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Aggregation effects for microgrid communities at varying sizes and prosumer-consumer ratios

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Abstract

Self-consumption is an increasingly economically attractive solution for electricity generated by distributed energy resources, which also reduces transmission losses, power line overload and grid instability. Yet, at single-building scale, production and demand do often not coincide. Microgrids are proposed as a means to trade surplus energy produced with local prosumers and consumers, allowing to take advantage of complementary load profiles. Here we define a consumer as a single metered residential unit, a prosumer as a consumer with a photovoltaic system, and the microgrid as a collection of both prosumers and consumers. In this article, we systematically analyze to what extent varying sizes and prosumer-consumer ratios of microgrids affect local self-consumption and self-sufficiency rates. To that end, we developed a simulation model that uses real-world load profiles from 4190 residential buildings as input data. We find that the prosumer-to-consumer ratio is more important than the absolute microgrid size, for microgrids sizes greater than ten. The results also indicate that prosumer-to-consumer ratios in the range of 40%-60% have the best performance for the various production to demand ratios analyzed. Each simulation is also compared to the baseline scenario of a stand-alone prosumer, which shows significantly better self-consumption ratios and self-sufficiency ratios for microgrids due to aggregation effects. Finally, this work may also be used as a reference to design residential microgrid communities for various prosumer-consumer compositions and various production-to-demand ratio.

Keywords: Microgrids; self-consumption; self-sufficiency; prosumers; aggregation effects

1. Introduction

Distributed energy resources (DER) from photovoltaic (PV) systems are considered to be an important avenue to meet global energy demands and simultaneous emissions reduction targets [1]. Country-level strategies also propose a significant increase in PV to meet local targets, including the Swiss Energy Strategy 2050 [2] and the 2000-Watt-Society [3] in Switzerland. Specifically, an additional 15 Terawatt-hours of PV are expected to help meet energy demands in Switzerland by 2050 [4]. However, the intermittent nature of renewable energy sources creates many challenges for independent prosumers, independent consumers and for the greater electricity grid. For example, excessive energy production from grid-tied distributed PV systems can cause overloaded power lines, major grid instabilities and can also be a significant source of wasted power generation [5]. Other studies illustrate how feed-in-tariffs for grid-tied prosumers can cause an increase in the overall grid fee, negatively impacting non-prosumers [6]. The local consumption – on site or at substation level – of the energy generated from distributed renewable energy sources could help mitigate these issues. In order to increase grid stability and minimize overall transmission losses, it becomes critical to match local energy supply and demand load profiles to maximize hours of self-consumption.

The concept of self-consumption was initially promoted at the single building scale (i.e., using the electricity generated on one's own rooftop), however many limitations still exist to fully utilize the on-site energy generation. Typical self-consumption rates for single buildings are in the range of 15-56% depending on installed PV capacity, location and household energy consumption profile [7]. Battery storage systems (0.5-1 kW) can increase that share by 13-24% points and demand side management strategies by 2-15% points [8].

By moving from stand-alone single-building self-consumption to an approach that allows consumption within the local community, it is possible to take advantage of complementary local prosumer/consumer load profiles, known as load diversity. In fact, this is recognized and addressed through new legislation in Switzerland, which aims to promote self-consumption at the community scale ('Eigenverbrauchgemeinschaft'), which are physically implemented as microgrids [9]. Yet, no specific design criteria exist to inform optimal microgrid configurations. As the number of self-consumption communities increase, it is important to explore the potential impacts of size and composition of such communities for a range of annual production-to-demand ratios (PDR).

In this article, we use a large dataset of real-world load profiles from 4190 residential buildings [10] to quantitatively assess aggregation effects in microgrid communities. To that end, we built a simulation model that systematically varies the size and composition of a microgrid community, assessing random combinations of load and production profiles. If prosumers and consumers are interconnected in a defined microgrid, the random load - production coincidences decrease the quantity of surplus energy supplied to the grid, thus maximizing the on-site energy utilization. We explore two key questions: First, what are the best microgrid compositions to maximize self-consumption and self-sufficiency when considering different prosumer-to-consumer ratios? Second, to what degree does the microgrid aggregation effect depend on the total number of community members? To put it simple from a practitioners' point of view: How many prosumers and consumers should typically come together in a microgrid to maximize the share of locally produced electricity?

2. Background

2.1. Transition from the single-building approach to microgrid communities

A large body of research currently focuses on self-consumption strategies for single-building prosumers [6] [8] [11]. At the prosumer level, full self-sufficiency typically requires oversized roof-top systems and/or battery systems [8], however economic analysis indicates that significant cost reductions are required before this can become a viable solution at scale [11]. Conversely, the energy produced during peak hours of production typically exceeds the demand of individual residential prosumers [7]. Microgrid communities are comprised of clearly defined, interconnected energy consumers and energy producers that have a single point of connection to the greater electric grid [12], and therefore have a greater potential to share locally produced electricity from DER.

Microgrid communities can be realized via peer-to-peer networks or other intra-community agreements to trade surplus energy produced from the PV system(s) with other prosumers/consumers located within the same microgrid [13]. This can be advantageous for all microgrid community members as well as for the greater grid operator. Numerous studies have analyzed different parameters for microgrid design, including technology constraints and drivers of microgrids [13], and strategies to optimize system component sizes for remote microgrids [14]. Another study also looks at the aggregation of prosumers and their potential to sell excess electricity to the grid [15]. However, the principal question regarding prosumer and consumer compositions and diverse microgrid size, have not yet been addressed systematically in literature. Therefore, the objective of the study is to compare various microgrid community compositions, which are modeled to maximize the use of time-sensitive surplus energy generated within the microgrid in the absence of a battery storage system.

3. Modelling framework

3.1. Energy load profiles

The energy consumption load profiles used in this analysis are taken from the Commission for Energy Regulation (CER) data set [10]. This is a high-frequency smart-meter data set, which contains complete data from 4190 residential buildings. The data is processed to evaluate a full calendar year, from December 26, 2009 to December 26, 2010 with a measurement frequency of 30 minutes. The average annual electricity demand per consumer is 4304 kWh with a standard deviation of 2164 kWh. The specific residential type is given as 31.7% semi-detached, 26.5% detached, 25.5% bungalow, 1.7% apartment unit, and 0.2% unknown. This data was used in a similar previous study, which evaluates the economic potential for photovoltaic battery systems on an individual household level [11].

3.2. PV production calculations

The renewable energy calculations used in this study are based on the translation equations from [16], which consider the operating temperature and irradiance conditions to model the PV system power at a given time period. The typical meteorological year (TMY) weather data from [17] for the city of Zurich was used for the sub-hourly power production calculations. The metadata from the CER data set does not include roof-top orientation, tilt angle or size [10]. Therefore, the azimuth angle of the PV system (orientation relative to south) and the collector slope angle (tilt angle relative to a horizontal plane) were derived by random sampling from probability distribution functions from related work [11]. The energy production potential is derived from the annual demand, using a fixed ratio for all prosumers in each microgrid configuration. This is defined as production to demand ratio (PDR), the ratio of the total annual electricity produced and the total annual demand per prosumer.

3.3. Self-consumption microgrids

In this context, we define a consumer as a single metered residential unit, a prosumer as a consumer with a PV system, and the microgrid as a collection of both prosumers and consumers (Fig. 1). Two measures of performance used in the analysis are a) self-consumption ratio (SCR), i.e., avoided electricity exported to the grid, and b) self-sufficiency ratio (SSR), i.e., avoided electricity imported from the grid.

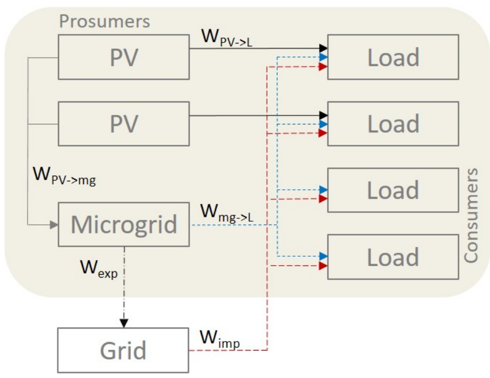

Fig. 1: Schematic representation of the microgrid community

The energy flows between the photovoltaic system (PV) from each prosumer, the load (L) at each household (j), the microgrid (mg) for community size (N_{mg}), and the grid (G) are calculated at each time step (k). When calculating the microgrid aggregation effects (the avoided export to the grid), the energy balance for each prosumer ($W_{PV\text{->}L}$) is simulated first. The residual electricity production from each prosumer ($W_{PV\text{->}mg}$) is sent to the pool of available resources for the entire microgrid. The sum of all residual production is supplied to the sum of consumer loads within the microgrid ($W_{mg\text{->}L}$). Finally, the excess electricity production (W_{exp}) is supplied back to the grid and required remaining electricity is imported from the grid (W_{imp}). The simulation is described by eq. 1 through eq. 6.

$$\begin{pmatrix} P_{PV\to L}^{(j,k)} \\ P_{PV\to mg}^{(j,k)} \\ P_{mg\to L}^{(j,k)} \\ P_{exp}^{(j,k)} \\ P_{imp}^{(j,k)} \end{pmatrix} = f\left(P_{PV,resid}^{(j,k)}, P_{L,resid}^{(j,k)}\right) \qquad \text{(eq. 1)}$$

The quantities $P_{m\to g}^{(j,k)}$ describe the individual power flows between each component {PV, L, MG, G} designated by (m) and (g) depending if it supplies or receives power. Transported energy (W) is calculated by introducing a time interval Δt with power (P) via (eq. 2).

$$W_{m\to g}^{(j,k)} = P_{m\to g}^{(j,k)} \cdot \Delta t \qquad \text{(eq. 2)}$$

$$P_{PV,resid}^{(j,k)} = \sum_{j=1}^{N_{mg}} P_{PV\to mg}^{(j,k)} \qquad \text{(eq. 3)}$$

$$P_{L,resid}^{(j,k)} = \sum_{j=1}^{N_{mg}} P_{mg\to L}^{(j,k)} \qquad \text{(eq. 4)}$$

The quantities $P_{exp}^{(k)}$ and $P_{imp}^{(k)}$ represent the total imported and exported power for any time step k. With this, the self-sufficiency ratio of the community (SSR_c) and the self-consumption ratio of the community (SCR_c) are calculated.

$$SCR_c = \frac{\sum_k \left(\sum_j P_{PV}^{(j,k)} - P_{exp}^{(k)}\right)\Delta t}{\sum_k \sum_j P_{PV}^{(j,k)} \Delta t} = 1 - \frac{W_{exp}}{W_{PV}} \qquad \text{(eq. 5)}$$

$$SSR_c = \frac{\sum_k \left(\sum_j P_{L}^{(j,k)} - P_{imp}^{(k)}\right)\Delta t}{\sum_k \sum_j P_{L}^{(j,k)} \Delta t} = 1 - \frac{W_{imp}}{W_{L}} \qquad \text{(eq. 6)}$$

We also calculate a baseline scenario for each microgrid community (N_{mg}), which is sum of the self-consumption and self-sufficiency ratios for the number of prosumers in each scenario. This makes it possible to compare the performance of isolated prosumers to an equivalent microgrid. Each simulation represents a fixed microgrid size (N_{mg}) which is the total number of prosumers and consumers in the microgrid, and for a fixed prosumer ratio. The results for each configuration are obtained by repeating the simulation 30 times where a given load profile from the CER data set [10] is only used once.

4. Results

The primary simulation results, shown in Fig. 2 and Fig. 3, evaluate the SCRc and SSRc for various prosumer ratios and various microgrid community sizes (Nmg). In each plot, the black line indicates the results of the baseline scenario, which is the sum of the self-consumption and self-sufficiency ratios for the number of prosumers in each scenario. The analysis presents four scenarios for production to demand ratio (PDR= 0.25, 0.5, 1.0 and 2.0), where for example, a PDR of 1.0 represents a net zero energy building. The microgrid community sizes included in this study range from small scale Nmg=2 to large scale communities Nmg=100.

The results show that $N_{mg} \leq 10$ have similar characteristics for PDR of 0.25 and 0.5. However, in the larger systems sizes represented by PDR of 2, all community sizes perform similarly except for very small communities, N_{mg}=2. High SCR of 98% can be achieved for PDR=0.25 and PDR=0.5 for prosumer ratios up to 75% and 35% respectively. The self-sufficiency ratio behaves almost linearly for small PDR, and increases with higher prosumer ratios. For larger PDR, the benefits as measured by the SSR has diminishing returns as the prosumer ratio increases.

Intuitively, the SCR (avoided exported electricity to the grid), decreases as the fraction of prosumers increases until it nearly converges with the baseline scenario that does not consider aggregation effects. Similarly, the SSR (avoided imported electricity from the grid), is smallest for low prosumer ratios in the microgrid configuration and increases as

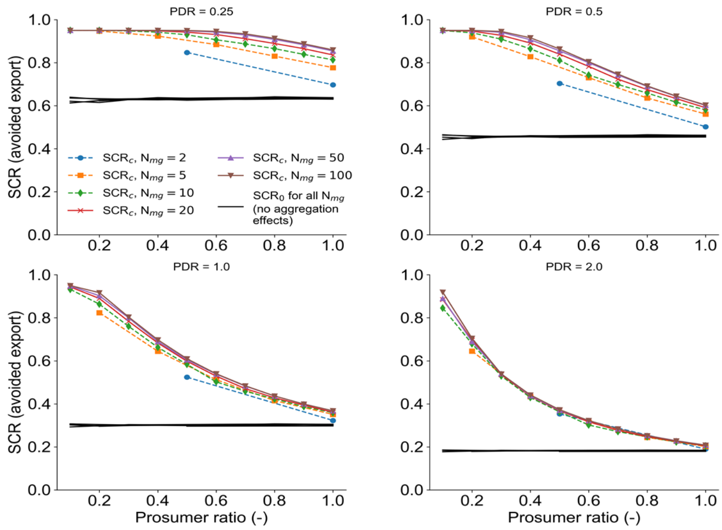

Fig. 2: Self-consumption ratios (SCR) for various prosumer ratios and various microgrid community size (N_{mg}), compared to the baseline SCR for stand-alone prosumers (black line= no aggregation effects).

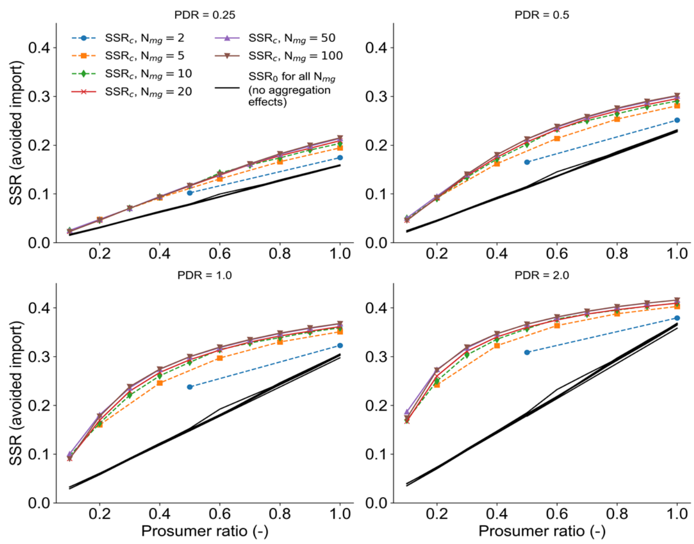

Fig. 3: Self-sufficiency ratio (SSR) for various prosumer ratios and various microgrid community sizes (N_{mg}) compared to the baseline SSR for stand-alone prosumers (black line= no aggregation effects).

the number of prosumers increases. There is a trade-off between self-consumption and self-sufficiency, where the 'optimal point' between the two is when SCR is equal to the SSR, which is also referred to as Net Zero Energy [8]. Given this, the best community composition in our study is 60% prosumer to consumer ratio for a PDR of 2.0.

5. Conclusion

The article investigates aggregation effects in microgrid communities at varying sizes and prosumer-consumer ratios, based on a simulation model that uses real-world load profiles from 4190 residential buildings as input data. The key contribution of this paper is the result that the prosumer-to-consumer ratio is more important (for communities greater than 10) than the absolute number of community members in the microgrid. Furthermore, this work may be used as a reference to design residential microgrid communities when considering various resource options as calculated by production-to-demand ratio. In this study, all microgrid community scenarios presented in the results perform better due to aggregation effects than the baseline scenario with only stand-alone prosumers. This study thus supports the value of aggregation effects to locally produce, consume and share energy resources.

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