Two-Stage Framework to Determine Tariff Structures in the Day-Ahead Market for Distribution Networks with Energy Communities

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ABSTRACT

The integration of distributed energy resources challenges the financial stability of distribution companies and, thereby affects their future investment capacity. This work presents an innovative two-stage optimization framework to determine efficient tariff structures in the day-ahead market, with a focus on the charge management of plug-in hybrid electric vehicles that providing cooperative service to members of an energy community. This methodology was applied in a 4-node medium voltage distribution network with an energy community. The results demonstrate a 29.4% improvement in the load factor when considering the dawn tariff structures, reducing the need for major infrastructure investments while securing stable revenues for distribution companies. These findings highlight the importance of infrastructure and investment planning in response to transition challenges, ensuring a resilient and adaptable electricity system.

Keywords: Day-ahead, Energy Communities, plug-in hybrid electricity vehicles, management program, two-stage problem.

INTRODUCTION

The growing adoption of distributed energy resources (DERs) poses the challenge of defining tariff structures that guarantee the financial health of the distribution company (DisCo) to make future investments in the distribution network (DisNet) viable. In addition, these tariffs should be designed to support the integration of energy communities (ECs), organized groups of consumers who collaborate to generate, consume, and manage their energy. Creating an appropriate tariff environment is essential to guarantee the financial sustainability of DisCo. This can result in a reduction in peaks of demand and help DisNet's efficient operation.

Recent studies in high-impact journals explore the creation of energy ECs and evaluating tariff structures. A mixed integer program was proposed in [1], while optimization models using mathematical approaches were determined by the authors in [2, 3]. These studies underscore the necessity of integrating advanced optimization and management techniques to develop tariffs that lower costs while fostering active, sustainable consumer engagement in energy management. This work aims to determine tariffs that reflect the operational and financial conditions of the DisCo.

PROPOSED METHODOLOGY

A two-stage optimization methodology is proposed, which is shown in Fig 1. In the first stage, we use a mathematical model to select a tariff structure that maximizes DisCo's revenue, subject to DisNet's operation constraints. The second stage involves executing a management program to minimize energy import payments for the EC by optimizing local and external plug-in hybrid electricity vehicle (PHEV) charging schedules to assess the state of charge.

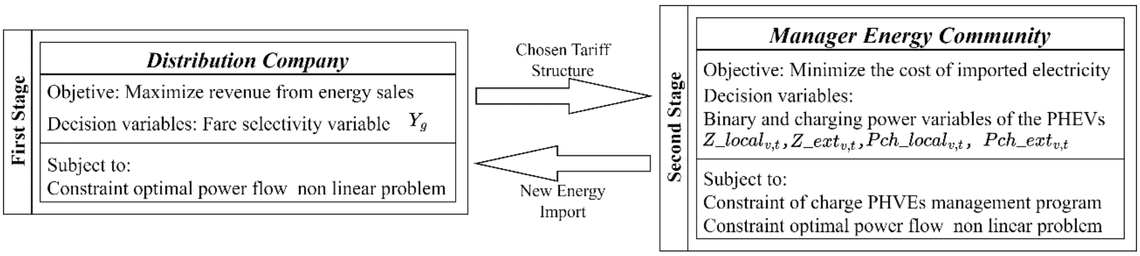

Figure 1. Flowchart Two-Stages Optimization Methodology.

A.) First Stage Problem Formulation

The objective function (1) is to maximize DisCo's revenue from selling energy.

$$\text{Max} \sum_{t=1}^{T} \sum_{i=1}^{N} \text{TE}_{g,t} * (\text{P}_{\text{EC i,t}} - \sum_{ij=1}^{C} (\text{P}_{\text{loss ij,t}})) * \Delta_t \quad \text{Eq. (1)}$$

Subject to:

$$\sum_{g=1}^{G} \text{Y}_g = 1 \quad \text{Eq. (2)}$$

$$\text{TE}_{g,t} = \text{Y}_g * \text{M\_Tariff}_{g,t} \quad \text{Eq. (3)}$$

Where $\text{TE}_{g,t}$ is the tariff selected by Y_g , a decision variable that chooses the most suitable tariff structure from the set of tariffs $\text{M\_Tariff}_{g,t}$; $\text{P}_{\text{EC i,t}}$ is the power consumed by the EC, and $\text{P}_{\text{loss ij,t}}$ represents the power losses in the DisNet.

B.) Second Stage Problem Formulation

The objective function (4) is to minimize EC's payments of buying energy.

$$Min \sum_{t=1}^{T} \sum_{e=1}^{M} \left((\mathrm{Tar}_{local} * \mathrm{Ptot\_EC}_{e,t}) + (\mathrm{Tar}_{ext} * \sum_{v=1}^{V} \mathrm{Pch\_ext}_{v,t}) \right) * \Delta t \qquad \text{Eq. (4)}$$

Subject to:

$$\mathrm{Z\_local}_{v,t} + \mathrm{Z\_ext}_{v,t} \leq 1 \qquad \text{Eq. (5)}$$

$$\mathrm{SOC}_{v,t} = \mathrm{SOC}_{init} + \frac{\mathrm{Pch\_local}_{v,t} * \Delta t * n}{\mathrm{E}_{max}} + \frac{\mathrm{Pch\_ext}_{v,t} * \Delta t * n}{\mathrm{E}_{max}} - \frac{\mathrm{VE}_{ruta,v,t} * \Delta t}{\mathrm{E}_{max}} \qquad \text{Eq. (6)}$$

Where $\mathrm{SOC}_{v,t}$ is the PHEV charging state variable, which takes into account the PHEV battery conditions; $\mathrm{Pch\_local}_{v,t}$, $\mathrm{Pch\_ext}_{v,t}$, $\mathrm{Z\_local}_{v,t}$ and $\mathrm{Z\_ext}_{v,t}$ are the decision variables that determine the power and time of local and external charging of the PHEVs, subject to maximum and minimum power conditions; n is the charging efficiency; and Δt is the time step.

Also, both stages are subject to the optimal power flow constraints found in [4].

RESULTS AND DISCUSSION

Methodology was applied to the 4-node medium voltage's DisNet shown in Fig. 2, which considers an EC with a characteristic demand and PV generation of a typical Brazilian city obtained from [5]. Fig. 3 presents the daily driving routine of 3 PHEVs. Three scenarios for charging PHEVs that provide community service to the EC were evaluated. This service moves residents to other parts of the city and is paid for by the EC.

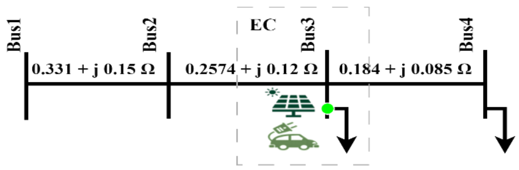

Figure 2. 4-buses network tested.

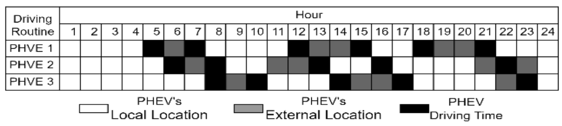

Figure 3. Driving Routine Plug-in Hybrid Electricity Vehicles.

Fig. 4 shows six tariff structures defined by the regulatory agency. After applying the methodology, the white tariff and the dawn tariff 1 meet the objectives of the EC and DisNet in Scenario 1. In Scenarios 2 and 3, the dawn tariff 2 meets these objectives.

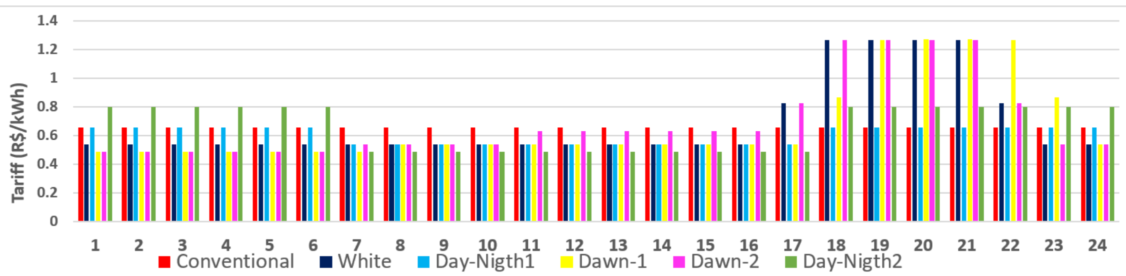

Figure 4. Tariff structures.

Fig. 5 shows the demand and PV generation curves resulting from managing the charging of the PHEVs for each scenario, as well as the PV generation and EC's fixed load.

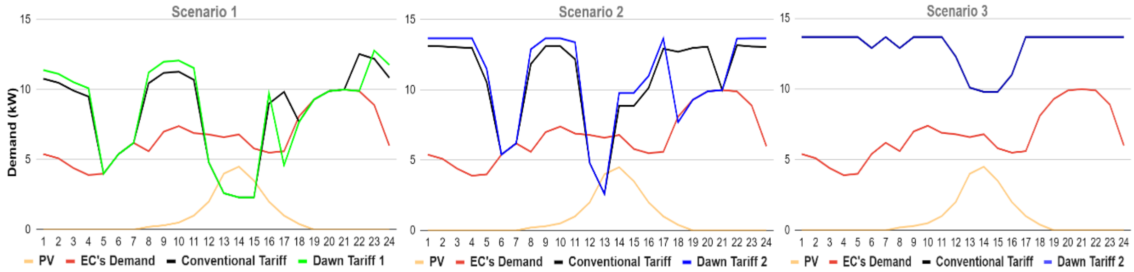

Figure 5. Energy Community Demand Curves Post-management.

Table 1 shows that the selected tariff structure increases DisCo's revenue by between R$5.136 and R$13.136, increasing the EC's bill compared to the conventional tariff. In Scenario 3, EC requires up to R$61.74 for external charging of the PHEVs. In the other scenarios, the charging of the PHEVs is taken care of by DisNet, reducing EC payments by up to 25.9% compared to Scenario 3.

Table 1. Economic Results.

Scenarios								
1 PHEV			**2 PHEV**			**3 PHEV**		
Revenue DisCo(R$)	*Tariff Structure*	*Payment EC (R$)*	*Revenue DisCo(R$)*	*Tariff Structure*	*Payment EC (R$)*	*revenue DisCom(R$)*	*Tariff Structure*	*Payment EC (R$)*
133.476	*Conventional*	133.479	171.411	*Conventional*	171.410	204.457	*Conventional*	225.156
142.035	*White*	140.461	178.828	*Dawn 2*	176.550	217.593	*Dawn 2*	238.29
142.389	*Dawn 1*	140.948	176.548	*Dawn 2*	176.550	217.593	*Dawn 2*	238.29

Scenario 3 demonstrates a 29.4% increase in load factor due to the more homogeneous demand behavior of the EC. This contributes to a more balanced load on the DisNet and positively impacts operating parameters, reducing the need for infrastructure investment, lowering operating costs, and ensuring the financial sustainability of the DisCo [2, 3]. Although tariffs can reduce peak demand and consumption costs, this work indicates that while peaks are not permanently reduced, the load factor can improve, and EC's payments can decrease through effective PHEV charging.

However, the tariff structures used may be somewhat simplified. Incorporating more sophisticated models, varying tariff structures, and detailed PHEV routines would provide a fuller understanding of DisNet's impacts. Additionally, external factors like government policies, market changes, or consumer preferences were not considered. Nonetheless, the results underscore the technical and economic benefits for both DisCo and EC, offering valuable insights for short-term planning in the day-ahead electricity market.

CONCLUSION

This work proposes a two-step methodology for ECs to manage the charging of PHEVs and reduce energy payments. At the same time, DisCo ensures its sales and financial sustainability. The interaction between the Disco and the EC was analyzed, demonstrating the technical and economic impacts of the tariff structures chosen, emphasizing the importance of planning in the operation of both sectors. Future works could explore the design of tariffs, considering pricing and the effects of operation and maintenance costs on the DisNet and the different types of ECs.

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REFERENCES

[1] M. Tostado-Véliz, S. Mouassa, and F. Jurado, "A MILP framework for electricity tariff-choosing decision process in smart homes considering 'happy hours' tariffs", International Journal of Electrical Power & Energy Systems, vol. 131, p. 107 139, 2021, ISSN: 0142-0615. DOI: https://doi.org/10.1016/j.ijepes.2021.107139.

[2] B. Velkovski, V. Z. Gjorgievski, D. Kothona, A. S. Bouhouras, S. Cundeva, and N. Markovska, "Impact of tariff structures on energy community and grid operational parameters", Sustainable Energy, Grids and Networks, vol. 38, p. 101 382, 2024, ISSN: 2352-4677. DOI: https://doi.org/10.1016/j.segan.2024.101382.

[3] A. Anees, T. Dillon, S. Wallis, and Y.-P. P. Chen, "Optimization of day-ahead and real-time prices for smart home community", International Journal of Electrical Power & Energy Systems, vol. 124, p. 106 403, 2021, ISSN: 0142-0615. DOI: https://doi.org/10.1016/j.ijepes.2020.106403.

[4] J. A. Pinzon, P. P. Vergara, L. C. P. da Silva, and M. J. Rider, "Optimal management of energy consumption and comfort for smart buildings operating in a microgrid", IEEE Transactions on Smart Grid, vol. 10, no. 3, pp. 3236–3247, 2019. DOI: 10.1109/TSG.2018.2822276.

[5] C. Palacios, G. Garcia, A. Martinho, J. Melo, and J. Lopez, "Analysis of the installation of photovoltaic systems in densely urban centers for the formation of energy communities: A case study in the metropolitan region of São Paulo, Brazil", International Symposium on Energy: Energy Transition, Green Hydrogen and Sustainable Industry, vol. 1, no. 1, 2023. DOI: 10.55592/ISE.2023.7909429.