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Siphon-type hydroelectric plants: application for power generation in a low head dam in southern Brazil

Usinas hidrelétricas do tipo sifão: aplicação para geração de energia em uma barragem de baixa queda no sul do Brasil

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Resumo
A energia hidrelétrica continua sendo o recurso renovável mais representativo do mundo, respondendo hoje por 40% da capacidade instalada. A disponibilidade de água, aliada às tecnologias de geração de energia elétrica a um custo razoável, tem sustentado o sucesso desse tipo de geração ao longo dos anos. Continuar a alavancar o setor hidrelétrico é ainda mais desafiador hoje, pois há uma demanda mundial crescente por energia, ao mesmo tempo em que os locais mais atrativos do ponto de vista econômico já foram beneficiados. O contexto atual refere-se a abordagens de exploração de água destinadas a explorar potenciais de menor escala e estruturas hídricas existentes que operam de forma multifuncional. Solidificado nesta conjectura, o objetivo deste estudo é contribuir, no sentido de atribuir alternativas, para a geração de energia em barragens de baixa queda existentes através do pré-dimensionamento de uma usina sifão. Esse tipo de usina faz parte de um nicho específico e ainda em evolução para geração descentralizada de energia. Os requisitos estruturais reduzidos (gerador, turbina e tubo de sucção), bem como a intervenção mínima na estrutura existente da barragem, a cessação de novos impactos socioambientais e econômicos relacionados à construção de uma nova usina são os principais fatores favoráveis características dessas instalações. O estudo de caso de uma planta inoperante e as ferramentas disponíveis no Software Homer para simulação de dados foram utilizados como recursos metodológicos. Duas configurações básicas foram consideradas: uma com matrizes 100% renováveis e outra incluindo um gerador a diesel. A partir deles, foram simulados diferentes sistemas híbridos, para determinar uma configuração ótima em termos de custo presente líquido. Dentre as simulações realizadas, a solução ótima mais promissora foi a híbrida, considerando entre seus componentes um conjunto de turbinas sifão totalizando 271 kW, mais 50 kW em módulos fotovoltaicos e 140 kW em sistema de apoio a diesel. Um banco de baterias com 32 baterias de 200 Ah complementava este sistema. O

custo de energia para este sistema é de $ 0,164 por kWh. Para um sistema sem diesel e com 0% de falhas de serviço, os resultados viáveis aparecem apenas até 2600 kWh de carga.
Palavras-chave: Usinas sifão. Energias renováveis. Software Homer. Sistemas híbridos. Módulos fotovoltaicos flutuantes

Abstract
Hydroelectric energy continues to be the most representative renewable resource in the world, accounting today for 40% of installed capacity. The availability of water, combined with the technologies for generating electricity at a reasonable cost, have sustained the success of this type of generation over the years. Continuing to leverage the hydroelectric sector is even more challenging today, because there is a growing world demand for energy, at the same time that the most attractive places from an economic point of view have already been benefited. The current context refers to approaches to water exploitation aimed at exploiting smaller-scale potentials and existing water structures that operate in a multifunctional way. Solidified in this conjecture, the purpose of this study is to contribute, in the sense of attributing alternatives, for the generation of energy in existing low head dams through the pre-dimensioning of a siphon plant. This type of plant is part of a specific and still evolving niche for decentralized power generation. The reduced structural requirements (generator, turbine, and suction tube), as well as the minimal intervention in the existing structure of the dam, the cessation of new socio-environmental and economic impacts related to the construction of a new plant are the main favorable characteristics of these facilities. The case study of an inoperative plant and the tools available in the Homer Software for data simulation were used as methodological resources. Two base configurations were considered: one with 100% renewable matrices and another one including a diesel generator. From them, different hybrid systems, to determine an optimal configuration in terms of net present cost, were simulated. Among the simulations performed, the most promising optimal solution was hybrid, considering among its components a set of siphon turbines totaling 271 kW, plus 50 kW in photovoltaic modules and 140 kW in a diesel support system. A battery bank with 32 200 Ah batteries complemented this system. The energy cost for this system is $0.164 per kWh. For a system without diesel and with 0% service failures, viable results appear only up to 2600 kWh load.
Keywords: Siphon plant. Renewable energy. Software Homer. Hybrid systems. Floating photovoltaic modules

1. Introduction

Renewable energy sources, despite being recently impacted by the Covid-19 pandemic, the Russian-Ukrainian war and the consequent economic crisis, accounted for 90% of global capacity expansion during the years 2020 and 2021 (EPE, 2021; IRENA, 2021). During this period, the hydroelectric and wind matrix stood out, reaching the highest annual increase in the last twenty years, an increase of 4%, equivalent to a power of almost 200 GW in 2020 alone (International Energy Agency, 2021).

On the other hand, the share of renewable energy sources reduced its growth in Brazil, marked especially by the drop in the supply of hydraulic energy (48.5% to 44.7%). The scarcity of rain caused a reduction in the level of the reservoirs of the main hydroelectric plants in the country, consequently there was a reduction in the supply of hydroelectricity and the activation of thermoelectric plants (causing variation in the price of fuels) as a compensation measure (EPE, 2021). Even so, hydroelectric energy is responsible for about 53.4% of the electricity offered in the country (EPE, 2021), corresponding to a power of 1.01 MW divided into 1363 hydroelectric plants in operation (ANEEL, 2023).

Dams intended for power generation currently represent only about 14% of the total dams registered in the National Information System on Dam Safety (SNISB). The others are dedicated to water supply (21%) and irrigation (34%) (ANA *et al*., 2023), and provide economic benefits through flood control, drought mitigation, navigation or recreation does not have its energy potential explored (Hansen *et al*., 2021).

With the growing demand for energy, hydroelectric use still represents an important element in expanding the supply of electricity in the National Interconnected System (SIN). In addition, the water source acts in harmony with the current substantially decarbonized network, which sustains its satisfactory performance among the top 10 in the Organization for Cooperation and Development (OECD) energy security ranking (World Energy Council,2021).

Strategic locations for large hydroelectric developments have already become scarce, but the potential provided by the development of small-scale power plants (PCH) and Hydraulic Generator Centers (CGH) represent only 6% of the installed hydropower (ANEEL, 2023), thus having ample space of development. In addition to the increase related to the energy potential, this type of power generation brings benefits of a structural nature, such as the energy decentralization of the Brazilian electrical matrix.

Exploiting this smaller-scale water potential gap has also proven to be favorable in acting synergistically with other renewable sources such as wind, biomass and photovoltaics, ensuring operational flexibility for the systems. In this sense, this study is dedicated to the simulation of a real case study exploring the energy potential in a low-head supply dam with a complementary nature of the water source. This article consists of four sections, in addition to this Introduction. A review of the literature on the subject is presented below. Sections 3 and 4 present a dam in southern Brazil used in this work to study the feasibility of installing a set of siphons. The last section concludes the article.

2. Hydropower generation in low head dams

The generation of energy from hydroelectric plants naturally started from places where the energy potential and the financial return offered would be maximized. These environments offered heights of waterfalls and high available flows favoring the installation of structures with large reservoirs.

The exponential technological evolution of the last decades allowed the development of hydraulic turbines that made water the first renewable energy source used on a large scale. The most widespread turbines were the Pelton, Francis and Kaplan types. The first turbine appeared in 1903 to meet production requirements where there were large waterfalls (from 100m to 1300m) and small flows (0.005 to 2.1 m^3/s) being used on a large scale in the upper part of the hydrographic basin. After the Safe World War, the axial turbines (Francis and Kaplan) gained notoriety and with them the total unevenness of the dams began to be exploited. The Francis turbine is generally accommodated in the central part of the basins, where lower heads (between < 50 and 110m) and higher flows (from 0.4 to 23 m^3/s of flow) are available (Voith, 2021) as in Hydroelectric Power Plants (UHC) Binacional Itaipu and Xingó/BR.

Over time, the unavailability of these more favorable locations for building new large plants began to collide with the growing demand for energy in various sectors. This issue made the hydro energy sector needing particular strategies for continued expansion (Beluco, 1994). The most recent hydroelectric design then began to direct and add efforts to decentralizing aspects (Comino *et al*., 2019) with the exploration of smaller scale potentials (power plants with low head dams) and the use of water structures with a multifunctional character (Ak *et al*., 2017; Alidai and Pothof, 2015; Loots *et al*., 2015; Zhou *et al*., 2019).

These small and micro-scale plants have the advantage of making it possible to take advantage of dams with very small falls and much smaller areas of flooding. The negative impacts from an environmental, social, flora and fauna point of view are also very small compared to large plants. In addition to providing power, small-scale hydropower infrastructure can help manage water resources for vital public services such as irrigation, flood protection and water distribution. From a social perspective they impact the development of remote areas, since they can be installed in areas where centralized energy supply is not available (Azimov and Avezova, 2022).

In line with this concept, in the late 19th and early 20th centuries (Sari *et al*., 2018), Kaplan-type turbines began to be improved. Ideal in places with smaller waterfalls (10 to 50m) and water volume greater than 2.8 to 30m³/s, these axial machines have mobile blades and are usually built in the dam massif (Voith, 2021). These characteristics made it interesting for exploration in potential regions such as the Passo Real/RS Hydroelectric Power Plant and the Ferreira Gomes Hydroelectric Power Plant, located in the Amazon Hydrographic Region.

The challenge of this type of power plant is intimately conditioned by its lower economic attractiveness (Ciric, 2019; Filho *et al*., 2017), which often ends up implying disproportionately higher capital costs per unit of installed energy (Stark *et al*., 2011) when compared to power plants such as Itaipú Binacional or Belo Monte/PA. In circumstances far removed from the water crisis, this condition can be even more intensified, since the more expensive its viability becomes.

In the context of dams with low heads, even with the wide dissemination of Kaplan turbines, other configurations assumed a particular margin of contribution, as is the case of modular siphon-type plants. These facilities basically consist of transporting water from one reservoir upstream to another downstream, with the particularity of being installed over water structures (such as a dam or dam) (Loots *et al*., 2015; Mardiani-Euers, 2012) intervening minimally in the existing massif. Thus, they are also distinguished by the absence of sudden local interference, maintenance is facilitated and the socio-environmental impacts related to the construction of a new plant ceased. Low head plants with Kaplan type turbines theoretically tend to make an energy generating plant more easily viable. However, from the perspective of existing structural use and generalized impacts, siphon plants are more advantageous.

Siphons have already shown potential in dams with low available height that do not only release small volumes for environmental purposes. In the bypass structure attached to an irrigation system in Idaho in the USA (Martinez *et al*., 2019), the outlet spillway of a wastewater treatment plant (Loots *et al*., 2015) in Africa and the Chinese hydroelectric plant in Gaoliangjian, (Zhou *et al*., 2019) are some models in operation.

Another strategic axis for harnessing energy from low heads with siphon plants is the increase in potential in abandoned dams and/or those without energy purposes, such as those for supply. Today, there are numerous infrastructures (dams) that already operate with more than one purpose, rivers with dams, reservoirs, water pressure release valves, gates, water treatment plants and water supply systems, can also be potential sources of energy (Zhou and Deng, 2017), as analyzed by Comino *et al*., (2020), Loots *et al*., (2015) and Titus and Ayalur (2019).

The positive reflection also includes the cost of the work, since, in the distribution of investments in a hydroelectric power plant, the costs related to civil construction (which include any infrastructure development necessary to access the site) represent, on average, 40% of the total amount (IRENA, 2020; Ogayar and Vidal, 2009). Another advantageous economic factor is the absence of long power lines in view of energy decentralization.

Many of the plants with lower generating potential were deactivated a few decades ago (SUDESUL, 1980). In that period, the movement was strongly influenced by expensive costs related to the absence of automation and the low cost of oil, which made them more expensive. On the other hand, the current scenario is controversial, the rising price of oil tends to persist (Ahmad and Zhang, 2020), automation is a technological reality and environmental goals, especially alluding to renewable energies, are engaged in public policies.

This hydro-energetic potential gap guides the proposal of this study to cover areas where there are dam structures for repowering with the use of symphonic power plants. In parallel, the complementarity of the system with photovoltaic modules under the water surface will also be considered, with the purpose of amortizing the intermittency characteristic of renewable energy sources and optimizing the viability of the system.

3. Case study - Santa Cecilia Dam, southern Brazil

This section has three subsections, subsequently dedicated to the dam that is the focus of this case study, the Homer Legacy software, used for a pre-feasibility study for hydroelectric generation at this dam, and the results obtained with this study.

3.1 The Santa Cecilia Dam, in the municipality of Estrela, in southern Brazil

The delimited area was the Santa Rita plant (latitude 29°31'17.6"S and longitude 51°54'23.8"W) located in the south of Brazil, in the state of Rio Grande do Sul (Figure 1). The former plant was located on the Arroio Estrela watercourse, a sub-basin of the Taquari River in southern Brazil, about 8 kilometers away from the urban area.

Inaugurated in 1914 and currently inoperative, the plant with 228kW of installed power was intended to supply the city of Estrela/RS, playing the role of supplying local electricity for the development of small industries. Given its limited dam condition (small accumulation), its use for irrigation purposes was disregarded.

Given its limited dam condition (small accumulation), its use for irrigation purposes was disregarded (SUDESUL, 1980). The context of the time, the high operating costs, the lack of technology for automation and the availability of greater potential, made this one of the small plants (less than 300kW), deactivated at least 40 years ago.

The territory is currently characterized by a strong representativeness of generation from the hydroelectric matrix, currently emanating 51.81% of its total energy from this source (EPE, 2021). Given the available renewable energy potential and the possibility of contributing to regional sustainable development, it is proposed to reactivate the hydroelectric plant. For this, the installation of a siphon-type plant will be considered under the massif of the old dam, which has a drop height of 8 meters.

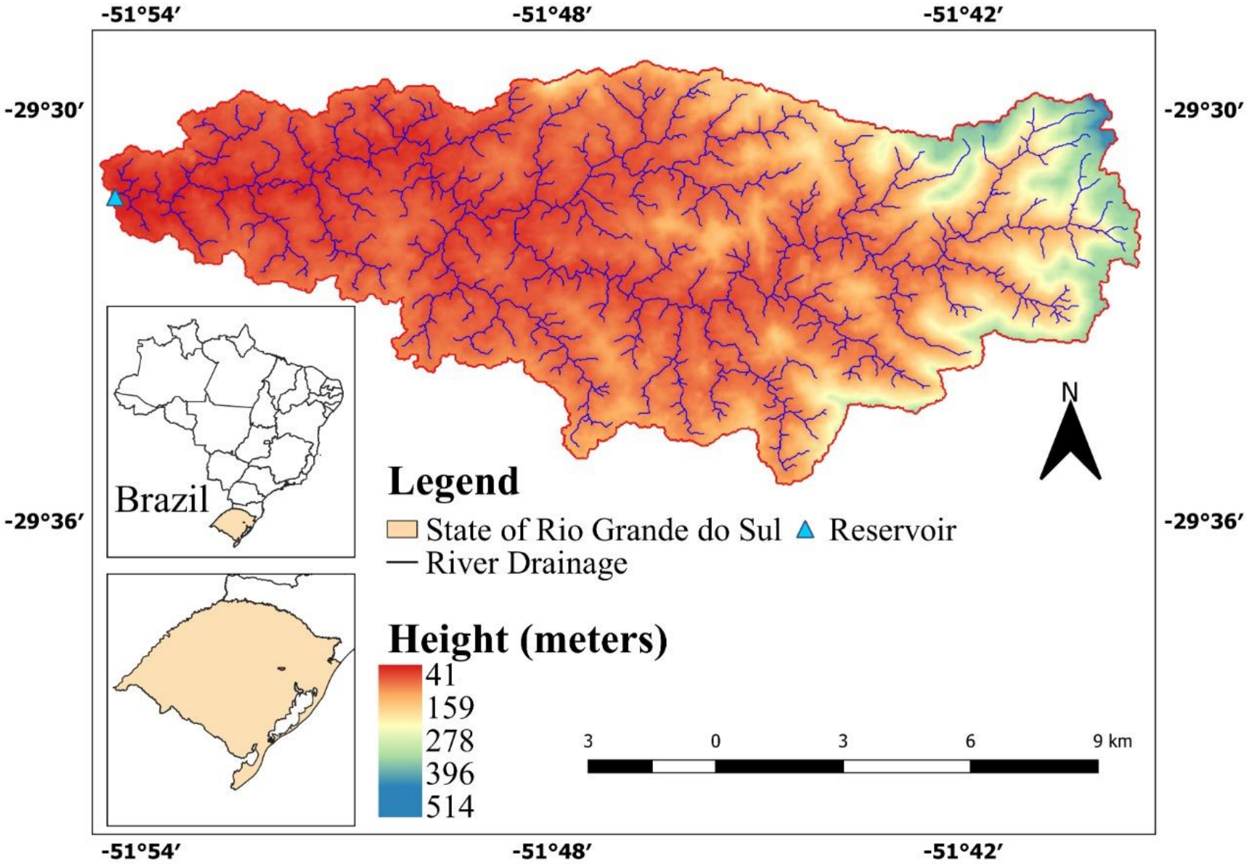

Figure 1 - Location of Santa Cecilia dam.

3.2 Simulations with Homer Legacy

The assertiveness of the systems that offer optimized configurations and viable solutions for this study will be linked to the Homer Legacy software. The ability to work with variations in resource availability, as required by renewable energies, especially solar and hydro that this work comprises, was decisive in choosing this tool.

Developed by the National Renewable Energy Laboratory (NREL), Homer Energy is currently the most used software (Sinha and Chandel, 2014) to simulate (I), optimize (II) and perform sensitivity analysis (III) of hybrid systems.

In the first stage of several configurations of a system are simulated, based on the calculation of the energy balance for each hour of the year. The viability of these configurations is estimated (whether they meet the electrical demand under the specified conditions) and the cost of installing and operating the system during the lifetime of the project (replacement, operation and maintenance, fuel and interest).

In the optimization step, configurations with the lowest total net present cost, or also known as life cycle cost (NPC), are displayed by Homer. The NPC is the present value of all installation and operating costs of the system minus the present value of all revenues over its lifetime (Homer Energy, 2021). Equations (1) and (2) are used to calculate the NPC (Lambert *et al.*, 2006).

The average energy production cost per kWh (COE) is also estimated and can be important to compare the energy supply cost in different systems. Finally, in the sensitivity analysis phase, the optimization process is repeated for each specified variable in order to measure the effects of uncertainties or changes in the model inputs (Homer Energy, 2021).

$$NPC = \frac{C_{annual}}{CRF\ (i,n)} \quad (1)$$

where Cannual is the total annual cost of the system; CRF(i, n) is the capital recovery factor, defined by Equation 2 based on a real interest rate i, in % and an estimated useful life of the project n, in years.

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

where

$$i = \frac{i' - f}{1 + f} \quad (3)$$

where i' is the nominal interest rate and f is the annual inflation rate.

3.3 Available energy resources

The lack of measurement stations for local hydrological variables compromises local monitoring. It was necessary to use computational tools to estimate the affluent flow indirectly.

The methodology to estimate the flow consisted of using a concentrated hydrological model of rain-flow transformation using historical series of the monitoring stations (pluviometric, fluviometric and evaporation) of the National Water Agency (Galdino, 2021).

Figure 2 shows the average monthly flows equivalent to the average year of 2014. The estimated average flow was 5886 L.s-1, with the highest volumes found during the winter and spring seasons.

In order to mitigate the difficulties of small hydro plants without accumulation reservoirs (seasonal changes due to rainfall regimes and consequently the water flow can be less intense compared to low energy generation) and to expand the renewable energy potential, the complementarity with other energy matrices can be favourable.

The solar resource for photovoltaic production will be considered as complementary energy to the hydro system due to the floating photovoltaic modules helping the hydro microsystems during hot seasons when the average rainfall tends to be lower (Hoseinzadeh *et al.*, 2020) as well as in demand peaks during the day (Rauf *et al.*, 2020).

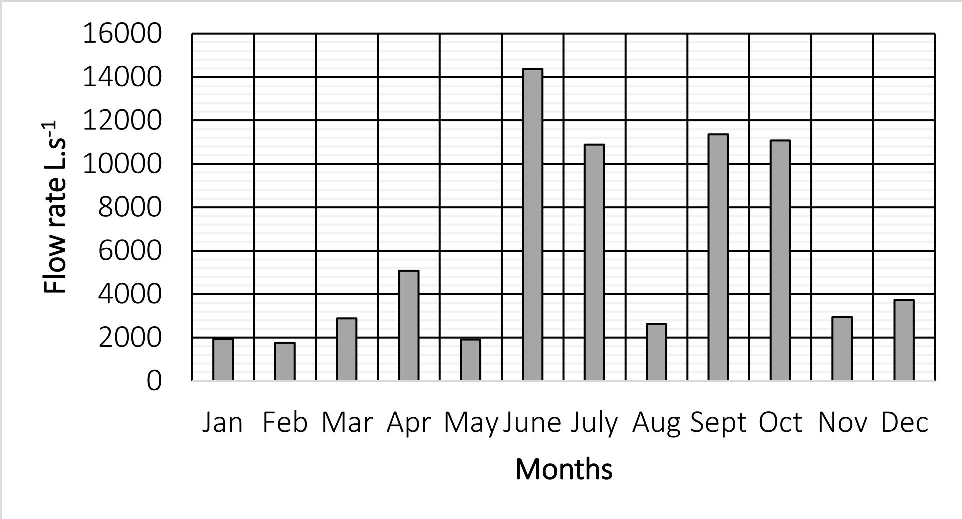

Figure 2 - Average monthly stream flow for the year 2014 for the Santa Cecilia dam session.

The annual solar irradiation profile and the clarity index (percentage of clear sky and the influence of clouds) of the plant with their respective monthly average values are represented in Figure 3. The data represented in the graph were obtained from the NASA database by through the local geographic coordinates in the HOMER Energy software. The local global average solar radiation is 4.38 kWh.m-²day-1, with higher values in the summer and spring seasons (from September to March).

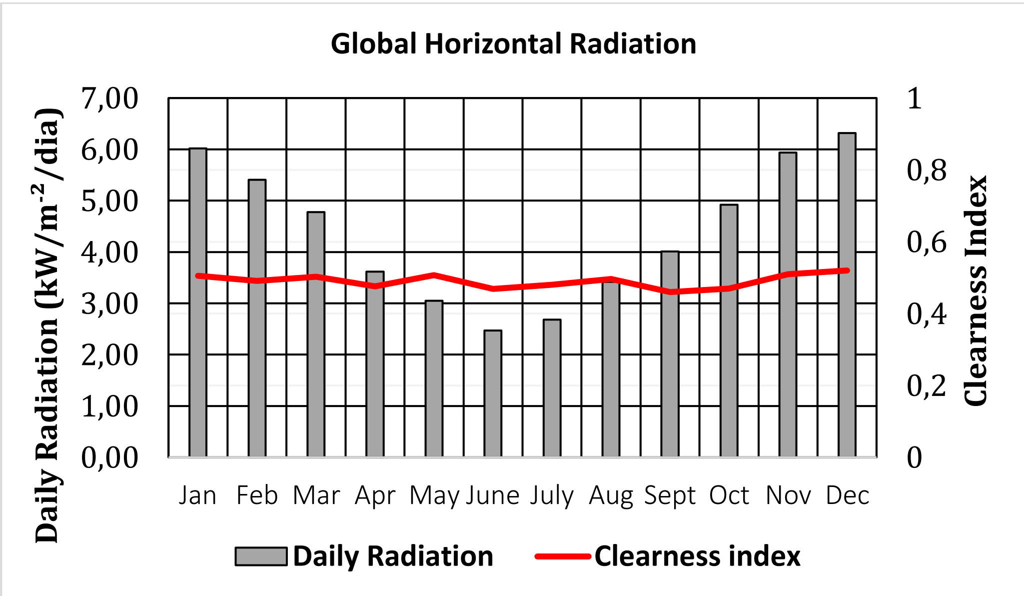

Figure 3 – Monthly average daily incident solar radiation and clarity index.

3.4 Description of the system and components for simulations

The following components were considered to supply an AC (alternating current) load: diesel generator, hydraulic turbine, photovoltaic modules, batteries for energy storage and a bidirectional AC-DC (direct current) converter. Figure 4 represents the schematic diagram with the system components including the diesel generator and Figure 5 considers the same components without including the diesel generator.

The unit specifications were chosen from the HOMER Energy software component library, in models similar to those on the current market. The load was determined from the turbine output power specifications for 160kWh to validate the model under different demand conditions.

The costs of the components referring to installation, replacement and O&M (operation and maintenance) are presented in Table 1. The costs of the photovoltaic modules, converters and batteries were estimated based on the acquisition values of the components and their installation obtained from surveys for the Brazilian market and suppliers in this period (EPE 2018; IRENA, 2020; Neosolar, 2020).

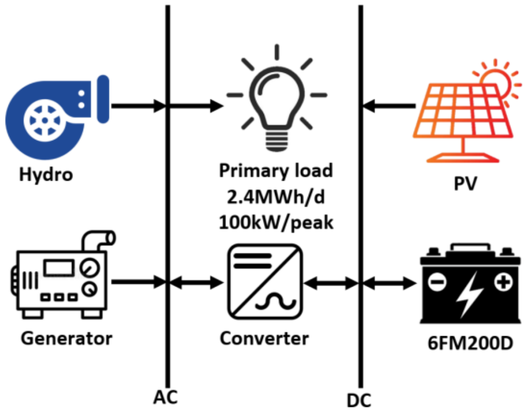

Figure 4 - Schematic diagram for the system including diesel generator.

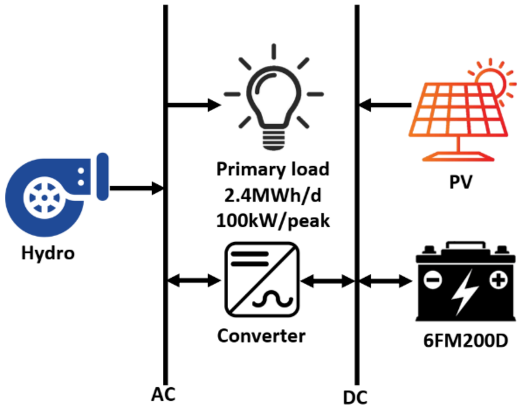

Figure 5 - Schematic diagram for the system without diesel generator.

The battery bank consists of Vision 6FM200D model strings, with a nominal voltage of 12V and a minimum useful life of 5 years. Photovoltaic modules do not have a tracking system and a useful life of 20 years was considered. The inserted converters have a useful life of 15 years and efficiency of 90% for rectification (AC-DC) and 85% for inversion (DC-AC) (Ansong and Mensah, 2017; Vieira and Carpio, 2020).

The exchange rate considered was US$1 = R$5.60 and the estimated useful life was 25 years. Maintenance operation costs equal to 5% of the acquisition value and equal to 80% of the initial value for replacement were also considered. The characteristics of the turbines are presented and the diesel generators considered (Zdenek, 2020) are also presented in Table 1.

4. Results and discussion

Figure 6 to Figure 18 present the results of a pre-feasibility study, which has just intended to understand the impact of the use of the siphon turbines and their combined use with renewable resources. The results of Figure 6, Figure 8, Figure 9, Figure 10, Figure 11 and Figure 12 include diesel generators between the options, while the results of Figure 13 to Figure 18 do not include them.

Figure 6, Figure 8 and Figure 9 show the results for Figure 4, with design flow rate equal to 5012 liters per second, respectively for PV capital cost multiplier equal to 1.0, 0.8 and 0.6. These three figures, as well as the next three, present optimization spaces considering the diesel price as a function of the primary load.

Figure 6 shows most of the optimization space corresponding to solutions with combinations including diesel generators, which appear in brown. A part of this area, with hatches, includes batteries in solutions. The smallest portion of the optimization space in pink includes PV modules.

Table 1. Component costs for economic evaluation.

Component	Installation cost (US$)	Replacement cost (US$)	O&M cost (US$)
Photovoltaic modules	3000 US$/kW	2700 US$/kW	30 US$.kWano
Converter	800 US$/kW	720 US$/kW	40 US$/kWyear
Batteries	220 US$/kW	196 US$/um	10 US$/kWyear
Turbine TM 5	57000 US$	45600 US$	2850 US$/year
Turbine TM 10	200000 US$	160000 US$	10000 US$/year
Generator 8 kW	2500 US$	2000 US$	125 US$/year
Generator 35 kW	4300 US$	3440 US$	215 US$/year
Generator 100 kW	14000 US$	11200 US$	700 US$/year
Generator 140 kW	25000 US$	20000 US$	1250 US$/year

The costs for the modular turbine and diesel generator were obtained from the supplier Mavel.

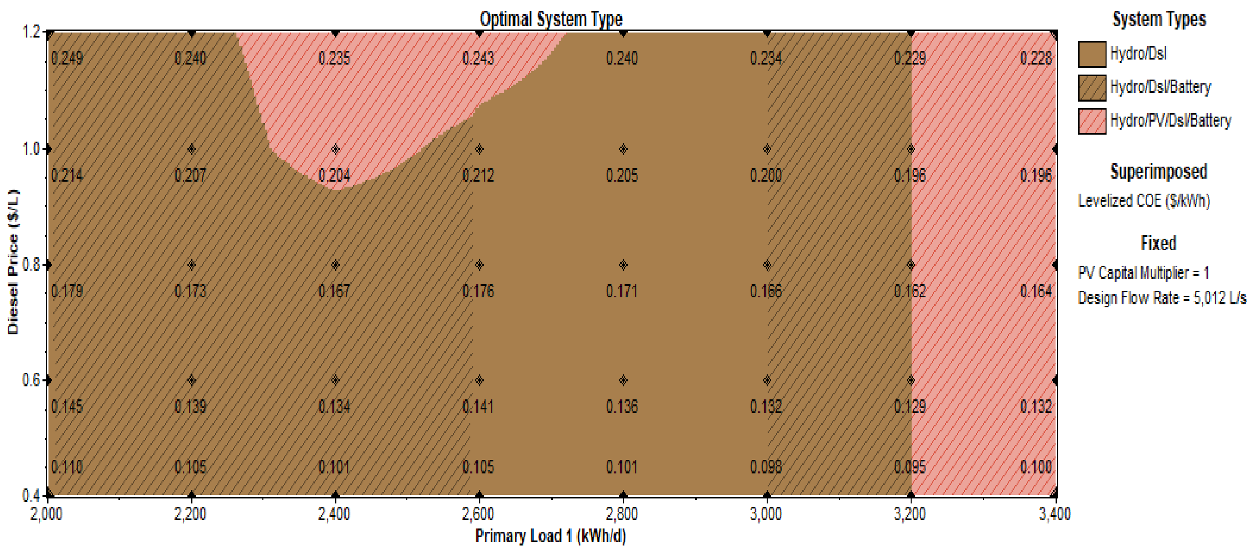

Figure 6 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 1.0 and design flow rate equal to 5,012 L/s, with cost of energy indicated on the values of the sensitivity variables.

From this previous figure, the information corresponding to the system is obtained, which can be considered as the optimal solution, considering that the system has diesel support. Figure 7 shows an excerpt of the Homer Legacy screen indicating the combination of components. So the optimal solution will be composed of a set of siphon turbines totaling 271 kW, plus 50 kW in PV modules and 140 kW in a diesel support system. A battery bank with 32 200 Ah batteries complements this system. The cost of energy for this system is US$ 0.164 per kWh.

Primary Load 1 (kWh/d) 3,400 Diesel Price ($/L) 0.8 PV Capital Multiplier 1 Design Flow Rate (L/s) 5,012

Double click on a system below for simulation results.

	PV (kW)	Hydro (kW)	Dsl (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Dsl (hrs)	Batt. Lf. (yr)
	50	271	140	32	50	$ 351,468	176,018	$ 2,601,568	0.164	0.69	196,999	4,401	5.9

Figure 7 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 1.0 and design flow rate equal to 5,012 L/s, with cost of energy indicated on the values of the sensitivity variables.

A 20% reduction in the costs of PV modules, with results shown in Figure 8, above, indicate a fairly reasonable expansion in the portion of solutions including PV modules. A further reduction in the costs of PV modules, taking 40% in relation to the results of Figure 6, with results shown in Figure 9, below indicate further expansion in the portion of solutions including PV modules.

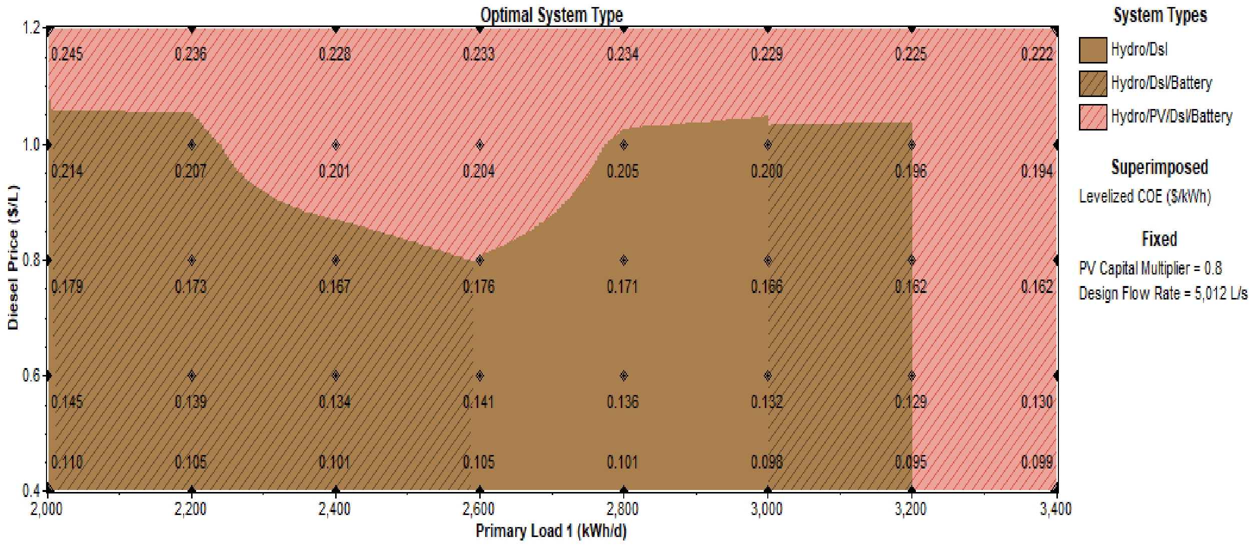

Figure 8 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 0.8 and design flow rate equal to 5,012 L/s, with cost of energy indicated on the values of the sensitivity variables.

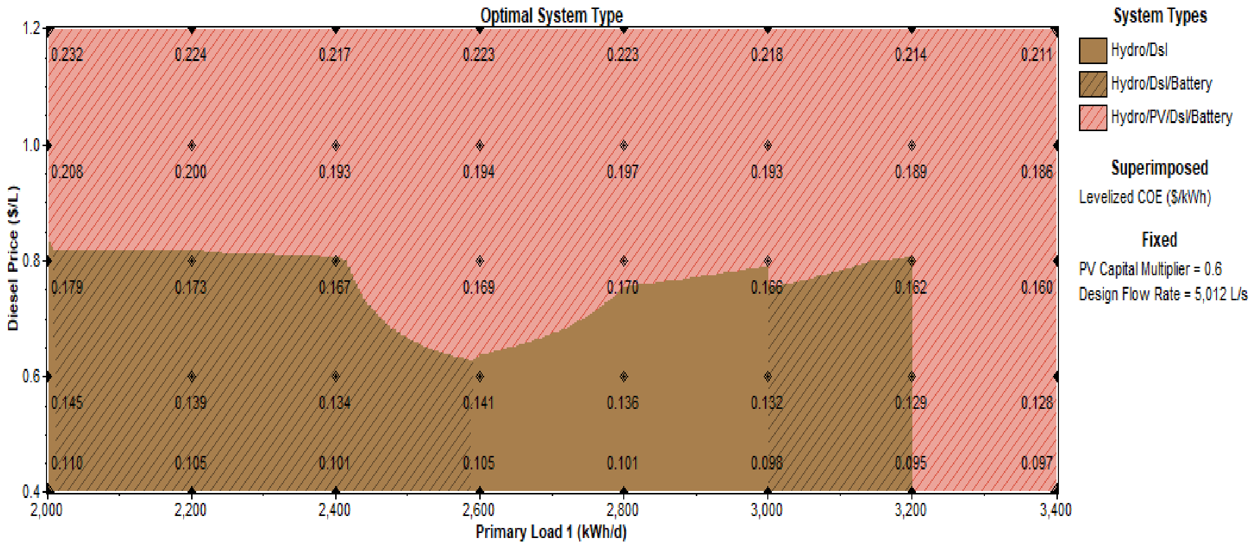

Figure 9 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 0.6 and design flow rate equal to 5,012 L/s, with cost of energy indicated on the values of the sensitivity variables.

Obviously, in these three figures above, the higher costs of energy appear in the areas in brown, always reduced in the points that end up being swallowed by the areas in rose. The same behavior will be observed in the next three figures.

Figure 10, Figure 11 and Figure 12 show the results for Figure 4, with design flow rate equal to 710 liters per second, respectively for PV capital cost multiplier equal to 1.0, 0.8 and 0.6. A lower flow in relation to the previous results already carries the optimization space of Figure 12 to be dominated by solutions including PV modules. The results of the following figures, with 20% and with 40% respectively lower costs of PV modules, lead to optimization space with all solutions including PV modules in the last of these three figures.

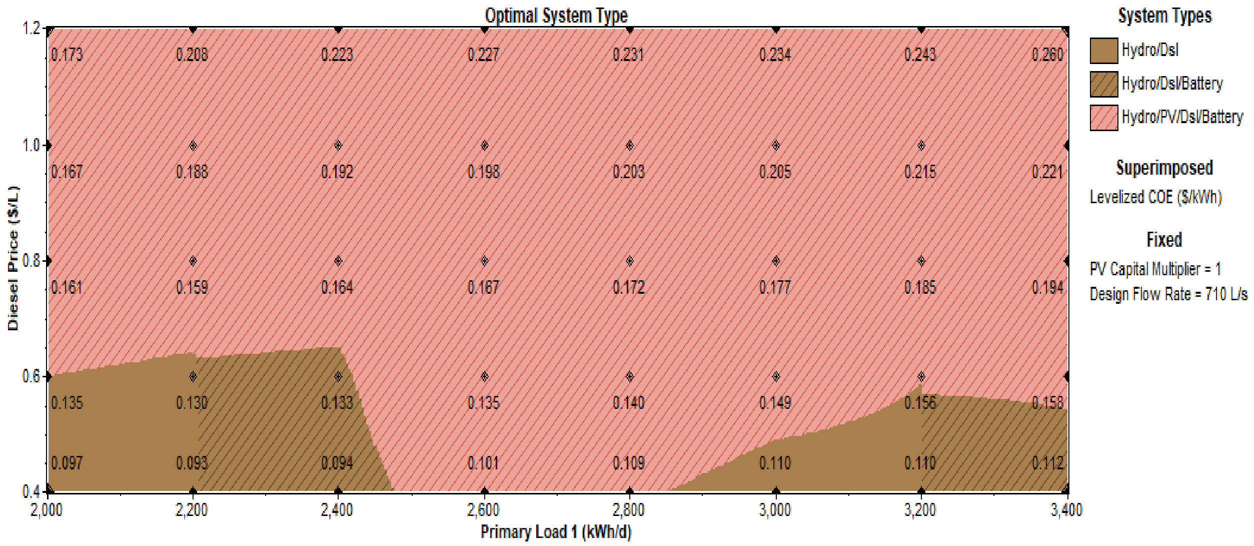

Figure 10 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 1.0 and design flow rate equal to 710 L/s, with cost of energy indicated on the values of the sensitivity variables.

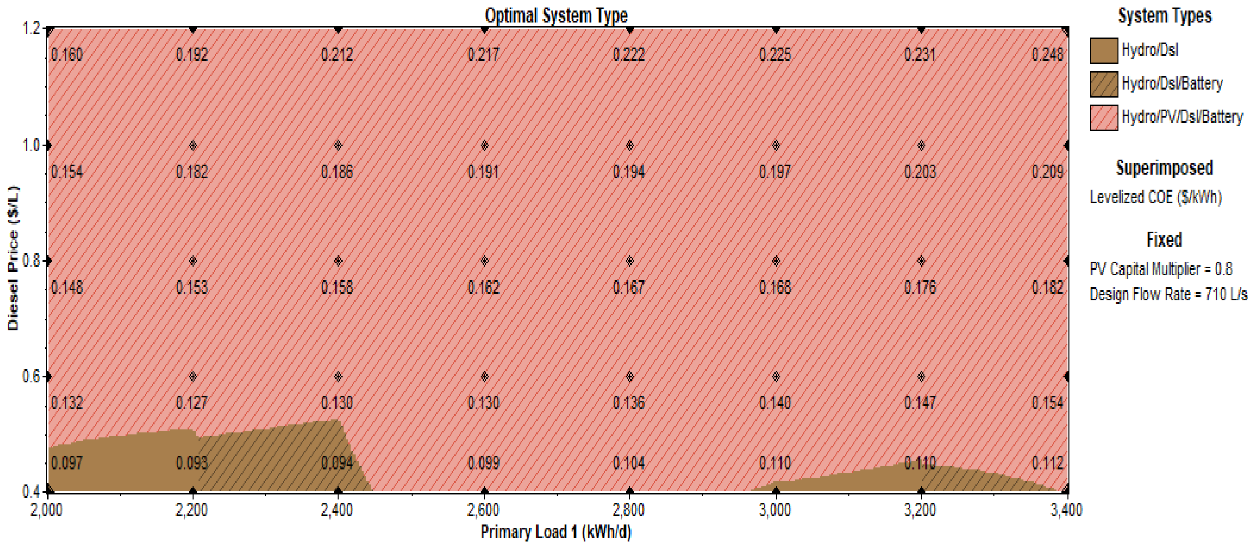

Figure 11 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 0.8 and design flow rate equal to 710 L/s, with cost of energy indicated on the values of the sensitivity variables.

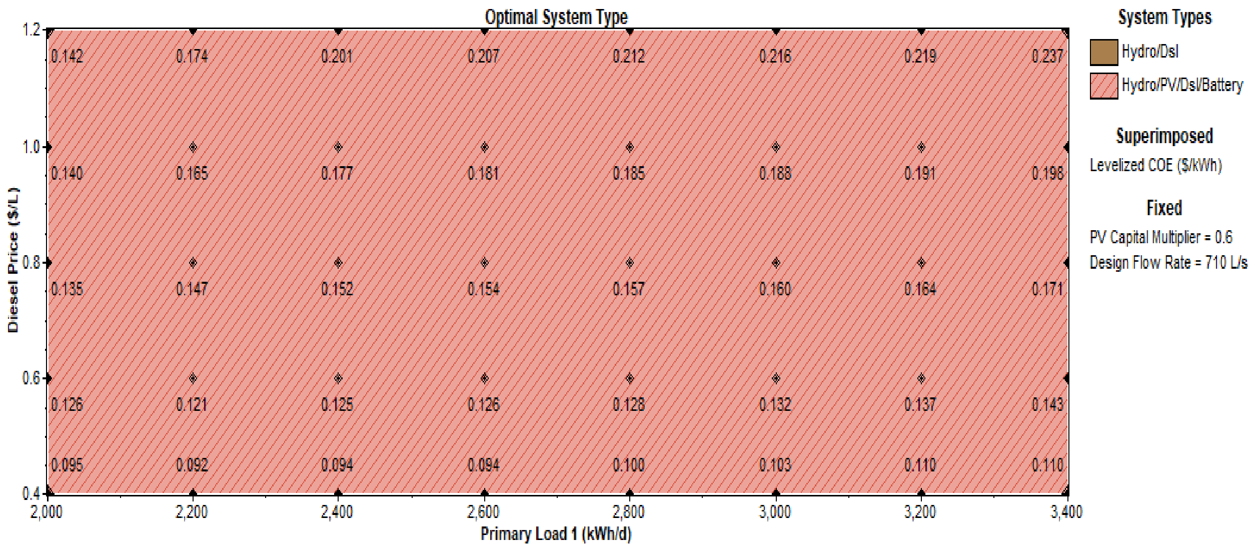

Figure 12 - Optimization space considering diesel price as a function of primary load, for the system of Figure 4, with PV capital cost multiplier equal to 0.6 and design flow rate equal to 710 L/s, with cost of energy indicated on the values of the sensitivity variables.

Figure 13, Figure 14 and Figure 15 show the results for Figure 5, with design flow rate equal to 5,012 liters per second, respectively for maximum annual capacity shortage equal to 0%, 3% and 10%. These three figures, as well as the next three, present optimization spaces considering the PV capital cost multiplier as a function of the primary load.

For 0% of service failures, viable results appear only up to 2600 kWh of load. By accepting higher failure rates, the optimization spaces once again contain viable solutions in their entirety in the subsequent figures. Energy costs also show significant reductions, above 50%.

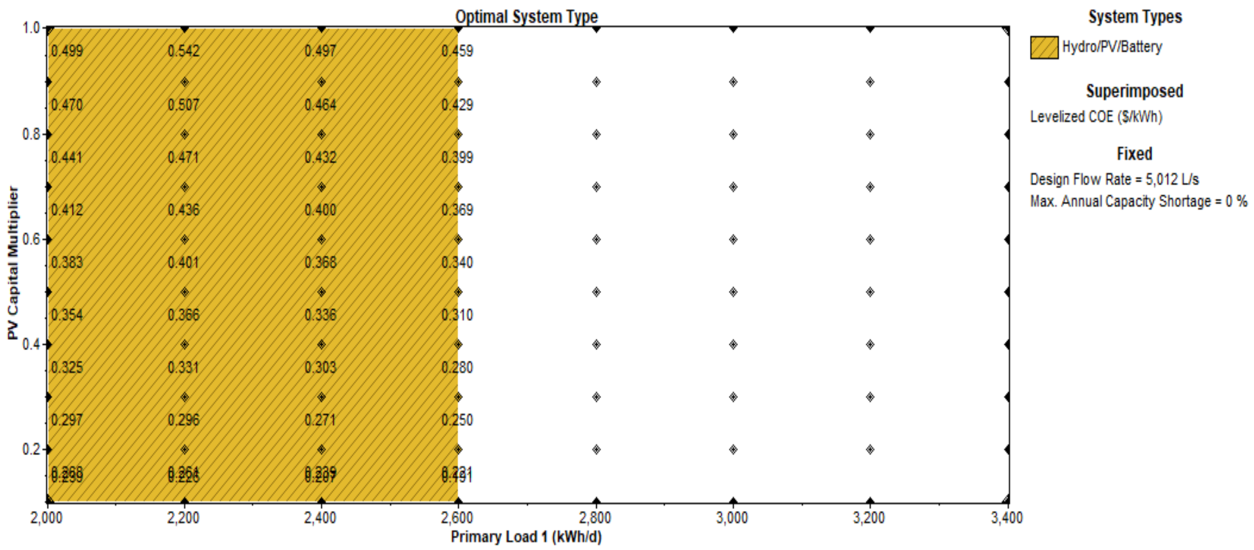

Figure 13 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 5,012 L/s and 0% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

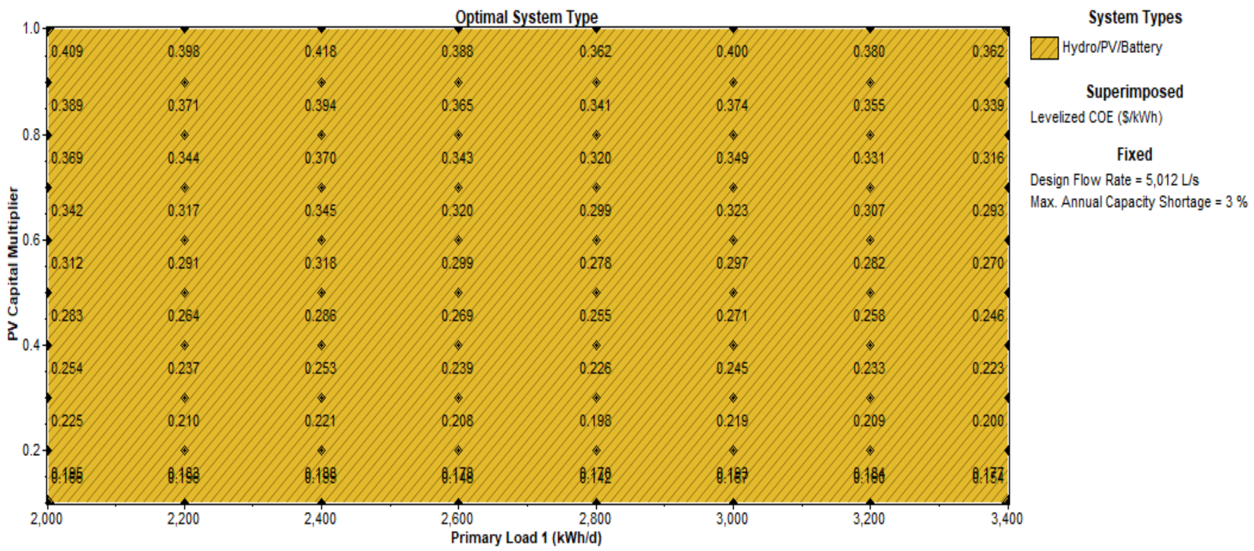

Figure 14 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 5,012 L/s and 3% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

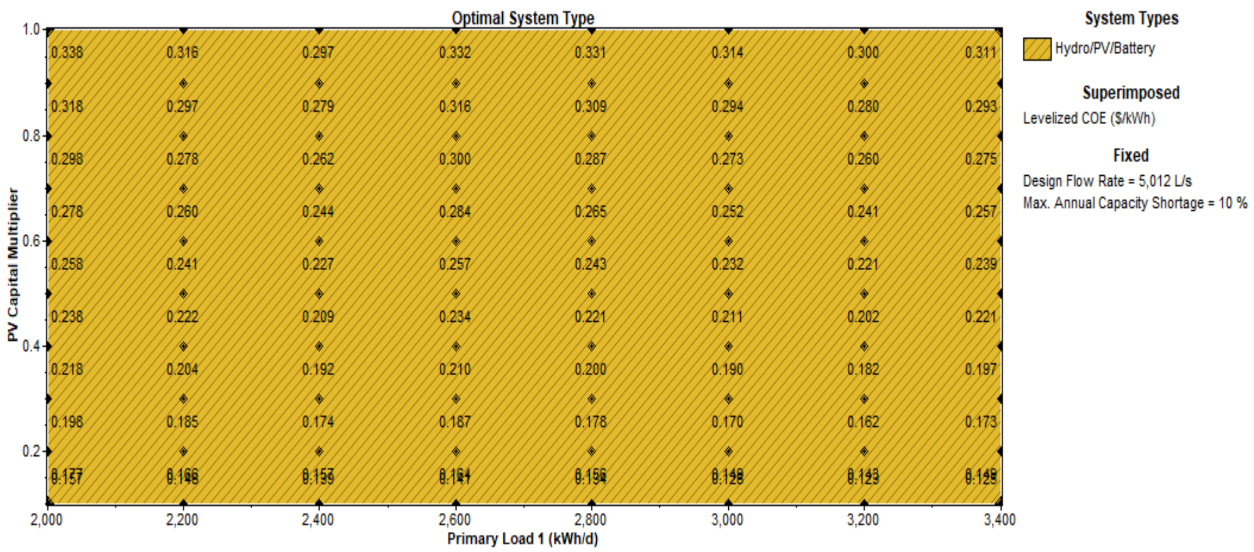

Figure 15 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 5,012 L/s and 10% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

Figure 16, Figure 17 and Figure 18 show the results for Figure 5, with design flow rate equal to 710 liters per second, respectively for maximum annual capacity shortage equal to 0%, 3% and 10%. Comparing these next three figures with the three previous figures, it is observed that the optimization space of the first figure is complete, comparing Figure 13 and Figure 16, and that the reductions in energy costs along the three figures are not so intense.

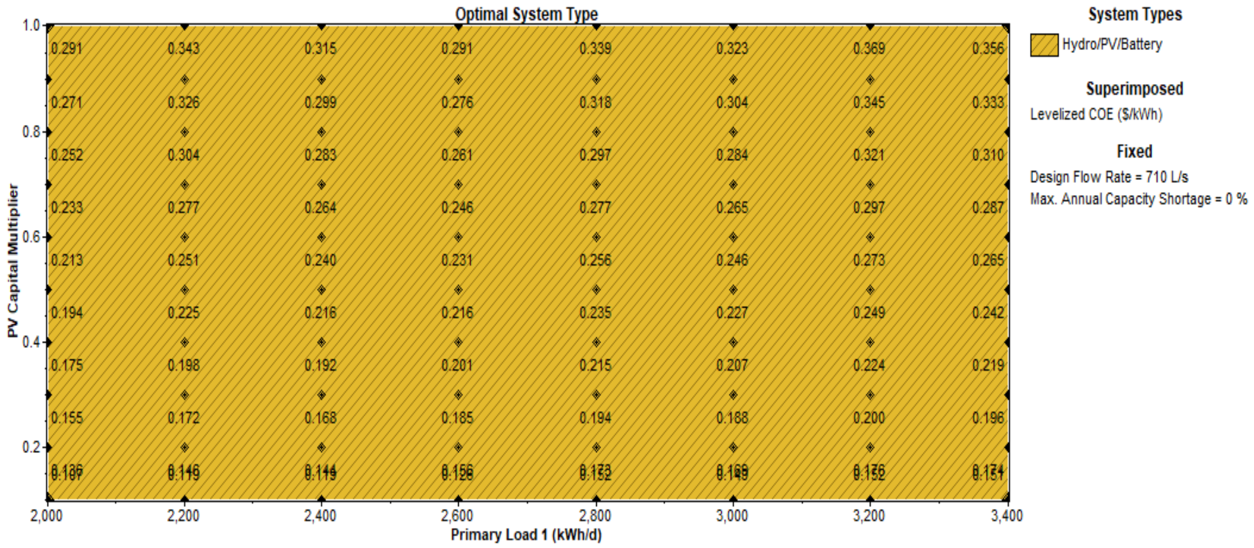

Figure 16 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 710 L/s and 0% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

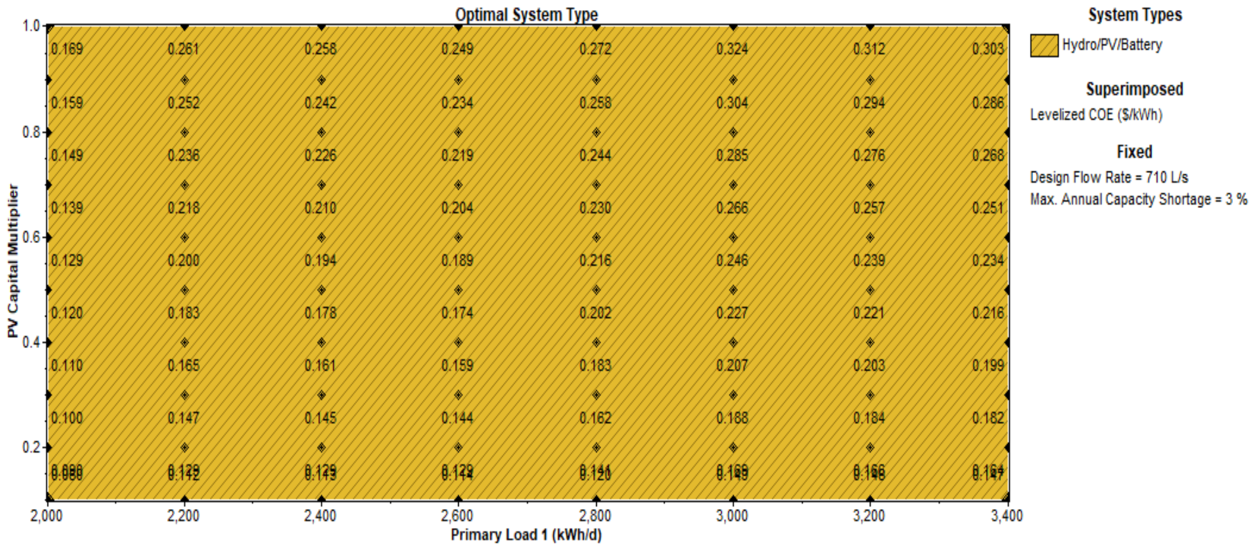

Figure 17 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 710 L/s and 3% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

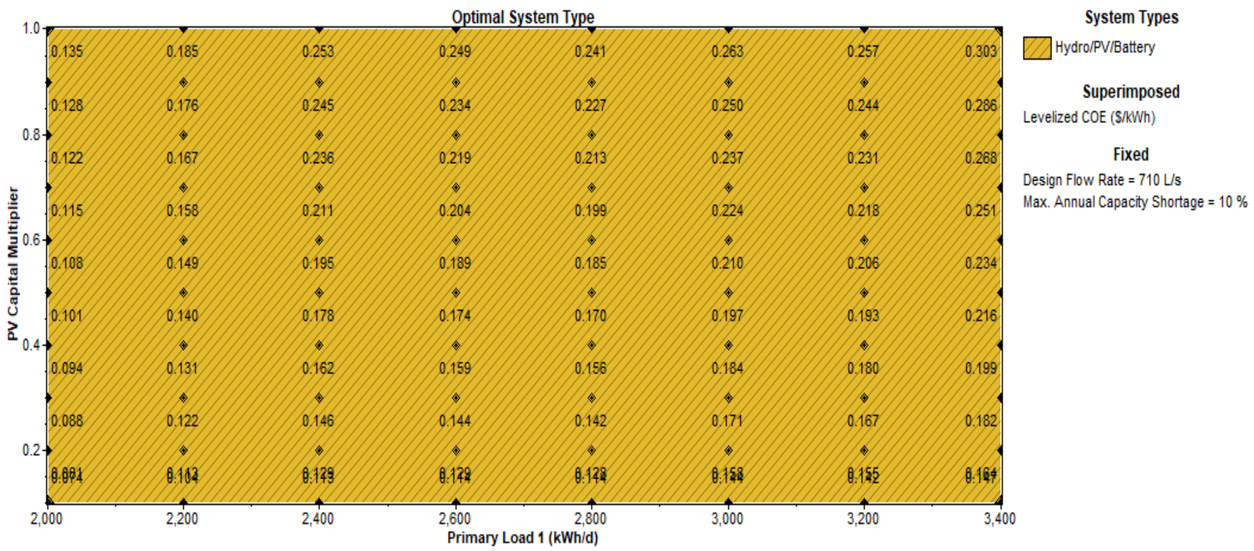

Figure 18 - Optimization space considering PV capital cost multiplier as a function of primary load, for the system of Figure 5, with design flow rate equal to 710 L/s and 10% as maximum annual capacity shortage, with cost of energy indicated on the values of the sensitivity variables.

5. Final remarks

According to the simulations carried out, a cost equivalent to 0.164 US$.kWh-1 was verified in the system considered as an optimal solution (composed of a set of siphon turbines totaling 271 kW, 50 kW in photovoltaic modules, 140 kW in a diesel support and a battery bank with 32 batteries of 200 Ah). The renewable fraction represented 69% of this system. The direct cost comparison of this condition seemed more reasonable in periods of high energy demand on the grid (6:30 pm to 8:00 pm). Intervening factors such as fees charged by local concessionaires and economic and social factors must also be considered and thoroughly evaluated in this context.

It is believed that accounting for the total potential available for power generation in low head locations (with characteristics similar to the case addressed, especially flow and height) is a starting point for countries to evaluate future investments in the sector. In addition, case studies for comparative purposes would also be scientifically relevant given the scarce bibliography available on the subject.

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