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Socio-Environmental Evaluation of MV Commercial Time-Shift Application Based on Battery Energy Storage Systems

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Abstract: The urgent need to curb climate change calls for an energy transition to cleaner, more resilient and sustainable solutions. Combined designs of energy storage systems and demand management strategies are becoming more frequent in the literature. However, are these solutions really sustainable from a multi-dimensional approach and in real-world applications? To answer this question, this work performs a local and scaled-up field-based evaluation of the social and environmental impacts of a pilot project in Brazil, which consists of replacing diesel generators with a Battery Energy Storage System (BESS) in a peak power plant of a Medium Voltage (MV) commercial load. For this, the combined RCPA-LCI method is applied, which allows characterizing both energy alternatives jointly considering the Life Cycle Inventory (LCI) and the multi-dimensional evaluation perspective of the Resource Complete Potential Assessment (RCPA). Then, the scalability of this commercial solution at the national level is analyzed through two main lenses: GHG emissions reduction and job generation. The benefits are estimated at a potential 15.4 million tons of CO_2 avoided and 113 new job opportunities per year. The results demonstrate the positive socio-environmental performance of BESS-based peak plants for MV commercial applications in Brazil.

Keywords: distributed energy resources; life cycle inventory; resource complete potential assessment; social-LCI; integrated resource distribution planning; GHG reduction; job creation

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1. Introduction

In response to the criticality of climate change, the United Nations established, during the Paris Agreement in 2015, a maximum increase in global temperature of 1.5 °C above pre-industry levels. According to the study presented in 2021 by the International Renewable Energy Agency (IRENA) [1], energy-related Greenhouse Gas (GHG) emissions increased by an average of 1.3%/year for the period 2014–2019. Under current government energy plans and targets, global emissions will only stabilize with a slight decrease by 2050, but they will not be reduced enough to guarantee the allowed global warming limit. Therefore, it is urgently needed to build a roadmap towards an energy transition, which allows reaping all the socio-economic and environmental benefits of the transition. The main drivers of change, according to the IRENA report, include: the transition to clean and renewable energy resources, both at generation and consumption points; and energy demand reduction strategies through improvements in energy efficiency and conservation.

The penetration of intermittent renewable energies and the abandonment of stable fossil fuel-based energy sources pose several challenges: to balance energy generation and consumption; the correct voltage level regulation; and the maintenance of the energy power quality through harmonics reduction [2]. In this context, Battery-based Energy

Storage Systems (BESSs) play a key role, mainly thanks to their ability to improve the grid's flexibility and reliability through many ancillary services [2,3]. Through a detailed literature review, Balducci et al. (2018) [4] present a taxonomy on the most advantageous applications of BESSs. The categories mentioned are: raw energy regulation (peak shaving and energy arbitrage techniques), ancillary services provision (frequency and voltage regulation, among others), transmission and distribution applications (grid decongestion and consumption deferral) and users' services (demand reduction and backup energy).

Energy arbitrage, also called energy time-shifting, is a technique that consists in decoupling the energy consumption from energy generation, by changing the energy consumption time period of a given power source. That is, to store energy for a certain period to consume it at another time. Despite the simplicity of the concept, time-shift requires BESSs with specific technical characteristics and great operational complexity.

The most popular time-shift application consists of buying and storing electrical energy in periods when prices are lower, to use or sell this energy when costs are high. This application allows reducing operating costs and increasing the return periods of energy investments. It also creates new opportunities to develop business models based on BESSs. Miai et al. [5] develop a multi-objective BESS optimization for energy arbitrage and frequency regulation, with the purpose to maximize economic benefits. The work is applied in real-time markets and considers BESS cell degradation. Cha et al. [6] perform an optimization scheduling analysis considering grid-connected BESSs installed in the Korean transmission system with the purpose to discuss new economic profitability schemes.

Renewable Energy (RE) time-shift is also a technique under discussion in the academic world. In this case, the energy stored is produced by a renewable source. This alternative enables improvement in the system flexibility by mitigating the uncertainties caused by intermittent generation [7]. Fan et al. [8] discuss BESS sizing and coordination strategies to avoid wind energy curtailment and optimize the net present value of the energy produced. Depth of discharge and time-shift strategies are discussed. In the same line, Ponnaganti et al. [9] evaluate the potential economic benefit of introducing BESS-based management strategies in wind farms. The authors analyze flexible charging–discharging strategies together with the forecast of energy prices in the daily electricity markets. They compare the profitability of electrochemical batteries and thermal accumulators.

A BESS can provide a wide set of benefits depending on its application location and on its technical characteristics (round trip efficiency, capacity) [4,6]. Hassan et al. [10] discuss energy scheduling optimization for smart grid application through an energy management system. Their purpose is to reduce residential electricity cost by reducing energy consumption and shifting loads during peak hours. Abdeltawab and Mohamed [11] expose a multi-agent energy trading model based on renewable energies and a BESS in a microgrid context. Balducci et al. (2018) [4] quantify the economic benefits of the different BESS applications. More specifically, they quantify the energy arbitrage's value considering the savings generated by the difference in prices at peak and off-peak hours and considering the BESS technical characteristics.

The majority of the works focus on the techno-economical aspects of BESS-based time-shift solutions [2–10]. Most of them discuss technological improvement strategies, such as the selection of the most appropriate BESS type or sizing [3,8,9], the technical parameters' optimization, such as the charge–discharge cycles [8], energy resource scheduling [6] and the multi-objective optimization of several auxiliary services [5]. BESS application economic profitability is also the focus of attention of several works. Guo et al. [7] assess the economic value of a BESS based on its ability to improve financial indicators, such as payback period and return rate. Other authors focus directly on the energy trading business models [11].

However, a multi-dimensional view is necessary to assess the positive and negative potentials of BESSs in real-world applications and provide a quantitative basis to design sustainable energy solutions. The socio-environmental impacts of incorporating BESSs in a grid are often disregarded. Among the few authors that address this issue, Ban et al. [12] evaluate the health impact of the time-shift of thermal power plants. The emissions produced for the generation of electricity can have stronger effects on people's health depending on the concentration of pollutants in the atmosphere. The authors optimize generation scheduling to reduce the social impact of environmental pollution. Sadhukhan and Christensen (2021) [13] perform a comprehensive evaluation during the entire life horizon of all the environmental impacts of a lithium-ion BESS. They assess the global warming potential of this technology of the BESS from an LCA perspective, compared to other renewable energy resources. Their findings highlight the main levers of change to ensure the sustainability of a BESS, which are: (1) to recycle phosphorus, which allows reducing emissions during production; (2) to increase the density of energy; (3) to develop more effective services in order to extend the BESS's useful life; (4) to increase the recyclability and number of lives of the BESS; (5) to use waste materials for BESS components; (6) and to deploy the multiple integrated roles of the BESS.

Furthermore, practical case studies and real-world time-shift utilization are scarcely discussed in the literature. Attention is almost exclusively paid to real-time energy prices [5]. The application context can be determinant as to whether or not a solution works. Chattopadhyay et al. [14] analyze the main applications of BESSs in developing countries and identify four main categories: frequency control; energy arbitrage; stabilization and avoidance of RE curtailments; and management of transmission line congestion and grid deferral investments. The authors highlight the high frequency of power outages and the BESS's usefulness supplying backup energy. Saurav et al. [15] report the same power outage situation in India, where diesel generators are commonly used. Due to the high operation cost, the authors propose an optimization model for multi-source generation scheduling, which includes renewable generation sources and both electrical and thermal loads. Results are applied in two real-world scenarios.

In Brazil, although 42% of the energy produced comes from renewable sources, national goals are not yet aligned with the 1.5 °C scenario. By 2030, global GHG emissions have to decrease 45% compared to 2010 levels [16]. Instead, they have increased by 7% in 2020 [17]. Furthermore, Brazil is considered a country vulnerable to climate change. Extreme weather events are responsible for hundreds of deaths and great economic losses each year. Among them, droughts put hydroelectric generation at risk, which is the country's main renewable source. Therefore, immediate adaptation actions are needed [16]. Buildings are one of the six main sectors of electricity consumption in Brazil and are also responsible for the generation of energy-related emissions. Despite this, they are very little studied in the scientific literature.

Most of Brazilian commercial consumers supplied in Medium Voltage (MV) buy energy in a variable cost energy market. Due to the high electricity prices and the frequent grid interruptions, diesel generators are often incorporated. They perform a double function, serving as backup during energy outages and being an alternative source of energy during peak hours. This type of installation is called a peak power plant [18]. However, to meet national and international GHG mitigation purposes, the use of fossil fuels must be reduced. Despite this, the transition of clean peak power plants is little discussed among Global South scholars.

In order to fill this literature gap, a two-stage multi-dimensional R&D project has been developed, addressing the utilization of BESS-based peak power plants in the commercial MV Brazilian sector, from a multi-criteria perspective. A preliminary theoretical study has first been conducted by the Energy Group of the Department of Energy and Electrical Automation Engineering of the Polytechnic School, University of São Paulo (GEPEA) [19]. Techno-economic aspects have been studied to determine the best battery type, dimensioning and dispatch strategy. The inclusion of renewable energies has been addressed, in addition to the development of an applicable and reproducible business model, based on real-world energy prices and real energy consumption profiles. In a second stage, a real Pilot Unit (PU) has been implemented and practical assessments have been carried out. The main objective of the present work is, therefore, to complete the knowledge generated in the previous project phase, through a broader BESS-based peak power plant sustainability analysis. The social and environmental impacts are modeled in a real-world and Global South application through a combined Multi-Criteria Decision Analysis (MCDA) tool, the RCPA-LCI methodology.

The work is structured as follows. The real-world pilot project is first characterized (Section 2), presenting both previous and new system configurations and equipment operational modes. Afterwards, the combined RCPA-LCI method is exposed (Section 3), including methodological considerations and justifications. Then, results and discussions are presented in three steps: the energy balances (Section 4), the RCPA-LCI application (Section 5) and the scalability of the technological solution (Section 6). The conclusions are finally presented (Section 7).

2. Case Study: Pilot Unit Characterization

This section describes the technical characteristics and operational modes of the different equipment installed in the PU. The most relevant aspects of the installed measurement instruments are also presented.

2.1. PU Equipment Description

The PU was implemented in a Service Station (SS) installed near Jundiai, on the highway between São Paulo and Campinas. The SS is composed of two Consumption Units (CUs), the fuel pump area and the restaurant area, and includes an electrical vehicle charging point. Table 1 summarizes the electricity generation resources of both the Reference Units (RUs) and the PU configurations. The RUs' main source of energy came almost exclusively from the utility grid (GRID), and a Diesel Generator Set (DGS) was used occasionally during grid interruptions and daily during peak hours to reduce energy expenses. The PU, in turn, incorporates a BESS to cover the role of the DGS. DGSs are kept as backup in order to provide more reliability to the new configuration. A photograph of the PU and its location are presented in Figure 1.

Table 1. Electricity generation resources used in each SS configuration.

Reference Unit (RU)	Pilot Unit (PU)
• GRID • DGS	• GRID • DGS • BESS

Figure 1. Google street view of the SS [20] and photograph [21] and location of the installed PU.

Figure 2 shows the location of the multi-functional meters within the single-line diagram of the complete PU electrical system, adapted from the Supervisory Control and Data Acquisition System (SCADA). Data recorded by SCADA account for 118 channels with a 1 min sampling rate. The complete list of variables measured and stored is presented in Figure 3.

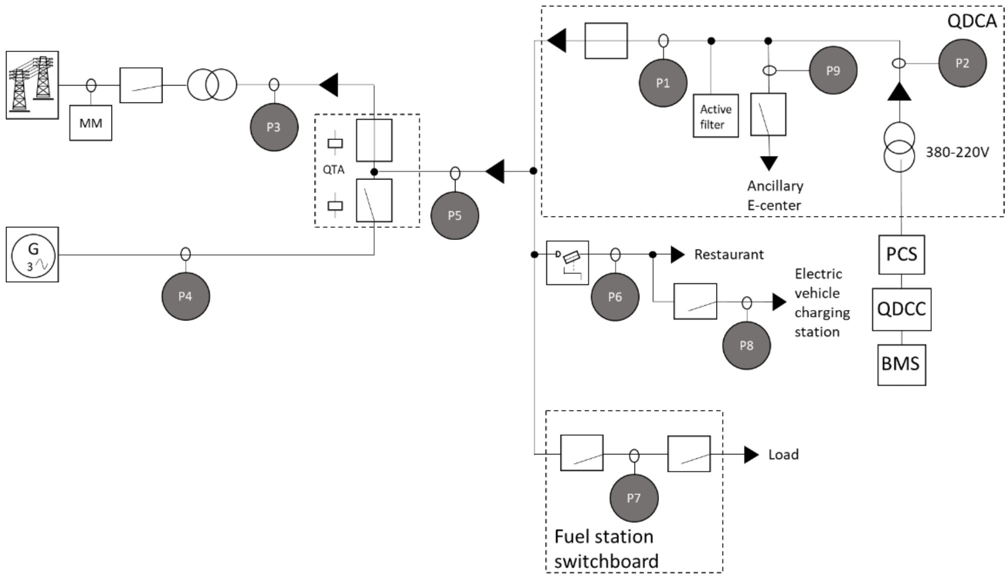

Figure 2. PU single-line diagram adapted from the Supervisory Control and Data Acquisition System (SCADA) [22].

Channel	Description	Channel	Description
1	CO emission [%]	61, 62, 63	M6: Current of lines A, B and C [A]
2	CO2 emission [%]	64, 65, 66	M7: Active (P7), reactive (Q7) and apparent (S7) power [kW]
3	Diesel tank level [L]	67, 68, 69	M7: Voltage of phases A, B and C [V]
4	Diesel consumption [L/h]	70, 71, 72	M7: Current of lines A, B and C [A]
5	Humidity inside the e-house [%]	73, 74, 75	M8: Active (P8), reactive (Q8) and apparent (S8) power [kW]
6, 7, 8	M1: Active (P1), reactive (Q1) and apparent (S1) power [kW]	76, 77, 78	M8: Voltage of phases A, B and C [V]
9, 10, 11	M1: Voltage of phases A, B and C [V]	79, 80, 81	M8: Current of lines A, B and C [A]
12, 13, 14	M1: Current of phases A, B and C [A]	82, 83, 84	M9: Active (P9), reactive (Q9) and apparent (S9) power [kW]
15, 16, 17	M2: Active (P2), reactive (Q2) and apparent (S2) power [kW]	85, 86, 87	M9: Voltage of phases A, B and C [V]
18, 19, 20	M2: Voltage of phases A, B and C [V]	88, 89, 90	M9: Current of lines A, B and C [A]
21, 22, 23	M2: Current of lines A, B and C [A]	91, 92, 93	PCS: Active power [kW], CC Voltage [V], CC Current [A]
24	M2: Frequency [Hz]	94	PCS: PF
25	M2: Power Factor (PF)	95, 96	BMS: CC Voltage [V], CC Current [A]
26, 27, 28	M3: Active (P3), reactive (Q3) and apparent (S3) power [kW]	97, 98, 99	BMS: SOC, SOH, DOD [%]
29, 30, 31	M3: Voltage of phases A, B and C [V]	100, 101	BMS Rack 1: CC Voltage [V], CC Current [A]
32, 33, 34	M3: Current of lines A, B and C [A]	102, 103	BMS Rack 1: SOC, SOH [%]
35, 36, 37	M4: Active (P4), reactive (Q4) and apparent (S4) power [kW]	104, 105	BMS Rack 2: CC Voltage [V], CC Current [A]
38, 39, 40	M4: Voltage of phases A, B and C [V]	106, 107	BMS Rack 2: SOC, SOH [%]
41, 42, 43	M4: Current of lines A, B and C [A]	108, 109,	Active Filter: THDv, THDi, PF
44, 45, 46	M5: Active (P5), reactive (Q5) and apparent (S5) power [kW]	111	Temperature inside eletrocentre [°C]
47, 48, 49	M5: Voltage of phases A, B and C [V]	112	Q1 status Flag (QDCA)
50, 51, 52	M5: Current of lines A, B and C [A]	113	BESS status Flag
53	M5: Frequency [Hz]	114	Operational mode Flag
54	M5: Power Factor (PF)	115	Peak Power time Flag+
55, 56, 57	M6: Active (P6), reactive (Q6) and apparent (S6) power [kW]	116	Diesel tank filling status Flag
58, 59, 60	M6: Voltage of phases A, B and C [V]	117, 118	Qta status Flag (Grid and Diesel Generator)

Figure 3. Measurement description [22].

2.1.1. Battery Energy Storage System (BESS)

The BESS nominal power is 200 kW, the nominal and useful energy capacities are 430/390 kWh, respectively. The chosen cell technology for the PU implementation [17] is based on Li-ion. The electricity is generated in 6Hz frequency and 220V voltage (phase–phase). The BESS active power (P_1) is measured through meter #1 (Figure 2) and is displayed in channel 6 (Figure 3). This channel presents positive and negative values, which quantifies the incoming and outgoing BESS active power ($P1_{IN}$ and $P1_{OUT}$ in kW).

2.1.2. Diesel Generator Set (DGS)

The DGS installed in the RU corresponds to a 2007 4-stroke 6-cylinder Mercedes motor coupled with a Cramaco G2R generator. The nominal power (Pm) is 340/310 kVA, nominal current is 816 A, the frequency is 60 Hz and the minimum Power Factor (PF) is 0.8. The motor rotation is of 1800 rpm and has an average oil consumption of 75.9 L/h.

Concerning the measured data, channel 37 recorded by meter #4 quantifies the DGS apparent power (S_4 in kVA). The fuel efficiency can be measured thanks to channels 3 and 4 that measure, respectively, the fuel tank level ($Tank_{level}$ in L) and the hourly fuel consumption (C_{fuel} in L/h). Thus, the tank level variation quantifies the absolute variation in fuel consumption and the hourly consumption quantifies the fuel consumption speed during the diesel generator operation.

For the calculation of CO_2 emissions, the reference value of the US Environmental Protection Agency [23] is considered: 10.180 kg of CO_2/gallon of diesel. That is, in International Units (IUs), 2689 kg CO_2/liter of diesel.

2.1.3. Utility Grid (GRID)

The energy supplied by the utility grid is measured by meter #3, and can be calculated according to the active power value recorded on channel 26. The current energy supplied by a regional utility company has been considered representative of the Brazilian offer. The Brazilian grid energy mix has been used in this study based on the 2021 Brazilian National Energy Balance [24], with the purpose to study the scalability of the commercial solution. The electricity generated in 2019 and 2020 is shown in Table 2 (in GWh/year).

Table 2. Energy consumption by source of the Brazilian electrical mix in 2019 and 2020 [24].

Source	2019	2020
Hydroelectric	397.877	396.327
Natural Gas	60.448	53.464
Wind	55.986	57.051
Biomass	52.543	56.167
Nuclear	16.129	14.053
Steam Coal	15.327	11.946
Petroleum Derivatives	6.926	7.745
Photovoltaic	6.655	10.750
Others	14.438	13.696
Total	626.328	621.198

The final energy consumed from all the electricity generated is also presented [24] and corresponds to 213,195 GWh for 2019 and 211,163 GWh for 2020. The 2019–2020 yearly values do not show large variations despite the exceptional situation of the pandemic experienced during the latter year. The 2020 data will therefore be taken as reference for calculation purposes. The global grid efficiency, which is the divergence between the energy generated and consumed, is 34%. In 2020, 78.8 kg/$MWh_{generated}$ of CO_2 were emitted for electricity production.

2.2. Operational Modes and Suppositions

This section describes the operation characteristics of each energy resource utilized in both the RU and PU and the differences existing among these two system configurations. In addition, the main considerations related to the multi-source system functioning are discussed.

2.2.1. BESS Operation

The BESS, only present in the PU, has two primary operation modes: the shift in consumption time (time-shift) and the supply of backup energy in case of utility grid power interruptions. A secondary BESS function consists of V/W and V/Var voltage regulation. The BESS functioning can be summarized as follows:

On working days and without grid interruptions, the BESS supplies the energy demanded by the SS, during the peak period (18 h to 21 h).

When there are grid interruptions, the BESS supplies the energy demanded by the SS during the interruption period until the available battery power runs out (considering the established maximum discharge depth).

After peak hours or when the grid energy is recovered after interruptions, the BESS is charged with energy from the utility grid. The dispatching BESS speed will depend on the SS energy consumption while the charging speed is a programmable parameter. However, the BESS must be fully charged before the new peak period, which corresponds to the time interval between 21 h and 18 h the next day.

2.2.2. DGS Operation

The DGS is present in both the RU and PU system configurations. In the RU, the DGS performs a double task: during the working day peak hours, it supplies the energy demand for a 3 h period (18 h to 21 h). In addition, when grid interruptions occur, the DGS is also launched, serving as backup energy. This operational mode allows the island mode functioning.

On the other hand, in the new configuration (PU), the main DGS purpose is to provide backup energy in cases where there is no other energy resource. That is, when there are power interruptions in the utility grid or during peak hours and, simultaneously, the stored energy of the BESS is depleted. In other words, the diesel generator is kept as a complement to the storage system, in case the capacity of the latter is not sufficient.

2.2.3. Grid Operation

The utility grid is the main source of energy. It is used directly when there are no interruptions and during off-peak hours. During weekends when there are not peak periods, the utility grid is the main electricity source. In addition, in the PU configuration, the energy from the grid is also indirectly consumed. This enables charging the BESS, to be used for the time-shift operation mode during peak hours or as backup energy during interruptions.

3. Methodology

To develop the present work, some data were measured and recorded during an observation period. Therefore, a first section presents the measurement considerations regarding data quality. Subsequently, the methodology selection is justified, based on its contribution to the state-of-the-art and resolution of the problem contemplated. Finally, the combined RCPA-LCI methodology is explained in detail.

3.1. Data Quality Considerations

Data collected by any monitoring system must be carefully reviewed through a data handling process in order to avoid the presence of outliers. Outliers are atypical results incompatible with the reality of the studied phenomenon. In this work, outlier detection has been carried out according to [25], based on the IEC 61724 Standard [26] and using a two-phase data quality verification, based on (1) the verification of the maximum and minimum physically reasonable limits for each monitored parameter; and on (2) the verification of the maximum variation rate between successive data. Considering the quantity and quality of monitored data, parameters detected as outliers have been eliminated from the database.

In addition, a Data Quality Index (DQI) has been calculated in order to measure the quality of the data monitored and collected by the SCADA system. The DQI measures the relationship between the values considered outliers and the total of measurements performed as a percentage. The results show that the data provided by the SCADA system of the multi-source system installed at the SS are of sufficient quality to carry out the efficiency analyses in this report, as they present a DQI of only 0.3% [25].

3.2. Methodology Selection Justification

The state-of-the-art review (Section 1) has evidenced the usefulness of BESSs to perform energy time-shifting. Demand management techniques provide flexibility and reliability to the grid and, at the same time, enable reduction in energy consumption and combating climate change. The development of energy time-shifting solutions is therefore a way to promote a sustainable and resilient energy transition. In emerging economies such as Brazil, where power outages are frequent, the use of diesel-based peak plants is common in the commercial sector. Incorporating BESSs into these peak plants has a great potential for benefits, especially socio-environmental ones. Although these studies have already been proposed theoretically, there is a great lack of evaluations of practical applications in developing countries. In fact, considering social and environmental impacts is an indisputable part of evaluating the sustainability of any energy-related project. It is within this framework that the present research was developed.

In addition, a trend towards the use of Multi-Criteria Decision Analysis (MCDA) for solving energy management-related problems is observed by Mardani et al. [27], who found the following method categories: the multi-attribute value theory or multi-attribute utility theory methods, which include the analytic hierarchy process [27–30]; outranking methods, which comprise the ELECTRE and PROMETHEE families [27,29–32]; elementary aggregation methods, such as the weighted sum method and the weighted product method; and complex aggregation methods, such as ASPID, which deals with fuzziness or lack of data [29,32,33]. Other less-used techniques are the distance-to-target methods, composed of four key methods: TOPSIS [27], VIKOR, gray relational analysis, and DEA [32], as well as the multi-objective mathematical programming methods [34], which include complex linear programming and goal programming [27,32,34]. Moreover, hybrid MCDA methods, which are a combination of various MCDA techniques, are increasingly used and are very useful for sustainability analysis [27,29,35].

For that reason, a combination of two methodologies has been applied. In the first place, the Resource Complete Potential Assessment (RCPA) tool was used, which allows visualizing the impact of any energy resource, according to a multi-criteria perspective that covers all dimensions of sustainability. This method can be applied both to the individual analysis of a given resource and to a comparative study, and allows the selection of the most appropriate resources for a given context. It also includes a wide range of indicators from each dimension, which allows the decision maker to have an overview of all the consequences of their selection and build various approaches according to the criteria considered. On the other hand, the Life Cycle Inventory (LCI) strategy was chosen with the intention of systematically collecting all the energy and emissions inputs and outputs generated during a series of stages of the life cycle of a given resource. In this way, a comparable and reproducible method is presented, helping to expand global knowledge on the experimental performance of innovative and more sustainable commercial solutions. The theoretical foundations of both methodologies are presented in the next section.

3.3. RCPA-LCI Combined Method Description

RCPA is one of the main stages of the energy resource ranking phase of the integrated resource planning methodology developed by the GEPEA [36–38]. The RCPA allows valuing the total cost of each energy resource, considering equally all sustainability dimensions (environmental, political, social and technical–economic), in order to classify each resource according to the best balance of positive/negative impacts.

This work pursues the socio-environmental evaluation of two energy configurations. For that end, both attributes and sub-attributes from the environmental and social RCPA dimensions have been considered. The environmental dimension covers all the changes produced by certain energy resources in the environment, considering terrestrial, aquatic, aerial and biotic magnitudes. The terrestrial criterion considers the liquid and solid pollutants, as well as the land occupation. In the aquatic medium, the water consumption for energy generation, the water quality variation, the water pollution and the water flow changes are considered. For the aerial medium, atmospheric pollutants are considered. Finally, the biotic environment reflects the change in the fauna and flora biodiversity. The social dimension considers the impacts produced by the energy projects on the society where they are introduced. This category includes the quantity and quality of jobs generated; the impact of the space occupation; the influence on development, both economic and human; the variation in the comfort perception; and the health and agricultural impacts of environmental imbalance.

The Life Cycle Inventory (LCI), in turn, is a first stage of the life cycle assessment methodology, whose purpose is to assess the environmental impacts of a given product or service throughout the entire life cycle [39,40]. The LCI consists of two stages: the definition of the object and scope and the inventory. The first step consists of identifying the intended application and purpose, the target audience and the dissemination means. Then, the scope definition consists of the characterization of the studied system and the different process units that compose it. Each process unit has a function, a functional unit and a reference flow that must be defined and consistent with the objective of the study. Input and output data (In/Out) are normalized based on this functional unit. When it comes to comparing systems, the same functional unit and the same methodological considerations should be used.

In addition, the system boundaries, the In/Out considered and the criteria applied for both must be defined. The assumptions and hypotheses, the limitations, the type and format required for the study, the data and sources needed as well as the treatment of missing data should also be mentioned. Data collection is necessary to quantify In/Outs. These data can be obtained through measurements, estimation or calculation, and must be presented individually for each process unit. The main data categories are: energy, raw materials, auxiliary services, products, by-products and waste and emissions to air, soil or water. Data calculations must be documented, validated and justified, and must be calculated in reference to the process unit flow and shown on a functional unit basis.

Both methodologies have already been implemented in a theoretical SS study, published in [41]. The combined RCPA-LCI method therefore consists in: (1) determining the relevant attributes and sub-attributes for the study based on the RCPA criteria; (2) defining the purpose and scope of the study according to the LCI method; (3) defining the process units, the study limits, the functional unit and the reference flow and characterizing the In/Out; (4) collecting the necessary data based on the literature search and the data measured during the pilot application; (5) aggregating these values by alternatives; and (6) evaluating the scalability of each solution.

4. Energy Balance Characterization and Considerations

In this section, the SS energy consumption is evaluated and adjusted under the pandemic scenario, and the energy balance of each energy resource is performed according to data measured during the observation period. For that end, the yearly RU data are first presented, then the measured monthly PU data and, finally, both RU and PU balances are resumed and discussed.

4.1. Yearly RU Data

The SS annual consumption from the regional utility grid is shown in Figure 4. The monthly energy consumption during peak and off-peak hours is presented for a one-year period. The monthly power demand is also plotted, presenting the real power charged by the utility company under COVID-19, and the expected variation considering the

Brazilian National Electricity Balance [24] without the pandemic scenario. The annual energy balances are shown in Table 3.

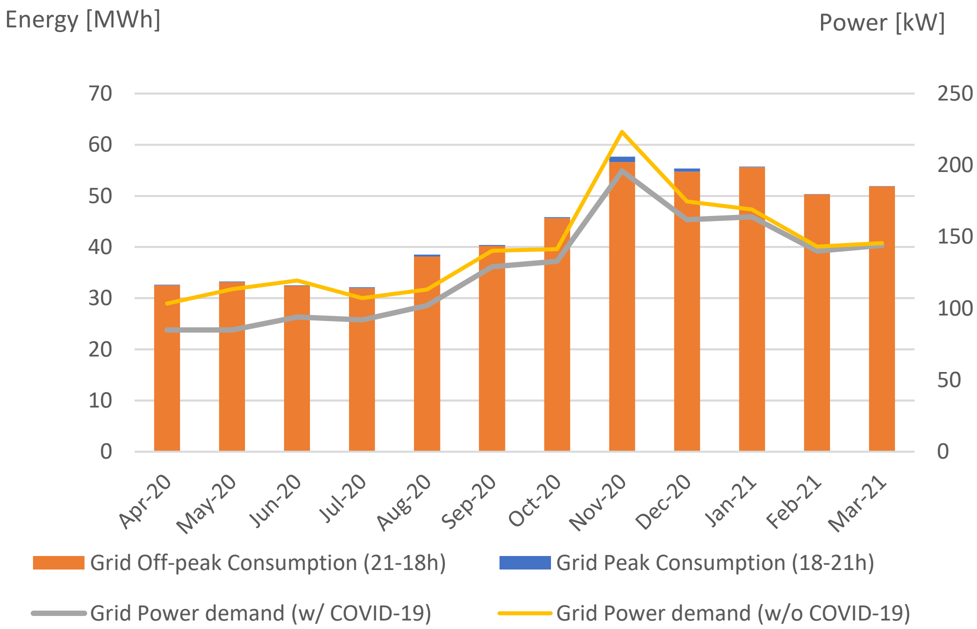

Figure 4. Monthly grid energy consumption (MWh) during peak and off-peak hours [42] and monthly power demand (kW) with [42] and without [24] pandemic scenario.

Table 3. Annual grid energy consumption (kWh/year) with and without pandemic scenario (rows) during peak and off-peak hours (columns).

Grid Energy Consumption	Peak Hours	Off-Peak Hours
With COVID-19	3222	523,084
Without COVD-19	3637	581,549

The maximum power was consumed in November 2020, accounting for between 196 kW and 223 kW with/without the pandemic scenario. The average power demands are, respectively, 121 and 141 kW.

The DGS, in turn, is launched during peak hours and/or grid interruptions (Section 2). The energy consumed during interruptions can be estimated according to the statistical information on continuity indicators [42]. Two indicators are measured yearly, the Individual Interruption Duration per CU (DIC) and the Individual Interruption Frequency per CU (FIC). DIC correspond to a CU's yearly sum interruption hours and FIC to the number of discontinuities that occurred in a year. For the RU, DIC and FIC are, respectively, 14.3 and 8.71. This is, 14.3 h of energy interruption within the year, with an average duration of 1.64 h/interruption. The maximum interruption duration is also presented, which is 2.54 h and validates the necessity of a 3 h autonomous BESS for the PU.

Considering the average off-peak energy consumption and the yearly grid interruption time, the SS consumes 960 and 1067 kWh/year from the DGS with/without COVID-19 during interruptions. Assuming the same average energy consumption during peak and off-peak hours (flat consumption), between 74,726 and 83,078 kWh/year are provided by the DGS during peak hours in the RU configuration.

4.2. Measured PU Data

The BESS was installed in the PU in January 2021 and started its operation in April 2021. Data were recorded from 5 April to 5 May 2021, accounting for an observation period of one month (31 days). Due to the presence of some "outliers" (see Section 3), data were treated considering statistical approximations. All values presented correspond to 1 min samples integrated each 5 min to reduce the calculation time.

4.2.1. BESS

The samples obtained during the first week are presented in Figure 5. Three types of flows can be observed:

- Positive values during working days (5th to 9th) in the peak hours (18:00–20:55). The average power during that period corresponds to 71.7 kW. This behavior corresponds to the BESS dispatch.
- High negative values during working days (5th to 9th) after the peak hours (18:00–20:55). The majority of these values appear in the figure from 21–6 h. The average power during that period corresponds to −41 kW. These data show the BESS charging phase.
- Low negative values during the whole week (5th to 11th). The average power during that period corresponds to −4.5 kW. These values reveal the existence of an anomaly: there is a reverse energy flow from the grid to the BESS, out of the BESS loading phase. This reverse flow could be eliminated by balancing loads, for example, with a closed-loop control system. The BESS ends up consuming more energy than expected, which will worsen its efficiency.

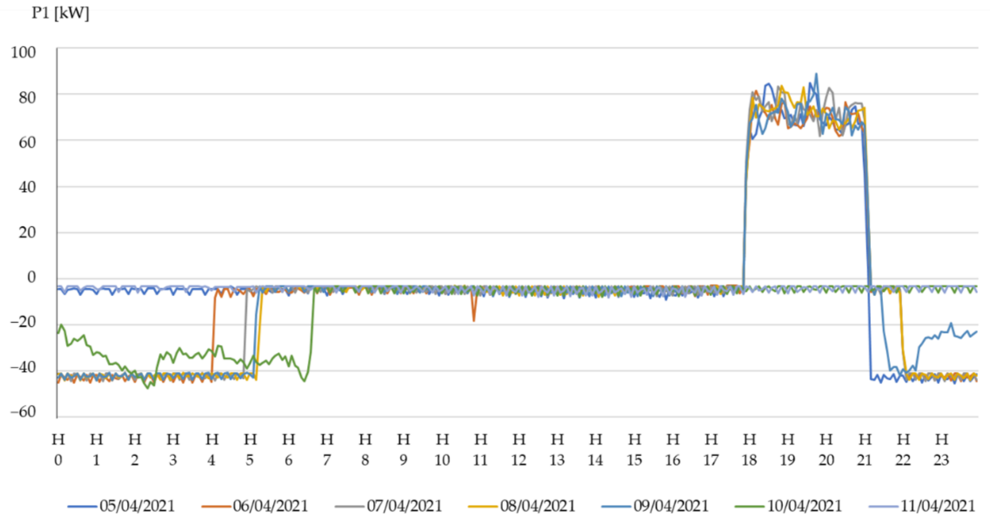

Figure 5. BESS active power flow (P1) measured with meter #1 during the week of 5 April 2021 (kW).

The effective BESS energy is calculated by integrating the active power through time (1).

$$E_1 = P_1 * \Delta t \tag{1}$$

where Δt is expressed in h and E_{ESS} in kWh.

The energy balance obtained from the measured data and Equation (1) reveals the following gross values:

$$P1_{out} = \sum\nolimits_{\mathrm{p1}>0} \mathrm{P1} = 56.115 \text{ kW} \rightarrow E1_{out} = 4.676 \text{ kWh},$$

$$P1_{in} = \sum\nolimits_{\mathrm{p1}<0} \mathrm{P1} = -102.092 \text{ kW} \rightarrow E1_{in} = -8.508 \text{ kWh}.$$

However, to obtain a more generic result, these values have to be analyzed more deeply. For that end, the BESS round-trip efficiency has to be calculated, which depends on the BESS State-of-Charge (SOC). Figure 6 presents the BESS active power flow (meter #1) along with the BESS SOC.

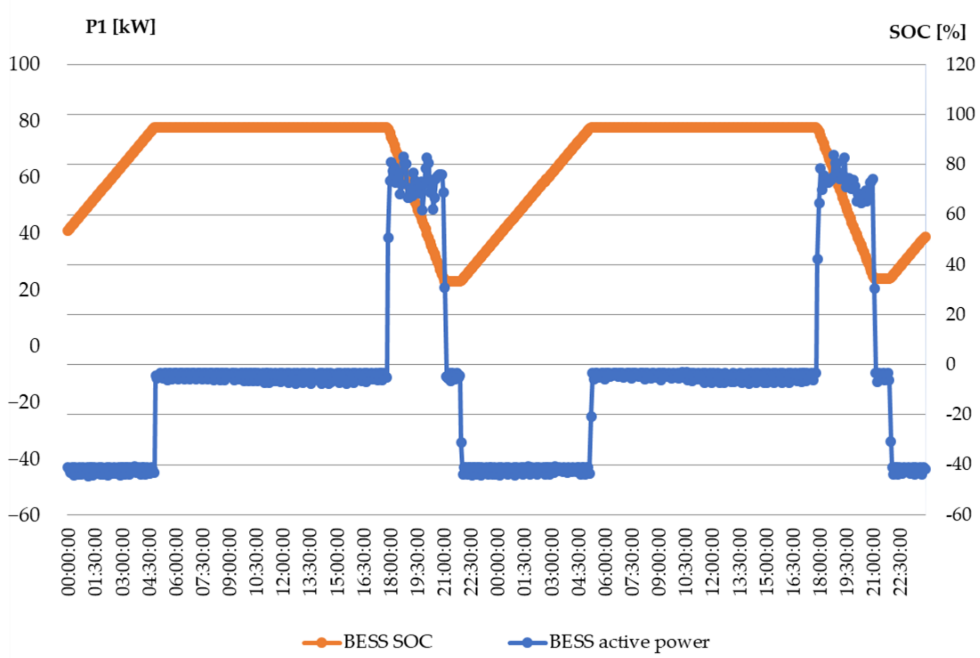

Figure 6. BESS active power (P1) and SOC dynamics on 7 April and 8 April 2021.

The BESS round-trip efficiency can be calculated according to the following equation:

$$ef_{round-trip} = \frac{\sum_{SOC_-}^{SOC_+} P1_{out}}{\sum_{SOC_+}^{SOC_-} P1_{in}} \quad (2)$$

where SOC_+ and SOC_- represent, respectively, the BESS high (+) and low (−) levels of charge.

$P1_{out}$ is the BESS active power consumed by the load and

$P1_{in}$ is the active power used to recharge the BESS.

To estimate a generic $ef_{round-trip}$, some considerations have to be contemplated.

First, the round-trip efficiency depends on the BESS charge and discharge rate, on both SOC levels and on the Depth-of-Discharge (DOD). In addition, the global BESS efficiency (ef_{ESS}) depends on the presence of auxiliary load and on the BESS container local temperature. The work carried out by Romel et al. [25] presents all these contributions and an average value of $ef_{ESS} = 82.14\%$.

4.2.2. DGS

The DGS generates apparent power and active power measured by meter #4. To quantify the DGS energy balance and avoid outlier values, only values higher than 1 kVA have been considered, corresponding to:

$$S_{DGS} = S4_{|S4 \geq 1\ kVA}. \quad (3)$$

During the observation period, 86 measurements have been collected. The DGS ran for a total of 430 min distributed across 5 days. The average DGS apparent power was 51.3 kVA and the average active power was 49.8 kW. The 5 min interval integration of the average active power resulted in 357 kWh of DGS monthly dispatching.

Even though fuel consumption has been measured during the DGS operation, data recorded by the SCADA system presented a lot of volatility and a significant delay in relation to the electrical power measurements. For that reason, the work carried out by

Romel et al. [25] faced this challenge by establishing a mathematical relationship (4) between fuel consumption and electrical output power, which minimizes measurement errors.

$$C_{fuel} = \begin{Bmatrix} \forall P_e \neq 0 \ : \ 0.07 \times P_{nom} + 0.24 \times P_e \\ P_e = 0 \ : 0 \end{Bmatrix} \quad (4)$$

where:

P_e = DGS electric power (kW);

C_{fuel} = diesel consumption (l/h);

P_{nom} = nominal DGS electric power (kW).

Five grid interruption occurred during the observation period. Figure 7 presents the diesel consumption (L/h) according to Equation (4).

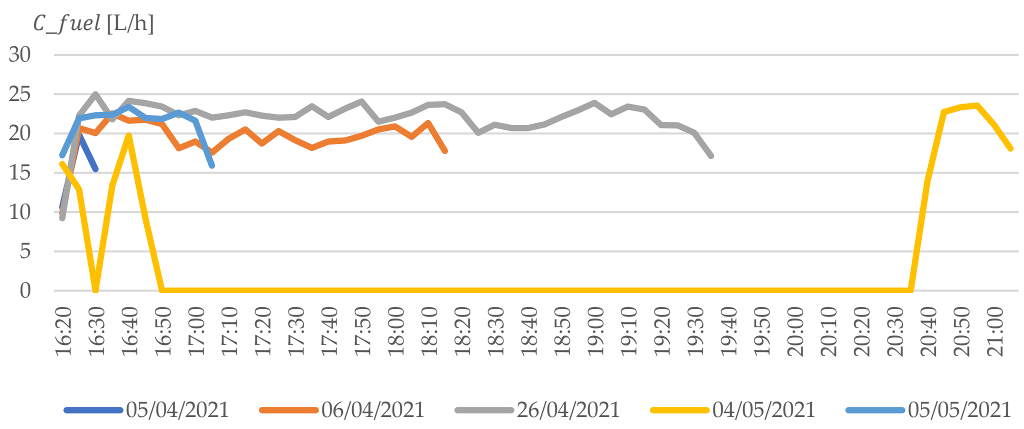

Figure 7. DGS monthly oil consumption based on Equation (2).

Eighty-eight data have been recorded (considering the 5 min integration), which correspond to the reading of 7.3 h. The average consumption value is $C_{fuel-real}$ = 20.4 L/h, accounting for 150 L of diesel fuel consumed in 1 month.

4.2.3. Grid

The electric energy consumption from the utility's grid is measured by meter #3. In total, the energy supplied during off-peak hours accounts for 41,807 kWh, consumed during 632.33 h. During 63.5 of the peak hours, a reverse flow can be observed, adding up to −485 kWh.

4.2.4. Load Consumption

The PU consumption is measured by the combination of meters #6 and #7. All the observation period has been considered, which corresponds to 744 h (31 days). The energy consumed by the SS corresponds to 35,385 kWh.

4.3. RU and PU Energy Balances

The final energy balance according to Equation (5) is summarized in Table 4, for both systems (RU and PU)

$$E_{GRID} + E_{DGG} = E_{BESS} + E_{LOAD} + E_{LOSSES} \quad (5)$$

To estimate the RU balance, some hypotheses were considered. First, the RU DGS energy corresponds to all energy supplied by the BESS in the PU configuration (4.7 MWh), plus the energy dispatched by the DGS during outages (0.4 MWh). The RU grid energy is the same as the PU grid consumption (41.8 MWh), discounting the energy flow used to charge the batteries in the PU configuration (8.5 MWh). Finally, the total energy consumption is the same for both configurations.

Table 4. Energy consumed by each energy resource for the reference unit (left column) and the pilot unit (right column) based on SCADA measurements (MWh/month).

Energy Consumption by Source (MWh)	RU	PU
Load Consumption (E_{LOAD})	35.4	35.4
BESS Energy (E_{BESS})	0	4.7
Grid Energy (E_{GRID})	33.3	41.8
DGS Energy (E_{DGS})	5.0	0.4
System Losses (E_{LOSSES})	2.9	2.2

The yearly data presented in Section 4.1 show a wide consumption variation between consecutive months (37% reduction between April 2020 and March 2021). This variation is due to the global pandemic situation experienced since March 2020, with much more drastic effects at the beginning of the health crisis. Annual energy consumption has thus been calculated according to measured data. Considering an identical consumption during all months of the year, the estimated annual values are presented in Table 5.

Table 5. Energy consumed by each energy resource for the reference unit (left column) and the pilot unit (right column) based annual estimations (MWh/year).

Estimated Annual Consumption by Energy Resources (MWh)	RU	PU
Load Consumption (E_{LOAD})	416.6	416.6
BESS Energy (E_{BESS})	0.0	55.1
Grid Energy (E_{GRID})	392.1	492.2
DGS Energy (E_{DGS})	59.3	4.2
System Losses (E_{LOSSES})	34.7	79.8

5. Local Socio-Environmental Impacts: The RCPA-LCI Application

Once the comparative RU–PU energy balance is obtained, the two alternatives are assessed under the combined RCPA-LCI method, presented in Section 3. The aim is to evaluate the social and environmental impacts of the technological solution presented in this research (PU) in contrast to the original situation (RU). As this is a comparative assessment, only the differentiated impacts associated with the new elements brought by the PU were considered.

5.1. The Resource Complete Potential Assessment (RCPA) Tool

Table 6 presents the main results obtained from the RCPA application on the social dimension. There are no human impacts arising from the occupied space due to displaced or injured persons, nor due to the existence of historical sites. Influence on development is negligible for both economy and infrastructure and human development. There are no major impacts on agriculture nor on building, concerning environmental imbalance in the social environment. The job creation has been calculated based on the PU's implementation conditions and similar works [43–45]. In particular, [43] has been consulted for the DGS and BESS job creation. The quantity of jobs created by the grid's operation was calculated considering the Brazilian electrical mix and the job generation associated with the utilization of hydroelectricity, wind, natural gas [45] and biomass [44]. The comfort perception indicators have been calculated through the consultation of the GEPEA research project [38] and based on the DGS and the BESS technical specifications [25]. In addition, to calculate the grid's job generation, the Brazilian electrical mix has been considered, normalizing 91% of energy resources (hydrogeneration, natural gas and wind energy and biomass).

Table 6. Social dimension assessment under RCPA tool for GRID (3rd column), the DGS (4th column) and the BESS (5th column).

		GRID	**DGS**	**BESS**
Job generation	Jobs	0.54 jobs/GWh	0.14 jobs/GWh	10 jobs/GWh
	Quality and security	High	High	High
Space occupation impact	Displaced people	-	-	-
	Archaeological sites	-	-	-
Influence on development	Economy and infrastructure	-	-	-
	Human development	-	-	-
Env. imbalance in the social environment	Health impacts	-	-	-
	Agricultural impacts	-	-	-
Comfort perception	Noise polution	-	65–86 dB (1.5 m)	-
	Visual polution	-	-	-
	Olfactory polution	-	Polluting emissions	<1% gas leaks
	Thermal polution	-	-	-

Table 7 presents the main results obtained from the RCPA application on the environmental dimension. Impact on the aquatic environment is not significant for any of the energy resources considered in the PU. For this reason, the attribute referring to water quality was not analyzed, nor its sub-attributes. The GHG emissions have been calculated through the consultation of the GEPEA research project [37] and based on the DGS and the BESS technical specifications [25].

Table 7. Environmental dimension assessment under RCPA tool for GRID (3rd column), the DGS (4th column) and the BESS (5th column).

			GRID	**DGS**	**BESS**
Terrestrial environment	Waste	Liquid	-	-	-
		Solid	-	-	-
	Land occupation		-	-	-
Aquatic environment	Water consumption		-	-	-
	Water quality	Δ_{pH}, Δ_{Temp}, DQO, DBO	-	-	-
		Pollutant emissions	-	-	-
	Flow change		-	-	-
Air environment	Atmospheric pollutants	MP, CH_4, SO_2, NOx	-	-	-
	Greenhouse gas (kg CO_2eq/energy)		0.079 kg/kWh	2.14 kg/kVAh	-
	Ozone layer		-	-	-
Biotic environment	Biodiversity	Fauna and flora	-	-	-

5.2. The Life Cycle Inventory (LCI) Tool

This section presents the comparative LCI of each energy resource, according to the methodological description presented in Section 3.3. For this purpose, the objective and scope of the study are firstly presented. Therefore, all inputs and outputs are described and detailed.

5.2.1. Purpose, Scope, System Boundaries and Input/Output Characterization

The purpose of the present LCI application is to evaluate a cleaner and more sustainable technological alternative, based on a BESS instead of a polluting DGS, and which, additionally, enables off-grid operation, strengthening its resilience to utility grid interruptions. The results are expected to be disseminated through the scientific community and the Brazilian electrification promoters and actors. In the case of positive findings, either local or considering the scalability, they are intended to promote the commercialization of the proposed technological solution.

This comparative study covers the evaluation of each energy resource separately, the function of which is to contribute to the SS energy demand. The functional unit is the energy supplied by each resource, expressed in kWh. Reference streams are therefore expressed in kWh. The boundary of the studied system is located in the Operation and Maintenance (O&M) processes. Both the RU and PU O&M processes begin with the on-site presence of all the equipment necessary for the proper functioning of the facility, and end with shutdown and disposal, carried out by an external company and therefore not included in the scope. Neither the manufacture, assembly, implementation, end-of-life nor the transportation processes were considered due to the lack of sufficient information related to the RU process, and a comparative LCI must be made with the same system boundaries.

The Inputs (In) considered correspond to the energy and material consumption of each energy resource O&M. The outputs (Out) are the products and waste produced by this equipment, which are, respectively, the electrical energy supplied by each system and their emissions and energy losses. The exclusion criterion used to characterize the In/Out was based on the importance of the contribution of these elements in the global calculation of the socio-environmental impacts. More specifically, CO_2 emissions are studied, due to their importance in the context of climate change and the possibility of monetizing their impact. The data used in this study are estimates based on measurements or justified by references to recent scientific articles.

5.2.2. Energy Resource LCI

In this section, the information is compiled and the In/Out flows of the evaluated elements are presented. The functional units are: (1) the existing network in the RU and the necessary extensions for the new system (PU); (2) the BESS based on a lithium-ion battery, installed in the PU; and the DGS, existing in the RU. In addition to the incorporation of a new energy resource, the LCI considers the changes in functions attributed to each system. Each functional unit's LCI is presented in Table 8.

Table 8. LCI of each functional unit (columns) including all inputs/outputs (rows).

	Functional Unit	GRID	DGS	BESS	BESS + GRID
IN	Energy consumed (kWh_{in}/kWh_{out})	1.130		1.217	1.376
	Diesel consumed (L_{diesel}/kWh_{out})		0.675		
OUT	Energy losses (kWh_{loss}/kWh_{out})	0.130		0.217	0.376
	CO_2 emissions ($kg_{CO_2,eq}/kWh_{out}$)	0.089	1.815		0.108

To carry out GRID's LCI, the 2020 national Brazilian energy mix has been used as a reference instead of the regional utility grid's statistical information, with the purpose of studying scalability. Concerning the Li-ion BESS's LCI, it has been considered that, despite being able to be charged by any energy source, in the actual PU configuration, only energy from the grid will be used. The complete LCI is presented in the BESS + GRID column. The losses have been calculated considering the round-trip efficiency presented in Section 4.2.1. Auxiliary services have not been included due to the scalability evaluation purpose. Finally, the DGS includes the losses produced during DGS operation. Diesel extraction, refinement and transport were not included in the work's scope.

6. National Socio-Environmental Impacts: Scalability Assessment

Once quantified, the social and environmental impacts are evaluated considering the scalability of the proposed commercial solution. For that end, some specific RCPA indicators are assessed from a macro-perspective.

6.1. Scalability of Environmental Impacts

With the energy consumption values by energy source and the emissions data by source, obtained in the previous sections, the comparative RU–PU emissions balance is presented in Table 9. The difference between the annual emissions of each system's configuration is 85,070 kg_{CO_2eq}/year, which corresponds to 85 t_{CO_2eq}/year avoided. Considering the carbon credit price of 10 USD/t_{CO_2eq}, the economic benefit of reducing emissions is 850 USD/year.

Table 9. Summary of annual energy and CO_2 emissions balances for each RU and PU energy resource.

		Energy Consumption (kWh/year)	**Emissions (kg_{CO_2}eq/year)**
RU	DGS	59,261	107,560
	GRID	392,070	34,894
	TOTAL	451,332	142,454
PU	GRID	492,241	43,809
	BESS	55,059	5946
	DGS	4203	7628
	TOTAL	496,444	57,384

The BEN [24] presents the total commercial energy consumed in Brazil in 2019 and 2020 and analyze the pandemic's impact on energy consumption. To analyze results' scalability, 2019 data has been considered, which account for a total of 93.6 TWh consumed by the Brazilian commercial sector. Therefore, there is a potential for reducing emissions if the technological solution presented in this work was applied on a national scale. This potential corresponds to 15.4 million tons of CO_2, equivalent to a potential monetization of USD 154 million per year.

6.2. Scalability of Social Impacts

The comparative RU–PU job creation balance is presented in Table 10. Comparing the RU and PU configuration, with the technical solution presented in this work, 0597 jobs/year are created. With the scalability evaluation based on 2019 data, it has been estimated that there is a potential for the creation of 113 new job opportunities per year. The relation between energy consumption (kWh) and job creation (new jobs) is defined in Table 6 (Section 5.1).

Table 10. Summary of annual energy consumption and job creation for each RU and PU energy resource.

		Energy Consumption (kWh/Year)	Job Creation (Jobs/Year)
RU	DGS	59,261	0.008
	GRID	392,070	0.212
	TOTAL	451,332	0.221
PU	GRID	492,241	0.267
	BESS	55,059	0.551
	DGS	4203	0.001
	TOTAL	496,444	0.818

7. Conclusions

In this paper, the environmental and social impacts of a commercial energy solution are evaluated from the sustainability perspective. This solution consists of integrating a Battery Energy Storage System (BESS) into a Medium Voltage (MV) commercial unit, to perform the energy time-shift during peak hours. In addition, this BESS allows performing several auxiliary services, such as backup source of energy during utility grid energy outages, which are frequent in Brazil. After demonstrating the techno-economic feasibility of this solution, this R&D project verifies, in a real-world application, the socio-environmental impact of the solution. This work aims to validate the sustainability of the application of BESS-based peak power plants in MV commercial units installed in developing countries.

For that end, the combined RCPA-LCI method is applied. The first allows highlighting all the criteria to be considered in the evaluation of socio-environmental impacts. The LCI application, in turn, shows the importance of defining the scope and objectives when building a comparative study, as well as the need to use a standardized method, internationally accepted and trackable. LCI was applied to the Operation and Maintenance (O&M) stages, due to the comparative nature of the study and the need to have the same study limit for both peak plant configurations. The method application shows both configurations' main Inputs (In) and Outputs (Out), providing comparable data on the energy consumption, generation and losses. Due to their relevance concerning climate change and social issues such as poverty and inequalities, CO_2 emissions and job generation have been assessed for each configuration (RU and PU). Finally, the commercial solution's scalability has been studied regarding the CO_2 emission reduction and its potential monetization, as well as the annual job generation.

The results show a potential emission reduction equivalent of 15.4 million tons of CO_2 that could lead to an economic saving of USD 154 million, and a potential to generate 113 new jobs per year. The socio-environmental assessment provided a positive response to the use of storage systems to replace fuel-based peak plants in the commercial sector. As the technical–economic viability was already proven [25], the BESS-based peak power plant solution's sustainability is fully demonstrated.

Future research should go further and include the evaluation of all socio-environmental RCPA indicators and a complete LCI, including from the energy resource manufacturing to their disposal. This will allow for a more comprehensive evaluation of alternatives and fully sustainability-focused decision making. For this, all energy project actors must join the common objective of building a database on the LCI and social LCI of the different stages of each commercialized energy resource and for several application contexts.

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