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Optimized allocation of self-generated energy: a case study of a brazilian company

Alocação otimizada de energia autogerada: estudo de caso de uma empresa brasileira

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ABSTRACT
Usually, agents in the Free Energy Contracting Environment (ACL) in Brazil, as self-producers and independent producers with their loads, must be carried out an accounting routine named allocation of self-generated energy (AGP). Considering the lack of specific works to solve such typical and necessary routines of these agents, this work presents a methodology to optimize the allocation of self-generated energy. The main contributions of this work are: (i) the elaboration of the allocation of self-generated mechanism as an optimization problem; (ii) development of a free software that provides the values to be allocated to each consumer unit in order to obtain the greatest gain with the distribution of the agent's generation and (iii) enable an allocation analysis in order to obtain the predictability of earnings with allocation in a given future period. In case study, we used data based on a large Brazilian organization in the Steel/Metallurgy/Mining sectors. In a

comparative analysis, the simulation using the optimization process guarantee a financial gain of 17%, which represents savings of 3.6 million in Brazilian currency.

Keywords: free energy market, self-generated energy, optimization.

RESUMO
Normalmente, os agentes do Ambiente de Contratação Livre de Energia (ACL) no Brasil, como autoprodutores e produtores independentes com suas cargas, devem realizar uma rotina contábil denominada Alocação de Energia Autogerada (AGP). Considerando a falta de trabalhos específicos para solucionar rotinas tão típicas e necessárias desses agentes, este trabalho apresenta uma metodologia para otimizar a alocação da energia autogerada. As principais contribuições deste trabalho são: (i) a elaboração da alocação de mecanismo autogerado como um problema de otimização; (ii) desenvolvimento de um software livre que forneça os valores a serem alocados para cada unidade consumidora a fim de obter o maior ganho com a distribuição da geração do agente e (iii) possibilitar uma análise de alocação a fim de obter a previsibilidade dos ganhos com alocação em um determinado período futuro. No estudo de caso, utilizamos dados baseados em uma grande organização brasileira dos setores de Siderurgia/Metalurgia/Mineração. Em análise comparativa, a simulação pelo processo de otimização garante um ganho financeiro de 17%, o que representa uma economia de 3,6 milhões em moeda brasileira.

Palavras-chave: mercado livre de energia, energia autogerada, otimização.

1 INTRODUCTION

The free energy market brings some advantages for the consumer as: freedom to choose the power energy supplier; cost savings due to the negotiated price, volume, and contract conditions; budget forecast knowing exactly how much to pay for the power energy in the future; and competitiveness to the sector. However, there are some risks as: higher fees than the planned ones; miscalculation of energy volume contracted.

In Brazil, the free market of electrical energy (ACL) is organized and viable due to Chamber of Electric Energy Commercialization (CCEE) (CCEE, 2022). ACL commercialization model brings important differences in relation to ACR contracts. The financial aspects treated as a single payment in the captive environment (ACR) are broken down in the free environment (ACL), generating specific financial routines, that must be monitored by the agents.

So, the energy contracts in the ACL must be well investigated before any decision. Junior (2020) demonstrates that migration from captive energy market to the free energy market is technically feasible and has very significant economic benefits for the company analyzed. In a similar way, Ribeiro (2020) indicates that the model of free energy market can be applied in Distributed Generation to achieve a more sustainable and chipper energy framework, although there are regulations difficulties.

Such model of free contract energy is also discussed worldwide. For instance, Nykyri (2022) proposes the use of blockchain based balance settlement in open electricity markets. Besides, the blockchain mitigates the need for any central entity for balance settlement and ensure fair sharing energy (NYKYRI, 2022). This work demonstrates that the regulatory problems can be overcome with this strategy.

Back to Brazilian free energy market scenario, the agent pays for the contracted energy through a monthly bill, generated by the energy supplier, separately from the cost for the use of the transmission and distribution system, who's the fees continue to be charged by the local distributor in the invoice referring to the tariff for use of the electricity system. In Brazil, such fees are called TUSD for distribution system and TUST for transmission system.

In this environment, the financial aspects are treated in a disjointed way. Sector charges, for example, retained by distributors in TUSD/TUST invoices, refer to unmanageable costs passed to consumers, and the electricity price itself, is negotiated between the energy supplier and the final consumer. Among the sector charges, there are the Energy Development Account (CDE) and the Incentive Program for Alternative Sources of Electric Energy (PROINFA), which represent significant percentage in electricity bills.

As defined by Aneel, the CDE charge was created by Law nº. 10.438/2002 with the objective of promoting the universalization of the electric energy service in the national territory, giving discounts in the tariffs of rural and poor classes, and guaranteeing the competitiveness of the energy produced from wind power, small hydroelectric plants, biomass, natural gas, and mineral coal.

Since the sanction of the law 12.783/2013, quotas are defined based on the resources needed to achieve the purposes of the CDE, with the cost being calculated by Aneel and apportioned by all consumers served by the SIN (ANEEL, 2022). Also, Aneel seeks to encourage increasing the participation of alternative renewable sources, in particular, a small hydroelectric plant, wind farms or even biomass thermoelectric projects, through PROINFA (created by law nº. 10.438/2002 and regulated by decree nº. 5.025/2004).

Similar to the CDE charge, the costs of the PROINFA program are shared among consumers, and their calculation takes into account: (i) the Annual Plan prepared by Centrais Elétricas Brasileiras S/A (ELETROBRAS) and (ii) the verified energy market (captive market and free market).

Over the years, incentive policies have been created, which use discounts to promote the use of renewable energy sources and self-production of energy, aiming the reduction of environmental impacts and/or increasing pulverized energy generation. This is the case of the discount attributed to the CDE and PROINFA charges, obtained through the procedure of allocation of self-generation energy (AGP), subject of this work.

Thus, the main contributions of this work are: (i) the elaboration of the allocation of self-generated mechanism as an optimization problem; (ii) development of a free tool that provides the values to be allocated to each consumer unit in order to obtain the greatest gain with the distribution of the agent's generation and (iii) enable an allocation analysis in order to obtain the predictability of earnings with allocation in a given future period. The previous work (DE LIMA et al., 2021) is used as a base for this paper. The major difference between than lays on more accurate and detailed data presentation, recent literature review and, more important, the translation for English language to better spread updated results.

The next sections of this article are organized as follows. Section 2 presents a literature review. Section 3 explains the methodology used in this work. Section 4 aims to present a case study, which the results are exposed in Section 5 where the gains obtained with the use of the proposed tool are discussed. Finally, Section 6 presents the conclusions and points to future work.

2 LITERATURE REVIEW

Many works propose optimization models, destined to energy distribution agent, as presented by Ramos and Susteras (2006), which uses Genetic Algorithm (GA) for supporting energy commercialization. In the same way, Lopes (2014) has established a robust strategy, using Genetic Algorithm and Differential Evolution, which was applied in a simulation of energy acquisition carried out by a distribution system operator (DSO) aiming to minimize the costs.

Other approaches can also be found, such as the one proposed by Bourges (2012) that brings a new methodology for allocating electrical losses between generators and loads, in order to achieve a fair compensation scheme in electrical transmission systems when considering different companies acting in the market.

In addition to these works, there are studies that seek to predict the market price in the short term, given the uncertainties involved in the price of energy and the multivariable aspect, often with low predictability, as shown (PEREIRA, 2018) and (DE AMARANTE, 2018). In this context, Lima and Paula (2021) have proposed a methodology for big electricity consumers in the free energy market in Brazil, which considers a statistical model that correlates scenarios of energy and peak demand with the spot price scenarios.

It is also worth mentioning that the financial savings offered in this free contracting environment (ACL) are attractive, enabling the migration of consumer units, as shown by Vasconcellos (2012). In this work, it is conducted a study of case that shows the economic advantages of contract migration from ACR to ACL.

Fonseca (2015) has proposed a feasibility study aimed the migration to the incentivized free market, which, despite having a higher energy cost, is subject to discount policies, due to the insertion of renewable sources. In an international scenario, there is some works that bring reflections on policies of discount on energy tariffs and their impacts on energy costs. It is possible to observe that the Brazilian mechanism (allocation of self-generated energy) is in accordance with the policies worldwide.

For example, Feet (2019) studied the impacts that hybrid photovoltaic generation systems, using storage, can have on electricity prices in Germany. To this end, the authors studied a technical-economic model, concluding that the abolition of the remuneration mechanism through feed-in tariffs appears as an alternative to reduce electricity prices. Similar to what is presented in Germany, the authors in (ZHANG, 2021) indicate that the cancellation of remuneration through feed-in tariffs in distributed photovoltaic generation projects does not impact the investment return in this type of energy project.

To confirm this trend, the work presented by Samper (2021) indicates that the incentive mechanisms of the Net-Billing and Net-Metering are more profitable than the incentive of the Feed-In mechanism. This study was conducted in Argentina, where incentive mechanisms have brought great advances to the dissemination of distributed photovoltaic generation.

Cejka (2021) discussed the Energy Communities in Austria (self-consumption energy system), concluding that the large number of grid operators (DSOs) brings a heterogeneous structure to the energy market, in the manner of to the Brazilian grid. Although such structure makes difficult the dissemination of these Energy Communities, there are significant deductions in the network tariffs for such projects.

So, it is important to say that the recent energy policies adopted in Brazil is consonant to the worldwide energy strategies, especially regarding the incentive mechanisms, bringing Net-Metering as the main strategy. Again, the allocation of self-generated energy shows as an appealing strategy for some companies in Brazil.

Given this scenario, more specific aspects related to the routine of agents in the free market and the specific requirements by each activity are not completely addressed in the literature. One of the factors that can contribute to this reality is the fact that the free energy market is a relatively new environment in Brazil, whose specific knowledge about its operation is still concentrated in professionals working in the area, through companies that provide the specialized services for the representation of agents in the free market.

Considering the lack of specific works to solve these typical and necessary routines of agents in the free market, the next section presents an optimized allocation of self-generated energy (AGP). The AGP is a procedure that demand time and a previous analysis of agents with specific consumption and generation characteristics, which requires data compilation and processing to obtain the best distribution of the generated energy.

It is important to mention that in this kind of accounting routine, called AGP, there are agents who's the pattern of energy consumed monthly exceeds the amount of self-generation in the same period. Besides, some agents have their loads located in different parts of the country, which makes them subject to different tariffs for the use of the distribution and transmission system, identical to the case of Austria (CEJKA, 2021).

3 METHODOLOGY

3.1 DEFINITION OF THE OPTIMIZATION PROBLEM

Allocation of Self-Generated Energy (AGP) is a procedure destined to agents into the categories of self-producers, independent producers with their own loads and consumers participating in consortium or Special Purpose Society (SPE) (private legal entity). These agents have the right to allocate their generation to meet their own loads, to obtain exemption in part of the TUSD/TUST, referring to the CDE and PROINFA sector charges[1].

Our methodology is based on the regular agent's routine for AGP in the free market to receive the benefit of exemption in part of the TUSD/TUST, as follows:

1) obtain the generation to be allocated (g_a) from *n* generating units of the agent:

$$g_a = \sum_{i=1}^{n} [[(g_{F_i} + g_{S_i} + g_{T_i}).pc_i] - g_{V_i}], \qquad (1)$$

Taking into account the generation of the plant with its loss of energy (g_F), the energy produced in excess, called secondary energy (g_S), the generation under test (g_T), the energy destined for predefined contracts of sale of incentivized energy (g_V) and, finally, the percentage of participation of the consumer agent in that plant (pc).

2) obtain the list of energy that must be allocated for loads (v_a);

3) define the list of allocation percentages (p_a) to be insert in CCEE system:

$$p_a = \frac{v_a}{g_a} \qquad (2)$$

The procedure of allocation of self-generated energy in the CCEE system consists in declaring the percentage of energy that must be allocated in each load, prioritizing the generation from the SPE and eventual leftovers. In this case, the commonly used strategy is allocating the self-generated energy in a proportional way, considering the percentage volume of consumption of each consumer unit.

This is a non-optimized process, and the agent is not guaranteed to get the maximum possible discount. Therefore, the main objective of this methodology is to maximize the total discount amount received by the exemption in part of the TUSD/TUST charge given by:

$$D(v_a, d) = \sum_{k=1}^{m} v_{a_k}.d_k, \qquad (3)$$

[1] The CDE and PROINFA charges are imposed at TUSD/TUST fee and vary by distributor, state, submarket (SE/CO, S, NE, N), voltage subgroup (A1, A2, A3, A4, AS, etc.) and tariff modality (Blue, Green, etc.).

Where:

D is the total discount value of the agent's consumer units (economic gain obtained); d_k is the discount over TUSD/TUST charge of a k-consumer unit, resulted from the subtraction between the TUSD/TUST tariff and the TUSD APE tariff (according to Aneel's current homologation resolution).

In this way, the optimization problem can be described as:

$$v_a^* = argmax_{v_a} D(v_a, d)$$

Subject to:

(4)

$$\sum_{k=1}^{m} v_{a_k} \leq g_a,$$

$$0 < v_{a_k} \leq V_{max_k}.$$

Where:

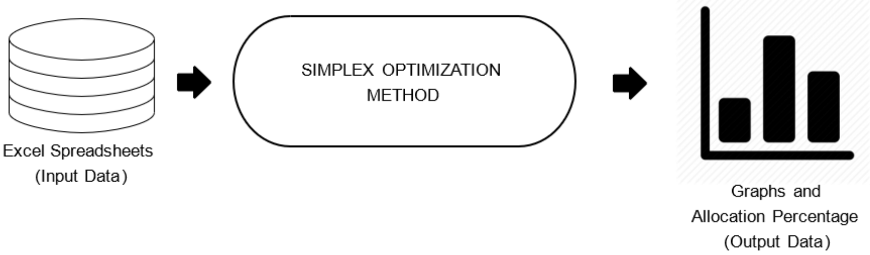
v_a* is the list of the optimal values for allocation in each consumer unit and V_{max_k} is the maximum possible value of allocation in consumer unit k, which corresponds to the total consumption value without loss of energy of the unit in the period. It should also be considered that plants from SPE can only allocate their generation (g_a) to the k-load (v_{a_k}) whose demand is greater than 3MW.

To illustrate the expected results of using such optimized method, Figure 1 demonstrates how energy allocation can be done to obtain the biggest discounts. So, we can use this optimization procedure as an alternative to the current CCEE's method, ensuring greater efficiency and gains for the agent.

3.2 SOFTWARE FOR OPTIMIZED ALLOCATION OF SELF-GENERATED ENERGY

The software to provide the optimized allocation of self-generated energy was developed in Python 3.6+ language and it is freeware, available on GitHub. The software architecture used for this allocation is presented in Figure 2.

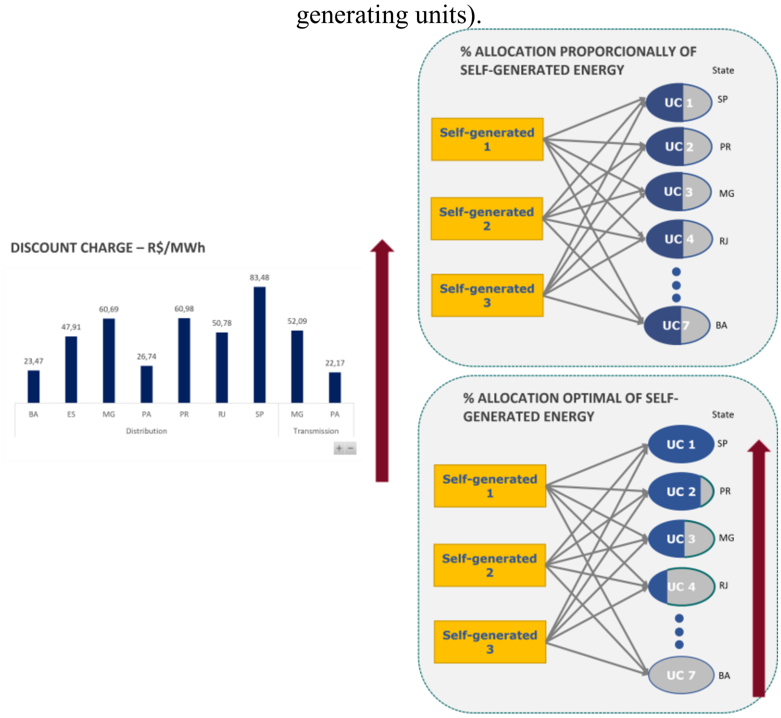
Fig. 1: Software architecture for the allocation of self-generation energy.



Source: Authors.

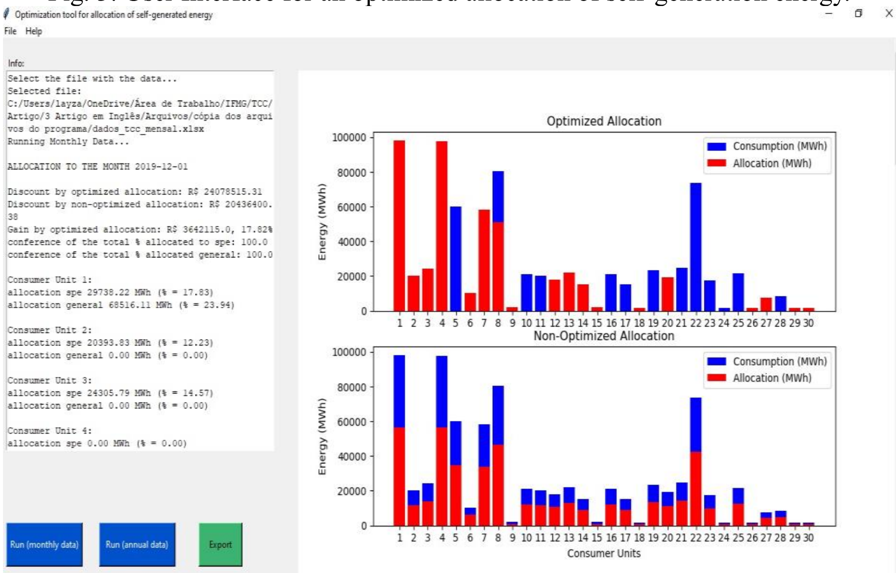
We chose the classic deterministic method called Simplex to solve the optimization problem, whose approach is easy to apply and compatible with the linear programming problem in question. The premises of the method, which are proportionality, divisibility, additivity, and certainty, were met. To apply it, the *lpsolve* library for Python provides the necessary functions.

Fig. 2: Illustrative comparison of allocation of self-generated energy (m = 7 consumer units and n = 3 generating units).



Source: Authors.

Fig. 3: User Interface for an optimized allocation of self-generation energy.



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The software's interface was developed using the *tkinter* library. In Figure 3, it is possible to see the File menu (for selecting the input file and the folder to save the results), the Run button (to start the allocation process), the *log* (destined to present information to the user) and, finally, a space to visualize the results in graphical form. In addition to this graphical view, the software provides the values of the percentages that must be declared by the user in a specific CCEE system, according to Equation 2.

It is important to highlight that the software can be used for projection simulations, considering a future period. To do so, the data entry may contain more than one month, and the results will be provided both monthly and on a consolidated basis in the evaluated period. This information is useful for analysts which, for example, perform the company's annual budget and need to include the projection of economic gains with the allocation of their self-generation.

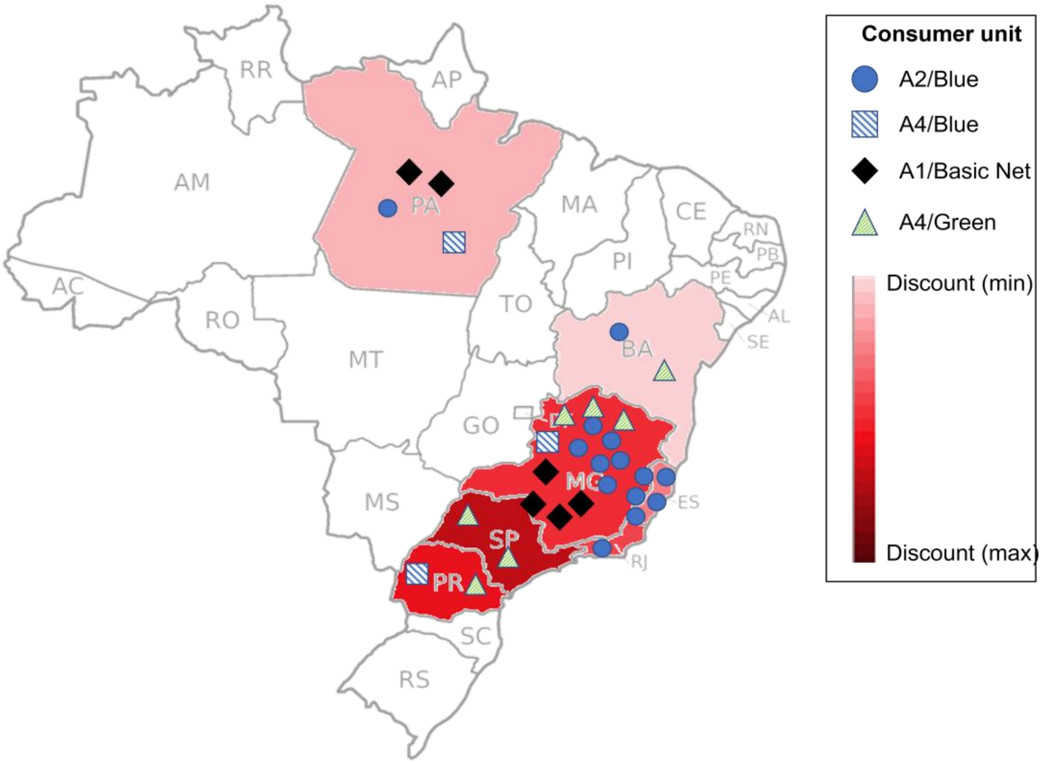
4 CASE STUDY: A BRAZILIAN COMPANY

A case of study will be carried out for a fictitious company, whose data used are based on a large Brazilian organization in the Steel/Metallurgy/Mining sectors to exemplify the methodology proposed. This company profile normally fits into the self-generation categories defined by the CCEE and has a consumption higher than its generation, being able to obtain gains in the process of allocation of self-generated energy.

The company under study has 30 (thirty) consumer units throughout Brazil, 22 (twenty-two) of them are located in the Southeast (SE) and Midwest (CO) regions, where the TUSD/TUST tariffs are higher than the rest of the country. Figure 4 indicates the location of each consumer unit of the company.

The company's average monthly consumption totals 800,000 MWh, and the monthly generation of the 10 (ten) plants owned by it add up to an approximate 450,000 MWh of self-generation, which 160,000 MWh refers to projects under the SPE regime. The data of this scenario is shown in Table I, considering the generating units, and Table II (Appendices), considering consuming units.

Fig. 4: Consumer units of a company (December/2019) relative to Table II.



Source: Authors.

The first analysis was performed based on the individual data of each consumer and generating unit of the company for a given month, in this case, December 2019.

The second analysis performed was an annual study of the company's cash flow forecast for the year 2020. To this end, knowing that for the analyzed company profile the typical variation of each plant is a maximum of 2%, the data were generated varying the values within a proportional distribution between the defined maximum values. In order to guarantee information with statistical reliability, the program was executed one hundred times for each month under study.

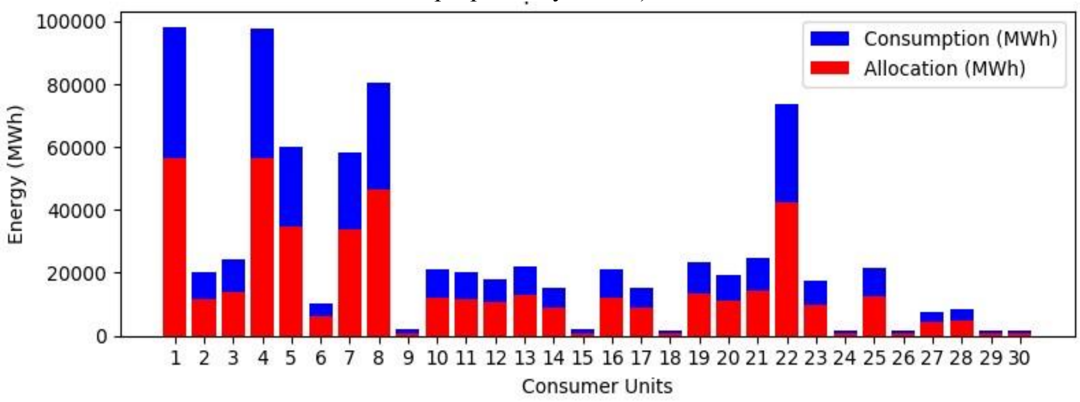
5 RESULTS AND DISCUSSION

The process of allocating self-generation under study is complex, since the company has consumer units at different connection points in the national interconnected system (SIN), with loads subject to different charges. Thus, it is common to allocate the energy following the approach of proportional distribution regarding the consumption of each unit, as seen in Figure 5.

The software developed in this work makes possible the processing of data from different plants and different locations, generating an optimal allocation, solving the optimization problem (Equation 4) by the Simplex algorithm. The result of this allocation to the company's thirty consumer units can be seen in Figure 6.

Note that for consumer units 5, 10, 11, 16, 17, 19, 21, 22, 23, 24, 25 and 28 no energy has been allocated. However, the units that had a higher discount charge value (d_k) were privileged by the Simplex Algorithm, as expected. Thus, comparing the optimized result with the non-optimized result, there was a financial gain of R$3.6 million, which represents an increase of 17.93% in benefit in the month.

Fig. 5: Allocation of self-generation for December/2019, using non-optimized allocation (distribution proposed by CCEE).



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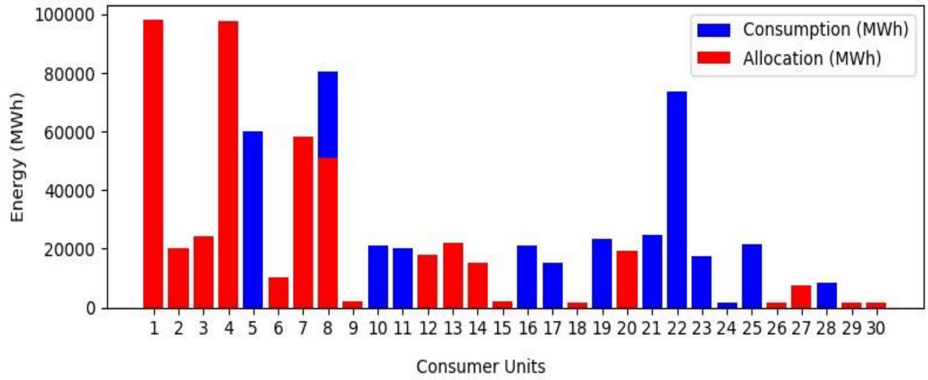
The results of the annual analysis, based on company data provisioned for the year of 2020, can be seen in Figure 7. With the optimization proposed in this work, it is possible for the company to have an average monthly discount of R$23.72 million, in contrast to the non-optimized strategy that brings a discount of R$20.15 million. In comparison with the non-optimized discount, in the period of one year, the gain from using the software would be 43.3 million reais.

Fig. 6: Allocation of self-generation for December/19, using optimized allocation.



Source: Authors.

To generate statistical reliable information, the program was executed 100 times for each month. In each iteration was performed a random variation of 2% in the input data of consumption and generation. Thus, the presentation of the results, structured through a box diagram, evidences the variability of the samples. In this kind of graph, the limits of the rectangular figure delimit the lower and upper bounds, and the central line the median of the data. Briefly, the block diagram displays a location of the most likely values. The annual gain results can be seen in Figure 8.

Fig. 7: Comparison between optimized and non-optimized allocation, with respect to discounts to be earned monthly during a provisioned year.

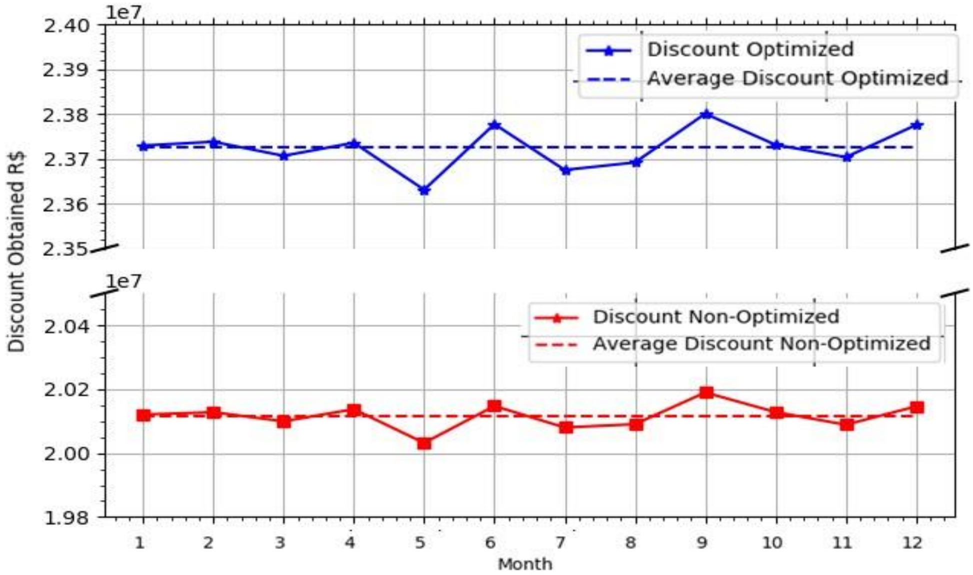


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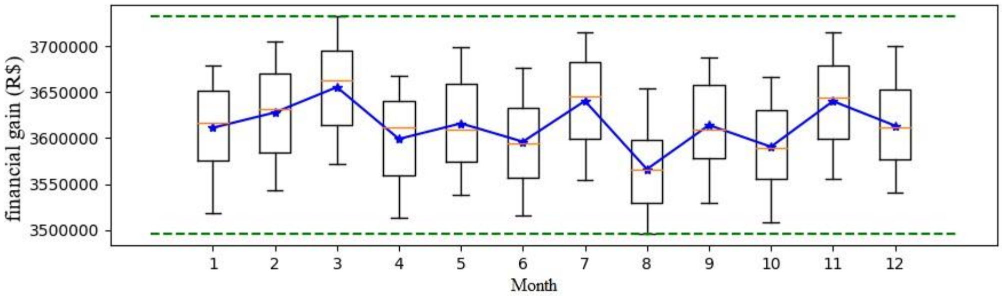
Fig. 8: Annual financial gain (2020) with optimized allocation of self-generated energy.



Source: Authors.

Clearly, the variation of the possible allocation value in each unit changes the discount to be obtained, the worst case can be seen in May 2020. However, the difference with the non-optimized discount is still very significant.

6 CONCLUSION

This work presented an optimization for support the decision of agents in the condition of allocation of self-generated energy, comparing the results between the proposed optimized distribution and the non-optimized conventional distribution, proposed by CCEE. The case study presented showed a financial savings of around 17% using the software, allowing the agent to maximize the gain with the self-generation discount through an optimized allocation.

From the results, it is expected that this software can facilitate the monthly routine, guaranteeing the best possible financial result for the agents, whose characteristics fit those presented in the studies. In addition, it is expected that this agent can use the software for annual forecasts, useful for carrying out the company's cash flow projection. The developed software can also make possible carrying out an investment analysis in new plant generation projects, since the discount value obtained by AGP is one of the financial aspects involved in verifying the viability of new plants. To do so, it is sufficient that the input data include the information of the project under study.

In future works, it is intended to expand the application of the software, including new variables, associating, for example, variables related to commercial decisions of purchase and sale of energy, to enable the maximization of the agent's result.

SUPPLEMENTARY INFORMATION

The data that support this study are available in https://tinyurl.com/37y27khj.

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APPENDIX A: DATA FROM STUDY CASE

Data from the generating and consumers units is shown in Table I and II, respectively.

Table 1: Data from the generating units of December/2019.

Unit	Generation (g_A) (MWh)	PGDA (p_{Ci})	Contract (C_V) (MWh)	SPE
01	103022.55	0.60	0	yes
02	65845.25	0.40	0	yes
03	56136.83	0.50	0	yes
04	86272.20	0.25	0	yes
05	96654.25	0.30	0	yes
06	59183.24	1.00	0	no
07	55819.64	1.00	0	no
08	98688.64	1.00	40000	no
09	57550.20	1.00	0	no
10	64912.88	1.00	10000	No

Source: Authors.

Table 2: Data from consumer units of a company (December 2019)

Unit	DSO	State	Sub market	Voltage/ Modality	Charge (R$/MWh)	C. APE (R$/MWh)	Consumption $Vmax_k$(MWh)	Demand (MW)	d_k (R$/MWh)
01	ONS	MG	SE/CO	A1/Basic Net	52.09	0.00	98254.33	161	52.09
02	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	20393.83	33	53.50
03	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	24305.79	40	53.50
04	ONS	MG	SE/CO	A1/Basic Net	52.09	0.00	97878.09	155	52.09
05	ONS	PA	N	A1/Basic Net	22.17	0.00	60016.70	98	22.17
06	CEMIG	MG	SE/CO	A4/Blue	89.65	28.96	10340.73	16	60.69
07	ONS	MG	SE/CO	A1/Basic Net	52.09	0.00	58477.93	94	52.09
08	ONS	MG	SE/CO	A1/Basic Net	52.09	0.00	80643.70	130	52.09
09	CEMIG	MG	SE/CO	A4/Green	89.65	28.96	1821.00	2.9	60.69
10	LIGHT	RJ	SE/CO	A2/Blue	81.27	30.49	21066.99	34	50.78
11	CELPA	PA	N	A2/Blue	41.08	16.57	20199.22	32	24.51
12	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	18134.13	29	53.50
13	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	22102.13	35	53.50
14	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	15132.68	24	53.50
15	CEMIG	MG	SE/CO	A4/Green	89.65	28.96	1858.98	2.9	60.69
16	EDP ES	ES	SE/CO	A2/Blue	55.83	7.92	20997.99	34	47.91
17	EDP ES	ES	SE/CO	A2/Blue	55.83	7.92	15219.83	25	47.91
18	CEMIG	MG	SE/CO	A4/Green	89.65	28.96	1454.30	2.3	60.69
19	EDP ES	ES	SE/CO	A2/Blue	55.83	7.92	23254.47	38	47.91
20	CEMIG	MG	SE/CO	A2/Blue	65.45	11.95	19260.71	31	53.50
21	EDP ES	ES	SE/CO	A2/Blue	55.83	7.92	24584.94	40	47.91
22	ONS	PA	N	A1/Basic Net	22.17	0.00	73535.22	120	22.17
23	EDP ES	ES	SE/CO	A2/Blue	55.83	7.92	17279.59	27	47.91
24	COELBA	BA	NE	A4/Green	50.43	26.96	1764.79	2.8	23.47
25	COELBA	BA	NE	A2/Blue	33.35	11.89	21400.27	34	21.46
26	COPEL	PR	S	A4/Green	79.79	18.81	1718.91	2.8	60.98

27	COPEL	PR	S	A4/Blue	79.79	18.81	7376.15	12	60.98
28	CELPA	PA	N	A4/Blue	88.74	62.00	8246.93	13	26.74
29	CPFL	SP	SE/CO	A4/Green	96.39	12.91	1687.96	2.7	83.48
30	CPFL	SP	SE/CO	A4/Green	96.39	12.91	1584.76	2.6	83.48

Source: Authors.

APPENDIX B: LIST OF ABBREVIATIONS

Table 3: List of abbreviations

Abbreviation	Description
ACL	Free Contracting Environment
ACR	Regulated Contracting Environment
AGP	Allocation of Self-Generated Energy
ANEEL	Brazilian Electricity Regulatory Agency
CCEE	Chamber of Electric Energy Commercialization
CDE	Energy Development Account
ELETROBRAS	Brazilian Electric Utilities Company
GF	Physical Energy Guarantee
GSF	Generation Scaling Factor
N	North region
NE	Northeast region
PROINFA	Alternative Sources Incentive Program
S	South region
SE/CO	Southeast / Midwest region
SIN	Brazilian interconnected power system
SPE	Specific Purpose Society
TUSD	Distribution System Use Tariff
TUST	Transmission System Use Tariff

Source: Authors.