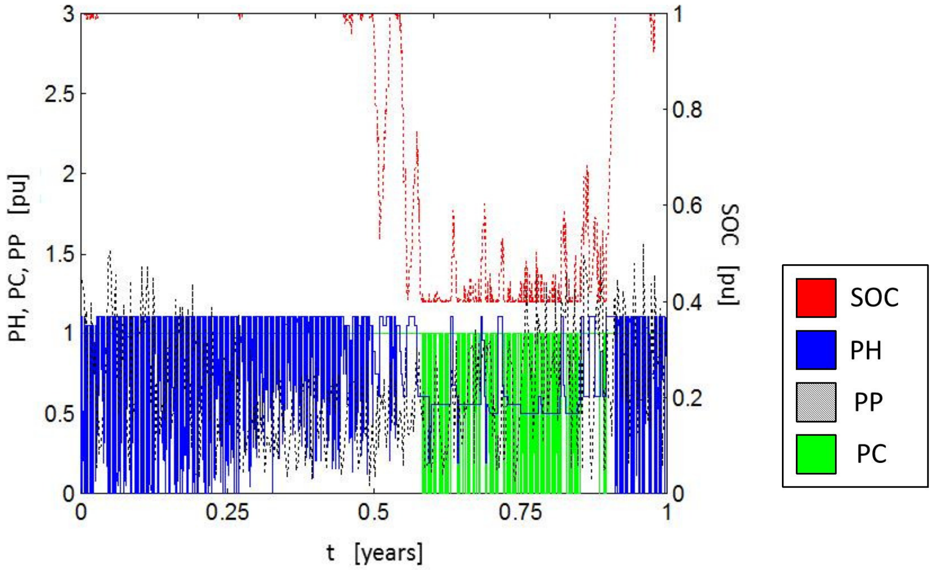


Figure 13. Simulation results for the seventh year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Figure 14 shows the results obtained for the eigth year. The system fails to meet demands of consumers in 2.78 days, corresponding to 0.76% of the total period. A year with fewer failures, like the second, fifth, sixth and tenth (shown later) years.

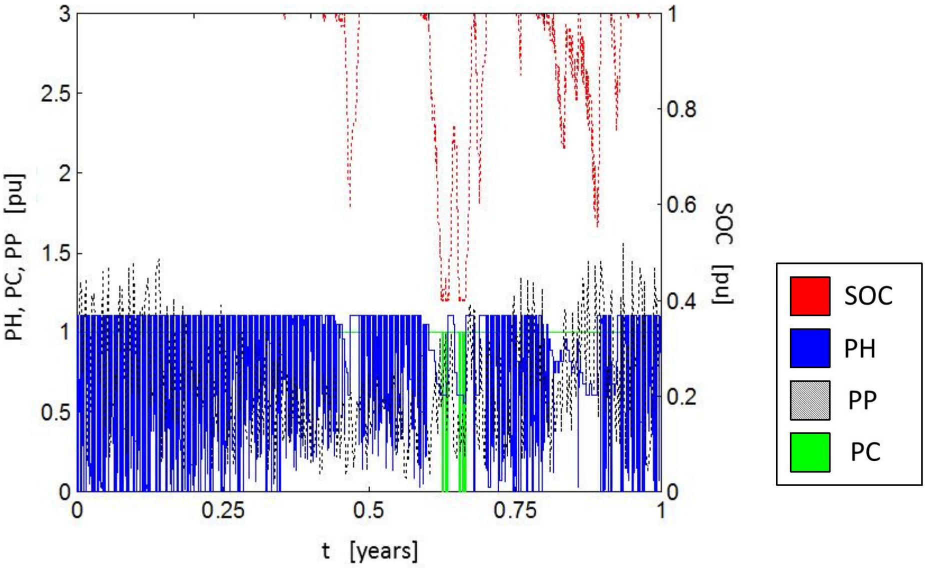


Figure 14. Simulation results for the eighth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Figure 15 shows the results obtained for the ninth year, where the system fails to meet demands of consumers in 44.90 days, corresponding to 12.30% of the year. Figure 16 shows the results obtained for the tenth year, where failures occur in 0.75 days, 0.21% of the year.

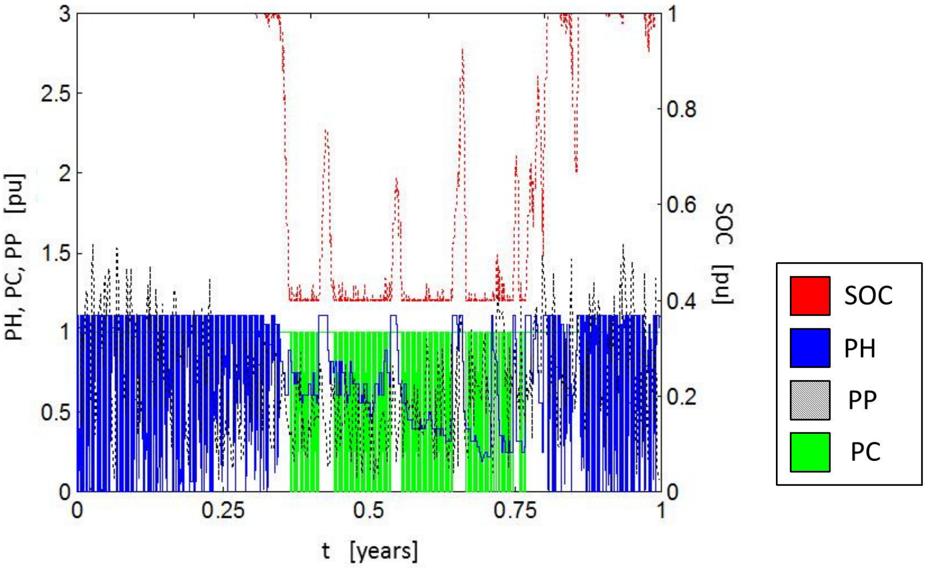


Figure 15. Simulation results for the ninth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

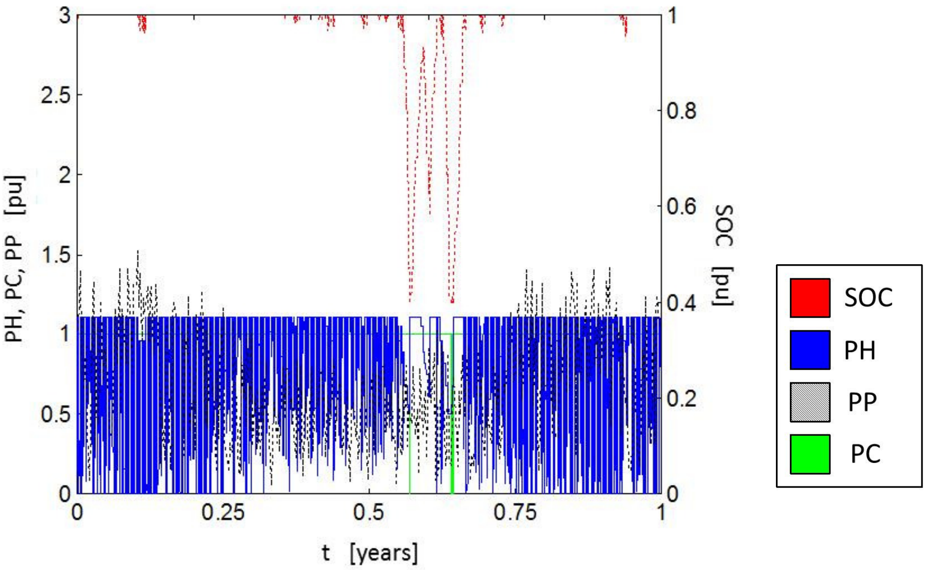


Figure 16. Simulation results for the tenth year. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

Summarizing the results, failure occurred in a total of 10.89 days, or 2.98% of the year, for the first year; 4.36 days or 1.20% for the second year; 36.42 days or 9 98% for the third year; 13.52 days or 3.70% for the fourth year; 0.75 days or 0.20% for the fifth year; 3.71 days or 1.02% for the sixth year; 27.58 days or 7.56% for the seventh year; 2.78 days or 0.76% for the eighth year; 44.90 days or 12.30% for the ninth year and 0.75 days or 0.21 % for the tenth year.

Figure 17 shows the results for a simulation carried out according to the method presented in this chapter, based on the determination of the boundaries of performance. In this figure, the system fails in 50.38 days or 13.80% of the year. The total time of failure is higher than that found with real data, but it is important to note that higher failures can occur with real data. This value should not be regarded as an upper limit.

The idealized curves used for description of hydro and solar availability can be seen in this figure. The gap between days with minimal availability was considered as equal to zero, thus resulting in null time complementarity. The idealized curves were constructed so that the system presents full energy complementarity and full complementarity between amplitudes, to better reflect the actual data available. The simulated system has battery banks for up to two days..

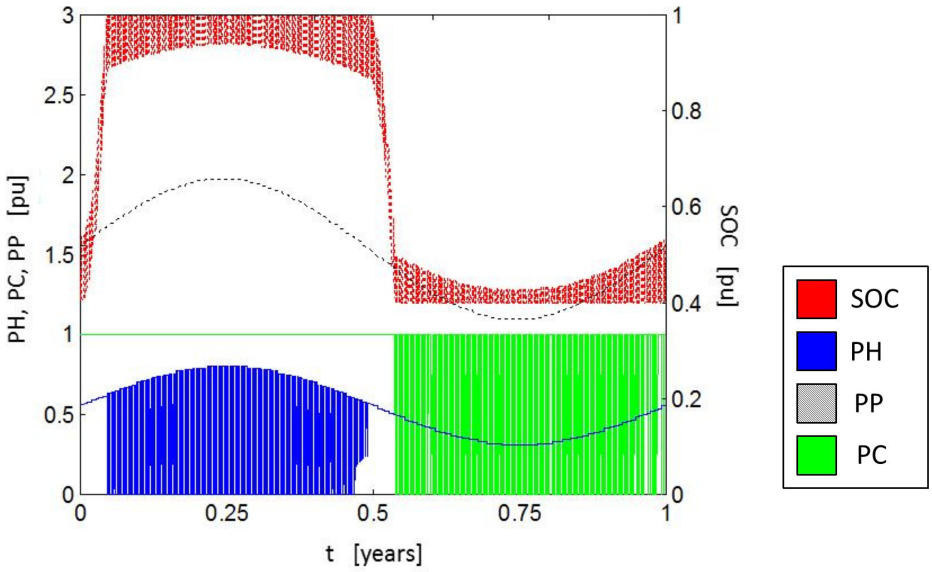


Figure 17. Simulation results for the idealized data as prescribed by the method of the boundaries of performance. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

The previous ten figures show similar results to what appears in this figure. Coincidentally, the total times of failure are lower than the total time to failure obtained for this last set of results, but this value should not be considered as a threshold value.

Figure 18 shows the results obtained with the manipulation of the results of Figure 7. Data were artificially delayed, so that it was reaching full complementarity in time. Thus, there are no failures in meeting the demands of consumers, mainly because they occurred in the first semester.

The gap created artificially leads to a situation in which the hydroelectric plant is constantly disconnected. As this is an energy resource without intermittency on the power supply, this result indicates that the installed capacity could be reduced. It is an example in which the comparison of this result with Figure 7 shows the usefulness of complementarity in achieving a hybrid system.

Figure 19 shows the results obtained with the data for the first year, Figure 7, with half of the PV modules. The total time of the failures grows to 11:07 days, 3.03% of the total period, reducing the disconnection of the hydroelectric plant. A natural result, since the total energy available decreased. It is a result that indicates that the failures in the results of the previous figures were not actually due to lack of available energy and could be lower in case of greater complementarity between energy resources.

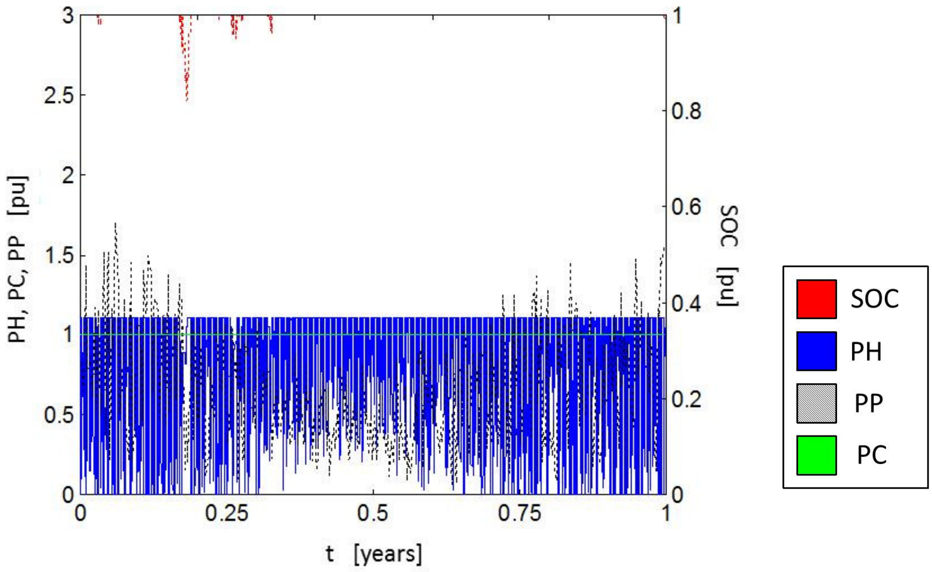


Figure 18. Simulation results for the data of Figure 7, artificially delayed in order to be reached full complementarity in time. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

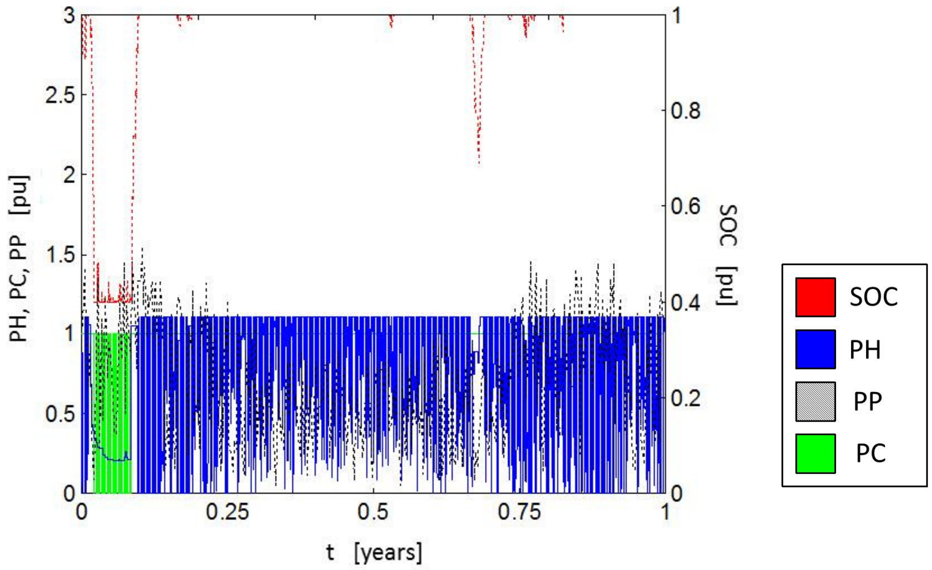


Figure 19. Simulation results for the data of Figure 7, with half of the PV modules. Conventions: SOC is the state of charge of the batteries, PH is hydroelectric power, PC is the power demanded by the load, PP is the PV power.

These results then provide a good measure of comparison between simulations performed with real data and the results obtained from the application of the method discussed in this chapter. The results for ten years of simulations led very similar to the results with idealized data. The application of the proposed method allows to evaluate the effects of complementarity without the influence of climatological or meteorological phenomena, among other effects.

9. FINAL REMARKS

This chapter was dedicated to energetic complementarity, discussing a concept of boundaries of performance. It is difficult to assess the complementarity with real data and this chapter also discusses a method to study the effect of complementarity on the performance of hybrid systems. The concept of boundaries of performance and the method discussed can contribute to specific systems, but its greatest utility appears as a management tool.

The basic principle is to describe the availability of energy resources with idealized mathematical curves, so that results free from the influence of climatological or meteorological effects are possible. These data can be used to build hybrid systems based on energy resources with different degrees of complementarity. Simulations with these data allow to relate different complementarities with total annual failure times in attendance of consumers.

The work related to energetic complementarity should continue, seeking more information about the performance of hybrid systems based on complementary energy resources, seeking to identify locations with greater complementarity between renewable energy resources and trying to relate complementarity between the harnessed energy resources and design parameters of hybrid systems and consolidating complementarity as a parameter for prioritizing projects.

REFERENCES

[1] Byrne J, Shen B, Wallace W. The economics of sustainable energy for rural development: a study of renewable energy in rural China. Energy Policy, 1998, 26, 45-54.

[2] Ekins P. Step changing for descarbonizing the energy system: research needs for renewables, energy efficiency and muclear power. Energy Policy, 2004, 32, 1891-1904.

[3] Dorian JP, Franssen HT, Simbeck DR. Global challenges in energy. Energy Policy, 2006, 34, 1984-1991.

[4] Software HOMER, version 2.68 beta. The Micropower Opyimization Model, Homer Energy. Available at www.homerenergy.com.

[5] Lambert, T.W. Gilman, P. Lilienthal, P.D. (2005) Micropower system modeling with Homer. In: Farret, F.A. Simões, M.G. Integration of Alternative Sources of Energy, John Wiley & Sons, p.379-418.

[6] Lilienthal, P.D. Lambert, T.W. Gilman, P. (2004) Computer modeling of renewable power systems. In: Cleveland, C.J. (ed.) Encyclopedia of Energy, Elsevier, v.1, p.633-647. NREL Report CH-710-36771.

[7] Himri Y, Stambouli AB, Draoui B, Himri S. Techno economical study of hybrid power system for a remote village in Algeria. Energy, 2008, 33, 1128-1136.

[8] Givler T, Lilienthal P. Using Homer software, NREL's micropower optimization model, to explore the role of gen sets in small solar power systems; case study: Sri Lanka. Technical Report NREL/TP-710-36774, May 2005.

[9] Weis TM, Ilinca A. The utility of energy storage to improve the economics of wind diesel power plants in Canada. Renewable Energy, 2008, 33, 1544-1557.

[10] Hoicka CE, Howlands IH. Solar and wind resource complementarity: advancing options for renewable electricity integration in Ontario, Canada. Renewable Energy, 2011, 36, 97-107.

[11] Denault M, Dupuis D, Couture-Cardinal S. Complementarity of hydro and wind power:

improving the risk profile of energy inflows. Energy Policy, 2009, 37, 5376-5384.

[12] Sovacool BK. The intermittency of wind, solar and renewable electricity generators: technical barrier or rhetorical excuse? Utilities Policy, 2009, 17, 288-296.

[13] Angarita JM, Usaola JG. Combining hydro generation and wind energy, biddings and operation on electricity spot markets. Electric Power Systems Research, 2007; 77, 393-400.

[14] Angarita JM, Usaola JG, Martinez-Crespo, J. Combined hydro wind generation bids in a poll based electricity market. Electric Power Systems Research, 2009; 79, 1038-1046.

[15] Benitez LE, Benitez PC, Cornelis van Kooten G. The economics of wind power with energy storage. Energy Economics, 2008, 30, 1973-1989.

[16] Anagnostopoulos JS, Papantonis DE. Simulation and size optimization of a pumped storage power plant for the recovery of wind farms rejected energy. Renewable Energy, 2008, 33, 1685-1694.

[17] Beluco A, Souza PK, Krenzinger A. A dimensionless índex evaluating the time complementarity between hydraulic and solar energies. Renewable Energy, 2008, 33, 2157-2165.

[18] Beluco A, Souza PK, Krenzinger A. A method to evaluate the effect of complementarity in time between hydro and solar energy on the performance of hybrid hydro PV generating plants Renewable Energy, 2012, 45, 24-30.

[19] Beluco A, Souza PK, Krenzinger A. Influence of different degrees of complementarity of solar and hydro energy availability on the performance of hybrid hydro PV generating plants. Energy and Power Engineering, 2013, 5, 332-342.

[20] Beluco A, Souza PK, Krenzinger A. PV hydro hybrid systems. IEEE Transactions Latin America, 2008, 6, 626-631.

[21] Bekele G, Tadesse G. Feasibility study of small hydro PV wind hybrid system for off grid rural electrification in Ethiopia. Applied Energy, 2012, 97, 5-15.

[22] Nfah EM, Ngundam JM. Feasibility of pico hydro and photovoltaic hybrid power systems

for remote villages in Cameroon. Renewable Energy, 2009, 34, 1445-1450.

[23] Kruangpradit P, Tayati W. Hybrid renewable energy system development in Thailand. World Renewable Energy Congress, 1996, 514-517.

[24] Fundação Estadual de Pesquisas Agropecuárias, Seção de Ecologia Agrícola. Agroclimatic atlas of the State of Rio Grande do Sul [in portuguese], 1989, Porto Alegre, Brazil, 3v.

[25] Software Radiasol. Universidade Federal do Rio Grande do Sul, Laboratório de Energia Solar. Available at solar.ufrgs.br.