GREEN HYDROGEN AS A TOOL TO COMPLETELY DECARBONIZE OFF-GRID AMAZONIAN COMMUNITIES

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Abstract

This paper explores the feasibility of utilizing green hydrogen (H2) for decarbonizing an isolated community in the Brazilian Amazon, focusing on the off-grid system of Oiapoque-AP. It assesses the optimal sizing of equipment required for this solution, considering the current energy supply that is given by a diesel plant and a PV system, as well as the planned addition of a hydroelectric plant. Findings indicate that a combination of lithium-ion batteries and green H2 fuel cell system is well-suited to comply with the short- and long-term storage needs to decarbonize the system. Simulations and sensitivity analysis determined the optimal sizing of components, including a PV system expansion of 25 MW, an electrolyzer of 3 MW and a tank of 2.5 M Nm³. A sensitivity analysis of electrolyzer and the additional PV system sizes revealed optimized combinations that can meet the H2 gas demand in the system. A system with additional 25 MWp in PV generation combined with a 3 MW. The study highlights the potential of H2 storage as a sustainable solution for off-grid communities and the results provide valuable insights into the integration of H2 technology and its advantages for decarbonization efforts in remote regions. The operational analysis shows the optimum sized electrolyzer operates on 51% of the year's days, with consistent hydrogen production from February to September. This suggests high component operation, which is important given its high system cost. For the studied community, a 4.2 MW fuel cell is projected to operate from September to January, indicating potential system inefficiency.

Keywords: Amazon region, green hydrogen, off-grid communities.

Introduction

Brazil hosts a vast interconnected electric grid controlled by a centralized operator, but due to technical and geopolitical challenges in constructing energy-related infrastructure, isolated microgrid systems have been adopted (Carvalho, 2006). These microgrids, primarily concentrated in the Brazilian Amazon Region, have traditionally relied on diesel generators for their energy needs due to low-capital costs, ease of installation, and portability (Ribeiro et al., 2012). However, as global efforts to address climate change intensify and renewable technology costs decline, off-grid renewable energy systems are emerging as a more sustainable alternative.

While the region experiences relatively low wind speeds and faces concerns of illegal deforestation associated with increased biomass demand, solar photovoltaic (PV) systems are considered the most suitable energy source for off-grid solutions. The abundant rainfall combined with an equivalent global horizontal irradiation to sunniest European countries make solar PV feasible (Pereira et al., 2017). However, to overcome the intermittent nature of solar energy, an energy storage system is required, either in the form of traditional battery technology or a hydrogen (H2) storage system (Suleman, Dincer and Agelin-Chaab, 2015).

Lithium-ion battery storage systems and hydrogen storage systems represent two crucial technologies for the storage of renewable energy. Each possesses its own set of advantages and disadvantages when considering factors such as utility, cost-effectiveness, efficiency, reliability, and safety (Sterner and Stadler, 2019). Lithium-ion battery systems offer notable advantages, particularly in terms of efficiency, that range from 85% to 95%. Furthermore, these systems exhibit a high energy density, enabling them to store significant energy quantities within compact spaces (Alshahrani et al., 2019).

In contrast, hydrogen serves as a high-energy-density fuel and also serves as a viable energy storage medium. Hydrogen demonstrates remarkable versatility, finding application as a fuel for vehicles, as a means for generating electricity via fuel cells, as a source of emissions-free heat generation, and in various chemical industry processes

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(Møller et al., 2017). Nevertheless, the storage of electrical energy using hydrogen involves more processes, producing an efficiency from 20 to 50%. Despite its low efficiency, hydrogen has the advantage of very small self-discharge ratio, so it is suitable for a long storage period. Lithium-ion batteries, on the other hand, have a medium self-discharge ratio and are suitable for a storage period not longer than tens of days (Chen et al., 2009). Given that, even with the financial barriers, a combination of green H2 and lithium ion batteries can be used to supply stored energy in communities where there is a mismatch between energy demand and supply (Oliveira et al., 2023).

This study investigates the viability of utilizing green H2 to decarbonize an isolated community in the Brazilian Amazon. The analysis evaluates the optimal sizing of the equipment necessary for this solution, assessing its technical feasibility. While the focus is on an extreme case of an off-grid community in the Amazon, the findings can be extrapolated to more conventional communities, particularly in terms of understanding the potential of long-term H2 storage and its advantages and trade-offs compared to conventional battery storage.

Methods

This analysis is focused on the off-grid system of Oiapoque. Oiapoque is a city in the state of Amapá, located about 550 km from the capital Macapá, bordering French Guiana. The system is currently supplied by an Independent Electric Energy Producer, contracted through an auction held in 2014, effective until November 2030. The electric energy is supplied by a 12.83 MW thermoelectric diesel plant and a PV system of 4.3 MWp. The first one is intended to be deactivated upon the construction of the run-of-river hydroelectric plant Salto Cafesoca (7.5 MW), scheduled to be finalized in 2024. However, the decarbonization of the energy production of this community is a complex problem, which requires the addition of energy storage systems in addition to non-dispatchable energy sources.

To solve this problem, lithium-ion batteries and H2 storage are two prominent technologies for storing renewable energy, each with their own advantages and disadvantages in terms of use, cost, efficiency, reliability, and safety (Sterner and Stadler, 2019). For short-term energy storage, lithium-ion batteries are well suited, given their high efficiency and high energy density. However, given their self-discharge, for long-term energy storage, the use of green H2 is a better fit. Given the mismatch of the load profile and of the hydroelectric generation potential (as shown in Fig. 1), a mix of both types of storage is recommended (Due to information limitations, data available in the public domain on the locality's load, provided on an hourly basis, and the estimated monthly production energy from the hydroelectric plant will be used). To optimize the appropriate size of both storage systems, data on energy demand and estimated generation of the hydroelectric and PV plants were analyzed (Empresa de Pesquisa Energética (EPE) and Ministério de Minas e Energia (MME/SPE), 2018).

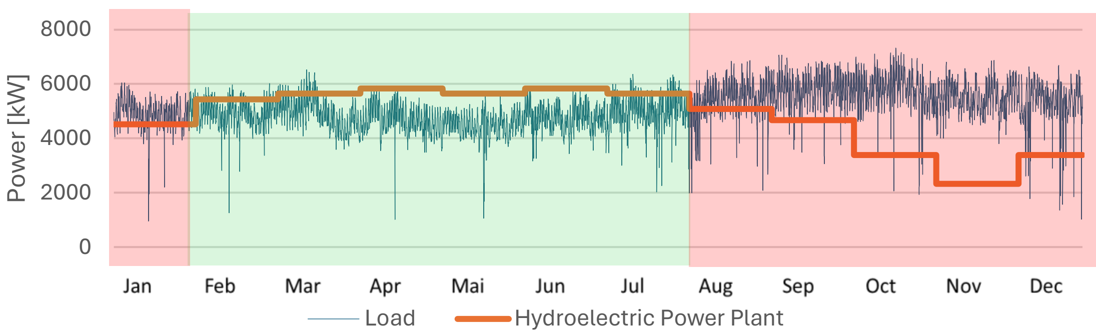

Fig. 1: Mismatch between load and Hydroelectric power plant generation.

To fully meet the energy demands of Oiapoque through a renewable system, it is necessary to combine a rapid response storage system to meet load variations and intermittent generation, with a storage system capable of storing large volumes of energy without self-degradation. According to Sterner M. and Stadler I. (2019), the battery storage system must be employed to compensate the daily load fluctuations, while the H2 storage system should address the annual variation in generation from the small hydropower plant. Therefore, in this study, for the sizing of the H2 system, it was considered that the surplus of hydro and solar energy produced is used for gas production. This generated gas is then used in the remaining months for the production of electric power. The sizing of the battery storage system was carried out to ensure the daily energy supply to the community, from February to July, bearing in mind that during this period, the use of H2 as an electricity source would not be required. For the evaluation of the calculated sizing, the amount of energy used to produce green H2 and the energy dispatch in the fuel cell was calculated in each timestep (1 hour) in a period of one year. For moments when there is an excess of renewable energy generation, the energy dedicated to H2 producing in the eletrolyzer (E_{el}) is determined by Eq. 1.

$$E_{el} = E_{PV} + E_{Hydro} - L - E_{Bat_{Charge}} \qquad \text{(eq. 1)}$$

In the equation, E_{PV} represents the amount of PV energy produced and E_{Hydro} represents the production of energy of the hydropower plant. The energy demand of the community is represented by L and $E_{Bat_{Charge}}$ corresponds to the energy that is feed into the battery, respecting its capacity and inverter limits. On the other hand, the energy supplied by the fuel cell (E_{FC}) when there is not enough renewable energy available, and the limits of the battery are achieved is given by Eq. 2.

$$E_{FC} = L - E_{PV} - E_{Hydro} - E_{Bat_{Discharge}} \qquad \text{(eq. 2)}$$

Here, the coefficients for energy production and energy demand remain the same as the Eq. 1, with the addition of $\boldsymbol{E_{Bat_{Discharge}}}$, which represents the energy that is provided by the battery to the system.

The expansion of the PV system was also considered as a possibility. A sensibility analysis of different combinations of sizing of the equipment was carried out, based on supplying the demand of the community in terms of power and energy, attempting to optimize renewable energy availability.

The operation of the electrolyzer must be carefully evaluated, especially with regard to its operating behavior over different periods and conditions. Given its position as the most expensive component within the energy system under analysis, the ideal goal is for the electrolyzer to be used for the longest possible period of time, thus maximizing its efficiency and return on investment.

Optimizing the operating regime of this device not only extends its usefulness within the system as a whole, but also contributes to the overall effectiveness of the configuration, directly impacting on metrics such as energy autonomy, sustainability and economic viability. Such considerations are fundamental to both the design phase and the execution and management of the system and should be incorporated into any subsequent technical analysis and strategic decision.

Table 1 shows the parameters used for the simulation and sizing of equipments to fully meet the energy requirements of the community. The parameters of the efficiency of the equipment are based in analysis of datasheets of commercial products. The sizing of power and capacity of the systems are variable and calculated during the simulations.

Table 1- Technical premises used for the simulation of the system.

Battery Storage System	Type	Li-ion	
	Round-trip efficiency	98%	
	Capacity	Variable	
	PCS	Variable	
	Time response	milliseconds	
PV system	Global Horizontal irradiation (year average)	4,94 kWh/m²/day	
	Performance ratio (PR)	0,78	
	Installation type	Fixed	
	Azimuth	0°	
	Tilt	10°	
	Size	Variable (0MWp -30MWp)	
Electrolyzer	Operational Power Range	PEM	(20%-100%)
		Alkaline	(80%-100%)
	Efficiency	5 kWh/Nm³	
	Size	Variable (0MW -10MW)	
Fuel Cell	Consumption	70g/kWh	
	Size	Variable	
Gas storage	Size	Variable	

Results

The battery storage system was designed to ensure the daily supply of electricity to the community. The system is used to store PV energy produced during the day to feed the grid when the hydro generation is not sufficient. To meet the community's energy needs during this time, a system capacity of 16 MWh, coupled with a 2 MW Power Conversion System (PCS) was estimated to be a minimum necessary. Fig 2 illustrates the storage system State of Charge (SOC) along the year using the minimum possible sizing. It can be noted during the months of February and July, there is practically no need to dispatch the storage system, as the hydroelectric generation system and the solar PV generation system are enough for the microgrid to function correctly.

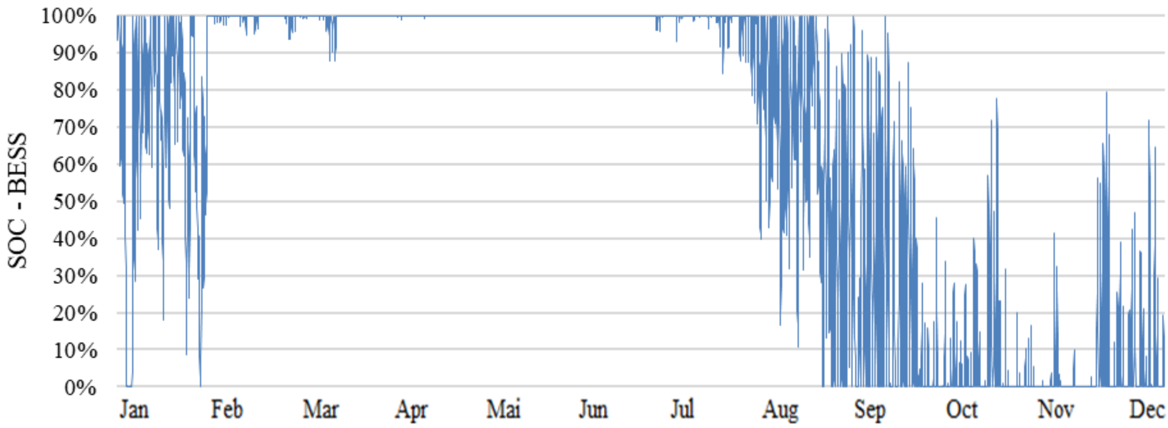

Fig. 2– Battery SOC that controls short variations in charge.

Simulations were performed using different strategies for the sizing of the components, which resulted in different full load hours of the eletrolyzer, the most expensive equipment in the analysis. The different sizing scenarios had a direct influence on the volumetric requirements of the hydrogen storage tanks. In the evaluated scenario, the optimally calculated system requires a storage capacity of approximately 2.5 x 10^6 Nm³ (224.7 tons of H2), with the target of completing the full load by mid-September. The sized tank is extremely large and would require a tank of 8,3 x 10^3 m³ at 300 bars. Therefore, the best option to optimize space would be a cryogenic solution. Fig. 3 shows the impact of different electrolyzer sizes on the proper operation of the hydrogen storage infrastructure.

The orange line shows a system with optimal sizing between the electrolyzer and the energy sources. This is seen when the hydrogen storage tank starts the year empty, reaches its maximum capacity at the end of September and subsequently discharges through the fuel cell in the following months, leaving no surplus hydrogen. When the electrolyzer is oversized, as indicated in blue, a premature filling of the tank occurs, observed in point A. In addition, excess hydrogen remains at the end of the year, leading to further underutilization of the electrolyzer in the following year, as shown in point B. On the contrary, an undersized electrolyzer results in premature emptying of the tank, as shown in point C, thus inducing an energy deficit in the system.

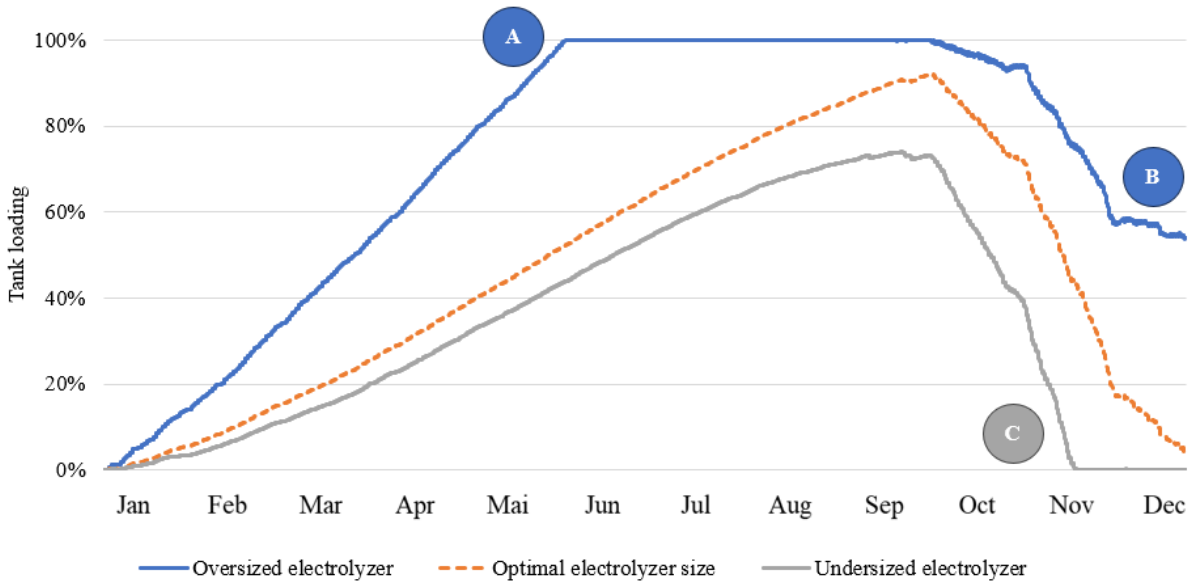

Fig. 3 - The Impact of Electrolyzer Sizing on the Hydrogen Storage System.

In order to assess the feasibility of incorporating green H2 production and consumption in the community, it is essential to carry out a sensitivity analysis of the size of the electrolyzer and PV system to be added to the 4.5 MWp system already installed in the community. Table 2 shows the annual energy deficit produced by each combination of systems considering an electrolyzer with PEM technology. In the table, the optimized combinations are highlighted in bold, and the best scenarios, which are cheaper, are highlighted in red.

Table 2- Maximum power shortage at each combination of PEM electrolyzer size and additional PV power (MWh).

		Additional PV Power plant						
		0MWp	5MWp	10MWp	15MWp	20MWp	25MWp	30MWp
Electrolyzer size	1 MW	3.35	1.96	1.48	1.26	1.12	1.02	0.96
	2 MW	3.06	1.53	0.98	0.71	0.55	0.44	0.36
	3 MW	2.95	1.26	0.60	0.28	0.08	**0.00**	**0.00**
	4 MW	2.93	1.09	0.31	**0.00**	**0.00**	0.00	0.00
	5 MW	2.98	1.01	0.10	0.00	0.00	0.00	0.00
	6 MW	3.05	0.97	**0.00**	0.00	0.00	0.00	0.00
	7 MW	3.11	0.97	0.00	0.00	0.00	0.00	0.00
	8 MW	3.18	1.00	0.00	0.00	0.00	0.00	0.00
	9 MW	3.23	1.03	0.00	0.00	0.00	0.00	0.00
	10 MW	3.29	1.08	0.00	0.00	0.00	0.00	0.00

For any size of electrolyzer, it is unfeasible to ensure total fulfillment of the community's energy demand without integrating additional energy production. It is necessary to integration an additional capacity of at least 10 MWp of

PV systems to fully meet the demand. For an electrolyzer with a capacity of 6 MW, it is essential to incorporate at least 10 MWp of PV generation. For a 4 MW electrolyzer, the requirement increases to a minimum addition of 15 MWp in PV capacity. Similarly, a 3 MW electrolyzer requires a minimum increase of 25 MWp in PV generation for effective operation. It can be concluded that electrolyzers with a capacity of less than 3 MW are undersized for this system, resulting in a lack of energy to suit the community.

The previously mentioned evaluations were carried out using PEM (Proton Electrolyte Membrane) type electrolyzers, which have a wide operating range, varying between 20% and 100% of their capacity. For comparison purposes and to improve the analytical scope, electrolyzers operating with alkaline technology were also investigated, whose operating range is notably narrower, oscillating between 80% and 100%. The energy deficit resulting from these technological variations is presented in Table 3, providing a more comprehensive and rigorous view of the limitations inherent in each type of electrolization technology.

Table 3- Power Shortage at each combination of Alkaline electrolyzer size and additional PV power (MWh).

		Additional PV Power plant						
		0MWp	5MWp	10MWp	15MWp	20MWp	25MWp	30MWp
Electrolyzer size	1 MW	3.45	2.05	1.57	1.34	1.20	1.11	1.04
	2 MW	3.41	1.85	1.28	0.99	0.82	0.69	0.60
	3 MW	3.49	1.74	1.00	0.65	0.43	0.27	0.16
	4 MW	3.62	1.74	0.85	0.36	0.09	**0.00**	**0.00**
	5 MW	3.78	1.81	0.77	0.18	**0.00**	0.00	0.00
	6 MW	3.90	1.90	0.76	0.06	0.00	0.00	0.00
	7 MW	3.93	2.05	0.79	**0.00**	0.00	0.00	0.00
	8 MW	3.94	2.19	0.91	0.00	0.00	0.00	0.00
	9 MW	3.94	2.37	1.05	0.00	0.00	0.00	0.00
	10 MW	3.94	2.51	1.23	0.07	0.00	0.00	0.00

With regard to the alkaline electrolyzer, its restricted operating range means that a larger PV generation system is needed to fully satisfy the community's energy demands. It can be seen that, in this specific scenario, it is not possible to guarantee the community's complete energy supply without the inclusion of an additional minimum of 15 MWp of PV generation. Furthermore, in order to achieve this goal with an additional 15 MWp of PV capacity, an electrolyzer with a capacity of 7 MW is required, which represents an increase of 75% compared to PEM electrolyzers. This comparative analysis serves not only to elucidate the differential performance metrics between the different electrolyzer technologies, but also provides a robust empirical substrate for making strategic decisions and evaluating operational efficiency.

In addition, Tables 4 and 5 show the amount of surplus energy generated in the system for each combination of electrolyzer and PV capacity, for the PEM and alkaline technologies, respectively.

Table 4 - Energy surplus for each combination of PEM electrolyzer size and additional PV power (MWh/year).

				Additional PV Power plant				
		0MWp	5MWp	10MWp	15MWp	20MWp	25MWp	30MWp
Electrolyzer size	1 MW	3.46	8.42	14.63	21.21	28	34.83	41.966
	2 MW	1.63	5.71	11.43	17.77	24.35	31.068	37.842
	3 MW	0.89	3.94	8.98	14.98	21.34	27.89	34.54
	4 MW	0.82	2.9	7.15	12.669	18.762	25.113	31.88
	5 MW	1.12	2.32	5.78	11.34	18.76	24.549	31.29
	6 MW	1.54	2.1	5.02	11.034	17.87	24.049	30.74
	7 MW	1.95	2.1	4.96	10.77	17.083	23.59	30.23
	8 MW	2.36	2.26	4.94	10.588	16.759	23.178	29.76
	9 MW	2.74	2.5	4.94	10.44	16.468	22.82	29.316
	10 MW	3.122	2.81	4.96	10.35	16.221	22.48	28.918

The values marked in red in the tables show combinations that result in the system being oversized, resulting in surplus gas stored in the H2 tank at the end of the annual cycle. It should also be noted that a residual amount of energy will always be present in the system. This is because the instantaneous remaining PV generation is not always fully absorbed by the electrolyzer in operation. This characteristic implies the need for refined control of the Maximum Power Point (MPPT) of the PV inverter, in order to prevent this excess generation from being translated into an unwanted variation in the frequency of the electricity grid. This observation highlights the importance of effective management and a rigorous control strategy to guarantee the stability and efficiency of the integrated system.

In addition, due to the limited operating range of alkaline electrolyzers, the implementation of this technology results in a greater accumulation of surplus energy in the system.

Table 5 - Energy surplus for each combination of Alkaline electrolyzer size and additional PV power (MWh/year).

				Additional PV Power plant				
		0MWp	5MWp	10MWp	15MWp	20MWp	25MWp	30MWp
Electrolyzer size	1 MW	4.12	9.05	15.24	21.82	28.55	35.377	42.239
	2 MW	3.878	7.77	13.32	19.56	26.06	32.68	39.4
	3 MW	4.38	7.04	11.54	17.34	23.58	29.97	36.56
	4 MW	5.21	7.02	10.57	15.521	21.39	27.52	33.909
	5 MW	6.25	7.47	10.09	14.36	19.57	25.5	31.57
	6 MW	6.98	8.08	9.99	13.56	18.336	24.4	31.11
	7 MW	7.23	9.04	10.204	13.089	17.751	24.1	30.724
	8 MW	7.25	9.94	10.94	12.91	17.634	23.8	30.39
	9 MW	7.27	11.01	11.89	12.98	17.53	23.7	30.16
	10 MW	7.28	12	13.03	13.64	17.5	23.64	29.84

Consequently, the application of PEM-type electrolyzers appears to be the most advantageous alternative. Specifically, the configuration that includes an increase of 25 MWp in PV generation combined with a 3 MW electrolyzer emerges as the most effective option. This finding is particularly justified by the fact that the electrolyzer is the most expensive component in the integrated system.

Fig. 4 outlines the annual behavior of the system in the scenario that incorporates a 3 MW electrolyzer. This graph is instrumental in elucidating the system's operating profile and efficiency over an annual cycle.

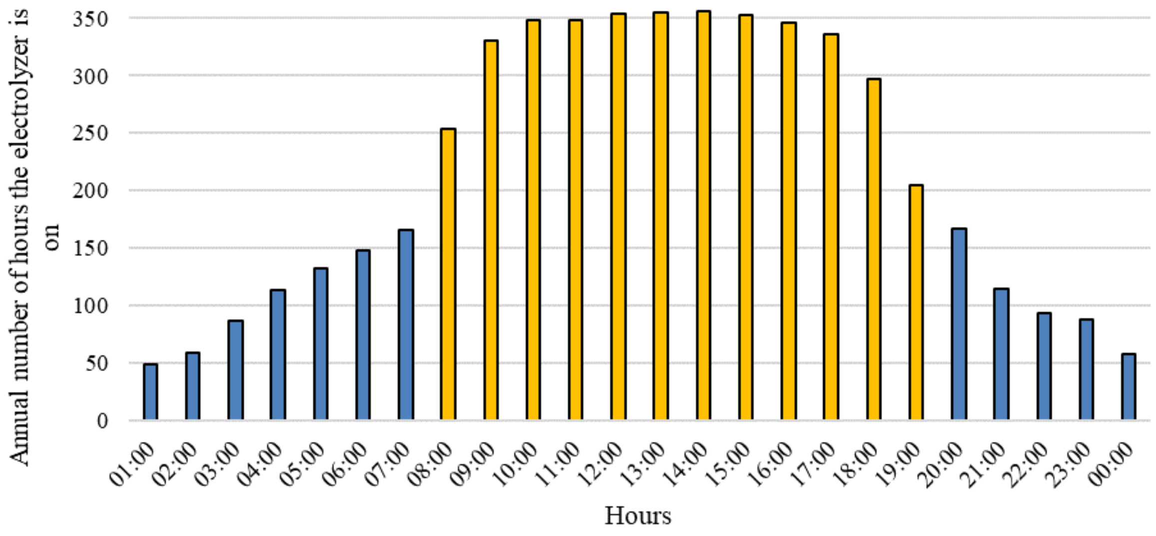

Fig. 4 – Electrolyzer annual operation.

This specific configuration results in an operating regime in which the electrolyzer is active for approximately 51% of the annual cycle. The columns highlighted in yellow denote the number of hours in which the electrolyzer is active, essentially due to the surplus of PV energy. In these moments of the day, there is a significant number of days of the year that the device operates, being practically active on more than 350 days throughout the year, specifically in the time interval between 10am and 4pm. The bars colored in blue are indicative of the periods that the electrolyzer operates because of a surplus in hydroelectric generation.

An analysis of Fig. 5 shows the annual operational profile of the optimized electrolyzer. It can be seen that, during the period from February to August, the device is in operation almost 100% of the time. Even in the months from September to January, when hydroelectric generation capacity is reduced, the electrolyzer is still activated, primarily to take advantage of the surplus of PV solar energy. However, it is crucial to point out that even in the months when the electrolyzer operates all the time, it is not necessarily working at full capacity. During these periods, it is common for the electrolyzer to operate at a load level of around 40%, as shown in the example of Fig. 6, that shows the electrolyzer load in May. This finding highlights the need for precise operational control in order to maximize the system's efficiency while maintaining the stability of the energy network.

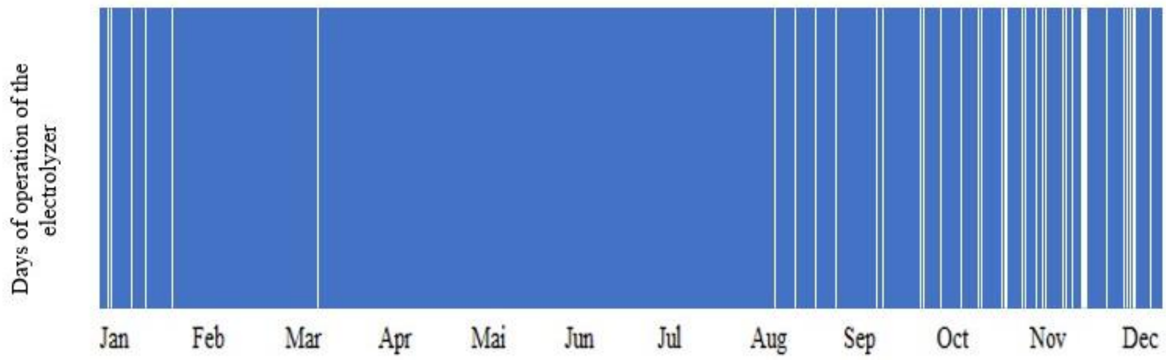

Fig. 5 - Days of operation of the electrolyzer during the year.

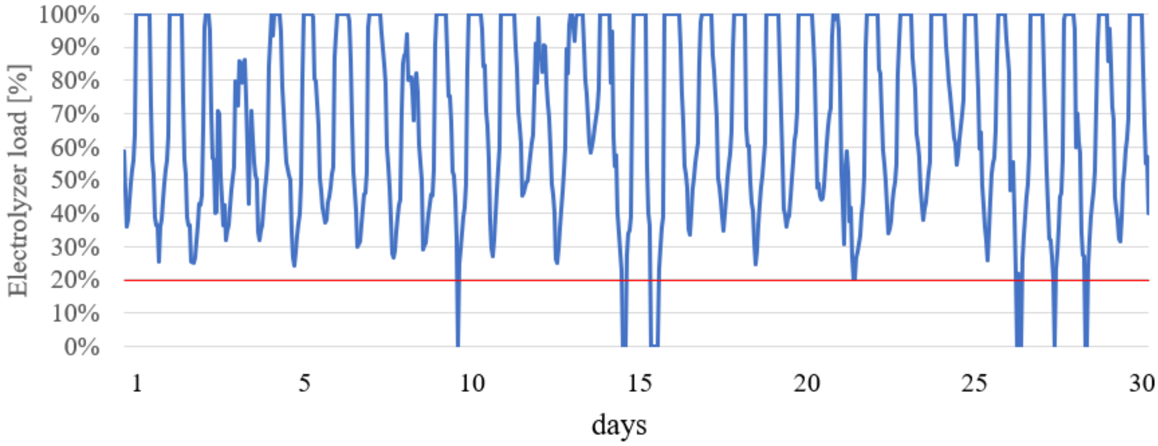

Fig. 6 – Electrolyzer load during the month of May.

Fig. 7 illustrates the fuel cell dispatch profile. The fuel cell is only required to operate between September and January. Its power peaks predominantly at the end of November, reaching values of around 4.2 MW. Given this scenario, it is imperative that the system has a fuel cell with a minimum capacity of 4.2 MW in order to fully meet the community demand. However, it is crucial to note that this component remains idle for a large part of the annual cycle.

The process of converting electrical energy into hydrogen, and subsequently hydrogen into electrical energy, presents an efficiency of approximately 25%. Although this figure is lower when compared to other energy storage methods, it is imperative to recognize the industrial value intrinsic to hydrogen. This aspect allows for an alternative sizing approach for the system, aiming for both energy autonomy and the promotion of sustainable local industrialization, thus contributing to the economic strengthening of the region in an ecologically responsible manner.

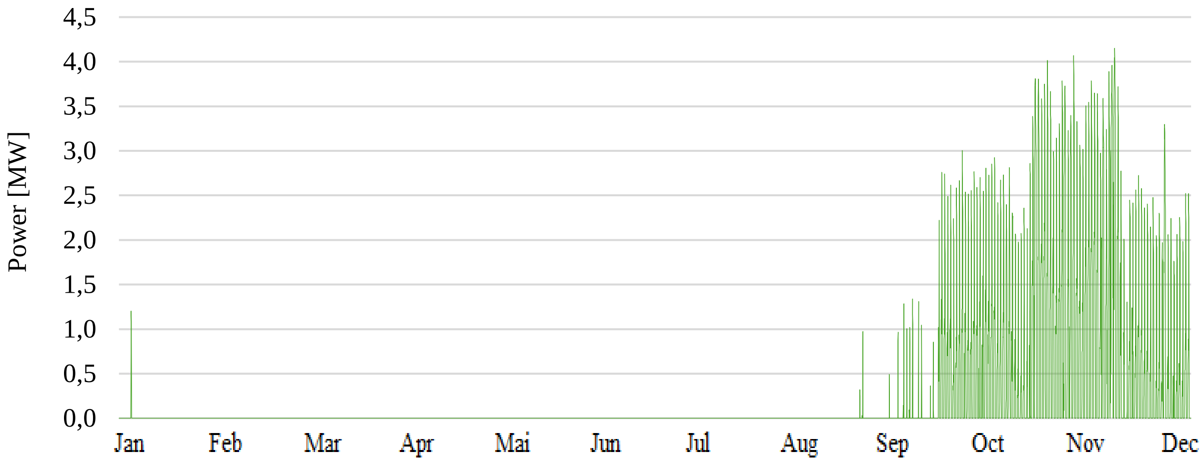

Fig. 7 - Fuel cell dispatch profile during the year.

In addition, it is worth noting that the PV generation system does not need to be centralized, which makes it possible to implement a distributed network for PV energy generation. This configuration is especially advantageous for the production of green hydrogen, since this element acts as a positive charge within the energy system. This panorama suggests an operational flexibility that can be exploited to optimize both the energy efficiency and the industrial and environmental impact of the integrated system.

Conclusions

The study provides insights into the potential of long-term H2 storage, and its advantages compared to conventional battery storage for off-grid communities, focusing on the case of an isolated community in the Brazilian Amazon. The findings of this study indicate that a combination of storage system is recommended to optimize energy supply, with lithium-ion batteries compensating for daily load fluctuations and the H2 storage system addressing annual variations in generation. Simulations and sensitivity analysis were performed to determine the optimal sizing of components, also considering the expansion of the PV system installed in the community. The results show that a battery storage system with a capacity of 16 MWh and a 2 MW Power Conversion System is necessary to meet the community's daily energy needs during high-usage months. It was also demonstrated the importance of the correct sizing of the H2 tank, in order to avoid energy losses and energy deficits. A tank of 2.5 M Nm^3 was calculated to be the optimal size for the analyzed system.

A sensitivity analysis of electrolyzer and the additional PV system sizes revealed optimized combinations that can meet the H2 gas demand in the system. A system with additional 25 MWp in PV generation combined with a 3 MW alkaline electrolyzer resulted in the most effective option. The operational analysis of this optimum sizing indicates that the electrolyzer is in operation on approximately 51% of the days of the year, with an almost constant production of hydrogen during the period from February to September. This behavior suggests a relatively high efficiency of this component, especially when we consider that it is the most expensive element in the energy system in question.

For the community under study, the projection is that the fuel cell will need to have a capacity of 4.2 MW and that its operation will be restricted to the months of September to January. The need for a 4.2 MW fuel cell to operate only in certain months of the year reveals a possible gap in the overall efficiency of the system, considering that the component remains inactive for a significant portion of the year. The results also indicate that a different system-sizing strategy that aspires to achieve not only energy autonomy, but also sustainable local industrialization can be beneficial, bolstering the region's economy in an environmentally responsible way.

The present study was limited to technically evaluating the incorporation of storage systems for the total decarbonization of Oiapoque. Given this, considerations to be evaluated for future work include the financial assessment, considering all the peculiarities of initial cost, logistical problems, financial incentives, and the local development of specialized labor. Furthermore, it is important that a future study also evaluates the prerogatives of greenhouse gas emissions in the complete energy production cycle in the locality, from the manufacturing process of the components to the disposal and recycling process, aiming for a comparison of greenhouse gas emissions in the project's lifecycle.

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