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HYBRID FUEL CELL-PHOTOVOLTAIC OFF-GRID POWER GENERATION USING ETHANOL REFORMING.

Lucas Alves Marçano
Renata Oliveira Vieira
Florian Pradelle
Sergio Leal Braga
Departamento de Engenharia Mecânica (DEM) and Instituto de Mobilidade e Energias Sustentáveis (IMES) Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rua Marquês de São Vicente, 225, Gávea, Rio de Janeiro, RJ, CEP:22453-900, Brazil
lucasmarcano99@aluno.puc-rio.br, renataovieira@gmail.com pradelle@puc-rio.br, slbraga@puc-rio.br

Renata Nohra Chaar Pradelle
Epifanio Mamani Ticona
Instituto de Mobilidade e Energias Sustentáveis (IMES) Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rua Marquês de São Vicente, 225, Gávea, Rio de Janeiro, RJ, CEP:22453-900, Brazil
renata.nohra@puc-rio.br, emt@puc-rio.br

Eduardo Torres Serra
ES+PS Consultoria, Rua Bogari, 82, Lagoa, Rio de Janeiro, RJ, CEP: 22471-340, Brazil
eduardoserra20@gmail.com

Cesar Luiz Coutinho Sobral Vieira
Energy Assets do Brasil Ltda, Av. Eng. João Fernandes Gimenes Molina, 1745, Jundiai, SP, CEP: 13213-080, Brazil
csobral@siemens-energy.com

Abstract. *This study explores the technical feasibility of an integrated system, utilizing a low-temperature proton exchange membrane fuel cell (PEMFC) powered by hydrogen derived from steam reforming of ethanol. The aim is to address the energy needs of isolated Amazonian communities, traditionally reliant on diesel generators, which pose environmental and health hazards. As photovoltaic systems gain popularity, their environmental impact, particularly with batteries, has raised concerns. To mitigate these challenges and achieve energy autonomy, a fuel cell and battery-based system is investigated. To optimize the overall system performance and economic conditions, the best parameters for designing and operating the system were determined by analyzing different scenarios using a developed numerical simulator for hybrid generation systems. This energy storage system could supply nine equivalent SIGFI45 users with 15 kWh (C100) or two SIGFI45 battery banks. A better solution is using this energy storage system with photovoltaic system excluding the custom monitoring, management, and control subsystem (SMGC) using a charge controller like any conventional PV off-grid system. In this case, the battery charge controller prevents overcharging the batteries. This integrated system serves as an advanced energy storage solution, promoting renewable energy adoption in remote regions of Brazil.*

Keywords: *ethanol steam reformer, PEM fuel cell, off-grid generation*

1. INTRODUCTION

In light of escalating energy consumption and environmental concerns, the pursuit of eco-friendly power generation methods has intensified in recent years. The world faces ecological challenges, including overshooting Earth's regenerative capacity, resulting in overconsumption of resources. Global warming poses a grave environmental threat, necessitating a rapid transition towards cleaner energy sources to meet climate goals (Yang *et al.*, 2019; Costa *et al.*, 2023).

Renewable energy sources have emerged as viable alternatives to traditional fossil fuel-based power plants. However, the intermittent nature of renewables necessitates energy storage solutions. Consequently, the power sector has witnessed substantial growth in renewable energy adoption, contributing to 30% of global electricity production in 2022 (REN21, 2023).

In Brazil, a vast nation with numerous remote regions disconnected from the national power grid, known as Isolated Systems, poses unique energy challenges. Approximately 212 isolated systems exist, primarily in the Northern region shown in Figure 1 (Empresa de Pesquisa Energética (EPE), 2023). These areas often lack access to reliable electricity, relying on outdated and inefficient diesel generators, leading to high energy costs (Costa *et al.*, 2023). All electricity consumers in Brazil pay a great part of this cost (da Ponte *et al.*, 2021).

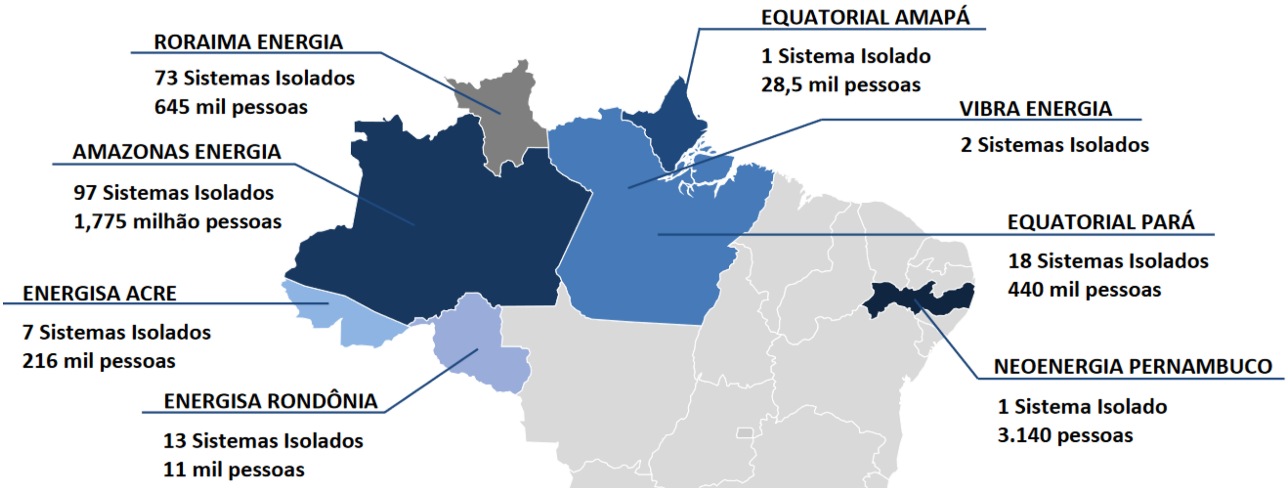

Figure 1. Brazilian isolated territory map (Empresa de Pesquisa Energética (EPE), 2022).

Furthermore, impoverished communities resort to dry cell and automotive batteries for limited energy needs, contributing to electronic waste concerns (Silva *et al.*, 2013). The surge in photovoltaic and battery production leads to diverse electronic waste streams, complicating recycling efforts (Kayla Kilgo *et al.*, 2022). The growth of lithium materials production raises environmental issues related to mining and processing activities (Costa *et al.*, 2021).

In this context, distributed generation (DG) has emerged as a sustainable solution, allowing consumers to produce energy from renewables and contribute surplus energy to the grid. DG offers numerous benefits, including reduced environmental impact, improved grid reliability, and diversification of the energy matrix (Maestri and Andrade, 2022).

Hybrid Power Generation Systems (HPGS) present a versatile approach, combining various energy sources and storage elements to ensure continuous power supply (Yang *et al.*, 2019). In regions with intermittent renewables like solar and wind, a Fuel Cell-Photovoltaic-Battery HPGS offers uninterrupted, clean energy production. It may be regarded as an eco-friendly fuel when extracted from renewable energy sources (Silva *et al.*, 2013). Among the renewable raw materials that supply hydrogen atoms, water (H_2O), biomass, and liquid and gaseous biofuels such as ethanol and biogas/biomethane can be used, for example (Empresa de Pesquisa Energética (EPE), 2021).

Fuel cells are electrochemical energy conversion devices that convert the chemical energy of a fuel directly into electricity (Dash and Bajpai, 2015). Nowadays PEMFC has been widely utilized in various fields. Compared with other fuel cell types, PEMFC has the advantage of fast startup, nearly zero-emission, high power density, high efficiency, and low operating temperature (Yang *et al.*, 2019). Fuel cells, specifically the new generation PowerCell S1 Proton Exchange Membrane Fuel Cells (PEMFC) with tolerance towards CO and reformate gas, are well-suited for hydrogen-based power generation. Ethanol reforming represents a promising method to produce reformate rich hydrogen gas efficiently, especially in regions with limited solar radiation. Ethanol's chemical energy can partially replace batteries in photovoltaic systems, reducing environmental impact.

In the present study, the ethanol reforming shall be duly contemplated as a potential avenue for the generation of hydrogen. This process presents a relevant option for the transportation sector as it circumvents the challenges associated with hydrogen storage, and its cost ranges in production are already competitive with the utilization of hydrogen in vehicle refueling stations (Empresa de Pesquisa Energética (EPE), 2021). The H_2 produced by the reforming process may supply fuel cells to produce electric energy during periods of little or no solar radiation. One of the most interesting applications of H_2 is its use as an energy vector in renewable energy systems, with the aim of providing energy for residential use in isolated areas (Silva *et al.*, 2013).

This work builds upon the findings of a prior R&D project that aimed to develop an autonomous ethanol/solar PV hybrid power system for a remote Brazilian house within the SIGFI45 framework. Initial laboratory testing involved components like the ethanol reformer, hydrogen storage, PEM fuel cell, photovoltaic panels, battery bank, and control systems. The electricity demand was simulated using ANEEL's load profile. The results highlighted significant energy consumption in the ethanol reformer and hydrogen storage system. Subsequently, the system underwent improvements, including reducing the reformer's energy consumption and removing the hydrogen storage. These changes led to a modified system producing a reformed gas consisting of 70-73% H_2, 1-3% CH_4, <3ppm CO, and 23-24% CO_2. To optimize the system's performance and economics viability, a numerical simulator was developed in Visual Basic for Applications (VBA) programming language in Microsoft Excel

2. METHODOLOGY AND MATHEMATICAL MODELS

The Figure 2 shows the final requirement that would need to be simulated to determine the sizing of the system. The numerical simulator was developed using a waterfall model (Royce, 1970), encompassing requirements, design, implementation, verification, and testing stages. The simulator allowed for the analysis of various scenarios and the uninterrupted operation of the integrated system. This approach aimed to reduce overall costs and simplify system operation while retaining the option to incorporate solar PV.

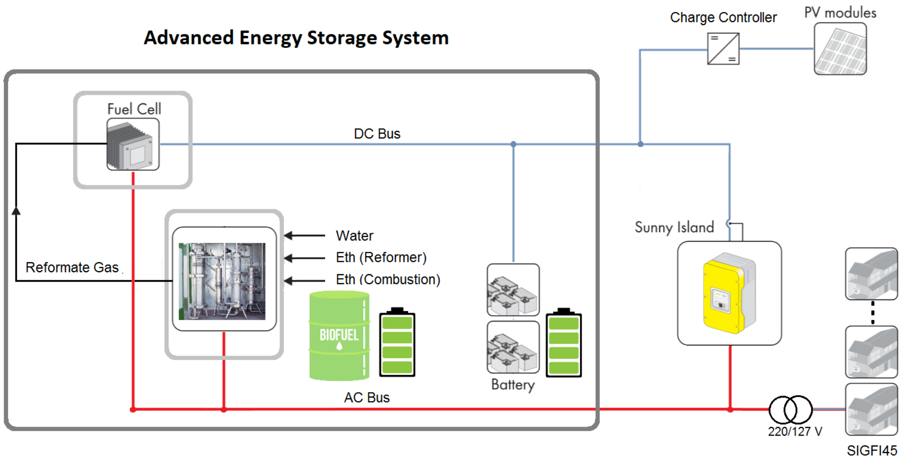

Figure 2. Final requirement of optimal advanced energy storage system.

To achieve an optimal sizing design, we implemented a first lab proposal configuration with the following components: 1 Nm^3/h hydrogen from ethanol reformer, low pressure hydrogen storage tank and a compression system up to 10 bar, 1 kW PEM fuel cell, photovoltaic panels, 7.5 kWh battery banks, 2.2 kW off-grid solar inverter, MPPT battery charge controller and an AC programmable load bank.

2.1 Theoretical models

Ethanol reforming for hydrogen production – According to Sun *et al.* (2012), many oxygenated hydrocarbons, such as bio-oil (acetic acid, ethylene glycol and acetone), glycerol, methanol, ethylene glycol and ethanol, have been used to produce hydrogen. Among all these resources, ethanol has attracted much attention in recent years. Ethanol can be obtained from biomass through fermentation or chemistry method and is available widely in Brazil. Besides, it has higher hydrogen content and can be separated easier than other oxygenated hydrocarbons. Ethanol reforming for hydrogen production is a carbon-neutral process as the CO_2 generated in the process is consumed for biomass growth, which offers a nearly closed carbon loop (Sun *et al.*, 2012) Ethanol steam reforming (ESR) using an appropriate catalyst shows a very efficient way of renewable hydrogen production as represented by the following overall stoichiometric equations (Kumar Seriyala *et al.*, 2023):

$$Pre-reforming:\ C_2H_5OH + H_2O \rightarrow CH_4,\ CO_2,\ CO,\ H_2 \tag{1}$$

$$Ethanol\,reforming:\ C_2H_5OH + 3H_2O \rightarrow 2CO_2 + 6H_2 \tag{2}$$

$$Methane\,reforming:\ CH_4 + 2H_2O \rightarrow CO_2 + 3H_2 \tag{3}$$

$$Reforming\,reaction:\ C_nH_mO_k + (2n-k)H_2O \rightarrow nCO_2 + (2n + \frac{m}{2} - k)H_2 \tag{4}$$

$$WGS\,reaction:\ CO + H_2O \rightarrow CO_2 + H_2 \tag{5}$$

Most of the time, ESR is performed between 600 and 1000 °C, where CO production is favored by kinetics. The low temperature (< 450 °C) steam reforming reaction can decrease carbon monoxide (CO) and methane (CH_4) production and increase H_2 selectivity at the end products.

Battery model – To modeling the battery bank and implement in the numerical code, we used the model developed by Jackey (2007) and available in Matlab Simscape™. In the Jackey (2007) model, a single unit cell of batteries was simulated using a simple nonlinear equivalent electric circuit, which is shown in Figure 3. Under most conditions of operation of the battery cell, the main branch describes very well the electrical dynamics behavior, and the parasitic branch accounts for the behavior at the end of charge. Using this single cell model, to model a 12 V automotive battery the output voltage is multiplied by six and therefore it is possible to assemble any battery bank.

More details of this model is found in Ceraolo (2000) and is called third order model constituted by:

- an electric equivalent with two R–C blocks and an algebraic parasitic branch;
- algorithms for computing the state of charge and internal (electrolyte) temperature;
- equations for computation of the elements of the equivalent electric network as function of state of charge and temperature.

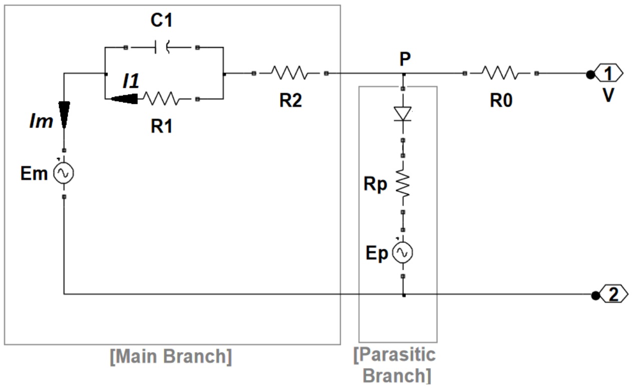

Figure 3. Battery cell equivalent electric circuit (Jackey, 2007).

The assumed state variables are the currents I_1, I_m, the extracted charge Q_e and electrolyte temperature θ. Ceraolo (2000) presented the following dynamic equations of his model in Equations (6, 7 and 8):

$$\frac{dI_1}{dt} = \frac{1}{\tau_1}(I_m - I_1) \tag{6}$$

$$\frac{dQ_e}{dt} = -I_m \tag{7}$$

$$\frac{d\theta}{dt} = \frac{1}{C_\theta}\left[P_s - \frac{\theta - \theta_a}{R_\theta}\right] \tag{8}$$

Where $\tau_1 = R_1 C_1$ and the equations for E_m, R_0, R_1 and R_2, are:

$$E_m = E_{m0} - K_E(273 + \theta)(1 - SOC) \tag{9}$$

$$R_0 = R_{00}[1 + A_0(1 - SOC)] \tag{10}$$

$$R_1 = -R_{10} ln(DOC) \tag{11}$$

$$R_2 = R_{20}\frac{e^{A_{21}(1-SOC)}}{1 + e^{A_{22}\frac{I_m}{I^*}}} \tag{12}$$

Where E_{m0}, K_E, R_{00}, A_0, R_{10}, R_{20}, A_{21} and A_{22} are constants for a particular battery cell. The state of charge SOC and Deep of charge DOC of the battery cell is calculated using the following equations:

$$SOC = 1 - \frac{Q_e}{C(0, \theta)} \tag{13}$$

$$DOC = 1 - \frac{Q_e}{C(I_{avg}, \theta)} \tag{14}$$

The state of charge measured the fraction of charge remaining in the battery cell. Depth of charge measured the fraction of usable charge remaining, given the average discharge current (Jackey, 2007). This model is available in Matlab Simscape™and we used the Simscape results to compare with the numerical code results implemented in this work.

2.2 Simulation scheme

The numerical simulator was implemented using the Visual Basic for Applications (VBA) programming language in Microsoft Excel. In the developed numerical simulator, the set of dynamics equations provided by the subsystems models was discretized and used numerical methods to solve simultaneously these equations. An energy balance approach is used within each time step. That is, the sum of all energy sources (photovoltaic, fuel cell, battery storage output) must equal the sum of all sinks (SIGFI545's load, battery storage input, energy losses). The Figure 4, shows the single standard load profile SLP SIGFI45.

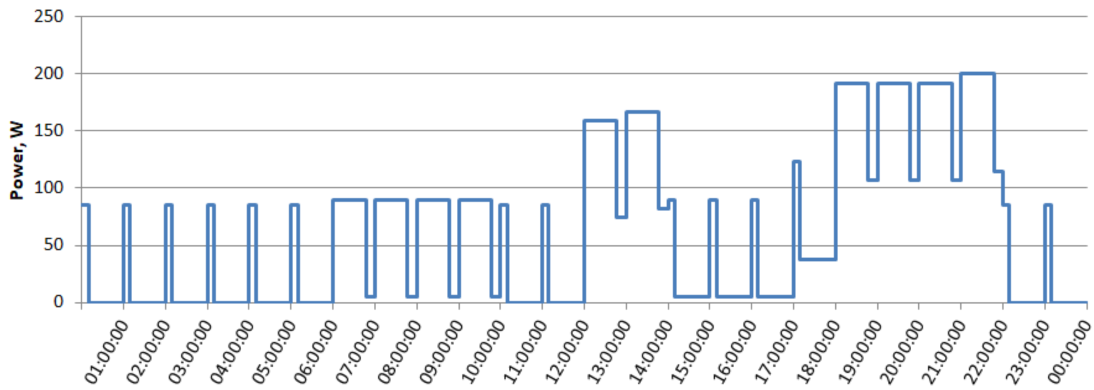

Figure 4. Brazilian National Electricity Agency ANEEL single standard load profile SLP SIGFI45.

The main assumptions made in the simulation of our final requirement systems are:

- The subsystems ethanol reformer and fuel are called integrate system SI operates continuously at its optimum set-point for durability. This SI inject constant current to the DC bus.
- Experimental data of photovoltaic modules arranged in grid-tie configuration was used i.e. the maximum available power in three weather conditions: sunny, cloudy, and partially cloudy days (Fig. 5);
- The parasitic branch of the battery model was not considered.

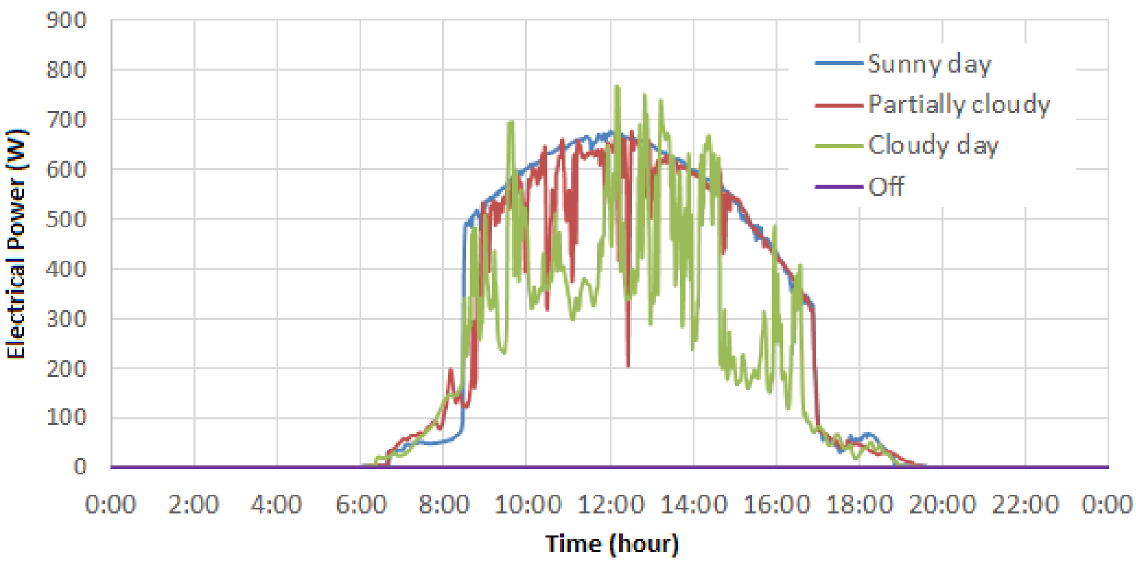

Figure 5. Photovoltaic power in different weather conditions.

3. RESULTS AND DISCUSSION

As mentioned, to verify or validate the software, we compared the numerical and experimental results, for other side, also we compared the numerical results with the literature. In Eletrobras (2021) technical guide, one requirement of the SIGFI45 generation system is the autonomy to provide energy during 48 hours without solar participation, in this scenario, a 7.5 kWh (C100) battery bank needs to supply energy to a single consumption unit. The Figure 6 shows the variation of the state of charge SOC of the battery bank and as it was expected, the autonomy of SIGFI45 is approximately 48 hours considering a depth of discharge DOD=60%.

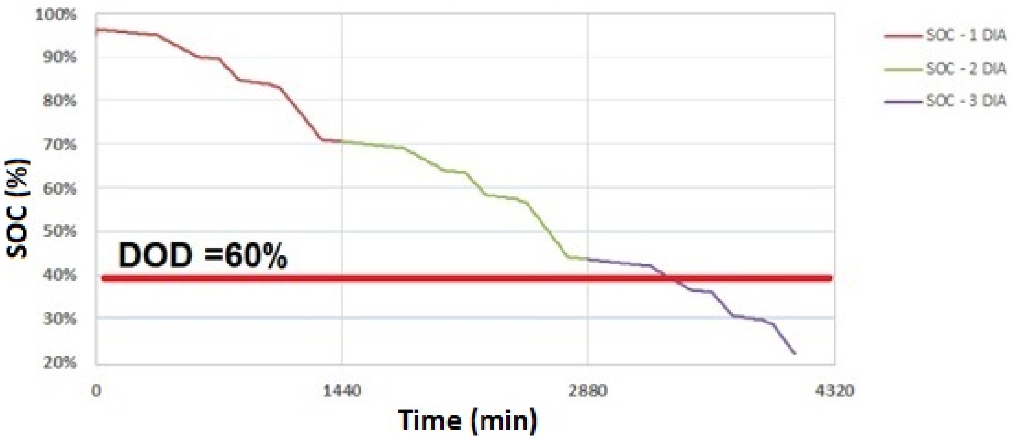

Figure 6. Variation of SOC to determine the autonomy of a SIGFI45 without solar PV participation.

In Eletrobras (2021), the components of SIGFI45 generation system are: a 7,5 kWh (C100) battery bank, battery charge controller, a 700 W (peak) photovoltaic system, and solar inverter. The Figure 7 shows the state of charge of battery bank in the worst scenario of consecutive cloudy days. At the start of this simulation the battery was intentionally discharged to observe the recovery of the system. The float voltage set in the charge controller limits the maximum SOC value and prevents overcharging the batteries.

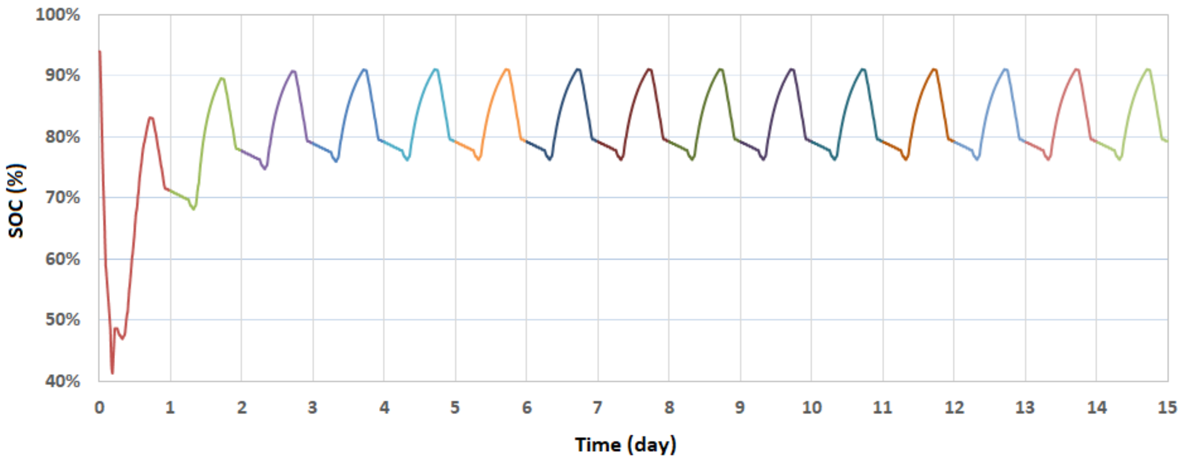

Figure 7. Variation of SOC of a SIGFI45 in cloudy days.

Finally, we did simulations for our final requirements (Fig. 2) in that, we needed to find the number o SIGFI45 users and battery banks without solar photovoltaic participation. The Figure 8 shows the variation of SOC with 10 SIGFI45 users and four battery banks. This figure clearly shows a power supply and load consumption unbalance despite the number of battery banks. The opposite trend of SOC variation was observed when the number of SIGFI45 users was six exceeding 100%, because the DC-DC converter subsystem of the fuel cell inject constant current to the DC bus.

We did more simulations and determined that this energy storage system could supply 9 equivalent SIGFI45 users with 15 kWh (C100) or two SIGFI45 battery banks. The Figure 9, shows the variation of state of charge and we observe that the power generation and load consumption apparently match. The simulations show a slight excess of power generation and eventually the batteries could be overcharged. The solution was using a dummy load resistance of 200 W and a simple controller that turns on the resistance to maintain the SOC below a certain value.

A better solution is using this energy storage system with photovoltaic system and charge controller like any conventional PV off-grid system. In this case, the battery charge controller prevents overcharging the batteries.

4. CONCLUSIONS

This research offers insights into the development of an innovative ethanol-based energy storage system. By minimizing conventional battery use, this system addresses the challenges posed by intermittent renewable sources. The modifications made to the ethanol reformer, including reducing energy consumption and eliminating the hydrogen storage, enhance overall system efficiency. This integrated solution represents a significant step towards achieving energy

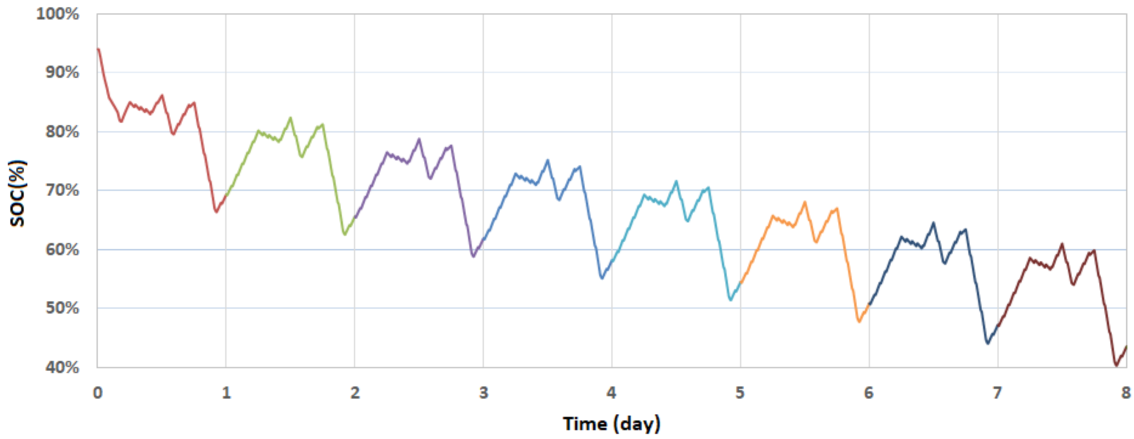

Figure 8. Variation of SOC to determine the autonomy of a SIGFI45 without solar PV participation.

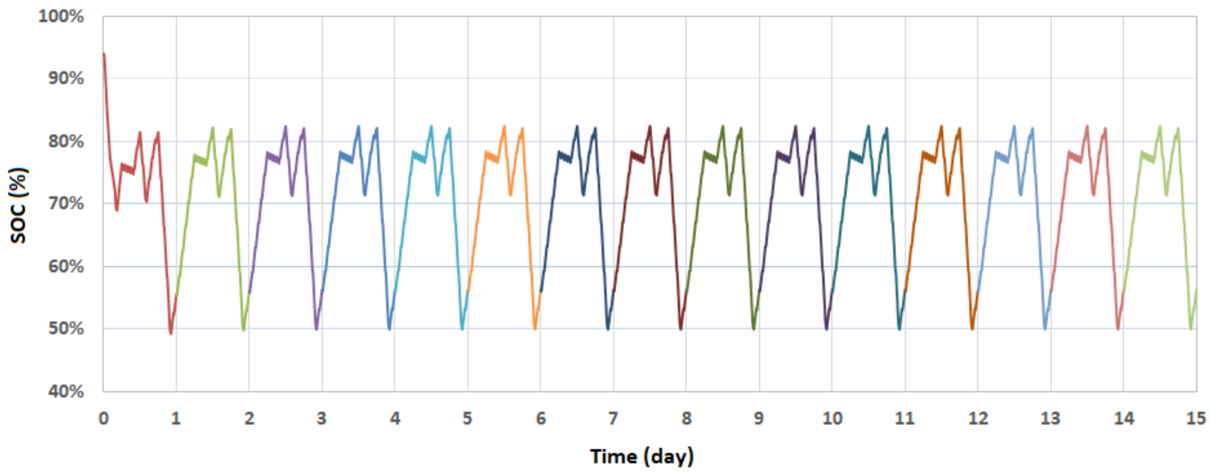

Figure 9. Final optimal sized advanced energy storage system to supply nine SIGFI45 users.

autonomy and promoting renewable energy adoption in isolated areas.

A combination of a fuel cell based subsystem that use ethanol to generate continuously constant power and conventional batteries is technically feasible to supply a small remote community. This advanced alternative energy storage system reduce the number of photovoltaic and battery bank required of a conventional system. In this optimized proposal, the code implementation of the monitoring, management, and control subsystem (SMGC) was reduced and simplified. This system alerts when the ethanol level in the tank is low and continuously calculates the SOC of the conventional batteries. If SOC is above a certain level due to a load consumption variation pattern, it turns on a dummy resistance load to prevent overcharging the batteries. A better configuration of the system is adding photovoltaic modules then it can operate continuously at it optimum setpoint for fuel cell durability to meet baseload power needs. This configuration avoids the requirement for a fuel cell power management controller and this function is transferred to the battery charge controller that prevents overcharging the batteries.

One characteristic of fuel cell systems is the low maintenance requirements due to the absence of moving parts; this permits continuous power generation for long periods of time. These systems are deployed in remote locations in off-grid telecom stations. At present, the ethanol fuel reformer still does not reach maturity and reliability for long time periods of operation. Assuming a good level of reliability and economic applicability of this system, technically these integrated energy storage systems are a good solution for the environment and sustainable.

5. ACKNOWLEDGEMENTS

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