A Model for Local Energy Community Management in the Presence of Distribution Network Time-of-use Tariffs

James Fitzpatrick[1], Juan Sepúlveda[2], Hélène Le Cadre[2], Luce Brotcorne[2], Victor Astapov[3], Paula Carroll[1], and Anna Mutule[3]

[1]School of Business, Univeristy College Dublin, Dublin, Ireland, ✉ james.fitzpatrick1@ucd.ie
[2]Inria, Univ. Lille, CNRS, Centrale Lille, UMR 9189 CRIStAL, Lille, France,
[3]Institute of Physical Energetics, Riga, Latvia,

Local Energy Communities (LECs) are seen as a mechanism for citizens to actively engage in the energy transition. The integration of LECs into the existing distribution networks is key to a future of clean, secure, and equitable energy. Current research, including studies like [3, 4], delves into critical questions about the construction, management, and operation of low-voltage electricity networks to facilitate LEC participation. There is an increasing need for detailed models that consider the diverse, and sometimes conflicting interests of various energy system stakeholders. These models should account for factors like energy loss, stochastic generation and demand, and infrastructure specific to LECs and the types of renewable generation and energy storage assets they may choose to invest in.

In this changing landscape, it is key to consider the point of view and interests of both the distribution network operator (DSO) and LECs and managers who may act on their behalf. The challenge for the DSO is not just to ensure the reliability of the system but also to enhance operational efficiency metrics, a task that increases in complexity in the presence of LECs. On the other hand, LECs management systems should ensure the maximisation of the LEC's own performance metrics, while taking into account the selfish interests of their members some of whom are prosumers i.e., customers who both produce and consume electricity. Members of the LEC have their own heterorgeneous preferences and aim to maximise their own utility functions. Ultimately, the effect of the LEC in the operation of the distribution system materialises in the resulting power flows in the lines and transformers of the grid system that hosts the LEC.

Different LEC business models and grid topology design decisions may affect the resulting power flows, allowing different points of view to tackle the problem of supporting the development and operation of LECs. From the planning perspective, studies in the context of smart grids, such as [2], have explored approaches such as network reinforcement or reconfiguration to achieve better distribution of flows. The authors use a MILP approach to minimise the costs of additional network cables and to minimise flows between the LEC members, hence promoting self sufficiency and controlling the LEC's electricity flows. This approach allows the technical requirements from a power systems network operation perspective to be explicitly included in the model. Emerging smart grid technologies manage flows at the physical and/or logical level. Another perspective involves the design of business models of LECs, eventually determining their energy consumption and production patterns, as in [3]. In response to the decision-making at the LEC management level, demand response models could be implemented to align the interests of members of an LECs and the DSO.

The interaction problem between the distribution network managed by the DSO and the LEC involving prosumers can be modeled as a noncooperative game [5] with coupling constraints capturing the bilateral reciprocity of the energy trades among the prosumers. Stackelberg games, and reformulations as bilevel optimization problems, have been used to capture the hierarchical decision process between DSO, LEC, and prosumers. For instance, the versatility of multi-level models is demonstrated in [1].

In this work, we propose a bilevel model that hierarchically incorporates, at the lower level, the LEC management system, and, at the upper level, the DSO. Resulting equilibria determine pricing strategies for the DSO, in the form of tariffs, which can be interpreted as signals for the active management of the LEC and the operation of the distribution network, and ultimately, determine the resulting network power flows. In this way, we aim to capture the complex interplay between LEC and DSO, and the real-time distribution network operation.

A branch-and-cut approach is employed to solve efficiently this complex, multi-level problem. This method allows us to systematically explore the solution space, cutting off non-promising branches to focus computational efforts on more likely solutions. By incorporating elements such as demand response, energy storage, and variable renewable energy sources into our model, we aim to reflect the actual conditions and challenges of modern electricity networks.

In summary, our bilevel model presents a strategic approach to integrating LECs into distribution networks, balancing the objectives of the participants of the LECs with the efficient operation of the distribution network. By applying a game-theoretic approach, this model adeptly manages the complex interactions between the DSO and LECs, enhancing its practicality by taking into account the strategic behaviors of both DSOs and LECs. This makes our model a significant contribution towards developing sustainable, efficient energy policies for the future. However, bridging the gap between the proposed model and its actual implementation presents significant challenges, indicating numerous opportunities for future research in this area. Among them, we highlight real-time data analytics to enhance the accuracy and responsiveness of the model, particularly under highly uncertain meteorological conditions. Also addressing the increased risk of cyber-threats due to the interconnected nature of modern energy systems, ensuring the security and privacy of data exchanged between LECs and DSOs, appears as a critical task. That direction could be tackled on the algorithmic side by taking advantage of the structure of the underlying network abstracted as a graph, to provide algorithmic approach for equilibrium computation. Decentralised (machine learning) based approaches, either single or double-loops, could be proposed to compute equilibrium, allowing both the speeding up of the convergence rate and protecting data privacy.

Finally, taking a broader perspective, distribution grid tariffs are a key element in coordinating the operation and network investment decisions, and traditional volumetric tariffs do not provide an adequate response to the challenge of increasing peak loads, caused by the electrification of heating and transport, which may require significant grid reinforcements. This change of paradigm requires us to investigate the impact of different tariff structures on the operation and investment decisions, as well as their indirect impact on the LEC. Interesting interpretations and tariff structure policy design might result from the long-term extension of our bilevel model.

Acknowledgements: This work emanates from research supported by the ERA-NET Cofund grant under the CHIST-ERA IV Joint Call on Novel Computational Approaches for Environmental Sustainability (CES), project “Supporting Energy Communities - Operational Research and Energy Analytics” (SEC-OREA). James Fitzpatrick is funded by the Irish Research Council.

References

[1] Didier Aussel, Luce Brotcorne, Sébastien Lepaul, and Léonard von Niederhäusern. A trilevel model for best response in energy demand-side management. *European Journal of Operational Research*, 281(2):299–315, 2020.

[2] Paula Carroll and Cristina Requejo. Smart grid topology designs. In *Darties, B., Poss, M.(eds.). Proceedings of the International Network Optimization Conference (INOC), June 12-14, 2019*. Open-Proceedings. org, 2019.

[3] Tarmo Korõtko, Freddy Plaum, Tobias Häring, Anna Mutule, Roberts Lazdins, Olegs Borščevskis, Argo Rosin, and Paula Carroll. Assessment of power system asset dispatch under different local energy community business models. *Energies*, 16(8):3476, 2023.

[4] Fabio Moret and Pierre Pinson. Energy collectives: A community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems*, 34(5):3994–4004, 2018.

[5] Ilia Shilov, Hélène Le Cadre, and Ana Busic. A generalized nash equilibrium analysis of the interaction between a peer-to-peer financial market and the distribution grid. In *IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids*. 2021, 2021.