A PV WIND HYDRO HYBRID SYSTEM WITH PUMPED STORAGE CAPACITY INSTALLED IN LINHA SETE, APARADOS DA SERRA, SOUTHERN BRAZIL

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ABSTRACT. The intermittency and variability of various renewable energy resources, such as wind power and photovoltaic solar energy, can be overcome with the use of these resources in conjunction with energy storage devices. The energy storage as hydraulic power, so before energy conversion, can guarantee high efficiency to the storage process. This study aims to identify the technical and economical feasibility of using wind power and PV modules in conjunction with a reversible hydroelectric power plant installed in Aparados da Serra, in the south of the Serra Geral, a geological structure in southern Brazil that allows topographical height differences of approximately 600 meters. In this work, specifically, a hydro power plant installed at Linha Sete with 610 kW and 400 meters height. This study explores the feasibility of this pumped storage plant operating in conjunction with existing wind turbines and PV modules installed on the surface of reservoirs. The work is based on simulations and optimization performed with well-known software Homer. The results indicate that a group of 10 to 50 2 MW wind turbines may have capacity factor increased from usual 0.34 to values between 0.50 and 0.60. The results also relate the power capacity and costs per kW installed for PV modules to be feasible. This work also indicates useful conclusions in the design process and implementation of the hybrid system under study.

KEYWORDS. Wind energy, wind diesel hybrid systems, Weibull shape parameter, southern Brazil, computational simulation, software Homer.

1. INTRODUCTION

Brazil is blessed with one of the largest water resource systems and one of the largest hydroelectric potential in the world. Thus, Brazil has in its territory some of the largest hydroelectric power plants and a lot of water reservoirs with large bodies of water artificially formed. As a result, Brazil is one of the few countries worldwide that have an energy system which is largely based on hydropower. As it is a non intermittent source of energy, a wide base made with hydropower favors the use of renewables.

The current time of crisis in the global scenario, for various reasons, contributes to the increasing encouragement of the use of renewable energy. Among the different alternatives, recent years have seen a considerable increase in the use of wind turbines and photovoltaic modules. Both for wind energy and photovoltaics, as for other alternatives for power generation, a greater number of new plants will result in higher production of equipment and a trend of reduction in installation costs as well as in operation and maintenance costs.

In this scenario, it is almost obvious consider installing photovoltaic modules on the water surface of reservoirs formed by hydroelectric plants. The PV modules will not shadow useful areas and, covering the surface flooded by the reservoirs, they will contribute to the reduction of water loss by evaporation. Thus, it will be possible to generate photovoltaic energy and to have a larger amount of water to hydroelectric power generation. The panels can be installed on floating structures modulated with a given power, possibly produced in series.

The association between hydroelectric power plants and photovoltaic power plants might seem strange in the past when photovoltaic plants with reasonable values of power did not exist. But hydropower is "constant" and “more available” while photovoltaics is "intermittent" by weather issues and "less available" by its own characteristics. It is precisely the constancy of hydroelectric power plants (and notoriously large hydropower with large storage capacity) that enables greater investment in photovoltaic farms.

A prime example is the hydroelectric power plant in Longyangxia Dam, on the Yellow River, in northwest China. The hydro power plant was installed in 1992, with 1,280 MW of installed capacity and four machines with 320 MW each. A few years ago a project for a PV hydro hybrid system was started culminating in the installation of 320 MW in 2013, a first phase covering 9 km^2, and a further 530 MW in 2015, covering another 15 km^2. The PV hydro hybrid system and the photovoltaic power plant now constitute the world's largest.

The design operation of photovoltaic hydro hybrid systems of this kind can also be decisively influenced by the possible energetic complementarity between hydro and solar energy availability. [1]-[2]-[3] The greater availability of solar energy can occur in periods of low water availability as well as less availability of solar energy can coincide with increased water availability. The use of stored water in the reservoir can be managed in order to increase this effect of energetic complementary.

This chapter presents a feasibility study for implementation of a pumped storage hydroelectric power plant (or reversible hydroelectric power plant) operating with wind turbines and photovoltaic modules. The study is based on results obtained with the well known software Homer. The next section describes the reversible power plant planned at a place called “Linha Sete”, in southern Brazil, and also describes how this plant will be simulated with Homer. Subsequent sections describe the components of the hybrid system under study, the results and discussions and finally the conclusions.

This chapter presents the results of an exploratory study related to a study of the operation of a pumped storage plant with a set of wind turbines in operation in southern Brazil, in the city of Osório, in a place with wind potential known and currently being explored. The project that resulted in this chapter have also resulted in an paper [4] reporting conclusions already obtained on the operation of this pumped storage plant.

2. THE LINHA SETE PUMPED STORAGE POWER PLANT

The hydraulic system considered in this work was identified in an earlier work of the research group [5]. It is a set of areas and storage volumes that allow the implementation of two reservoirs in a region in southern Brazil where there are strong topographical height differences. Fig. 1 shows the upper and lower reservoirs and their watersheds. The content of Fig. 1 was prepared from a region that appears on Google Maps and is located according to Ref. [6].

The reservoirs have been sized for a storage volume of 1,510,000 cubic meters. The lower reservoir has a maximum quota at 290 meters and the upper reservoir at 840 meters. The total height is 655 meters, whereas the machine room is placed 105 meters below the maximum level of the lower reservoir. Simulations have limited accuracy, since the variations in height resulting from operation of the pumped storage system are not simulated by Homer, as discussed below and presented by Canales and Beluco [7].

The natural flow available to the lower reservoir was determined by Canales et al. [4] and is equal to 0.539 m^3/s. This flow will be available for generation in addition to the flow rates obtained with the management of reversible plant, starting from the moment that the lower reservoir is full. Based on the Tennant method describer by Benetti et al. [8], 10% of the annual average flow was adopted as residual flow. Fig. 2 shows the stream flow rate available to turbine each month, already considering the residual flow.

3. COMPONENTS OF THE PV WIND HYDRO HYBRID SYSTEM

The hybrid system will consist of the pumped storage hydro power plant described in the previous section, operating in conjunction with wind turbines and photovoltaic modules with diesel generators support. The operation of the pumped hydro and wind turbines has been the subject of a recent article [4] pointing that the operation of the two reservoirs, even demanding higher initial costs, leads to lower environmental impacts.

Wind farms in Osório, in southern Brazil, were considered in this study. The three wind farms contain 75 turbines model Enercon E-70 E4, providing a total power of 75 MW operated at a capacity factor of about 34%. Based on Braciani [9], the average cost per installed kilowatt in wind farms in Brazil is around USD$ 2,156.50/kW. By using this value, the initial cost of each E-70 turbine was set at USD$ 4,313,000 in Homer.

Fig. 3 shows the wind data used for simulations with Homer. The monthly average wind speed in Osorio at 100m above ground was extracted from Silva [10]. These data were used to obtain a synthetic series of hourly wind speed data to the operation site of the wind turbines of the wind parks at Osorio. Fig. 3 shows two graphs. At first, the average wind speed for each month, the deviations around these averages and maximum and minimum values are shown. This graph shows the typical variability of the wind. The second graph, with strong variation in color, enhances the variability of the wind over days and months.

The photovoltaic modules will be installed on floating structures, as recently proposed by Ferrer-Gisbert et al. [11] and Redon-Santafé et al. [12]. The basic model for the floating structure considered in this study has dimensions suitable for 50 kW of PV modules. The total area of the water surfaces formed with the two dams is small but sufficient for several tens of structures having these dimensions. Fig. 4 shows the incident solar radiation data used in the simulations and obtained automatically by Homer in a NASA database.

Fig. 4 also shows two graphs. At first, the average incident solar radiation on a horizontal plane for each month, the deviations around these averages and maximum and minimum values are shown. The maximum insolation occurs in January, while the minimum occurs in June. In the second graph, it is evident the variation of sunlight available throughout the hours of the day, with the lowest values available in the first and the last hour of the day, and the available peak near midday. Also evident is the change in hours of the day throughout the year.

The cost of the PV modules was considered as USD$ 4,380 per kW and it is compatible with usual costs found for example by Feldman et al. [13]. The installation of floating structures, as suggested by Ferrer-Gisbert et al. [11] and Redon-Santafé et al. [12], raise the cost by 30%. The lifetime of the PV system is considered to be 12.5 years, the replacement cost of the PV system at the end of the useful life is 80% of the initial cost and annual cost of operation and maintenance is 5% of the installation cost. The reflectance of the water surface was considered to be 10% at the installation site. **Erro! Fonte de referência não encontrada.** shows parameters of the PV modules.

Diesel generator sets were considered as support in the simulations, for the times when the availability of renewable energy is not enough to meet the energy demand. The average cost per installed kilowatt for a thermoelectric plant in Brazil was set at USD$ 1,073.50/kW, according to Braciani [9]. Several generator sizes were considered, with the technical minimum load ratio set at 30%, according to Kaldellis et al. for heavy oil and diesel engines.

A connection to the grid was included, allowing the purchase of energy when there is not enough energy production to meet the consumers, and the sale of energy, when there is excess energy. The connection to the grid considered in the simulations has dimensions comparable to the possible installed powers of the diesel generator sets, allowing eventually the optimization process chooses one over the other.

4. SIMULATIONS WITH HOMER

Homer [15] is a software for optimization of hybrid energy systems. It was originally developed by National Renewable Energy Laboratory (NREL) and a version called "Legacy' is now available for universal access. Homer simulates a system for power generation over the time period of 25 years at standard intervals of 60 minutes. [16]-[17] The Homer software performs simulations of hybrid systems aiming to build optimization spaces according to different sensitivity variables, allowing a complete characterization of performance.

The Homer software simulates hydroelectric power plants operating as "run of the river" power plants. The simulation of hydro electric power plant with storage capacity and hydro electric for operation as a reversible plant can be performed as explained by Canales and Beluco [7]. The dc bus must contain only the hydroelectric power plant and a battery, adjusted to simulate a pumped storage power plant. The operation of the two reservoirs is simulated with the battery, while the supply of electricity to be transferred to the hybrid system is simulated by the hydroelectric plant. The converter has a single direction of operation.

Simulations with the system of Fig. 6 were performed. The optimization variables considered were the following: 0, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85 and 90 wind turbines; 0 MW, 10 MW, 20 MW, 30 MW, 40 MW, 50 MW and 60 MW for the installed power of the diesel gen set; 0 and 1 battery modeled as pumped storage plant; 0 and 722 kW for the converter capacity. The sensitivity inputs were the following: 100 MWh/d, 200 MWh/d, 300 MWh/d, 400 MWh/d and 500 MWh/d for AC load; USD$ 1/L, USD$ 2/L, USD$ 3/L, USD$ 4/L and USD$ 5/L for the cost of diesel oil; 6 m/s, 8 m/s, 10o m/s and 12 m/s for the wind speed. Simulations with the system of Fig. 6 were repeated with all these variables and a fixed value of 10 MW for the installed capacity of photovoltaic plant.

Simulations with the system of Fig. 7, with the PV modules assembled on floating structures installed over the flooded surface of the reservoir, were performed. The optimization variables considered were the following: 0, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85 and 90 wind turbines; 0 MW, 1,200 MW, 2,400 MW, 4,800 MW, 9,600 MW and 19,200 MW for the installed power of the diesel gen set; 0 kW, 100 kW, 200 kW, 400 kW and 800 kW for the capacity of PV modules; 0 and 1 battery modeled as pumped storage plant; 0 and 722 kW for the converter capacity. The sensitivity inputs were the following: 100 MWh/d, 200 MWh/d, 300 MWh/d, 400 MWh/d and 500 MWh/d for AC load; USD$ 0.50/L, USD$ 0.70/L, USD$ 0.90/L and USD$ 1.10/L for the cost of diesel oil; 6 m/s, 8 m/s, 10 m/s and 12 m/s for the wind speed; 0.0%, 2.5%, 5.0% and 10.0% for the maximum capacity shortage.

A constraint of 95% of energy supplies must be obtained from renewable resources limits the grid purchases. The values for AC load are adopted to determine the dimensions of the main components of the hybrid system. PV costs multipliers were chosen to assess the impact of floating structures, adding 30% to the costs, and to evaluate possible cost reductions obtained through some kind of financial or economic incentives on the price of PV modules.

5. RESULTS AND DISCUSSION

Fig. 8 to Fig. 11 show the results obtained with the first stage of the simulation, while Fig. 12 to Fig. 15 show the results obtained with the second phase. A very important result is that Homer did not indicate any optimal solutions in the different optimization spaces shown in these figures (and even others not shown) that contained PV modules. However, in several cases, as discussed below, some combinations containing photovoltaic modules were discarded by very small differences in relation to optimal solutions.

Fig. 8 and Fig. 9 show the optimization space obtained for the system of Fig. 6, respectively showing diesel price as a function of the local typical load and showing diesel price as a function of wind speed. The value currently practiced for diesel oil and the average wind speed for the area indicate that the optimal solution includes wind turbines and the pumped storage plant, in addition to supporting diesel generators. This system, considered as a starting point for this study was the subject of a recent article [4].

Fig. 10 shows the simulation results of this system with a photovoltaic plant with capacity of 10 MW. The optimal result indicates an energy cost of USD$ 0.469 per kWh operating with 20 wind turbines and diesel support system with 30 MW. The seventh system in this list operate without wind turbines and a higher cost, equal to USD$ 0.609 per kWh, with a variation of the charge state of the reservoirs shown in Fig. 11. The behavior of the curve, with energy at the beginning of the period identical to the energy in the end, indicates an acceptable performance.

Fig. 12 and Fig. 13 show the optimization space obtained for the system of Fig. 6, respectively showing diesel price as a function of the local typical load and showing diesel price as a function of wind speed. The lower load consumers, compared with the preceding figures, have given rise to areas on the bottom left of these optimization spaces, corresponding to combinations not including wind turbines. A lot of points of these optimization spaces show optimal results that led to discard combinations including PV modules for very small differences.

The complete output provided by Homer for each feasible option allows estimating and optimizing the capacity of pumped storage system for recovering rejected renewable energy. This can also be used for calculating the effective capacity factor of the wind farm with and without the pumped storage capacity. According to the simulation results and based on the wind resource inputs of this case study, the maximum capacity factor of the wind turbines reported by Homer is 35.6%, including excess electricity. The Osorio Wind Park, used as model for creating the wind turbines of this work, reports on its website a capacity factor equal to 32.3%. These values are within the range of values reported by Boccard [19], who gathered global results reported by transmission system operators or available in academic literature related to wind farm capacity factors.

Based on the results simulations, Fig. 16 presents the estimated duration curves for rejected power. As explained by Kaldellis et al. [20], large amounts of rejected energy also mean severe financial losses that discourage future investments in renewable energy projects. Without the pumped storage plant, the extremely variable wind profile would require more turbines at the wind farm along with a diesel generator of greater capacity, thus increasing the generation cost. As shown in Fig. 16 a, a system without storage capacity would reject power about 80% of the time, with 25% of the time rejecting more than 50MW. Conversely, with pumped storage capacity and using the same 50% of the wind farm capacity as benchmark, Fig. 16 b and Fig. 16 c show that this energy storage technology improves the wind energy absorption, limiting the occurrence of this value to less than 10% of the time and reducing the cost of energy for the system. In Homer, the cost of energy is the average cost per kWh of useful electrical energy produced by the system, which in this case is just the energy used to serve the primary AC Load (no grid sales, DC or deferrable loads are considered in the example).

Fig. 14 shows results presented in Fig. 12 and corresponding to the consumer load equal to 200 kWh per day and diesel sold at USD$ 0.90 per liter. The first system of this list is what defines the green color at the corresponding point in the optimization space shown in Fig. 12. This first system presents cost of energy equal to USD$ 0.407 per kWh, very close to the third system in the list that includes PV modules and provides energy at cost of USD$ 0.408 per kWh. This system includes 100 kW in PV modules, the pumped storage plant, twenty wind turbines and diesel support system with 19.2 MW.

Most systems in this list have small monthly variations of the state of charge of the reservoirs over a year. The tenth system, however, in the list shown in Fig. 14, presents a more pronounced change in the state of charge of the reservoirs. This system includes 100 kW in PV modules, the pumped storage plant and diesel support system without wind turbines. Fig. 15 details this change in the state of charge, indicating minimum values during the month of June. A further reduction in the past few months show that the energy available at the end of the year will be less than the energy in the beginning of the year, indicating an unsustainable situation.

6. FINAL REMARKS

This chapter presented the results of an exploratory study to design a photovoltaic wind hydro hybrid system with storage capacity. The optimal combinations obtained from the simulations did not suggest the inclusion of PV modules, mainly due to its high initial cost and the high cost of energy. Among the non-optimal solutions, it is possible to find solutions including PV modules and that show performance comparable to optimal solutions. Thus, this study suggested a hybrid system constituted by 100 kW in photovoltaic modules, 20 wind turbines and a diesel support system with 19,200 kW, also with the pumped storage plant, providing energy at a cost of USD$ 0.408 per kWh. This study also suggested a system with 10,000 kW in photovoltaic modules and a diesel support system with 30,000 kW, without wind turbines and with the pumped storage plant, providing energy at a cost of USD$ 0.609 per kWh.

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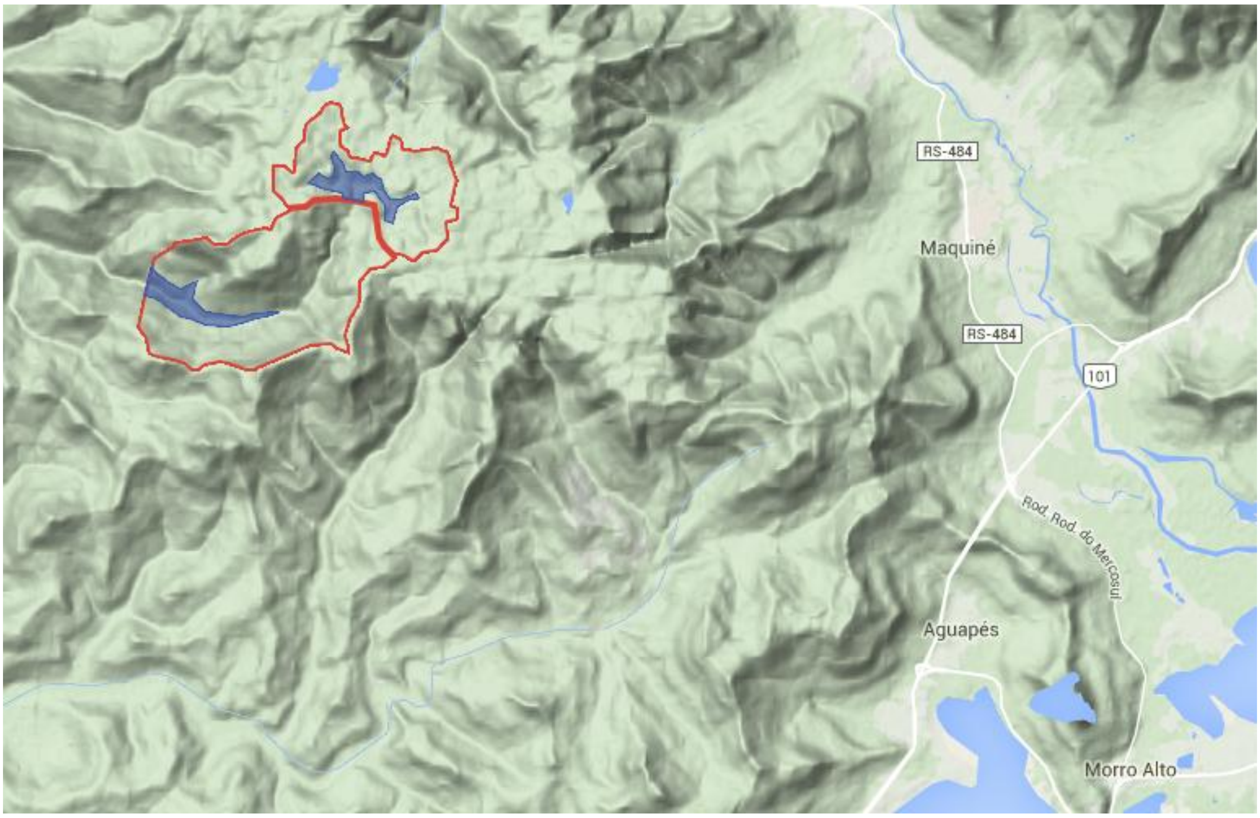


Fig. 1. Upper and lower reservoirs in "Linha Sete" and their watersheds.

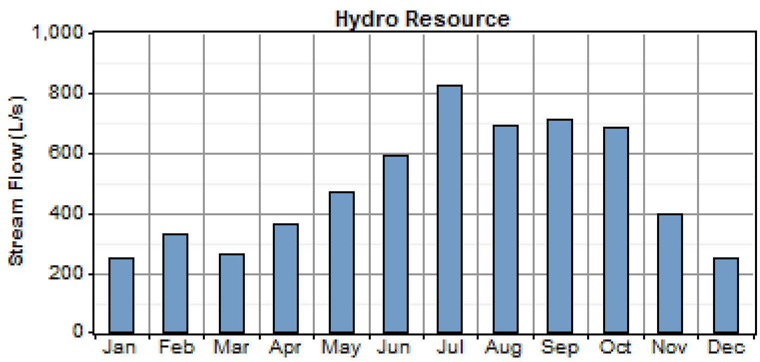


Fig. 2. Monthly average stream flow rate available to the turbine at power house, already considering the residual flow.

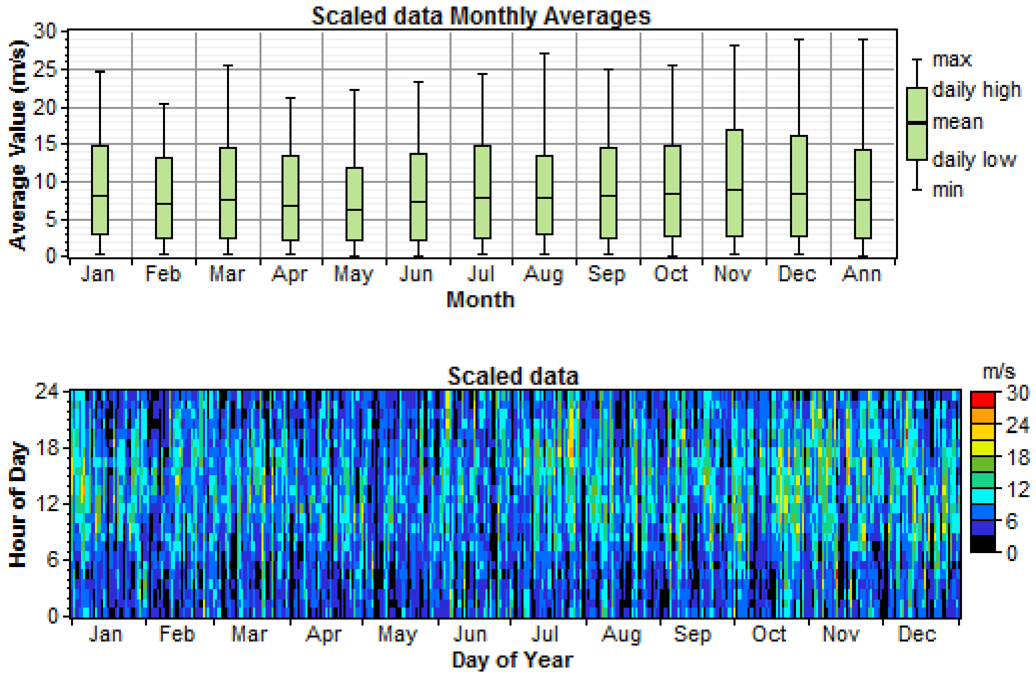


Fig. 3. Wind resource input for the case study.

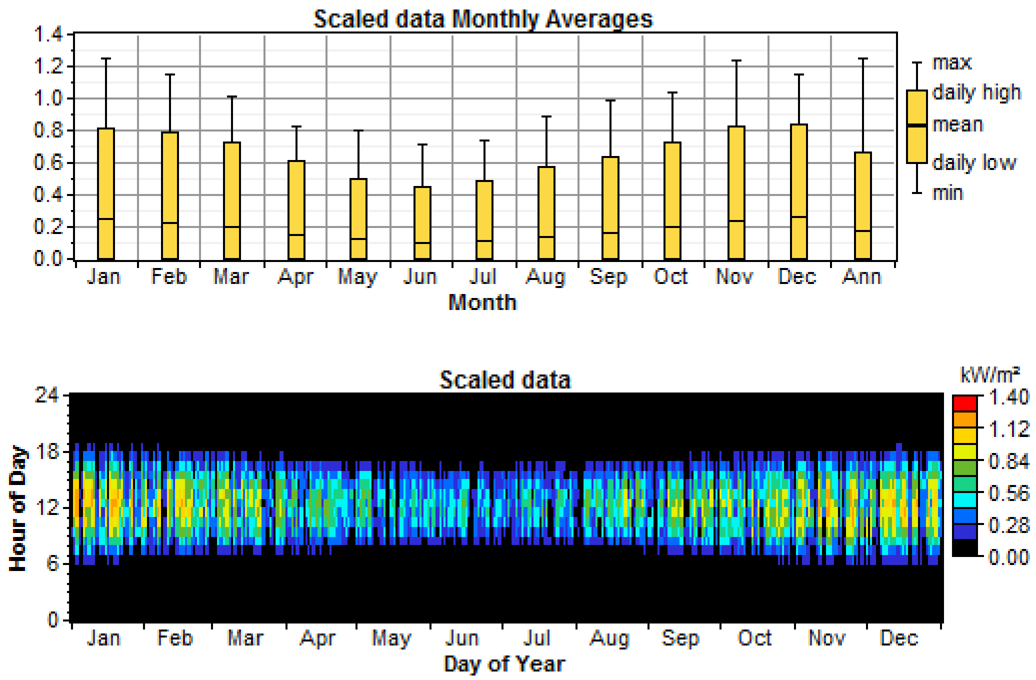


Fig. 4. Incident solar radiation on a horizontal plane for the reservoirs location, obtained with software Homer, considered in this study.

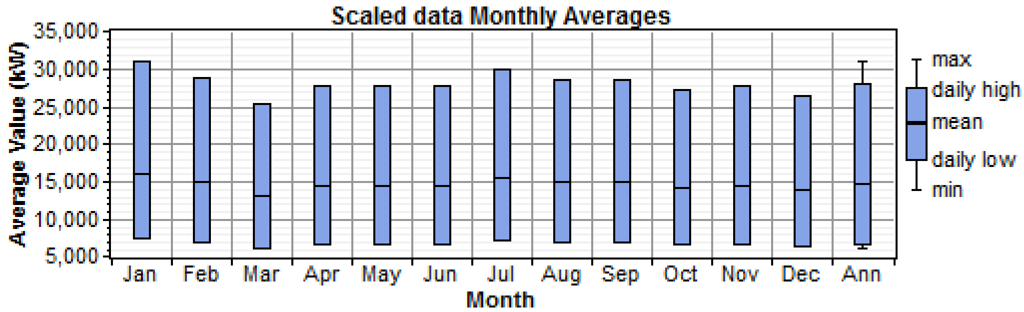


Fig. 5. Scaled monthly averages of load profile considered in this study.

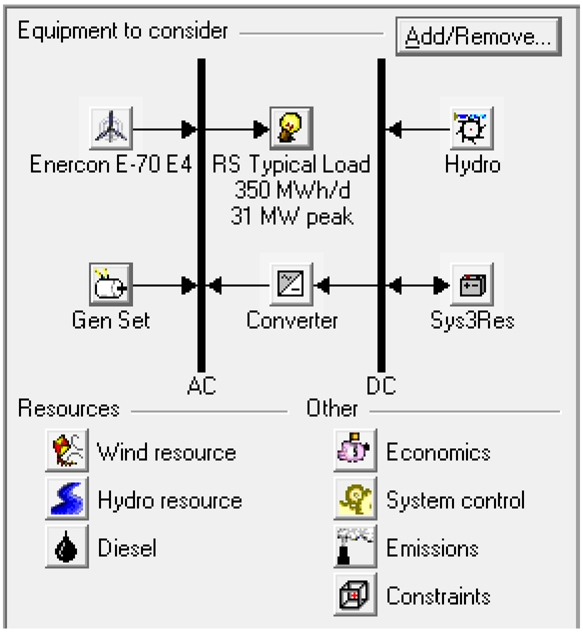


Fig. 6. Wind hydro hybrid system with water storage capacity.

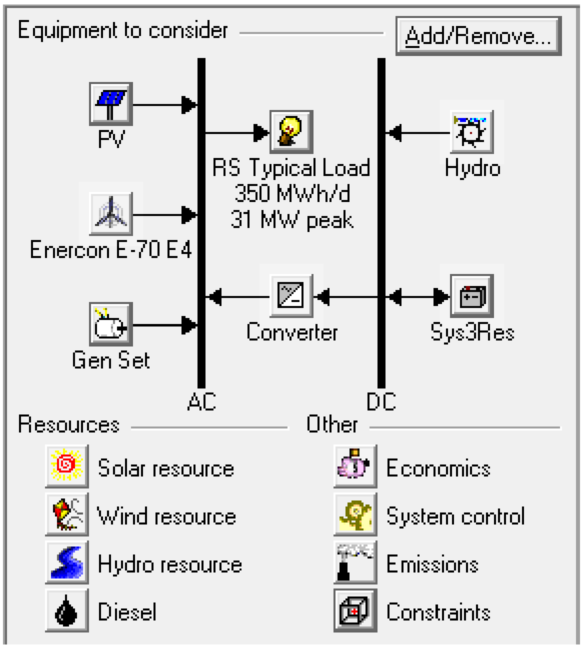


Fig. 7. PV wind hydro hybrid system with water storage capacity considered in this study.

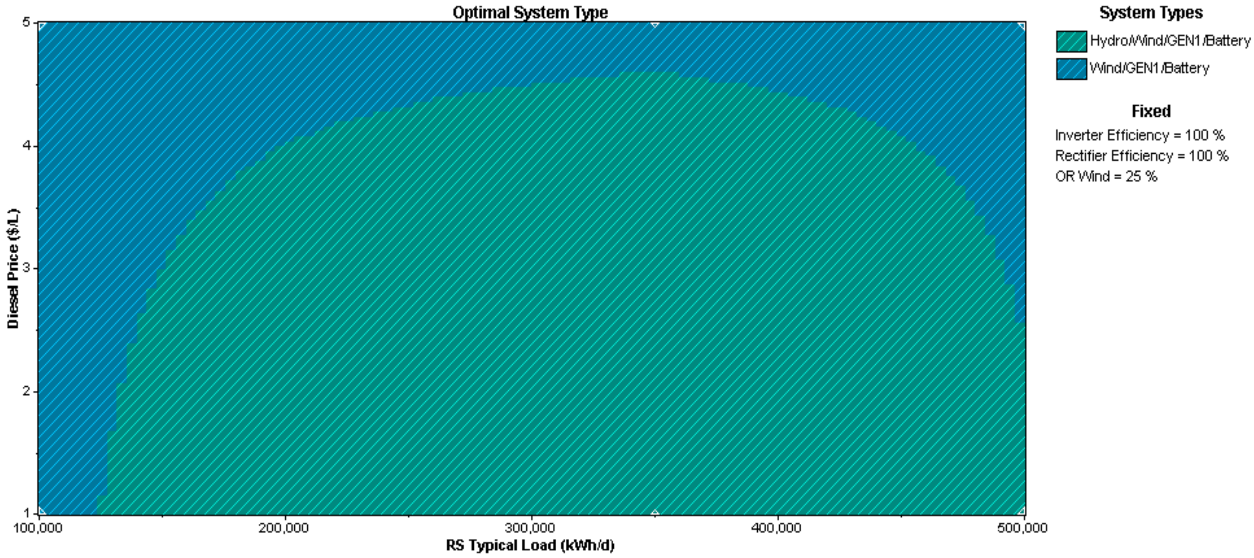


Fig. 8. Results for the optimization space obtained for diesel price as a function of local typical load for the system of Fig. 6.

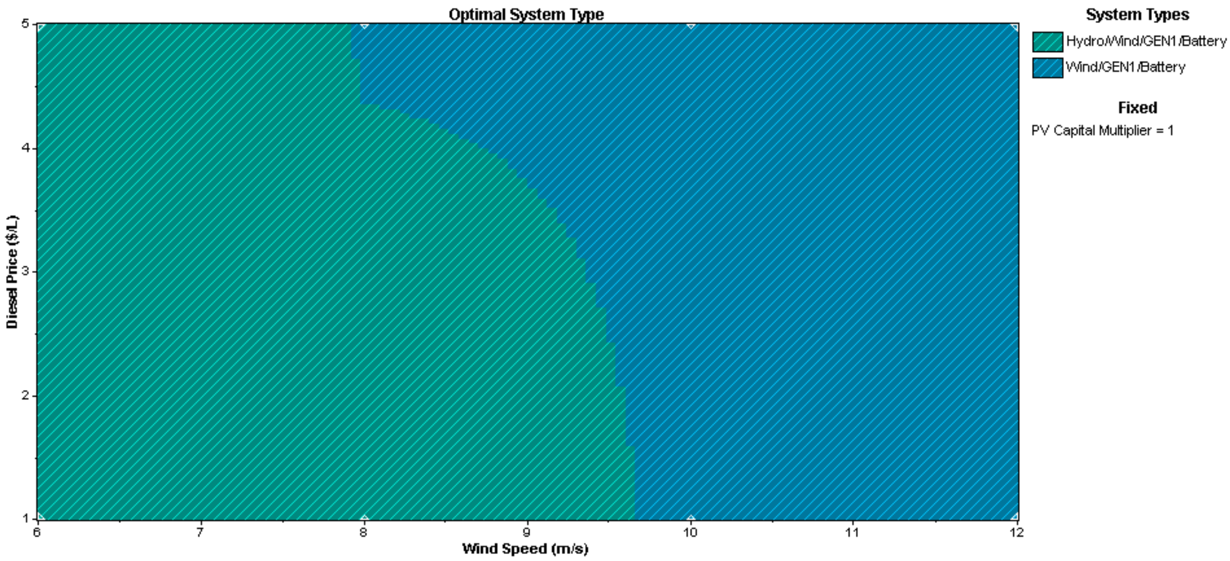


Fig. 9. Results for the optimization space obtained for diesel price as a function of wind speed for the system of Fig. 6.

Sensitivity Results | Optimization Results

Sensitivity variables

Wind Speed (m/s) 8 | Diesel Price ($/L) 1 | PV Capital Multiplier 1 | Max. Annual Capacity Shortage (%) 2.5

Double click on a system below for simulation results. Categorized | Overall | Export... | Details...

PV (kW)	E-70	Hydro (kW)	GEN1 (kW)	Sys3Res	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	GEN1 (hrs)	Batt. Lf. (yr)
10000	20	610	30000	1	722	$ 169,275,...	45,142,392	$ 687,054,6...	0.469	0.71	0.00	29,307,...	5,540	20.0
10000	20	610	30000		722	$ 169,004,...	45,721,328	$ 693,425,0...	0.473	0.70	0.00	29,736,...	5,603	
10000	10	610	30000	1	722	$ 126,145,...	54,844,576	$ 755,208,0...	0.515	0.52	0.00	37,150,...	6,972	20.0
10000	10	610	30000		722	$ 125,875,...	55,463,012	$ 762,031,3...	0.520	0.51	0.00	37,619,...	7,034	
10000	20	610	40000	1	722	$ 180,010,...	56,638,740	$ 829,651,9...	0.566	0.67	0.00	36,767,...	5,540	20.0
10000	20	610	40000		722	$ 179,740,...	57,329,376	$ 837,303,4...	0.571	0.67	0.00	37,254,...	5,603	
10000		610	30000	1	722	$ 83,015,000	70,572,432	$ 892,475,2...	0.609	0.15	0.00	50,119,...	8,760	20.0
10000		610	30000		722	$ 82,745,000	70,896,736	$ 895,924,9...	0.612	0.15	0.00	50,452,...	8,760	
10000	10	610	40000	1	722	$ 136,880,...	69,374,504	$ 932,600,1...	0.636	0.48	0.00	46,448,...	6,972	20.0
10000	10	610	40000		722	$ 136,610,...	70,086,392	$ 940,495,3...	0.642	0.47	0.00	46,959,...	7,034	
10000	20	610	50000	1	722	$ 190,744,...	68,435,848	$ 975,698,7...	0.666	0.63	0.00	44,528,...	5,540	20.0
10000	20	610	50000		722	$ 190,475,...	69,256,416	$ 984,840,6...	0.672	0.63	0.00	45,092,...	5,603	
10000		610	40000	1	722	$ 93,750,000	88,076,128	$ 1,103,976...	0.753	0.13	0.00	60,897,...	8,760	20.0
10000		610	40000		722	$ 93,480,000	88,286,496	$ 1,106,119...	0.755	0.13	0.00	61,115,...	8,760	
10000	10	610	50000	1	722	$ 147,615,...	84,327,584	$ 1,114,845...	0.761	0.44	0.00	56,169,...	6,972	20.0
10000	10	610	50000		722	$ 147,344,...	85,158,576	$ 1,124,107...	0.767	0.43	0.00	56,747,...	7,034	
10000		610	50000	1	722	$ 104,485,...	106,524,840	$ 1,326,316...	0.905	0.12	0.00	72,619,...	8,760	20.0
10000		610	50000		722	$ 104,215,...	106,682,520	$ 1,327,855...	0.906	0.12	0.00	72,785,...	8,760	

Fig. 10. Optimization results constituting the optimization space shown in Fig. 12.

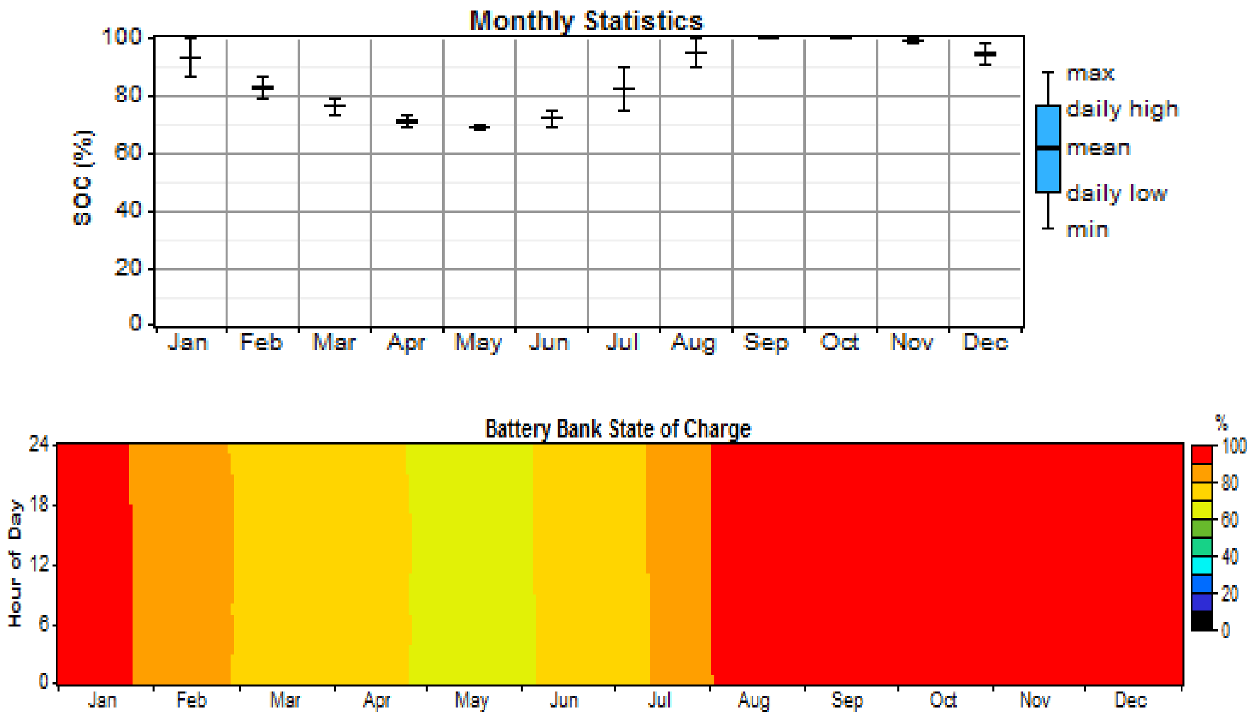


Fig. 11. Annual change in state of charge of the reservoirs for a hybrid system shown in Fig. 10 with COE equal to USD$ 0.609 per kWh..

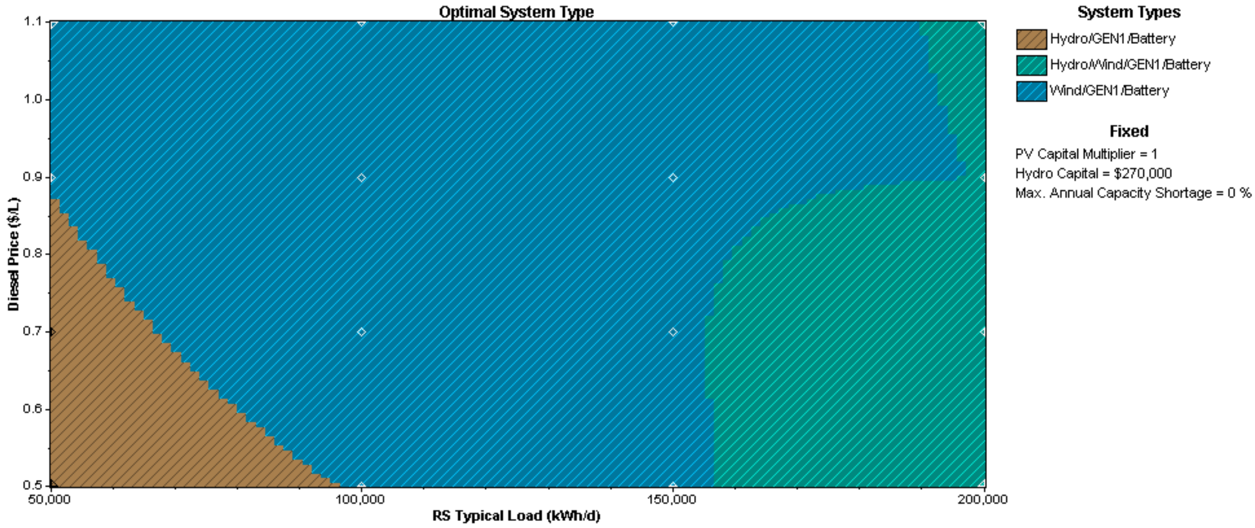


Fig. 12. Results for the optimization space obtained for diesel price as a function of local typical load, for the system of Fig. 7 with different values for diesel price and consumers load.

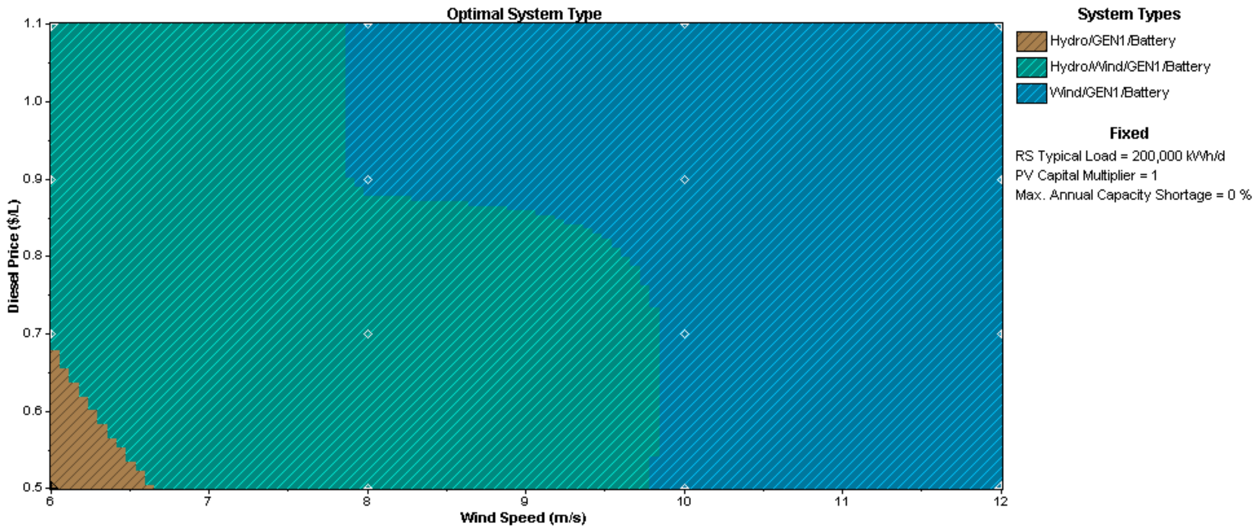
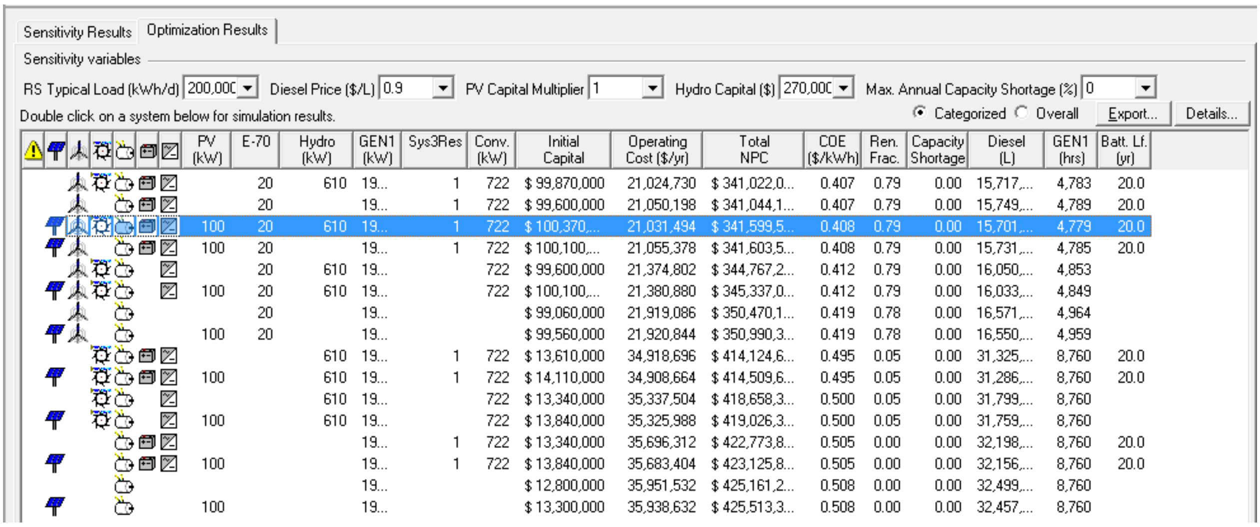


Fig. 13. Results for the optimization space obtained for diesel price as a function of wind speed, for the system of Fig. 7 with different values for diesel price and consumers load.



PV (kW)	E-70	Hydro (kW)	GEN1 (kW)	Sys3Res	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	GEN1 (hrs)	Batt. Lf. (yr)
	20	610	19...	1	722	$ 99,870,000	21,024,730	$ 341,022,0...	0.407	0.79	0.00	15,717,...	4,783	20.0
	20		19...	1	722	$ 99,600,000	21,050,198	$ 341,044,1...	0.407	0.79	0.00	15,749,...	4,789	20.0
100	20	610	19...	1	722	$ 100,370,...	21,031,494	$ 341,599,5...	0.408	0.79	0.00	15,701,...	4,779	20.0
100	20		19...	1	722	$ 100,100,...	21,055,378	$ 341,603,5...	0.408	0.79	0.00	15,731,...	4,785	20.0
	20	610	19...		722	$ 99,600,000	21,374,802	$ 344,767,2...	0.412	0.79	0.00	16,050,...	4,853	
100	20	610	19...		722	$ 100,100,...	21,380,880	$ 345,337,0...	0.412	0.79	0.00	16,033,...	4,849	
	20		19...			$ 99,060,000	21,919,086	$ 350,470,1...	0.419	0.78	0.00	16,571,...	4,964	
100	20		19...			$ 99,560,000	21,920,844	$ 350,990,3...	0.419	0.78	0.00	16,550,...	4,959	
		610	19...	1	722	$ 13,610,000	34,918,696	$ 414,124,6...	0.495	0.05	0.00	31,325,...	8,760	20.0
100		610	19...	1	722	$ 14,110,000	34,908,664	$ 414,509,6...	0.495	0.05	0.00	31,286,...	8,760	20.0
		610	19...		722	$ 13,340,000	35,337,504	$ 418,658,3...	0.500	0.05	0.00	31,799,...	8,760	
100		610	19...		722	$ 13,840,000	35,325,988	$ 419,026,3...	0.500	0.05	0.00	31,759,...	8,760	
			19...	1	722	$ 13,340,000	35,696,312	$ 422,773,8...	0.505	0.00	0.00	32,198,...	8,760	20.0
100			19...	1	722	$ 13,840,000	35,683,404	$ 423,125,8...	0.505	0.00	0.00	32,156,...	8,760	20.0
			19...			$ 12,800,000	35,951,532	$ 425,161,2...	0.508	0.00	0.00	32,499,...	8,760	
100			19...			$ 13,300,000	35,938,632	$ 425,513,3...	0.508	0.00	0.00	32,457,...	8,760	

Fig. 14. Optimization results constituting the optimization space shown in Fig. 12.

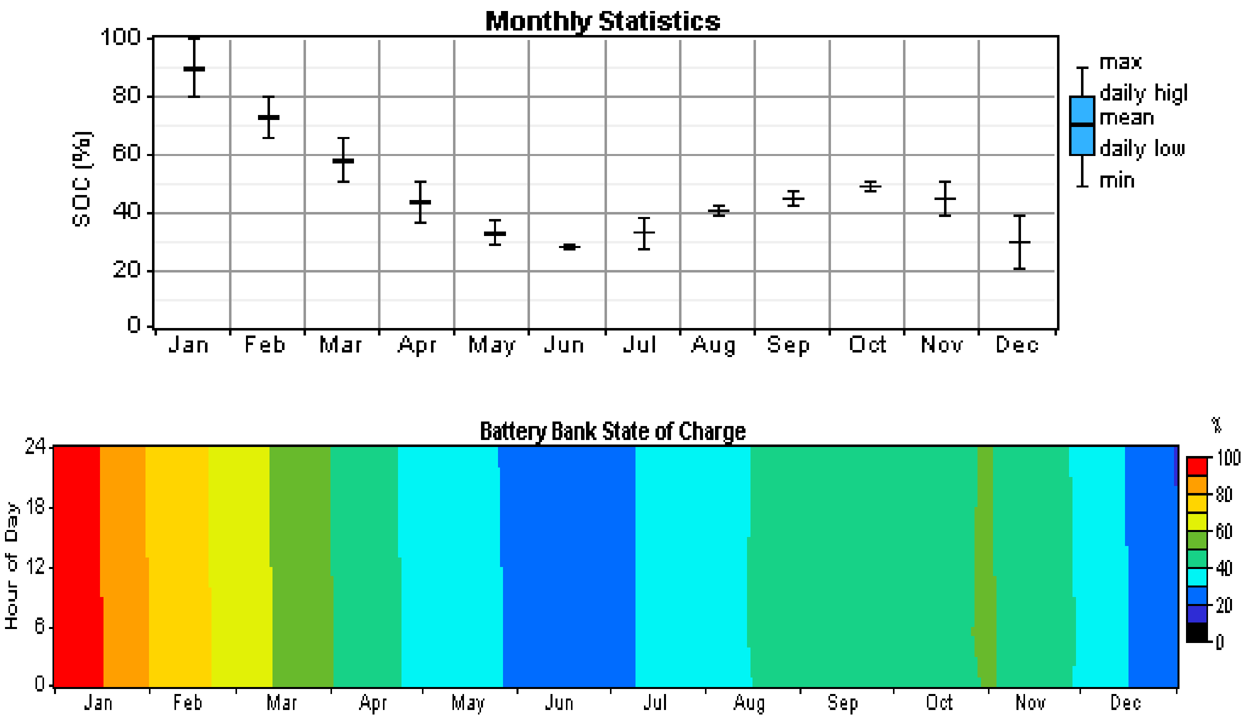


Fig. 15. Annual change in state of charge of the reservoirs for a hybrid system shown in Fig. 12 with COE equal to USD$ 0.495 per kWh..

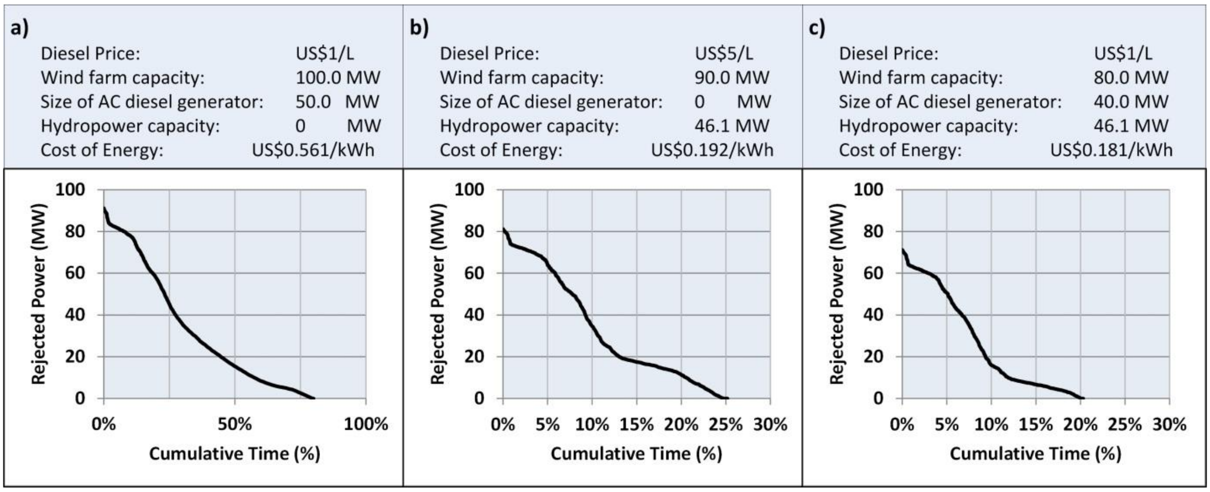


Fig. 16. Rejected power duration curves for an average daily load = 500MWh/d.