

Coordinating and Reducing Peak Electrical Loads in Households: A Technical Benefit of Energy Communities[#]

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ABSTRACT

Sweden has a low carbon emissions electricity production. However, peak electricity consumption challenges climate change mitigation and grid resilience. Energy communities could function as a framework to organize peak electricity power reduction. This paper addresses the dynamics of adding electricity demands and then capping the combined peak. This paper explores the number of apartments required to coordinate and how group size affects the electricity demand reduction across the population. A household electricity demand dataset of 558 apartments was applied to explore these questions in the Swedish context. The results show that at least 62 apartments are required to be grouped to make an effective reduction of the total peak. This paper demonstrates that efforts to reduce peak electrical power consumption in residential areas should be coordinated with several households to be effective.

Keywords: energy community, energy system, peak electrical power, power efficiency, peak shaving

1. INTRODUCTION

1.1. Background

In Europe, electricity generation relies on fossil fuels. Electricity production in Sweden was historically divided into nuclear and hydropower. Whilst both have their problems in terms of broader sustainability and carbon accounting, they are fossil-free electricity technologies. Lately, wind power has been added to the mix and accounts for a quarter of the energy production. So broadly, speaking the energy in Sweden is low carbon [1], [2].

Accounting for carbon emissions of electricity on an hourly basis is too complex to provide any insights. For example, energy in hydropower reserves can be stored (i.e. produced later) if the prices are low due to the imported solar merit order effect [3]. However, it is possible to state that carbon emissions for electricity are higher during the winter than in the summer [4]. Swedish combined heat and

power plants which heat 90% of multifamily buildings are forced to produce in heat-only mode during the coldest hours which in turn reduces local electricity production [1]. The low production and the higher demand mean that Sweden becomes an importer of electricity during the coldest and most polluting hours [2], [5], [6]. Besides mitigating climate change, reducing peak loads contributes to the resilience of the energy system since the grid is stressed during high demand. A combination of natural factors such as a dry year and cold winter could put into question Scandinavia's ability to supply its electricity needs during the winter. A similar pattern of thermal energy demand is seen in the remainder of Northern Europe with the added fact that the demand is covered by peaking natural gas turbines which are activated to cover the hours with the highest demand.

Furthermore, peak electrical power demand is a local problem. Larger cities such as Stockholm and Uppsala already have issues with supplying power during high-demand hours to their local electricity grids [7]. Even medium cities such as Gävle are prognosed to have issues with power capacity [8]. Undervoltage can happen in a subsection of a district (between the transformer and the household), or at the city scale where the connections between the city and the regional grid are not sufficient to supply the city's peak. Grid upgrades in tightly developed urban sectors are expensive and disruptive. As such there is a demand to solve these issues and the electricity of use of residents is relevant to both the residents and the grid operators.

In short, regarding the sustainability of Sweden's electricity sector, it is not the energy but rather the power that can have a disproportionate impact on reducing carbon emissions. However, in the residential sector, most energy efficiency measures also reduce the peak power demand [9].

It is a well-understood phenomenon that peak power demand does not scale linearly with the number of households. When sizing a grid, the lack of coincidence is well understood and numerically approximated. The aggregation of peak power and its non-linearity is an

[#] This is a paper for the Resilient-Applied Energy Symposium and Forum: Resilient energy systems (Resilient2025), Sep. 23-25, 2025, Västerås, Sweden.

established phenomenon. Energy sharing could be a solution to these issues [10], [11]. Research has already pointed out that shared energy tools can be beneficial. However, this paper will also address the scale of sharing that is necessary to reduce peak power consumption and the details of how summing households affects this process.

Energy communities are defined as grassroots organizations for sharing energy between residential actors. Unlike the concept of “energy sharing” as a whole, it is limited to individuals as private actors, small and medium companies, and local authorities including municipalities. As per Article 21 of 2023/2413, an Energy Community (EC) can be defined as a group that shares, produces, consumes, stores, and sells energy for environmental, social, or economic benefits. The relationship between electricity grid-owning companies and grassroots organizations is strained. Both in legal support and the number of communities, Sweden lags in the implementation of the new directive [12], [13], [14], [15], [16].

The legal transposition of European law into the Swedish legal system and lack thereof has shaped energy communities [16]. One debate where this is relevant is the role of the existing public grid for energy communities. Buildings, whether single-family or apartment complexes, are already connected with the public alternating current network. An energy community could take over the local grid within the building and present the building as a single client. This is assuming that the different apartments are still able to connect to the public grid as individual customers as per the voluntary definition of an energy community, members must opt-in and be able to opt-out. Between buildings, using the public electricity grid to share electricity would still imply a tax that is used to maintain that grid. The alternative would be implementing a secondary, direct current grid which is owned and operated by the energy community. This is problematic from an economic perspective as it could be difficult to justify a redundant electricity connection and could introduce risk as more actors start building and maintaining electricity grids. Furthermore, the direct current connection could become a stranded asset if members jump out of the energy community as is their right. This option is directly dissuaded in the European regulation [16]. The focus on apartments rather than single-family homes means that there is the possibility to connect more electricity users within a building. Thereby circumventing the currently problematized legal framework.

There is a trade-off to be made between the technical advantages of including more members in an energy

community (which will be explored here) and organizing in smaller groups. A review [15] highlights the importance of social internal factors: ‘smaller groups where members know each other is better than a bigger group’. Assuming that similar social dynamics take place, it is better to maintain the number of participants as low as possible. Furthermore, apartment complexes can be presented as entities to grid operators and if a small number of apartments would lead to power reduction, smaller buildings can be motivated to be relevant in this analysis.

This is an early exploratory study on the aggregation and then reduction to the overarching electricity peak, supposing that the energy communities can coordinate efforts to reduce their summed peak power. The paper assumes that there is a mechanism for reducing the peak power consumption. The exact mechanism of this reduction is not relevant although research presents that it is feasible. Whether by voluntary shifting of loads, self-consumption with production, which is available at peak consumption, or by using energy storage to cut their peak power consumption [10], [11], [17], [18]. It also implies a knowledge of when the peak electrical load is going to take place which is a complex problem [19], [20], [21]. A concrete example of this would be an apartment, a savvy individual could predict their peak energy demand and add a timer to the washing machine so the predicted peak is instead lowered.

This study is inspired by a white paper regarding improving the effectivization of peak power consumption which carries a similar method for single-family houses [9]. Apartment electricity demand data, rather than electricity-heated houses, are chosen for two reasons. The first reason is apartments in Swedish multifamily buildings are for the vast majority, heated with district heating. Conversely, single-family houses are heated by either direct electricity or with heat pumps [1]. This means that the electricity demand for apartments is expected to be less sensitive to outdoor temperature and as such have less of a coincidence factor when the peaks are happening. Secondly, Sweden recently changed its monopoly legislation regarding the establishment of non-concession networks to share electricity between buildings. The district of Tamarinden in Örebro challenged the definition and overturned previous decisions about EC’s ability to establish non-concession networks. This would require a secondary physical low-voltage network. The current legislation does not forbid sharing with virtual net but there are no economic incentives to sharing over virtual network. The law that guarantees grid monopolies states that charges should be representative of the cost and it follows that costs to maintain the grid if the peak demand in an area is lower. This paper explores how the clustering

of residential actors and therefore their ability to reduce their combined peak would be advantageous.

Multiple-family buildings have the possibility of having several households (with slightly different electricity use patterns in the same building) at the tradeoff of having a lower coincidence factor in their electricity use and thus requiring more apartments to impact the overall electricity consumption.

1.2. Research Questions

This paper will answer the following questions:

- What is the minimum number of apartment households coordinating to affect the peak power consumption?
- Does one group with a certain number of apartments reducing their peak power have different results than the same number of apartments spread out into more groups?

2. METHOD

2.1. General method

One year of hourly anonymized data on electricity usage in apartments in Gävle (60° N) was made available by the municipality-owned building caretaking company Gävlegårdarna [22]. The dataset is representative of newly built apartments as it only includes apartments built from 2011 forward.

Fig 1. presents how the data was organized and the method applied. The hourly data was organized into a matrix of 8760 rows (the number of hours in a year) by 558 columns (the number of apartments in this analysis). The order of the columns was randomized in each analysis. A seed is a value used to generate pseudo-random shuffling. The seed can be kept constant for reproducible results or varied as in the sensitivity analysis.

Next, each apartment is assigned a group and the group is summed. That is for each hour the power is summed so the group matrix is (8760x1) for a year of data. Then the peak power consumption is established by finding its maximum. A cap is set by multiplying the maximum by a certain percentage. If any of the values on the column are higher than the cap, they are replaced by the cap. Each group's maximum is diminished by making the cap smaller in increments of 1 percent. All the groups are then summed (again per hour) and the maximum is the returned result. Apartments that are not grouped and reduced also get summed. Equation (1) shows the method for generating the groups. Equation (2) shows how the cap is created based on the maximum for a given group and the reduction factor and (3) applies the cap to the hourly

values of the same group. Equation (4) then yields the hourly sum of the groups and leftover apartments (if there are any). The hourly maximum is the result presented going forward. The Python script which was devised for this study is available here [23] and the database is available upon request.

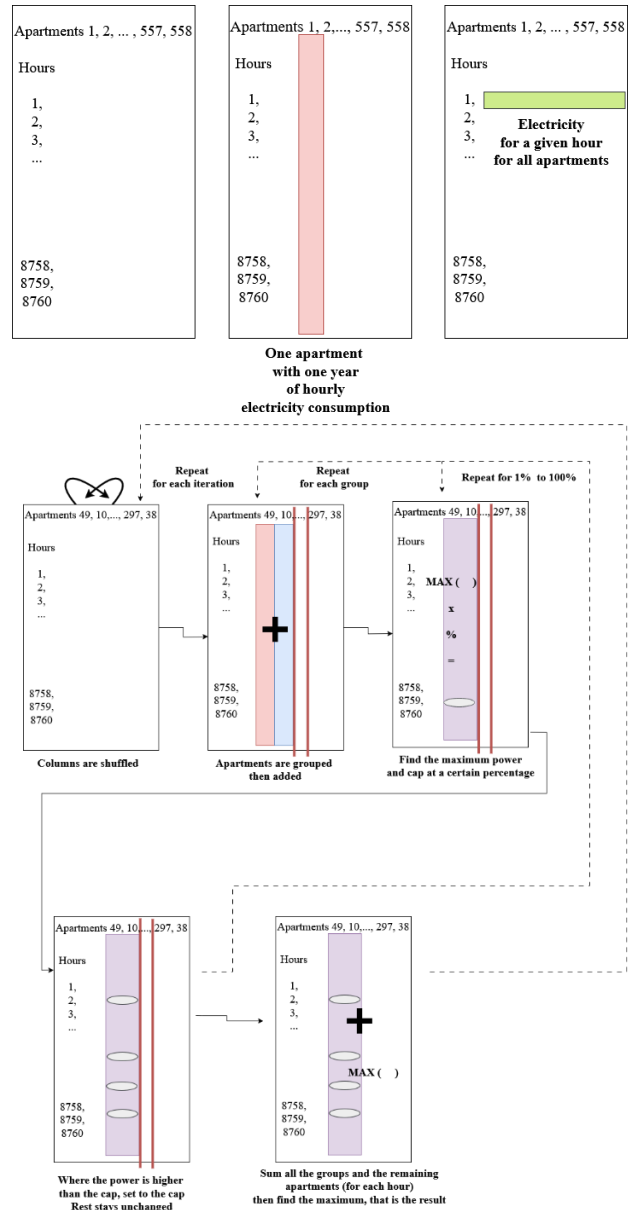


Fig. 1. Schematic representation of the method.

$$group_{n_{group}} = \sum_{i=n_{group} \times n_{apt}}^{(n_{group}+1) \times n_{apt}} apartment_i \quad (1)$$

$$cap_{n_{group}} = (1 - reduction\ factor) * \max_h (group_{n_{group}}) \quad (2)$$

$$P_{n_{group}, h'} = \min(P_h, cap) \quad (3)$$

$$P'_{max} = \max_h \left(\sum_{j=1}^j group'_j + \sum_{i=(n_{group} \times n_{apt})+1}^{n_{total}} apartment_i \right) \quad (4)$$

Where n_{group} is the number of groups with a starting index of zero,

n_{apt} is the number of apartments in one group with a starting index of zero,

apartment is a single apartment column with 8760 rows,

cap is the maximum peak power that a reduced group j can have after being reduced,

reduction factor is the number that determines the amount of reduction (later presented as a percentage on the x-axis),

h is the hour also the row in a column,

P is the power consumption at hour h ,

prime ' marks that the time has been reduced (if it goes over the cap),

n_{total} is the total number of apartments which is 558 in this case,

and P_{max}' is the maximum peak power consumption of the total population after n_{group} groups of n_{apt} apartments have reduced their peak power consumption by the reduction factor of their respective maximums.

2.2. Scenario Analysis

Three scenarios were devised to test the impact of grouping and number of apartments as well as simulate different rollouts of the energy community.

TABLE I. SCENARIOS

Scenario	Represents	Implementation
All Apartments Divided into Communities	Global rollout of EC in different degrees of collaboration.	The number of groups times the number of apartments per group is always equal to the total number of apartments.
Single Community	One EC in a neighborhood.	The number of groups is one, but the number of apartments per group varies.
Same number, different groups	Different levels of coordination between the same households.	The number of groups times the number of apartments per group is kept constant.

2.3. Sensitivity Analysis

The issue is that the results should be robust to different arrangements of individual apartments. Optimizing the grouping of apartments for energy sharing is possible. But without knowing beforehand the profile of the individual households, it is necessary to understand if the scenarios above are changing their peak power. Even with this relatively small dataset, there number of possible arrangements that can be made by grouping distinguishable apartments is equivalent to the "picking k from n " problem. This is a problem that scales with factorials and as such quickly becomes computationally impossible to solve. Picking 93 apartments from a set of 558 leads to about 10^{107} unique, non-repeating possible arrangements. To address this, the apartments were shuffled and then sorted into groups according to their order. To test the robustness of the results, 500 uniquely seeded iterations of the process were repeated for special cases. Changing the seed does not guarantee new grouping although it is probable. Neither does it create statistically representative samples. However, it does improve the understanding of the robustness of the results presented here.

3. RESULTS

3.1. Scenario Analysis

Although the figures are just one of many possible combinations, they show the trend of the impact of increasing the number of coordinating apartments acting together to reduce the total peak power. The results of the first scenario are presented in Fig. 2. The linear reduction is obtained if all 558 apartments were collaborating. It also establishes the maximum possible reduction for a given percentage reduction in peak power. As the number of coordinating apartments increases, the peak power approaches this line. Fig 2. shows also that uncoordinated efforts are very ineffective at reducing the total peak power, especially at lower percentages. The results here match the ones applied to single-family houses [9].

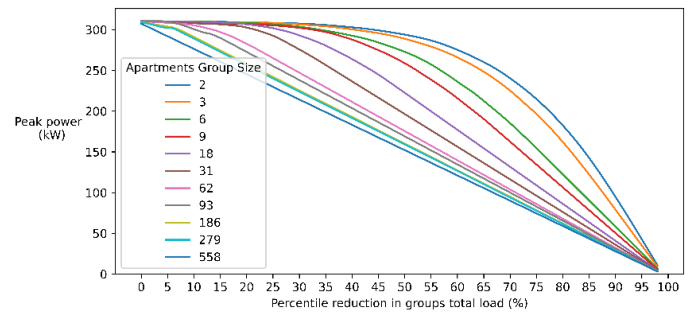


Fig. 2. The impact of grouping of apartments on the reduction of the total peak power is shown here. The

shade of green shows how many apartments are coordinated in one group.

Fig. 3 shows the impact of 1 group of coordinated members of different sizes on the total. As a single energy community in an area, this is the expected impact of one community being established in an area. Note however that there is an increase in the total number of members and the reduction can be in part due to increased collaboration but also due to increased active apartments reducing their peak consumption.

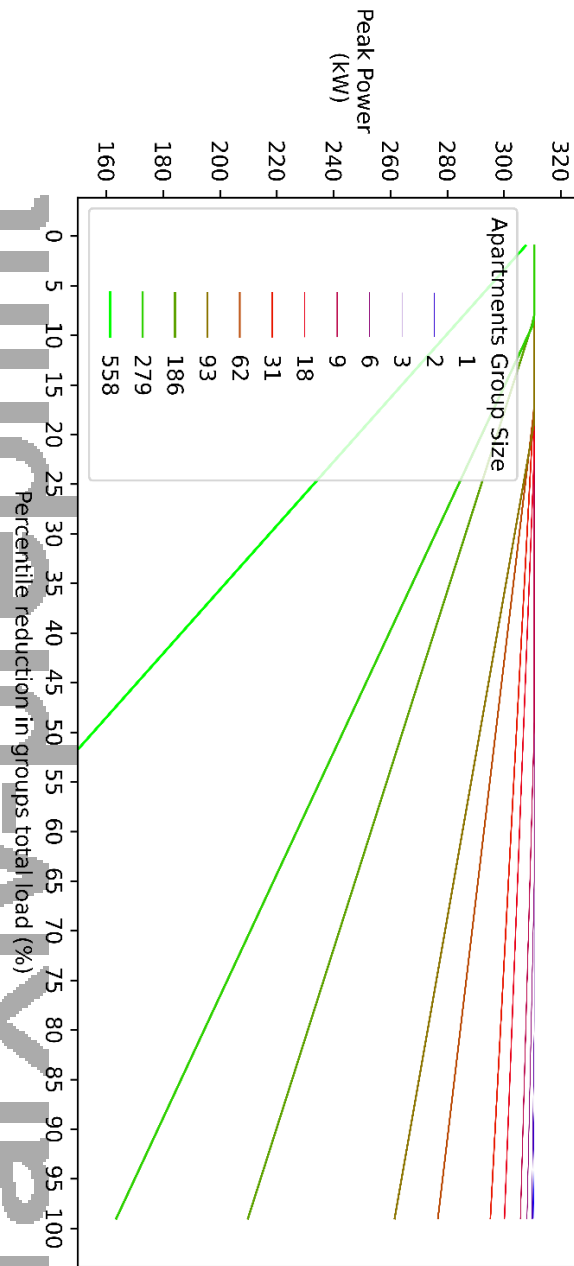


Fig. 3. One group reduced their peak power consumption. The shade of green shows how many apartments are coordinated which in this case is also the total number of apartments coordinating.

Fig. 4 shows that a different grouping of the same name of apartments leads to different results on the impact of peak reduction. There is an impact of the division of the different households into groups. Fig. 6 shows 279 apartments organized into different constellations where again the lower number of coordinated apartments leads to a higher peak in electricity demand. In all the results the impact was more clear in the lower end of the peak, capping under 40%.

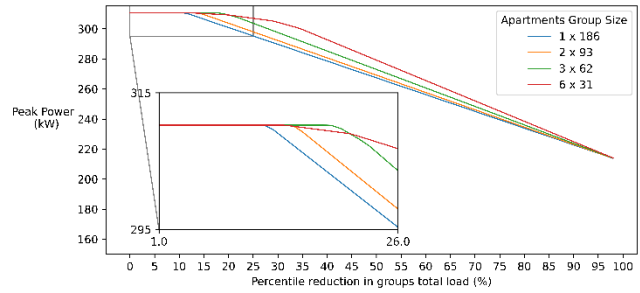


Fig. 4. Different groupings of 186 apartments reducing their electricity peak divided into either 1, 2, 3, or 6 groups. The inset graph shows the detail up to 25% reduction and from 295 kilowatts.

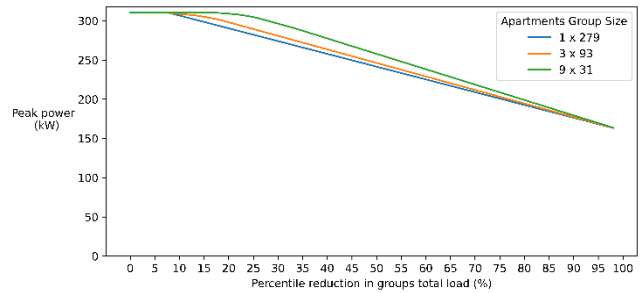


Fig. 5. Different groupings variations of 279 apartments grouped into either 1, 3, or 9 groups. The shade of green shows how many apartments are coordinated into a single group.

3.2. Sensitivity Analysis

To further test the robustness, 500 iterations of the 1 group of 62 apartments and 1 group of 93 apartments are carried out. The results are summarized in Fig.7. The results of the randomized grouping of the apartments show that at 62 apartments there are several combinations (43 out of 500) and a reduction of 25% on their peak leads to no change to the peak power of the total 558 apartments. In most cases, however, there is a reduction in the peak power, although not proportional to 25%. In a few cases (15 out of 500) the reduction in the peak power was greater than if each apartment contributed to the peak equally. The means do not change before a reduction in peak of 15%. The standard deviation, visible in the

whiskers, increases with the peak reduction. It is important to highlight that the results are not representative of all possible combinations of apartments as there are many (10^{83}) possible combinations. A further 500 iterations were carried out of the 1 group of 93 apartments with similar results shown in Fig. 8. In short, it is computationally impossible to prove that one group's peak reduction guarantees a reduction in the total population's peak, but the 500 iterations of grouping acted similarly.

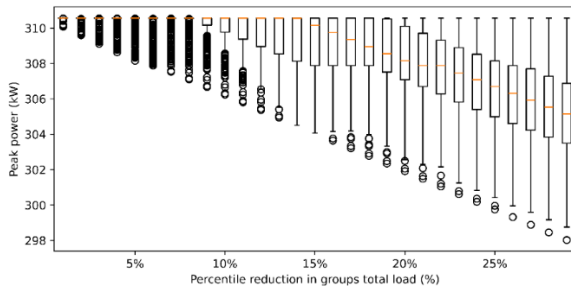


Fig. 6. Detail of box and whisker plot (mean in orange) for 500 iterations of 1 group of 62 apartments reducing their peak power.

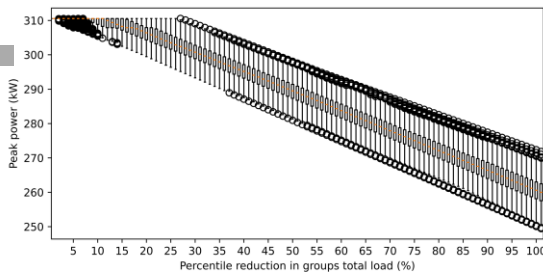


Fig. 7. Box and whisker plot (mean in orange) for 500 iterations of 1 group of 93 apartments reducing their peak power. Note that the y-axis starts at 250 kilo Watts.

4. DISCUSSION AND CONCLUSION

4.1. Discussion

The fewest possible number of apartments that still show a linear reduction is about 62 apartments. Whilst 93 apartments offer a better reduction profile, the effect of the additional apartments is marginal. Having more apartments in the energy community was expected to be better than having fewer as the peak load is known to be composed of several high but not necessarily peaking demands. This is concluded by analyzing the trend lines of the results. A more empirical metric could be worthwhile optimizing the gain in one additional household against the diminishing returns. The results also show that coordination is particularly valuable in the lower peak reduction, which is the most feasible real-world application (i.e. under 15% of the group's peak being capped). If the

results from the dataset ($n = 558$) can be generalized to represent one neighborhood, then 62 apartments correspond to 11% of the total which is an attainable target for an energy community.

The results also present the barrier that must be addressed for effective peak power reduction in EC: the number of residents that must be coordinated is high even for apartment buildings and reducing their coordinated peak power consumption enough (i.e. more than 15% of their with 62 residents) to ensure an impact on the total consumption can prove difficult [2]. If those are achieved, advantages can be shared among the interested parties, i.e. the energy community and the grid owner, to motivate collaboration between public grid owners and energy communities. The electricity companies could be involved in the process of energy communities as partners or collaborators, particularly in niches where peak power consumption is relevant to climate change mitigation and grid resilience for both actors [24]. Before these collaborations can take place, the Swedish regulatory bodies can improve implementation of energy communities. The implementation of a tax on peak power consumption signals a start with addressing the issue. Because of the nature of how individuals use electricity, this paper shows that attempts to curb one individual's peak power will be ineffective in reducing the peak of an apartment complex or a local electrical system. Policy aimed at regulating peak power is more effective if it considers the group dynamics. Energy communities can be a vehicle for the implementation of such a policy.

4.2. Conclusion

This paper tries to better understand the impact of aggregating and coordinating reductions in peak power consumption. It does not deal with the technical feasibility of reducing peak power consumption and the efforts to coordinate these reductions. This paper addresses only the dynamic process that leads to the peak power consumption of a group of residential apartments. The results are limited due to how the loads are capped by assuming a technical solution. Peak reduction by load shifting would lead to different dynamics. Furthermore, future studies can focus on analysis of the statistical nature of the process and setting up better measurements for coordination as well as applying the method to other settings. 62 apartments (or 11% of 558) in this dataset were seen as a minimum for approaching a linear relationship between the reduction of a single group and the total. Most importantly, the results show that if there are efforts to reduce the peak power in the residential sector, those should be coordinated with more households so that they effectively impact the overall grid.

ACKNOWLEDGMENT

The author thanks the support of Erik Dotzauer, Mathias Gustafsson, Nicholas Etherden, and Gireesh Nair for their support in writing this paper.

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