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Influence of Time Complementarity on Energy Storage through Batteries in Hydro PV Hybrid Energy System

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Abstract

The notion of energetic complementarity can be a tool for energy resource managers to prioritize energy generation projects based on renewable resources in both interconnected and independent systems. As a tool in decision-making, it is important to know better the influence of energetic complementarity on the performance of hybrid systems especially with regard to energy shortages but also in relation to other parameters. In recent years, hydro PV hybrid systems have become a growing target of researchers and designers for the idea of installing photovoltaic modules on the water surface of reservoirs. Energetic complementarity has three components: time-complementarity, energy-amplitude and amplitude-complementarity. This paper is dedicated to the study of the influence of time-complementarity on the storage of energy through batteries in hydro PV hybrid systems. The method applied is in the literature and suggests the simulation of the system under study with the idealization of energy availabilities, to remove the effects of climatic variations and the characteristic intermittency of renewable resources. Simulations were performed with the well-known software Homer. The results provided the variations of the states of charge of the batteries as a function of different time-complementarities, indicating as expected better performances associated to higher time-complementarities. The results indicated that the cost of energy for a hybrid system with 28 batteries was equal to US$ 0.502 per kWh and that this cost increased as the time complementarity between energy resources moved away from the situation corresponding to full complementarity. The simulations also showed that the maintenance of the zero failure condition supplying the demands of the consumer loads requires that the load be reduced to 52% if the complementarity is reduced from the full complementarity to zero complementarity, with the cost of energy going from US$ 0.502

per kWh to US$ 0.796 per kWh. The results also allow a better understanding of the influence of time complementarity on the performance of hybrid systems.

Keywords

Energetic Complementarity, Time Complementarity, Hybrid Systems, Hydro Power, PV Power, Hydro PV Hybrid Systems

1. Introduction

The climatological and geomorphological characteristics of the Brazilian national territory form a scenario of great hydraulic availability, which is currently used by the electric energy sector for power generation. This energy production corresponds to approximately 64% of the domestic supply generated by the system. In contrast, photovoltaic solar energy has only a 0.01% share in this offer, despite the great potential available [1].

Some of the factors that hamper photovoltaic utilization are the seasonal variability of the resource availability and the intermittence caused by the limited daily sunshine time. As a technical solution to these factors, accumulation systems transfer energy from the period of high energy availability to the period of low or zero availability at the cost of increasing the total investment of the system to guarantee the supply of the consumer loads.

The use of two or more energy resources in the same energy system can contribute to its feasibility, with technical advantages in its performance. In addition, a hybrid system can also have improved feasibility if there is complementarity between exploited energy resources. Energetic complementarity can influence the design of generating equipment and storage devices, and can also be better exploited as a consequence of the available storage media.

Energetic complementarity has been discussed for many years, but it was the work of Beluco [2] who first discussed the concept of complementarity more comprehensively and proposed that complementarity should be considered as a result of three components: time-complementarity, energy-complementarity and amplitude-complementarity. In addition, complementarity can be determined in one location (referred to as temporal complementarity) or at different locations (termed spatial complementarity).

The influence of complementarity on the performance of energy generation systems can be determined with the application of the method proposed by Beluco [3], based on simulation of hybrid systems with ideal energy availability. The work of Beluco [4] discusses the establishment of a performance limit for hybrid systems under the influence of energetic complementarity. In that way, precisely determining the influence of complementarity without the effects of intermittent renewable resources is possible.

Over the last few years, hydroelectric photovoltaic hybrid systems have focused increasing attention of researchers and designers with the idea of installing photovoltaic panels on the water surface of reservoirs. The works of Gisbert [5] and Santafé [6] proposed this solution. These hybrid systems even allow the study of the joint operation of both energy storages through reservoirs and through batteries.

The notion of energetic complementarity is somewhat instinctive, but more in-depth work on the subject has been unleashed in the last ten years. Several works, as shown above, are dedicated to the identification of complementarity between different renewable energy resources and their expression through maps. Another work front should identify the influence of energetic complementarity on the performance of hybrid systems.

Among the most recent studies related to energetic complementarity, Monforti [7] analyzes the complementarity between solar and wind resources throughout the territory of Italy and Widén [8] shows, by correlation analysis, how these two energy resources are complementary along the territory of Sweden. Cantão [9] study the spatial complementarity between historical flow rates and wind velocities throughout Brazil, presenting the results through correlation maps. Silva [10] show levels of spatial complementarity between water resources and offshore wind resources at points along the coast of Brazil.

An *et al.* [11] analyzes the photovoltaic hydroelectric project of Longyangxia, China, which proposes the smoothing of the characteristic intermittence of solar energy with the operation of the photovoltaic modules in a complementary way, an operational complementarity, with the operation of one of the hydraulic turbines of the hydroelectric power plant. Kougias *et al.* [12] Proposes a method that iteratively examines the possibility of improving the complementarity among the exploited energy resources by modifying the configuration of the system components and their respective locations in order to maximize energetic complementarity.

This article is inserted in the research process focused on the influences of energetic complementarity on the performance of hybrid systems, specifically with the application of the method proposed by Beluco [3] to establish the influence of time-complementarity on energy storage through batteries in hydroelectric photovoltaic hybrid system.

This article has four sections besides this introduction. The next section discusses the method applied to understand the influence of time-complementarity on storage through batteries. The following section describes the hybrid system being studied and the simulations performed with Homer. The two subsequent sections respectively present the results and conclusions.

2. Methodology

The influence of energetic complementarity in time on energy storage through batteries in hydro PV hybrid systems will be studied with the application of the method proposed by [3], hereinafter referred to as the Method of Beluco. This method suggests the use of idealized curves to describe the energy availabilities and understand the effects of complementarity on hybrid system performance without the consequences of variability of renewable resources.

With ideal energy availability describing the available renewable energy resources, the hydro PV hybrid system under study will be simulated with the well-known software Homer. The system under study will be simulated for several different time complementarities between full complementarity and zero complementarity, as defined by Beluco *et al.* [2]. The time-complementarity index, which allows to make this comparison, is defined in Equation (1).

$$\kappa_t = \frac{|d_1 - d_2|}{\sqrt{|D_1 - d_1||D_2 - d_2|}} \tag{1}$$

In this equation, D is the number of the day (or month) in which the maximum energy availability occurs and d is the day (or month) in which the minimum value occurs. Subscript 1 indicates one of the energy resources while the number 2 indicates the other. The denominator assesses whether energy resources have a 180-day (or six-month) interval between maximum and minimum energy availability, which also affects the complementarity in time between the renewable energy resources considered.

The software Homer [13], The Micropower Optimization Model, was developed by National Renewable Energy Laboratory (NREL) and is available for universal access in its version 2.68 beta, called Legacy. Homer simulates a hybrid energy system in a period of one year at intervals of 60 minutes, also presenting a feasibility study for the life time of the system, usually considered as 25 years. [14] [15].

The simulation of the same hydro PV hybrid system with different energy availabilities, between full complementarity and zero complementarity, with availability data established by the Method of Beluco, will provide the performance of energy storage through batteries as a function of the different complementarities. The difference of the results of this work for results obtained with real data is that this will require larger banks of batteries for the same performance.

3. Hydro PV Hybrid Systems under Study

The study undertaken in this work was based on the hybrid system illustrated in **Figure 1**. It is a photovoltaic hydroelectric hybrid system based on energy resources equally distributed between water and solar resources (therefore with full energy-complementarity), with a consumer load exactly adjusted to the energy made available with the generating equipment. The hydro power plant operating in ac and the PV modules operating on the dc bus, along with the batteries.

This system was simulated with idealized energy resources, as suggested by the Method of Beluco, simulating different values for the time-complementarity index. **Figure 2(a)** shows the water resources considered in the simulations and the solar resources are shown in **Figure 2(b)**, for 180 days lag and full complementarity, in **Figure 2(c)** for 150 days, in **Figure 2(d)** for 120 days, in

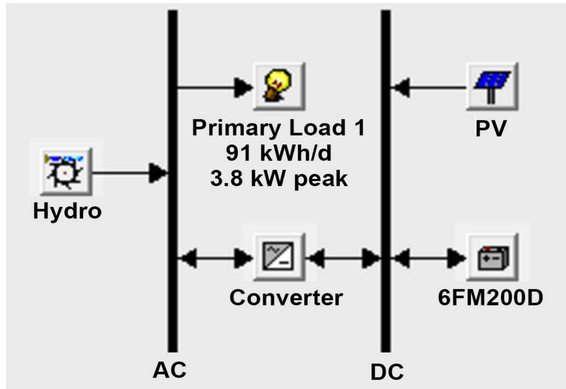


Figure 1. Hydro PV hybrid system simulated with Homer.

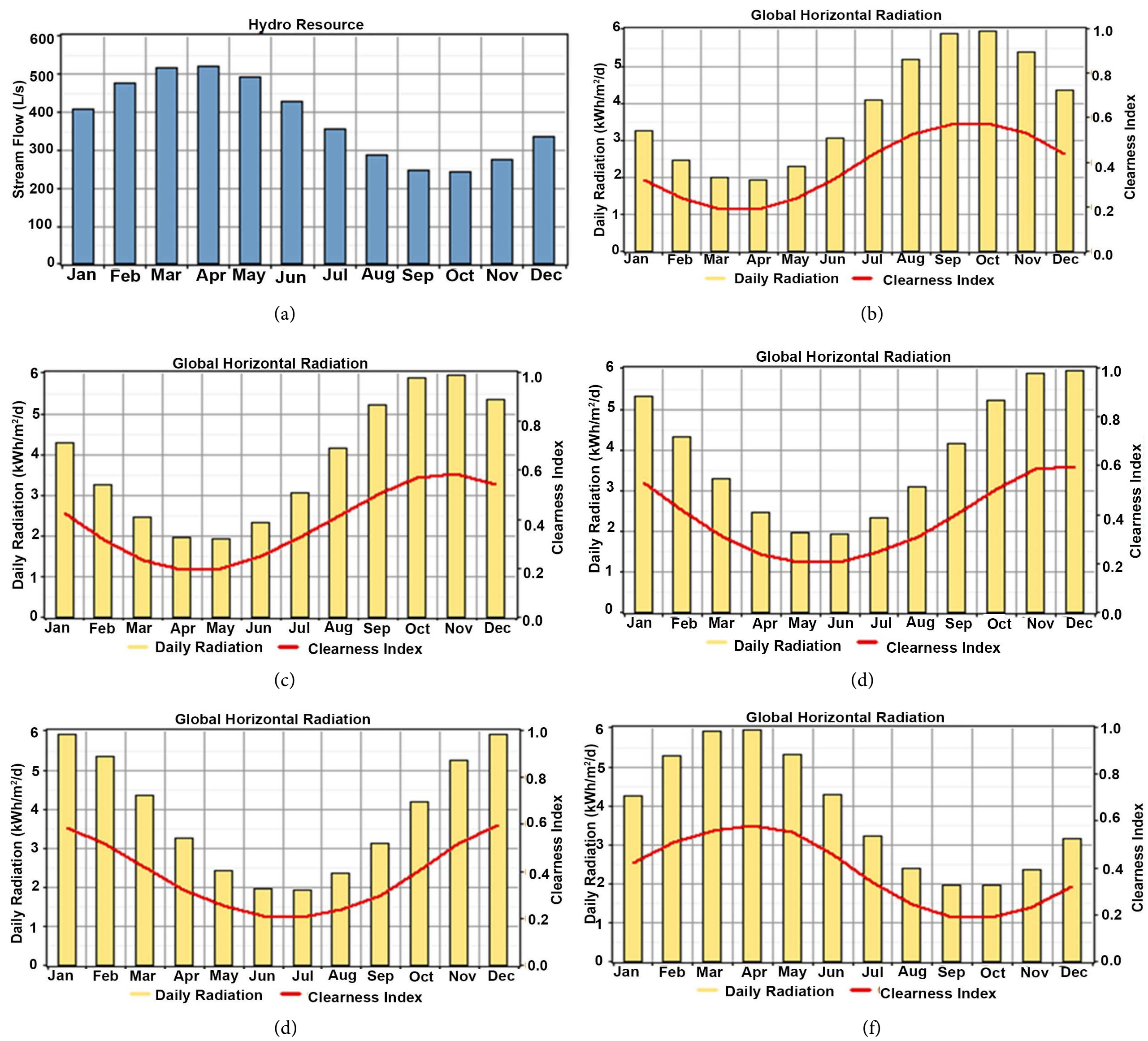


Figure 2. Energy resources. (a) Water resources considered in all simulations. Solar radiation incident on a horizontal plane for (b) maximum complementarity; (c) complementarity of 83.33%; (d) complementarity of 66.67%; (e) complementarity of 50.00% and (f) null complementarity, respectively, with water resources shown in (a).

Figure 2(e) for 90 days and in Figure 2(f) for zero complementarity. All curves has full amplitude-complementarity.

The hydroelectric power plant has 2.22 kW of installed power and its construction cost was considered as being equal to US$ 1750 per kW, with a useful life of 25 years. The photovoltaic modules sums 17,532 kWp and its construction cost was considered as being equal to US$ 3000 per kWp, with a useful life of 12.5 years. The converter costs $900 per kW, with 90% efficiency both as an inverter and as a rectifier, with 100% capacity for both. The consumer load is constant and dimensioned to present consumption equal to the available energy in the situation of full complementarity, with 3.8 kW of permanent consumption and 91.2 kWh of daily consumption.

The batteries selected for the simulations of this work were the model 6FM200D [16], because this model simulates most of the medium-sized automotive batteries that can be found in the market with relative ease. This model has rated voltage of 12 V and a nominal capacity of 200 Ah, resulting in an approximate capacity of 2.4 kWh. The useful life is estimated at approximately a little over 900 kWh, considering the total energy flows for accumulation and for consumption, without deep discharges. Battery costs were estimated at $200 for acquisition and $160 for replacement, with $10 a year for maintenance.

Two sets of five complete simulations for five complementarity values were performed. In the first, a set of 1476 simulations for 87 values of sensibility, for each complete simulation, were performed. In the second set, 1476 simulations for 48 values of sensibility, for each complete simulation, were performed. The values of the optimization variables and the sensitivity inputs are shown respectively in Table 1 and Table 2.

The results are presented and discussed in the next chapter.

4. Results and Discussion

The results for the system of Figure 1 simulated with hydro energy availability shown in Figure 2(a) and solar energy availability shown in Figure 2(b) can be considered as references for comparisons. This system presents complete complementarity between its energy resources, shown by the index κt shown in Equation (1) with a value equal to 1.0000. The simulations showed that this system, equipped with a bank containing 28 batteries, meets the demands of consumer loads without failures along one year.

Figure 3(a) shows the hourly variation of PV power, hydro power, AC primary load and state of charge of batteries along one year. This graph shows the idealized energy availabilities and the way these functions allow to understand the variations of the SOC of batteries without the influence of the climatic variations or the intermittence of the energy resources.

Clearly, battery charge variations occur between late night and early morning, until solar power is sufficient for energy storage. The minimum states of charge of batteries will be the lower the higher the contributions of solar energy. The

Table 1. Optimization variables and sensitivity inputs for the first set of simulations.

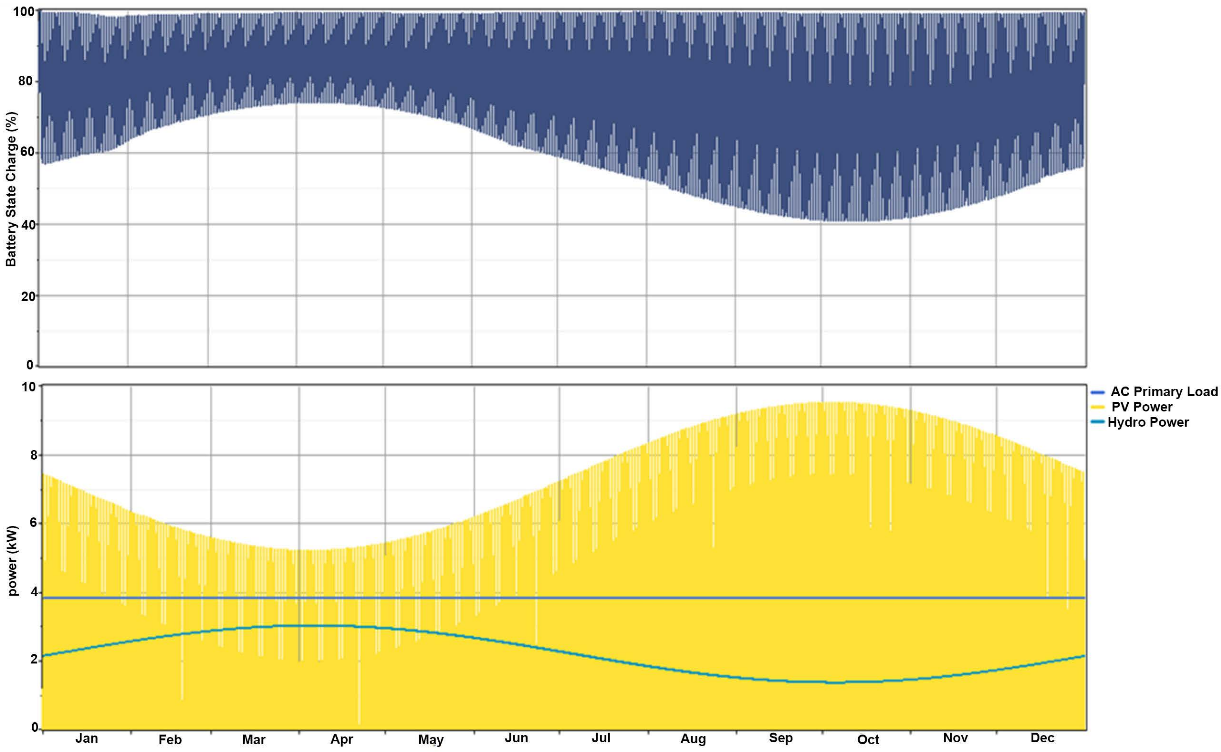
Optimization variables	Number of batteries[a]	0	1	2	3	4	5	6	7
		8	9	10	11	12	13	14	15
		16	17	18	19	20	21	22	23
		24	25	26	27	28	29	30	31
		32	33	34	35	36	37	38	39
	Converter capacity [kW]	0.0	0.2	0.4	0.6	0.8	1.0	1.2	
		1.4	1.6	1.8	2.0	2.2	2.4	2.6	
		2.8	3.0	4.0	5.0	6.0			
Sensitivity inputs	AC load [kWh/d]	91.200	86.640	95.760					
	Maximum annual capacity shortage [%]	0.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0
		5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
		13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
		21.0	22.0	23.0	23.0	25.0			

Table 2. Optimization variables and sensitivity inputs for the second set of simulations.

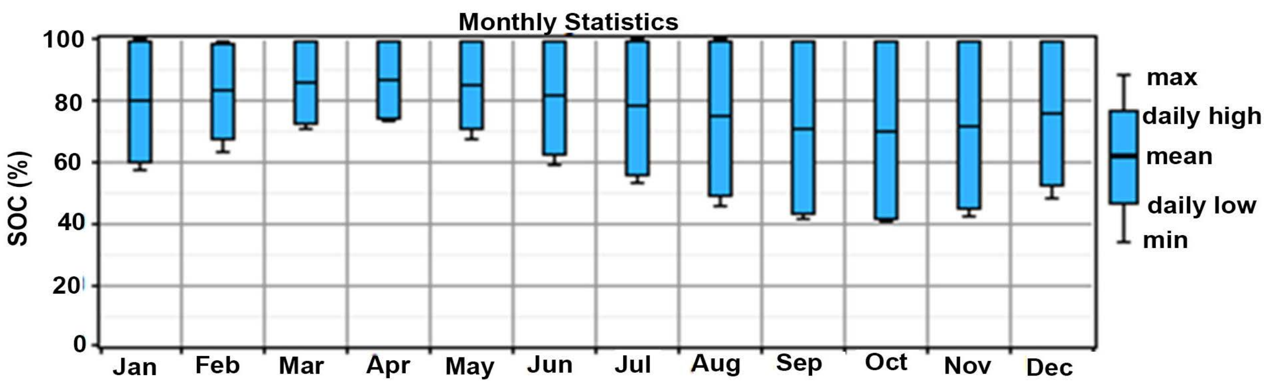
Optimization variables	Number of batteries[a]	0	1	2	3	4	5	6	7
		8	9	10	11	12	13	14	15
		16	17	18	19	20	21	22	23
		24	25	26	27	28	29	30	31
		32	33	34	35	36	37	38	39
	Converter capacity [kW]	0.0	0.2	0.4	0.6	0.8	1.0	1.2	
		1.4	1.6	1.8	2.0	2.2	2.4	2.6	
		2.8	3.0	4.0	5.0	6.0			
Sensitivity inputs	AC load [kWh/d]	90.288	89.376	88.464	87.552	86.640	85.728		
		84.816	83.904	82.992	82.080	81.168	80.256		
		79.344	78.432	77.520	76.708	75.696	74.784		
		73.872	72.960	72.048	71.136	70.224	69;312		
		68.400	67.488	66.576	65.664	64.752	63.840		
		62.928	62.016	61.104	60.192	59.280	58.368		
		57.456	56.544	55.632	54.720	53.808	52.896		
		51.984	51.072	50.160	49.248	48.336	47.424		
	Maximum annual capacity shortage [%]	0.0							

daily variations in the state of charge of batteries will be lower as the higher the hydroelectric contributions.

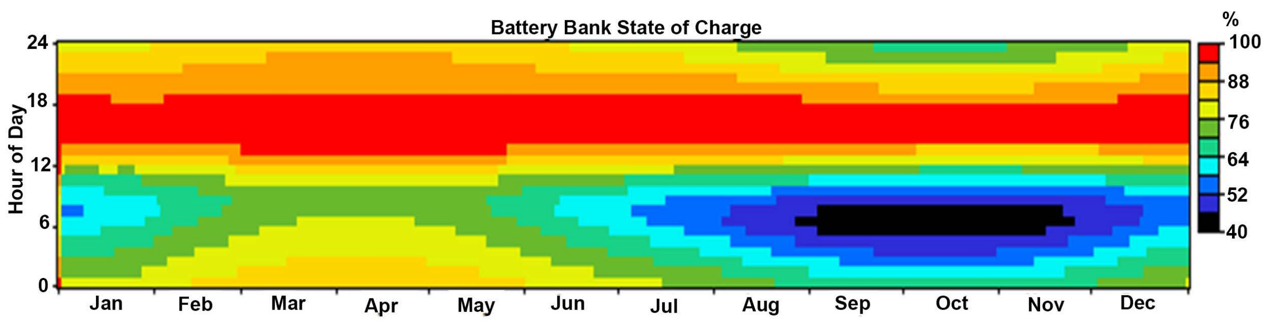
These results reproduce some results presented by Beluco [3]-[17]. **Figure 4** details the period between March 26 and March 31, in **Figure 4(a)**, and between September 16 and September 21, in **Figure 4(b)**, confirming that obviously the minimum states of charge occur at the end of the night. The largest variations in



(a)

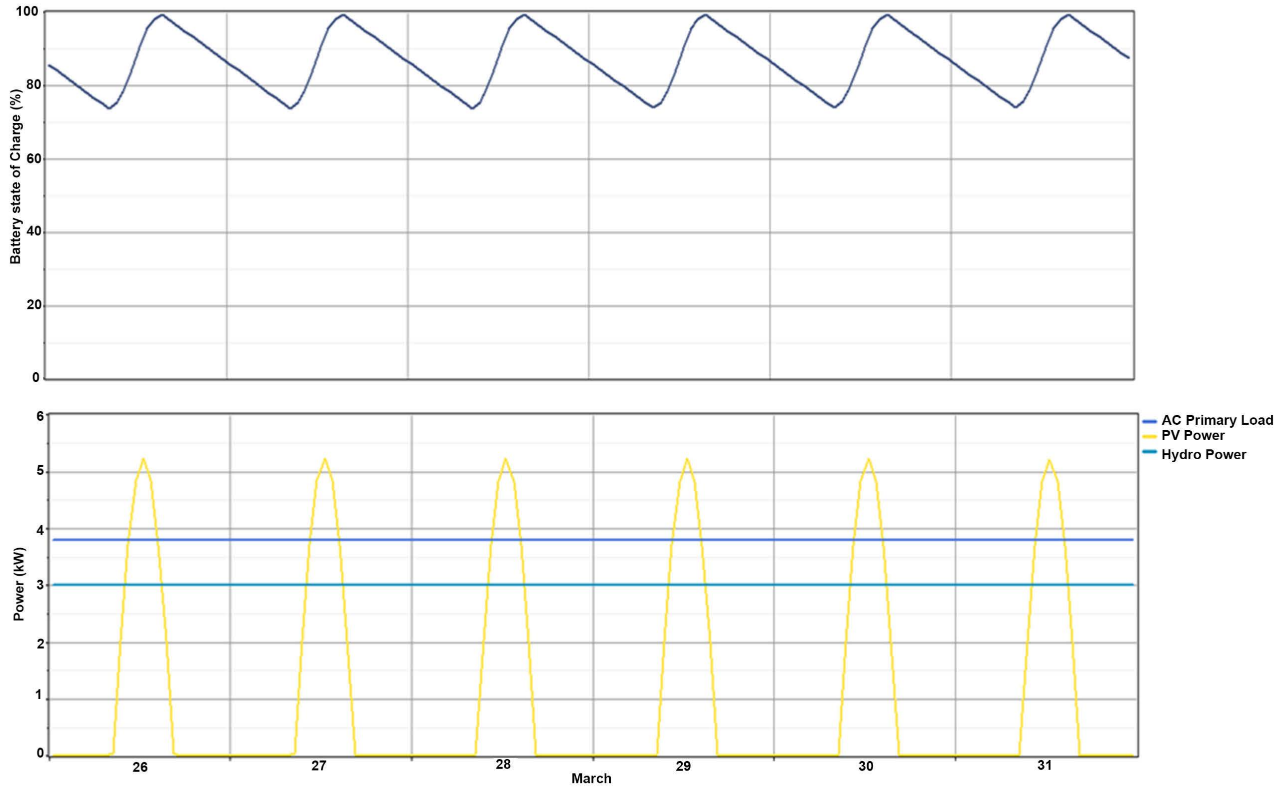


(b)

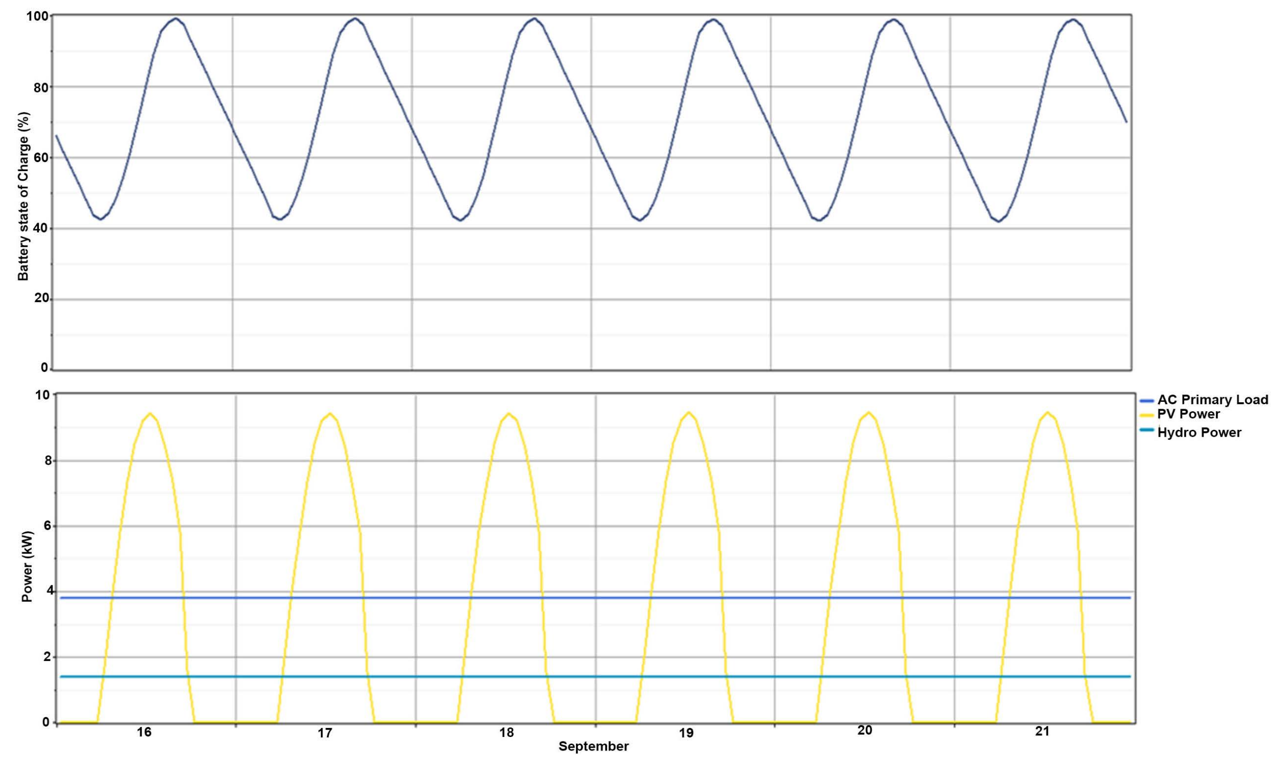


(c)

Figure 3. Results for the system of **Figure 1** with full complementarity and 28 batteries. for: (a) Hourly variation of PV power (in yellow), hydro power (in green) and AC primary load (in blue), in the bottom graph, and of state of charge (SOC) of batteries, in the graph above; (b) Monthly variation of the state of charge (SOC) of the battery bank; (c) Hourly variation of the state of charge (SOC) of the battery bank.



(a)



(b)

Figure 4. Hourly variation of PV power (in yellow), hydro power (in green) and AC primary load (in blue), in the bottom graph, and of state of charge (SOC) of batteries, in the graph above, for the system of **Figure 1** with full complementarity and 28 batteries. Details for the periods between (a) March 26 and March 31 and (b) September 16 and September 21.

the state of charge of the batteries in this work occur because the bank of 28 batteries considered allows a total autonomy of only 10.6 hours.

Figure 3(b) shows the average monthly variation over a year of the state of charge (SOC) of the batteries for this system. This figure shows the monthly average daily value of the SOC, the daily maximum and minimum daily average values and also the maximum and minimum daily values throughout the months of the year.

The full complementarity of this system allows the batteries to reach their maximum SOC at the end of every day of the year. The discharge depths vary throughout the year and are smaller when the maximum water availability is verified. The greater variability of the solar energy causes that the greater discharge depths coincide with the minimum values of water availability.

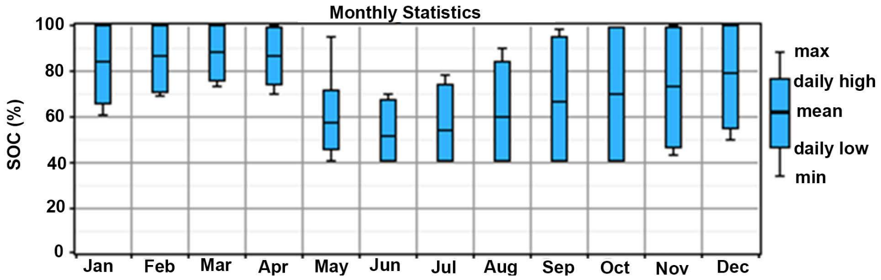
Figure 3(c) shows the hourly variation over a year of the state of charge (SOC) of the batteries for that same system. This figure shows a lot of condensed information in a small area. The red band in the middle part just above the center line shows that the batteries reach their charge limit shortly after the daily peak of solar radiation. Likewise, the black region in the second half of the year indicates that in this period the batteries have their load varying between the minimum and maximum values of load on every day. The batteries reach their minimum charge in the late hours and early mornings.

From this point, two sets of results were obtained. The first (Figures 5-8) corresponds to the results with the energy availability (Figure 2) and the consumer loads with equal power values. The second (Figures 9-11) corresponds to the results with the consumer load with decreasing values, so that there are no failures in the energy supply to the consumer loads even with the complementarity being reduced.

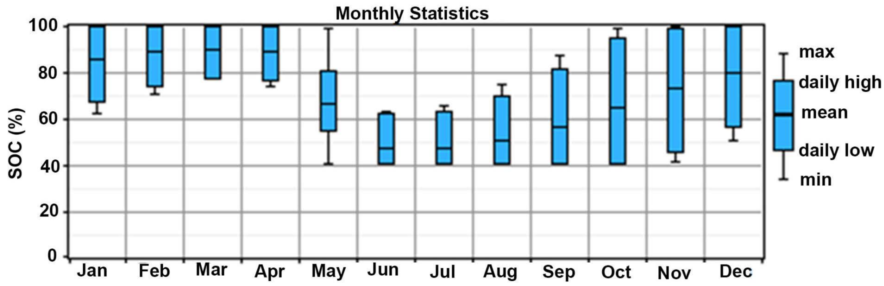
Figures 5(a)-(d) respectively show the evolution of the results in Figure 3(b) for complementarities of 83.33%, 66.67%, 50% and 0 %, or values of κt equal respectively to 0.8333, 0.6667, 0.5000 and 0.0000. Similarly, Figures 6(a)-(d) respectively show the evolution of the results in Figure 3(c) for complementarities of 83.33%, 66.67%, 50% and 0%. All these results were obtained for the system shown in Figure 1, operating with a bank of 28 batteries. In addition, Figure 7 shows the evolution of the frequencies of the states of charge as a function of the different time-complementarities and Figure 8 shows the energy shortage [%] and cost of energy [US%/kWh] as a function of time-complementarities.

Throughout these figures, to the extent that the period of greatest sunshine migrates to the first semester, coinciding with the period of greater water availability, the oscillations of the states of charge of batteries become smaller and the states of charge approximate their maximum values. Likewise, in the second half of the year, there are greater fluctuations in the states of charge of batteries and a greater approximation of their minimum values.

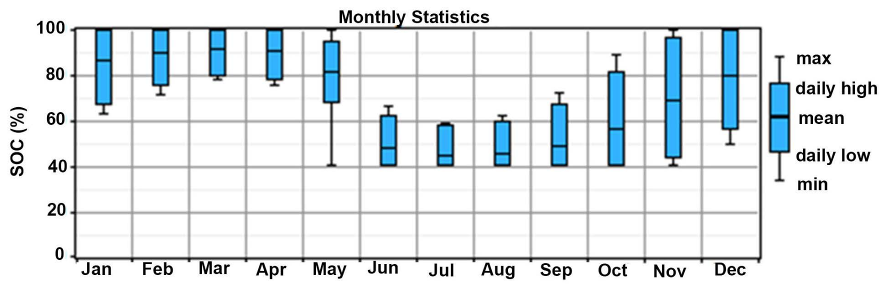
It is interesting to observe how the pattern of the images in Figure 6 shows an evolution along the complementarity variation and how this pattern presents differences with respect to Figure 3(c). These changes clearly reflect the



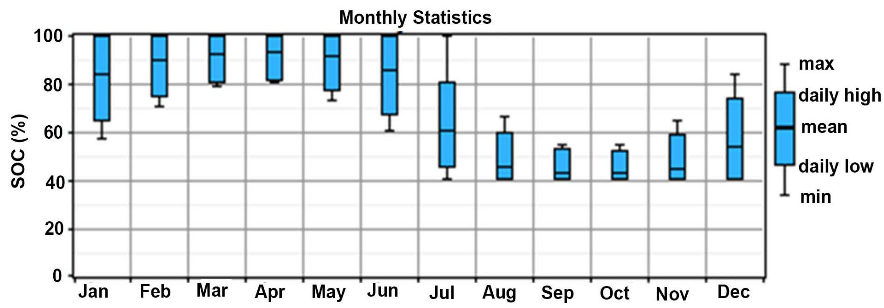
(a)



(b)



(c)



(d)

Figure 5. Monthly variation of the state of charge (SOC) of the batteries for the system of **Figure 1**, with 28 batteries, without energy excess, with: (a) complementarity of 83.33%; (b) complementarity of 66.67%; (c) complementarity of 50% and (d) zero complementarity.

displacements of the periods along the year with maximum states of charge and periods with minimum states of charge of the batteries respectively towards the first half and the second half of the year, as complementarity becomes zero.

This trend can be confirmed by the frequency histogram of the states of charge in **Figure 7**. For full complementarity, the most frequent states

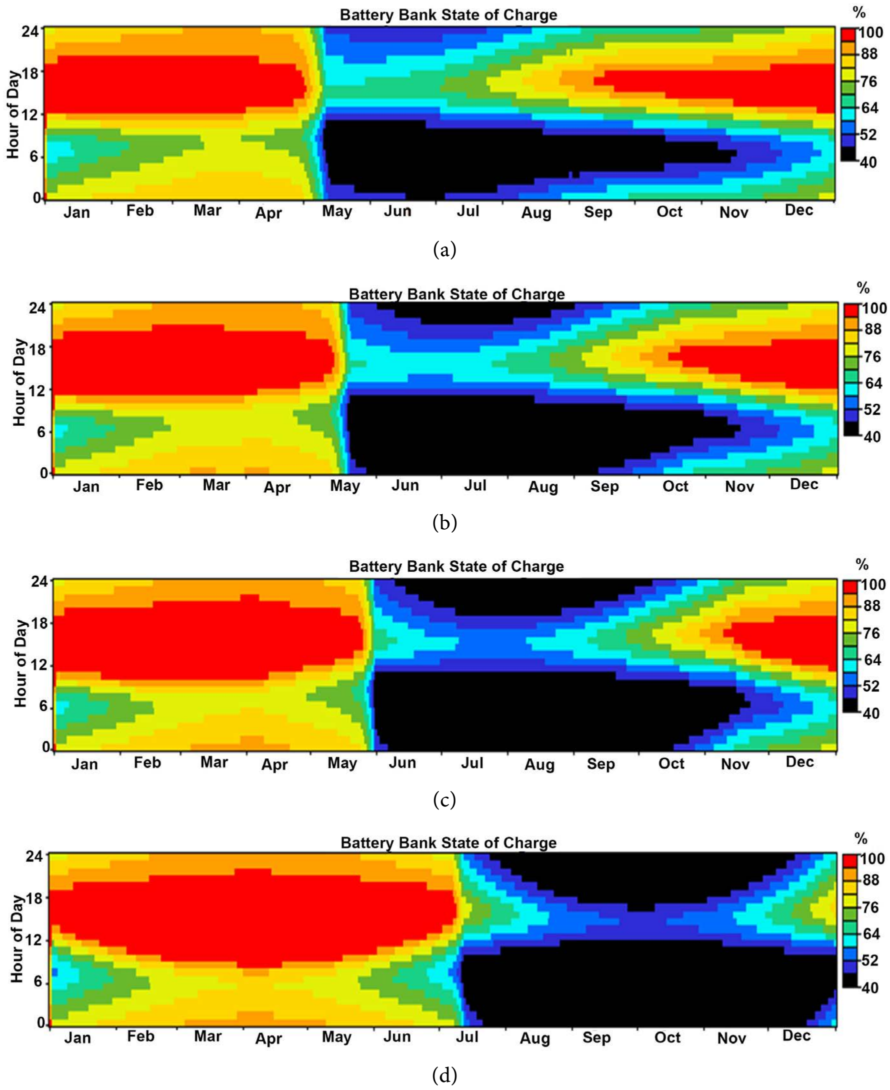


Figure 6. Hourly variation of the state of charge (SOC) of the batteries for the system of Figure 1, with 28 batteries, without energy excess, with: (a) complementarity of 83.33%; (b) complementarity of 66.67%; (c) complementarity of 50% and (d) zero complementarity.

correspond to the maximum states of charge of batteries. The intermediate lags present intermediate values of frequencies, with growth of extreme values. For zero lag, that is, with zero complementarity, the most frequent states of charge are the maximum and minimum values of charge of batteries.

With regard to energy shortage, as can be expected, Figure 8 shows that the energy shortage decreases as complementarity in time is greater. In the case of this simulated system, this energy shortage reaches zero with maximum values of time-complementarity. On the other hand, the maximum shortage, for zero complementarity, is equal to 12.60%. Although these results are relatively universal, they will be different for systems simulated with other parameters.

The cost of energy as a function of time-complementarity, by the method with which the simulations were executed, presents a lesser adherence to reality. Even

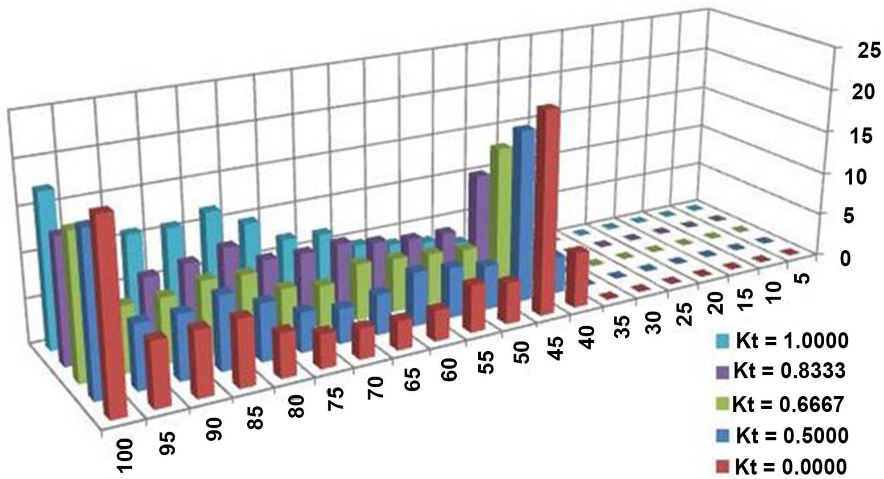


Figure 7. Histograms of frequencies of the states of charge (SOC) of the batteries for the system of Figure 1, with 28 batteries, without energy excess, with: (a) total complementarity; (b) complementarity of 83.33%; (c) complementarity of 66.67%; (d) complementarity of 50% and (e) zero complementarity.

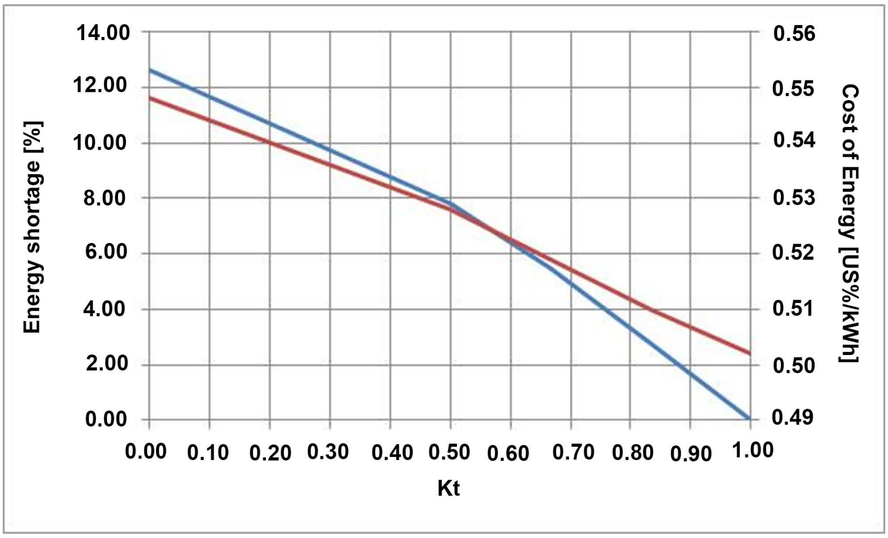
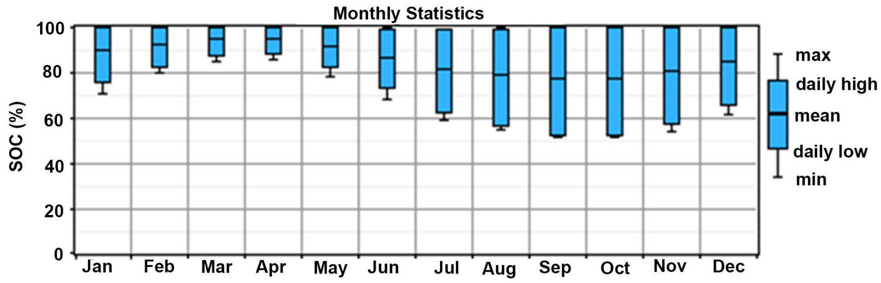


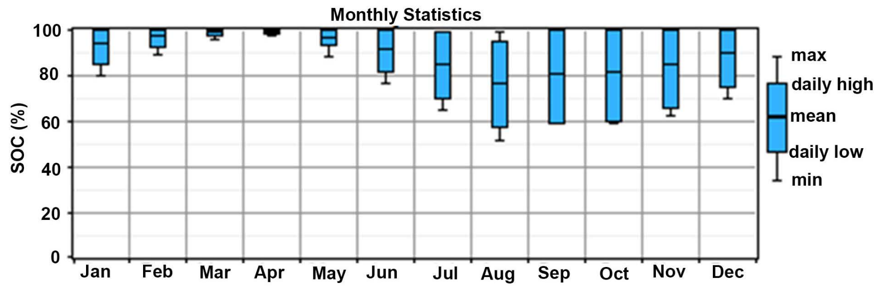
Figure 8. Energy shortage [%], in blue, and cost of energy [US$/kWh], in red, as a function of time-complementarity, for the system of Figure 1 with 28 batteries and without energy excess.

so, the cost of energy is also shown in Figure 8. The cost for complete complementarity was US$ 0.502 per kWh, while the cost for zero complementarity was US$ 0.548 per kWh. These values for the cost of energy can be interpreted as a lower limit for economic performance, since the performance obtained in this way consists of an upper limit of technical performance.

Figure 9 and Figure 10 show respectively the evolution of the results in Figure 3(b) and Figure 3(c) for complementarities of 83.33%, 66.67%, 50% and 0%, without failures in the energy supply to the consumer loads. Additionally, Figure 11 shows the energy shortage and cost of energy as a function of different time-complementarities. These results were obtained with the consumer loads



(a)



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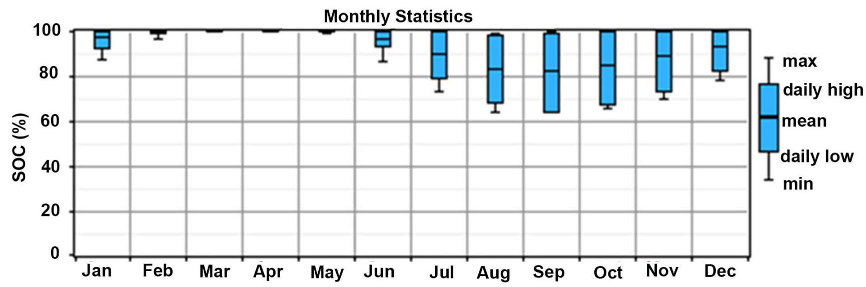

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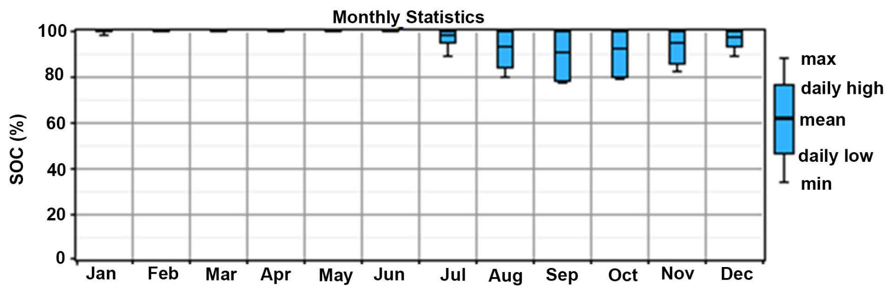
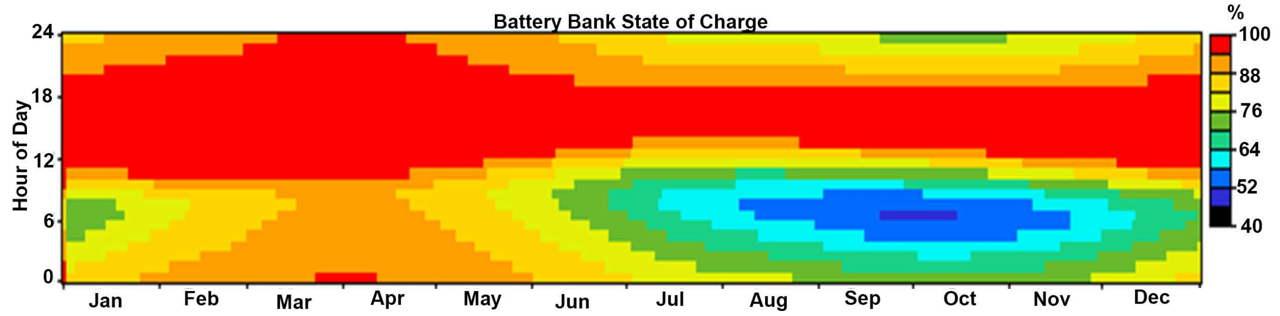


(d)

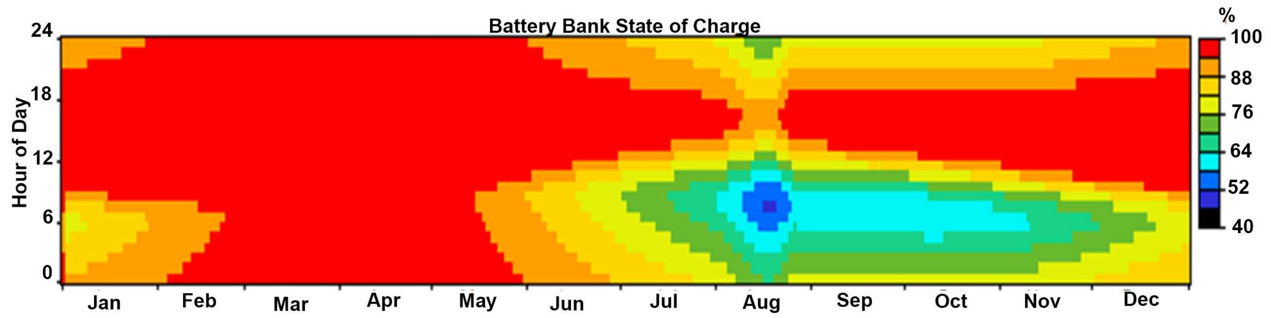
Figure 9. Monthly variation of the state of charge (SOC) of the batteries for the system of **Figure 1**, with 28 batteries, without failures in the supply to the consumer loads, with: (a) complementarity of 83.33%; (b) complementarity of 66.67%; (c) complementarity of 50% and (d) zero complementarity.

with decreasing values, so that there are no failures in the energy supply to the consumer loads even with the complementarity being reduced.

Figure 9 and **Figure 10** show the states of charge of batteries closest to the maximum states, even in situations of unfavorable availability, because more energy is available by the way these results were obtained. Of course, as



(a)



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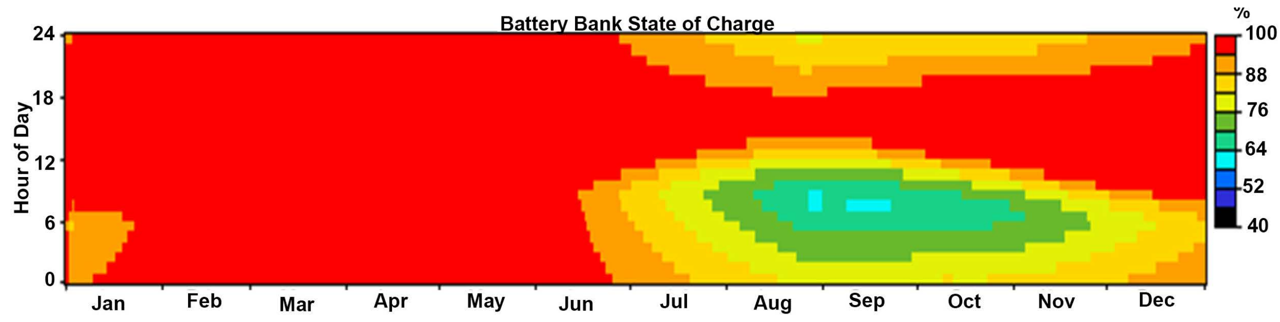
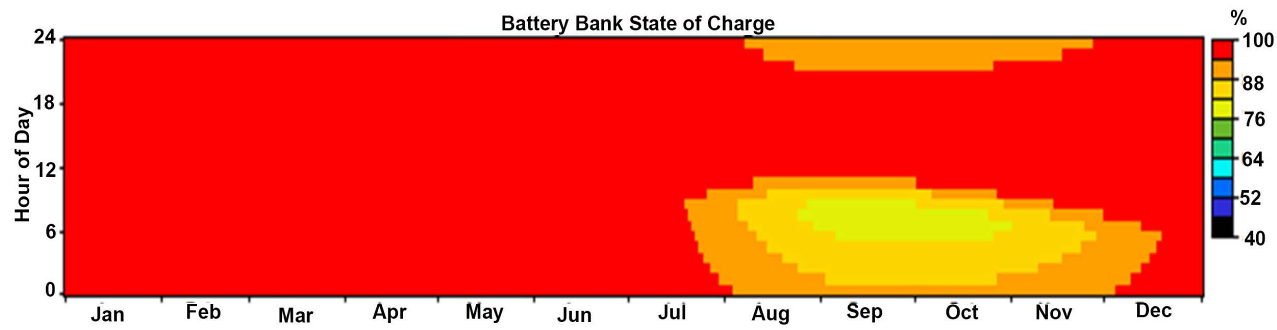


(c)



(d)

Figure 10. Hourly variation of the state of charge (SOC) of the batteries for the system of Figure 1, with 28 batteries, without failures in the supply to the consumer loads, with: (a) complementarity of 83.33%; (b) complementarity of 66.67%; (c) complementarity of 50% and (d) zero complementarity.

complementarity approaches zero and the available resources approach the combination between **Figure 2(a)** and **Figure 2(f)**, the largest charge variations are concentrated in the period of the lowest energy available.

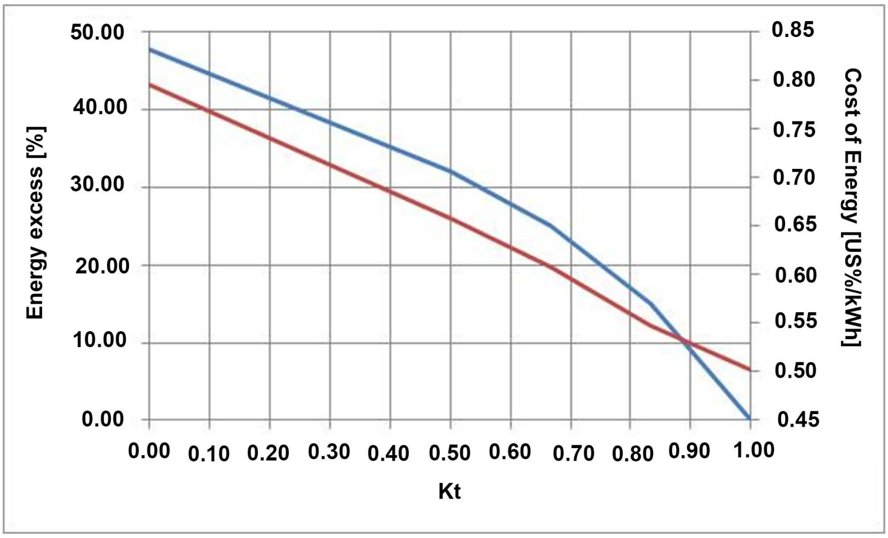


Figure 11. Energy excess [%], in blue, and cost of energy [US$/kWh], in red, as a function of time-complementarity, for the system of **Figure 1** with 28 batteries and without failures in the supply to the consumer loads.

Figure 11 shows that the lower the complementarity, the greater the need for energy so that there are no shortcomings in the supply of consumers. For zero complementarity, the excess is close to 50%. This figure also shows the costs associated with such excess energy, showing that the initial value of US$ 0.502 per kWh grows to US$ 0.796 per kWh for the worst situation.

5. Conclusions

This paper studied the influence of time-complementarity on the performance of energy storage through batteries in hybrid hydroelectric photovoltaic systems. The study was based on simulations with the well-known software Homer and the application of the Method of Beluco to study hybrid systems based on complementary resources.

The simulations showed the evolution of the performance of batteries over a year for different values of complementarity. The results indicated that the cost of energy for a hybrid system with 28 batteries was equal to US$ 0.502 per kWh and that this cost increased as the complementarity moved away from the situation with complete complementarity.

The simulations also showed that the maintenance of the zero failure condition supplying the demands of the consumer loads requires that the consumer load be reduced to 52% if the complementarity is reduced from the full complementarity to zero complementarity, with the cost of energy going from US$ 0.502 per kWh to US$ 0.796 per kWh.

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