Grid-aware Demand Response in Energy Communities

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Abstract

To tackle climate change, large amounts of distributed renewable power generation capacities will be installed over the coming years. At the same time, the electrification of the mobility and heating sectors will increase the amount of flexible loads connected to power grids. Energy communities can promote an increased consumption of locally generated renewable power by providing price incentives for community participants. Therefore, energy communities could help reduce the strain on distribution grids from increased distributed power generation and further electrification of energy consumption. We present a co-simulation approach for energy communities and respective grid infrastructure. Employing this co-simulation approach we evaluate different heuristic control algorithms and their effect on the power distribution grid. Communicating grid congestion to community members can help reduce negative effects on power grids. In the realistic scenarios we present, the flexibility offered by energy communities is not sufficient to avert negative effects completely.

1 Introduction

In the near future, the majority of our energy consumption will originate from renewable sources, to reach current climate goals and to mitigate the most devastating effects of human-made climate change [1, 2]. On the one hand, this will be achieved by introducing large amounts of distributed renewable generation capacities [2]. On the other hand, sectors such as mobility [3, 4] and heating [2] are electrified to minimize reliance on non-sustainable fuels [10]. EU's energy law is currently in constant movement [10]; e.g., the recast of the Building Efficiency Directive, requiring new buildings to be equipped with photovoltaic systems (PV) and electric vehicle (EV) chargers, was just approved by the EU Parliament during finalizing this article (12.03.2024) [5]. While the introduction of distributed energy generation systems and the increase of electric energy consumption in distribution grids provide challenges for the grid infrastructure, it also provides an opportunity for end-customers to become engaged in shaping their local energy system. Within an energy community, end customers can share their excess renewable energy [14], and manage energy generation or storage capabilities collectively [11, 12]. These energy communities consist of producers (e.g., PV), and consumers (e.g., EV chargers) as well as battery storage [11, 12] and, thus, have the potential to increase the sustainability and resilience of distributed energy systems. Real-time information on the generation of energy can be used to optimize the operation of other community members as well as energy communities themselves could respond to loading information from the local distribution grid infrastructure [16]. Co-simulation is widely used for the evaluation of control scenarios in the smart grid domain [19]. *Steinbrink et al.* determined cooperation between actors and investigation of social structures that affect power grids to be an important area for future research employing co-simulation [18]. The co-simulation approach can be used to evaluate grid parameters as well as communication technologies and control algorithm effects [15]. An appropriate simulation methodology is selected for each part of the system to reflect real-world conditions as closely as possible.

2 Legal definitions and compliance

The objective of this section is to assess the alignment of our approach with EU energy law to ensure compliance. Energy communities were introduced by EU's 'Clean Energy Package' in 2019 in two types [11, 12]: the 'renewable energy communities' (REC) in the Renewable Energy Directive (RED) [2] and the 'citizen energy communities' (CEC) in the Electricity Directive (ED) [6]. The latter further defines 'demand response' as "the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase [...], whether alone or through aggregation". 'Aggregation' is defined as the combination of "multiple customer loads or generated electricity for sale, purchase or auction", which can also be done by an 'independent aggregator', "who is not affiliated to the customer's supplier". Both types of energy communities are explicitly allowed to engage in aggregation as one of their energy services to provide to its members. EU Directives require member states to incorporate them into national law, with the ED's deadline set for the end of 2020. However, as of the current writing, Austria has not yet achieved

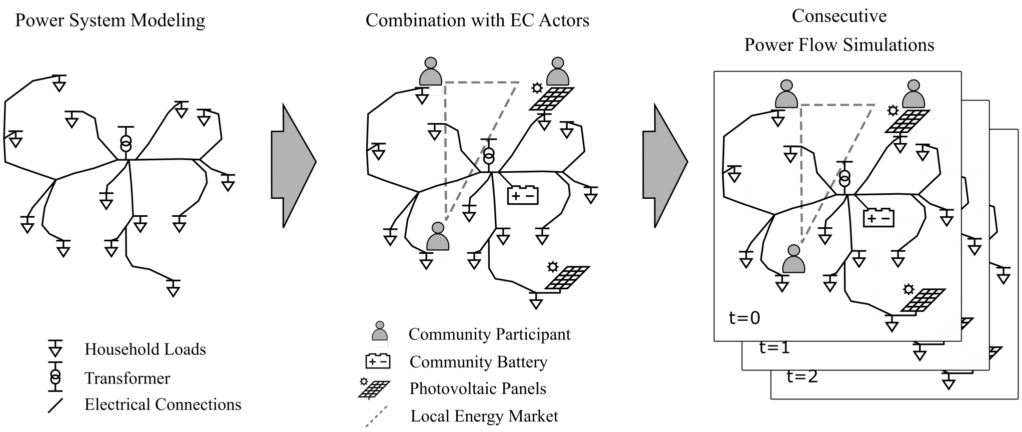

Fig. 1. Community simulation development from grid model.

full compliance, specifically in the areas of 'demand response' and 'aggregation,' which still await implementation.

3 Methodology

In our work, we explore the role of distributed loads, such as EV charging stations, heat pumps, and distributed storage systems, in supporting distribution grid operation through demand response actions. We implement a co-simulation of energy community participants and the local grid infrastructure. Energy community participants can include various flexible and inflexible loads as well as PV systems as electric energy generation capability in their in-house energy system. How the flexible components are managed depends on the implemented control algorithm and can be influenced by physical constraints.

On top of a power grid model, different customers are selected to be energy community participants at random. In the next step, generation capacities and flexible loads are distributed among customers connected to the grid according to a scenario. A local energy market connects community participants and traded energy is recorded for every time step. To evaluate the effects of the energy community and future distributions of generation capacities and flexible loads, yearly simulations are conducted employing quasi-static simulations for hourly consumption and generation values. The simulation methodology is shown in Fig.1.

4 Control Algorithms

The implemented heuristic control algorithms are explained in detail in this section. A general interaction model between community members and community management is shown in Fig. 2. The left side of the graphic shows community member households with generation capacity, inflexible and flexible consumption technologies. The home energy management system communicates with the community energy management system on the right side of the graphic to realize the central control algorithms.

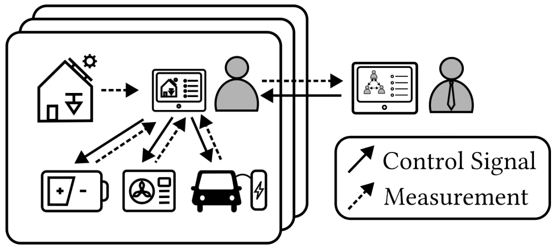

Fig. 2 Community interaction model to realize control algorithms.

4.1 Reference Control

To reflect the situation without coordinated management of flexibilities, a simple reference algorithm is implemented. This algorithm allows no reduction of consumption for EV charging and heat pumps, and distributed storage systems operate to maximize self-consumption within the household they are connected to.

4.2 Local Self-Consumption Maximization Control

As a second algorithm, an energy community control algorithm is implemented, where the flexible loads, such as EVs and heat pumps, are operated to maximize the use of power that is generated within the household. Household energy storage systems are operated to maximize self consumption within the household. Excess generation is not communicated to other community members for this control algorithm.

4.3 Community Self-Consumption Maximization Control

As a third algorithm, an energy community self consumption maximization control algorithm is implemented, which provides information about the current generation within the energy community to all members. This empowers members to manage their EV charging, heat pumps, and storage systems strategically, aiming to maximize the utilization of electrical energy during times when energy can be acquired from within the community.

4.4 Grid-aware Self-Consumption Maximization Control

The proposed grid-aware control algorithm tries to achieve the same goal as the community self-consumption maximization control algorithm. At the same time, it provides information about the state of the grid infrastructure to each community member. This includes voltage measurements of the members node and the loading of all lines as well as the transformer station. Whenever a loading or voltage violation occurs in the local power grid, the affected households are informed and the power of their flexible components is increased or decreased. Whether the load is increased or decreased depends on the cause of the problem in the grid. Acceptable voltage level transgressions occur when the voltage at a node is above 1.05 p.u. or below 0.95 p.u. Transformer and line loading transgressions occur when a component operates above 75% of the components nominal power for a simulation time step.

5 Scenarios

Simulations have been conducted for rural, urban, and suburban energy communities. The community sizes and the distribution of flexible loads, generation capacities are largely based on the scenarios for the year 2030 developed by *Cejka et al* [11]. The amount of installed PV capacity was adapted to reflect the goals presented in the federal plan for grid extension as issued by the Austrian Government [9]. Heat pump distribution numbers are adapted slightly to represent results from *Biermayr et al* [7, 8]. Residential battery storage system distribution is adapted to reflect results from *Solar Power Europe* and *Fechner et al* [13, 17]. The simulated scenarios reflect the uneven distribution of renewable installations between rural, suburban, and urban environments. Rural communities and grids will face the highest relative installed generation capacities due to the larger availability of space in those communities. Urban environments on the other hand do not offer enough space for extensive installation of renewable generation capacities. At the same time, it will be much more challenging to integrate renewable heating and cooling measures in urban communities. The simulated scenarios reflect the situation without any community-owned and operated storage or generation capacities.

6 Results and Discussion

Fig. 3 shows exemplary results from a simulation of a suburban distribution grid characterized by a high penetration of PV generation and a substantial number of flexible loads. The top graph illustrates the total active power for the entire distribution grid. The middle plot displays the maximum loading of the transformer for each simulation time step, while the third graph depicts the range of maximum and minimum voltage in the grid. The total active power reveals a significant reduction in power during peak times for the grid state-aware algorithm, consequently leading to a notable reduction in the transformer loading. This highlights the potential to alleviate negative grid effects by communicating grid congestion. The voltage levels indicate minimal impact from the introduction of

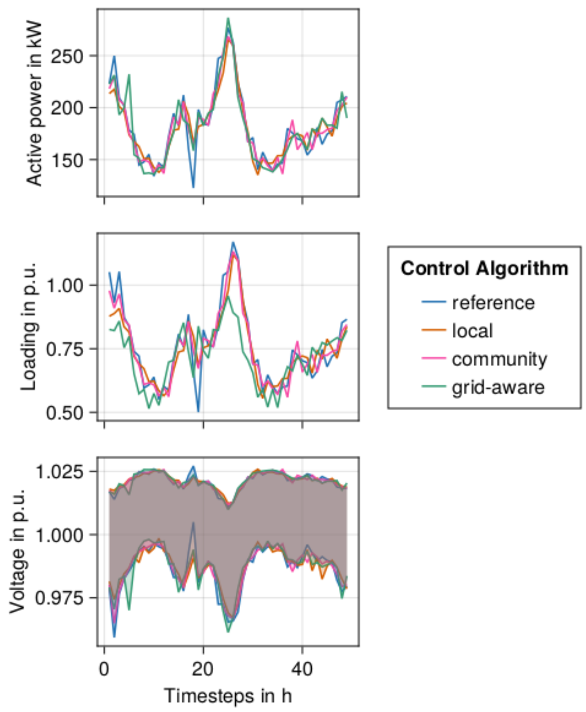

Fig. 3 Excerpt of simulation results in a suburban community in winter.

the grid-aware control algorithm, but throughout the pictures, simulation time does not reach critical levels.

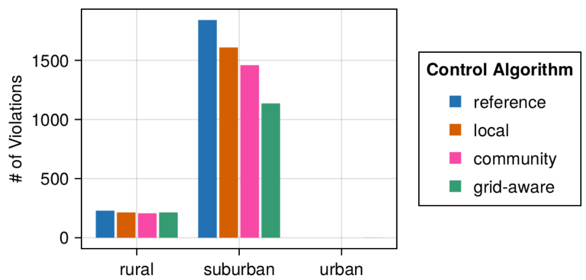

Fig. 4 Transgression of transformer loading threshold throughout a yearly simulation.

The amount of simulation time steps when the transformer loading exceeded the threshold of 75 % is shown in Fig. 4. In the rural community, the duration of transformer overloading remains unchanged due to the introduction of the grid-aware control algorithm. This is because transformer overloading occurred in periods of limited flexibility, primarily during summer when significant feed-in from PV systems occurred. In contrast, the grid-aware algorithm managed to reduce transformer overloading for the suburban community. However, achieving acceptable levels was not possible due to insufficient flexibility within the community. For the urban community, no transformer overloading occurred.

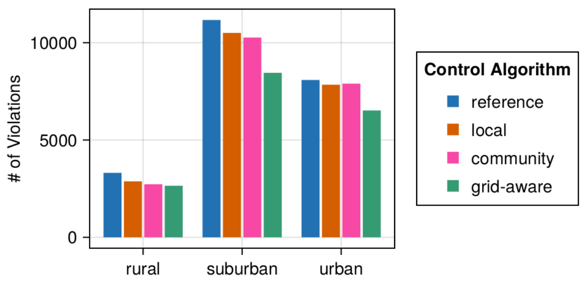

Fig. 5 Transgression of line loading threshold throughout a yearly simulation.

Fig. 5 shows the amount of recorded line loading violations determined by the annual simulations. For all communities, it was possible to achieve a reduction in line loading transgressions through the grid-aware control algorithm. Again, it can be seen that the flexiblity available in the community is not sufficient to completely avoid any line overloadings throughout the yearly simulation.

The amount of self-consumption of locally generated energy is defined as the amount fed into the grid E_{feedin} divided by the amount of energy generated within the local energy system $E_{generated}$. For the evaluation of community self-consumption, only the energy that remains unutilized within the households of community members is considered. Fig. 6 shows the portion of community self-consumed energy within rural, suburban, and urban communities. For the rural community, the community self-consumption remains constant regardless of the control algorithm utilized. This is due to the large amounts of PV generation connected to the rural grid, outweighing the total yearly consumption. In the rural community, most households have their own PV generation, leading to situations when excess energy is available without immediate demand. Conversely, suburban and urban communities experience a more notable rise in community self-consumption. The urban setting favours the community self-consumption algorithm, while the grid-aware algorithm performs equally effectively in suburban areas.

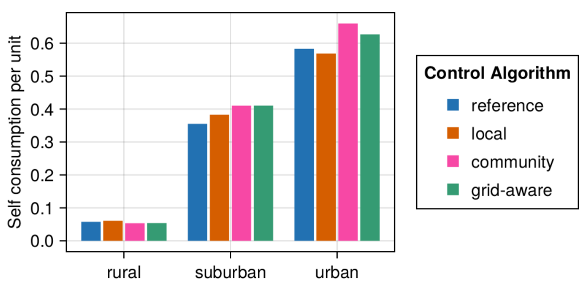

Fig. 6 Community self consumption in per unit of total generated energy.

Another performance indicator is the amount of in-house generated energy community members are able to consume. Fig. 7 shows the self-consumption within the household energy system for all implemented algorithms and rural, suburban, and urban communities. An increase in community member self-consumption can be seen for all algorithms over the reference control algorithm. It is surprising to observe the most substantial increase for the community and grid-aware algorithms, as the goal of the local control algorithm was to maximize local self-consumption.

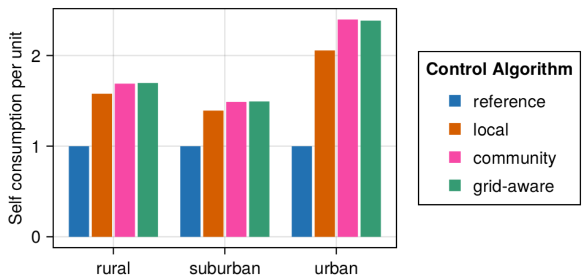

Fig. 7 Community member self consumption relative to the reference algorithm.

7 Conclusion

We present a co-simulation methodology to evaluate the impact of energy communities on power distribution infrastructure. Four different heuristic control algorithms are presented and evaluated considering various performance indicators. The simulated scenarios are based on generation, storage, and flexible load distribution projections for the year 2030 in rural, suburban, and urban regions. As the generation capacity will not be evenly distributed among regions, different effects arise for all three regions. Flexible loads considered include electric vehicles, heat pump systems, and residential battery energy storage systems. Photovoltaic systems serve as the main distributed power generation technology within the energy communities. The findings indicate that while controlling flexible loads can improve certain performance indicators, the flexibility offered by community members does not suffice to alleviate all problems caused by increased load and generation in distribution grids. Future research will focus on the analysis of community-owned energy generation and storage capacities on power distribution networks. Especially, community energy storage could help to maintain distribution grids within operational limits, when appropriately sized and strategically placed.

Acknowledgments

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