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RESEARCH ARTICLE

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Organizing prosumers into electricity trading communities: Costs to attain electricity transfer limitations and self-sufficiency goals

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Summary

Among household electricity end users, there is growing interest in local renewable electricity generation and energy independence. Community-based and neighborhood energy projects, where consumers and prosumers of electricity trade their energy locally in a peer-to-peer system, have started to emerge in different parts of the world. This study investigates and compares the costs incurred by individual households and households organized in electricity trading communities in seeking to attain greater independence from the centralized electricity system. This independence is investigated with respect to: (i) the potential to reduce the electricity transfer capacity to and from the centralized system and (ii) the potential to increase self-sufficiency. An optimization model is designed to analyze the investment and operation of residential photovoltaic battery systems. The model is then applied to different cases in a region of southern Sweden for year 2030. Utilizing measured electricity demand data for Swedish households, we show that with a reduced electricity transfer capacity to the centralized system, already a community of five residential prosumers can supply the household demand at lower cost than can prosumers acting individually. Grouping of residential prosumers in an electricity trading community confers greater benefits under conditions with a reduced electricity transfer capacity than when the goal is to become electricity self-sufficient. It is important to consider the local utilization of photovoltaic-generated electricity and its effect on the net trading pattern (to and from the centralized system) when discussing the impact on the electricity system of a high percentage of prosumers.

KEYWORDS

peer-to-peer electricity trading, residential electricity prosumers, community energy systems, photovoltaic battery systems, optimization modeling

1 | INTRODUCTION

Concomitant with the transition to low-carbon technologies in the energy sector, an increasing number of decentralized generation and storage units have been introduced to the electricity system in recent years. Most of these distributed units are owned by small-scale actors, such as individual households, companies, and communities. Decentralized electricity generation and electricity storage on a small scale typically involves the use of photovoltaic (PV) panels and battery systems, which due to an estimated further decrease in costs[1,2] are expected to increase in number in the years to come. Customers who now have the possibility to generate, store, and sell electricity, as compared to merely purchasing from an electricity retailer and supporting the traditional unidirectional electricity flow, are generally known as prosumers. Nevertheless, this phenomenon has only recently appeared, and solar PV-only systems are still more common than systems that also incorporate battery storage. There are also utilities that offer customers the opportunity to install rooftop PV systems, whereby both the investment and operation are covered by the utility and the customer is charged a reduced electricity fee in return. Such systems can be regarded as 'prosumer systems' from the technical point of view, although not from the business point of view. It is too early to say which business models will be sustainable in the longer term.

Several studies have investigated the operation of household PV battery systems from the perspective of the residential prosumer; some previous studies have focused on PVs combined with batteries for the self-consumption of in-house generated electricity,[3-6] while others have analyzed the potential savings in household electricity costs that could be achieved by the operation of PV battery systems.[3,7,8] If they increase in number, individual residential prosumers who are striving for self-sufficiency could be highly disruptive to the current centralized electricity system, as pointed out by Agnew and Dargusch.[9] A model-based investigation of the impacts on the electricity system of residential solar and storage systems in Germany has been reported by Schill et al.,[10] in which they highlight the importance of system-oriented design and operation of prosumer PV battery systems.

In addition to analyzing how individual prosumers interact with the centralized electricity system,[3-10] some studies have looked at how organizing electricity prosumers into an electricity community or local market affects their interactions with the centralized grid. Parag and Sovacoo[11] have proposed that the integration of prosumers into the energy system could occur through three different market models: (i) peer to peer, (ii) prosumer to microgrid, and (iii) prosumer group. These models differ with respect to their prosumer interactions and autonomy, as well as in terms of what incentives should be offered for the prosumer-generated electricity to be consumed locally or sold to the grid. Similar concepts with regard to prosumer interactions with the electricity system and applying different methods can be found in the literature in papers that use the following terms: peer-to-peer electricity supply[12], prosumer community groups[13], neighborhood electricity trading[14], and energy communities.[15] An example of a prosumer electricity trading project that is already implemented is the 'Brooklyn Microgrid,' as investigated by Mengelkamp et al.,[16] who examined the project against a set of components identified as being essential for a microgrid energy market. A review of consumer-centric peer-to-peer market designs, including advantages and challenges, is given by Sousa et al.[17] The authors compare a full peer-to-peer market to a community-based market and a hybrid market, concluding that the latter is the most suitable in terms of scalability and interaction with other market designs. The community-based approach with a community manager as supervisor for internal trade has been simulated in a system with 15 prosumers by Moret and Pinson.[18] Moret and Pinson evaluate the impact of the community manager on different prosumers applying fairness indicators. Moret and Pinson also compare the community-based approach to individual prosumers but, in contrast to the present study, chose the levels of PV battery capacity as input to the calculation.

In a set of proposals recently introduced by the European Commission in relation to the role of active consumers in the electricity market, various definitions of prosumer systems were proposed, e.g., the renewable self-consumer and the renewable energy community.[19-21] To provide frameworks and trajectories with the goal of establishing a more active role for electricity users in the energy system, a better understanding is needed as to what functions self-consumption and the aggregation of electricity consumers on different scales will have in a future electricity system. Research has been conducted on the topics of energy autarky and self-consumption on different scales, from individual buildings to neighborhoods and districts,[22] as well as on the clustering of prosumers to optimize power grid operation and reduce costs.[23,24] Community energy storage has been investigated in terms of economic benefits and possibilities to integrate renewable energy sources and demand-side management.[25-28] There have also been studies on the interactions that occur on local markets,[29-31] the different energy carriers in a local energy community or energy hub,[32,33] and the effects of different load curves on neighborhood clusters.[34]

The present study adds to the understanding of local grouping of residential prosumers of electricity through direct comparisons of investment and hourly operation of PV plus battery systems for (i) individual prosumers and (ii) prosumers acting as part of an electricity trading community, which has not been provided by studies cited above. We look at what benefit, if any, there is for residential prosumers of electricity to join together in an electricity trading community, and we analyze the patterns of trading to the surrounding electricity system for different cases. Comparing individual and community-organized prosumers, we investigate the following questions for a selection of prosumer households in southern Sweden, with price assumptions representing a future system in year 2030:

- Does a limited electricity transfer capacity to the centralized electricity system impose a lower cost on a community of PV battery owners than on individual PV battery owners?
- Does an electricity trading community for residential prosumers favor electricity independency (self-sufficiency), as compared to a situation with individual prosumers?
- How do the trading patterns to the centralized electricity system in the above two cases differ?

Limiting the electricity transfer capacity and imposing a requirement for a certain level of self-sufficiency represent two different perspectives for prosumer independence. A low electricity transfer *capacity* represents reduced possibility to trade electricity to and from the centralized system but also reduced reliance on the owner of the distribution grid, whereas a high level of self-sufficiency represents greater *energy* independence and reduced reliance on the energy utilities. A higher degree of self-sufficiency is not directly associated with lower grid dependence, since the electricity that is not self-generated will have to be supplied from the centralized electricity system. The imposition of a limit on the transfer capacity in a future scenario with more decentralized generation and storage systems could be relevant in terms of reducing distribution grid maintenance costs, accommodating additional loads (e.g., from the electrification of transport systems), and smoothing the trading patterns for residential prosumers to the centralized grid. The main contribution of the work presented in this paper is the analysis and direct comparison of increased independence in terms of capacity and energy and that this is investigated for both individual prosumers and prosumer within an electricity trading community. The paper is structured as follows: In Section 2, we describe the optimization model and the data utilized. Section 3 presents the most important results. These are further discussed in Section 4. Section 5 summarizes the conclusions drawn from the study.

2 | METHOD AND MODEL DESCRIPTION

To be able to analyze the effects of grouping residential prosumers in an electricity trading community, we model and compare the following:

a. *Individual prosumers*, who independently invest in and operate their own PV battery systems and buy and feed back electricity directly from and to the centralized electricity system; and
b. *A prosumer community,* in which the PV battery system capacity and operation are optimized for the entire prosumer community. Electricity generated within the prosumer community can be freely shared between all the member households to meet demand at a specific hour or to charge any of the batteries. The prosumer community also has the option to trade (buying and selling) electricity with the centralized electricity system.

Figure 1 is a schematic of the individual and community prosumer setups in the modeling. The concept of a prosumer community in the present study extends the principle of local self-consumption of electricity, i.e., several prosumers can share usage of their PV battery systems

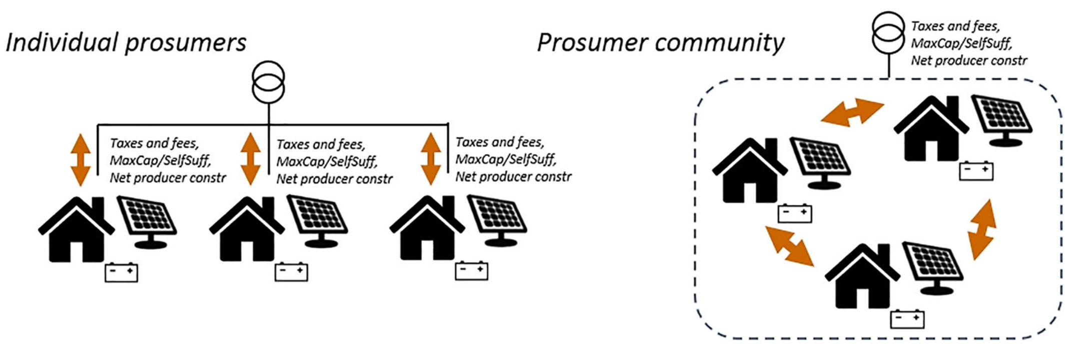

FIGURE 1 Schematics showing the setups for individual prosumers interacting with the centralized electricity system/electricity retailer (left panel) and the prosumer community trading concept (right panel). The formulation of the constraints on maximum transfer capacity (*MaxCap*) and self-sufficiency (*SelfSuff*) and the sensitivity analysis to avoid net producing prosumers are further explained in Section 2.1. [Colour figure can be viewed at wileyonlinelibrary.com]

without any interaction with the centralized system. We assume that the associated taxes and fees are paid only on electricity that is bought from the centralized electricity system, such that no value-added tax (VAT) is paid on electricity fed to the centralized system. Additionally, trade within the studied prosumer communities is assumed to take place behind the meter, i.e., without taxes and fees associated with the electricity grid. In the current Swedish electricity system, prosumers are not charged with VAT nor do they pay income tax for electricity that is fed from a prosumer household into the grid (if the value is under a limit of 30 000 SEK, i.e. 2815 EUR). As this regulation is set up in order to incentivize decentral prosumer PV battery systems, we chose to assume a similar regulation for prosumer communities, for which no regulations exist in Sweden yet. In addition, the constraints on the maximum transfer capacity, the self-sufficiency requirement, or the requirement to not become net producers of electricity (as used in the sensitivity analysis) are defined differently for the individual prosumers and the prosumer community, as presented in Section 2.1.2 and the following text. A similar concept of collective and virtual self-consumption has been defined by Lettner et al..[35] In the categorization of shared energy storage configurations described by Koirala et al.,[36] the concept of shared residential energy storage resembles the representation of the shared operation of PV battery systems within a prosumer community in the present study.

Regarding the three research questions listed above, we perform the modeling by applying the following constraints for both individual prosumers *(Individual*) and a community of prosumers *(Community)*:

- *Maximum capacity constraint (MaxCap)*, with a limitation as to the maximum electricity transfer capacity to the centralized electricity system
- *Self-sufficiency constraint (SelfSuff),* with a requirement to be able to meet a certain share of the total electricity load using locally PV-generated electricity

The pattern of trading to the centralized grid is analyzed using modeling of both of the above cases. We use the characteristics of southern Sweden as an example, and we vary the number of prosumers (either individual or in the community) for each of the cases (Table 1).

As indicated above, the constraints on maximum capacity (*MaxCap*) and prosumer self-sufficiency (*SelfSuff*) are formulated to represent two dimensions of prosumer independence. The *MaxCap* constraint represents less reliance on the owner of the distribution grid, i.e., less transfer capacity to the centralized system. The *SelfSuff* case corresponds to increased *energy* independence. Thus, these cases can be seen to represent two motives for households to participate in electricity trading within a prosumer community, and they are both analyzed with the method proposed in this work.

2.1 | Optimization model for prosumer electricity trading

We use an optimization model that minimizes the annual costs of all prosumer households with an hourly time resolution over a year, according to Equation 1:

$$C^{tot} = \sum_p \left(c_p^{el} + c_p^{inv} \right) \quad (1)$$

where c_p^{el} is the annual electricity cost across the set of all prosumer households, consisting of the costs for electricity bought from outside the electricity trading community minus the benefit from selling surplus in-house generated PV electricity to the centralized electricity system. Summing c_p^{inv} over the set of all prosumer households gives the annualized investment costs for PV battery systems. These costs depend on the respective PV and battery capacities invested in, which are variables in the model, as well as on the investment prices, discounting rates, and life spans. Details of both parts of the objective function are given in Appendix A. All prosumer households in the modeling have the option to invest in PV or battery systems or a combination of them. The decision on whether to invest and the size of the investment is part of the prosumer annual electricity cost minimization.

We compare the *Individual* case, in which prosumer households only interact with the centralized system to supply their electricity demand (and sell any eventual surplus), with the *Community* case, in which prosumer households additionally interact and share electricity from their PV battery systems with each other. For both

TABLE 1 Summary of modeling cases run in the study.

		Maximum capacity limit (*MaxCap*) *% of maximum load*	Self-sufficiency requirement (*SelfSuff*) *% PV generated of total electricity utilized*
Number of prosumers: *2, 5, 10, 23, 46, 101*	Community/Individual	10, 20, 30, 40, 60, 100, 150	30, 50, 60, 80, 95

of these cases, we apply constraints to either the amount of electricity that is allowed to be traded with the centralized system per hour (*MaxCap*) or to supplying a certain share of the demand using locally generated electricity from prosumer PV panels (*SelfSuff*). Table 2 gives an overview of the equations used for the modeling of the *Individual* and *Community* cases.

The electricity balance per hour ensures that the demand in each prosumer household is met. A set of battery equations calculates the electricity storage levels inside the prosumer batteries in relation to the charge and discharge of electricity to and from the battery. Details as to the imposed constraints for both of these aspects are given in Appendix A.

2.1.1 | Individual and community cases

The demand for electricity in a prosumer household can be met directly by in-house PV-generated electricity, electricity that was previously charged to the battery or electricity that was bought from the centralized electricity system. In the *Community* cases, prosumers have the additional option to obtain electricity from other prosumers within the community, if such electricity is available. When there is surplus electricity, prosumers have the option to sell to the centralized electricity system at spot market prices or, in cases with community trading in place, the option to share electricity with other prosumers within the community. A community balance equation ensures that each hour of electricity bought and each hour of electricity sold in the electricity trading community match, also taking into consideration an assumed loss of 1%:

$$\sum_p s_{p,h}^{Com} + Losses = \sum_p b_{p,h}^{Com} \tag{2}$$

where $s_{p,h}^{Com}$ is the electricity sold to other prosumers in the electricity trading community, over the set of all prosumers and the set of all hours, and $b_{p,h}^{Com}$ is the electricity bought by other prosumers within the electricity trading community, over the set of all prosumers and the set of all hours. No price is set for electricity transfer between prosumers that are members of the electricity trading community, as we analyzed the optimization of PV battery system operation and the investment made by all the prosumer households together.

2.1.2 | Constraints and calculation of the transfer capacity limit for the *MaxCap* cases

For the *MaxCap* case, a limit on the transfer capacity to the centralized system is assigned. This limit is set to each individual household in the model runs for the *Individual* cases and for the entire prosumer community in the modeling for the *Community* cases (see also Figure 1). A constraint imposed on the model limits the sum of the electricity bought and sold from and to the centralized system per hour to being lower than the transfer capacity limit, as described in Equation 3 for the *Individual* cases and in Equation 4 for the *Community* cases:

$$s_{p,h}^{Sys} + b_{p,h}^{Sys} \leq CapLim^{*}MaxLoad_p \tag{3}$$

$$\sum_p \left(s_{p,h}^{Sys} + b_{p,h}^{Sys} \right) \leq CapLim^{*}\sum_p MaxLoad_p \tag{4}$$

where $s_{p,h}^{Sys}$ and $b_{p,h}^{Sys}$ represent the electricity sold to and bought from the centralized electricity system over the set of all prosumer households and hours. *CapLim* is set as a percentage of the maximum load for the different cases, as summarized in Table 1. The maximum load in this calculation is the electricity consumption during the peak-load hour of each prosumer household, $MaxLoad_p$,

TABLE 2 Overview of equations for the modeling of the *Individual* and *Community* cases.

	Individual	Community
Objective	Minimize annual costs for all prosumer households (Equation 1)	
Community trading	–	Balance over electricity sold and bought within prosumer community (Equation 2)
MaxCap	Limit on transfer capacity for each household (Equation 3)	Limit on transfer capacity for whole community (Equation 4)
SelfSuff	Certain share of demand possible to be supplied by electricity generated within household (Equation. 6)	Certain share of demand possible to be supplied by electricity generated within community (Equation 7)
Sensitivity: no net producers	Households not allowed to sell more than they buy from the centralized system (Equation 8)	Community not allowed to sell more than it buys from the centralized system (Equation 9)
Additional constraints	Variables for electricity bought $b_{p,h}^{Com}$ and sold $s_{p,h}^{Com}$ within community fixed to zero for *Individual* cases	

for the *Individual* case, and the sum of the electricity consumption of all the households' individual peak-load hours for the *Community* case. Thus, we compare the setting of a transfer capacity limit on the fuse of each household in the *Individual* cases to the setting of a limit at the connection between the prosumer community and the centralized system in the *Community* cases. Both of these limits are currently assumed to be set according to the peak load that can occur.

2.1.3 | Constraints applied to the *SelfSuff* cases

For the *SelfSuff* cases, a set of constraints is applied to ensure that the prosumers invest in a PV battery capacity that is sufficiently large to supply a certain share of their electricity demand from locally generated PV electricity. Thus, energy independence is here assumed to be achieved by making sufficiently large investments so that prosumers have the option to limit their energy imports from the centralized system, while the operation of the PV battery systems is such that the total cost for prosumers is minimized. To incentivize investments in PV battery systems that are suitable for the desired degree of electricity self-sufficiency, we introduce a new set of variables similar to that used in the base model, with the difference that for this set of equations, which is exclusive to the modeling of the *SelfSuff* cases, electricity cannot be sold to the centralized electricity system. This means that investments in PV battery capacity are in the *SelfSuff* case not influenced by the incentive to sell electricity during high-price hours but instead are only influenced by the requirement to be able to supply a certain share of the demand from locally generated PV electricity. Equation 5 calculates how much electricity per hour has to be bought to cover the electricity demand that does not come from PV-generated electricity in the *SelfSuff* equations.

$$b_{p,h}^{SelfSuff,Sys} = Dem_{p,h} - g_{p,h}^{PV} + ch_{p,h}^{SelfSuff} - dch_{p,h}^{SelfSuff} * \eta^{dch} + curtail_{p,h}^{SelfSuff} - b_{p,h}^{SelfSuff,Com} + s_{p,h}^{SelfSuff,Com} \quad (5)$$

where $b_{p,h}^{SelfSuff,Sys}$ is the electricity bought from the centralized system, which in this set of equations is used to determine the PV battery capacity required to meet the self-sufficiency targets. $Dem_{p,h}$ is the demand profile of each prosumer household, $g_{p,h}^{PV}$ is the electricity generated from PV per hour in every prosumer household, and $ch_{p,h}^{SelfSuff}$ and $dch_{p,h}^{SelfSuff}$ are the amounts of electricity charged to and discharged from the prosumer batteries. $curtail_{p,h}^{SelfSuff}$ is the curtailment of unutilized PV-generated electricity per hour in this set of *SelfSuff* equations. $b_{p,h}^{SelfSuff,Com}$ and $s_{p,h}^{SelfSuff,Com}$ are the amounts of electricity bought and sold within the electricity trading community (fixed at 0 in the model runs for the *Individual* cases). In addition to Equation 5, a series of battery equations and a community balance equation are expressed in terms of the self-sufficiency variables. The structures of these equations are identical to their base-model counterparts [i.e., Equations A5–A9 in Appendix A].

Equation 6 for the *Individual* cases and Equation 7 for the *Community* cases ensure that only a certain share of the demand can be supplied by electricity bought from the centralized system, according to the *SelfSuff* case modeled.

$$\sum_{h}\left(Dem_{p,h} - b_{p,h}^{SelfSuff,Sys}\right) \geq SelfSuff^{*}\sum_{h} Dem_{p,h} \quad (6)$$

$$\sum_{p,h}\left(Dem_{p,h} - b_{p,h}^{SelfSuff,Sys}\right) \geq SelfSuff^{*}\sum_{p,h} Dem_{p,h} \quad (7)$$

where $b_{p,h}^{SelfSuff,Sys}$ is calculated from Equation 5, and *SelfSuff* is the share of electricity required to be sourced from locally generated PV electricity, as defined for the cases listed in Table 1.

For the *Individual* cases, the PV and battery investments need to be sufficiently large to fulfill the self-sufficiency requirement within each prosumer household, whereas for the *Community* cases, the PV and battery investments for all the prosumer households are shared so as to fulfill the self-sufficiency requirement for the prosumer community as a single entity. We apply a transfer capacity limit of 100% of the maximum load even in the *SelfSuff* cases. This is in order to avoid extreme peaks of prosumer selling during hours of high electricity prices, and it represents transfer capacity restrictions that are assumed to be in place in the local grid right now, whereby transfer capacities are set according to the maximum load.

2.1.4 | Sensitivity analysis: constraint imposed to avoid net-selling prosumers

For the base model, we chose not to limit or to apply additional costs for the scenario in which prosumers start to sell more electricity than they purchase from the centralized grid over a full year, i.e., when prosumers become net producers. The regulations for a case such as this are different in different countries. To test the impact that this assumption has on the results, we performed a sensitivity analysis, implementing an additional constraint whereby prosumer households were prevented from becoming net producers of electricity, as presented in Equation (8) for the *Individual* case and in Equation (9) for the *Community* case. From Figure 1, it is evident that in the *Community* case the prosumer community as a whole is restricted from becoming a net producer under this constraint, whereas in the *Individual* case this constraint is imposed on each individual prosumer household.

$$\sum_h b_{p,h}^{Sys} \geq \sum_h s_{p,h}^{Sys} \quad (8)$$

$$\sum_{p,h} b_{p,h}^{Sys} \geq \sum_{p,h} s_{p,h}^{Sys} \quad (9)$$

2.2 | Prosumer household input data and selection of prosumer communities

To represent the prosumer household demand, the hourly load profiles of different Swedish households have been utilized. The profiles were measured by E. ON within the household measurement project (conducted from February 1, 2012, to January 31, 2013). Out of the 2104 households, as prepared and utilized by Nyholm et al.,[37] a selection was made to represent neighborhood areas of different sizes. The selection was based on the geographical locations of the households, with the data on the respective five-digit postcode used as the selection criterion. For each prosumer community, first households with the same postcode were chosen. When sufficient numbers of load profiles were not available to generate the desired prosumer community size, household data from the next-closest postcode were included. As most of the measured household data were available for southern Sweden, this procedure resulted in households that have Swedish postcodes with 23 and 21 as the first two digits being chosen for the modeling runs. In total, there are 101 load curves for the chosen postcodes, resulting in a maximum prosumer number of 101 in the analysis. All of the selected areas lie within the southwestern Skåne County in southern Sweden. In utilizing the measured load profiles of the households, we naturally get a mix of households with different types of heating equipment and household appliances, as well as different occupant numbers and behaviors, which has been judged to be adequate to represent the household demand curves for the focus of this study.

2.3 | Inputs for electricity prices, solar profiles, and PV battery system cost

The wholesale electricity price, which is used as the basis for the hourly variable electricity price in the prosumer households, has been obtained from the EPOD dispatch model,[38,39] which is a linear cost-minimizing dispatch model that includes 50 European regions. For the purpose of this study, the price curve for the southern-most region of Sweden for year 2030 has been used. This was obtained from a scenario representing a European system pathway with a high share of renewable power generation, shorter lifetimes for nuclear power plants, and no carbon capture and storage (CCS) (for details, see the Green Policy scenario in Goop[39]). In addition to this hourly variable electricity price, prosumer households in our model have to pay an energy tax, grid fees, and VAT for the electricity that they purchase from the centralized system. For the electricity that the prosumers sell to the centralized system, they are paid the hourly wholesale electricity price plus a small reimbursement. Based on projections for the development of PV[40-43] and battery[2] technologies, the values summarized in Table 3 are used as the investment cost and the lifetime assumptions for residential PV battery systems for year 2030. Prosumers in this optimization model have perfect foresight regarding their load profile, the electricity prices, and the level of PV generation. The PV generation profile is based on the geographical location as presented in Norwood et al..[44] Figure 2 shows the hourly wholesale electricity price and the solar profile for one example household, as utilized in the modeling.

3 | RESULTS

3.1 | Benefit of aggregating prosumers within prosumer communities

The economic benefits that prosumers in an electricity trading community accrue compared to prosumers operating individually are, in our modeling, clearly greater when the transfer capacity to the centralized grid is limited rather than used for the purpose of becoming electricity self-sufficient. In Figure 3, the savings that the

TABLE 3 Assumptions made regarding the PV battery system investment cost and lifetime.

	Investment cost	Lifetime (years)
Battery	150 €/kWh	12.5
PV	1200 €/kW_p	30.0
Inverter	100 €/kW_p	15.0

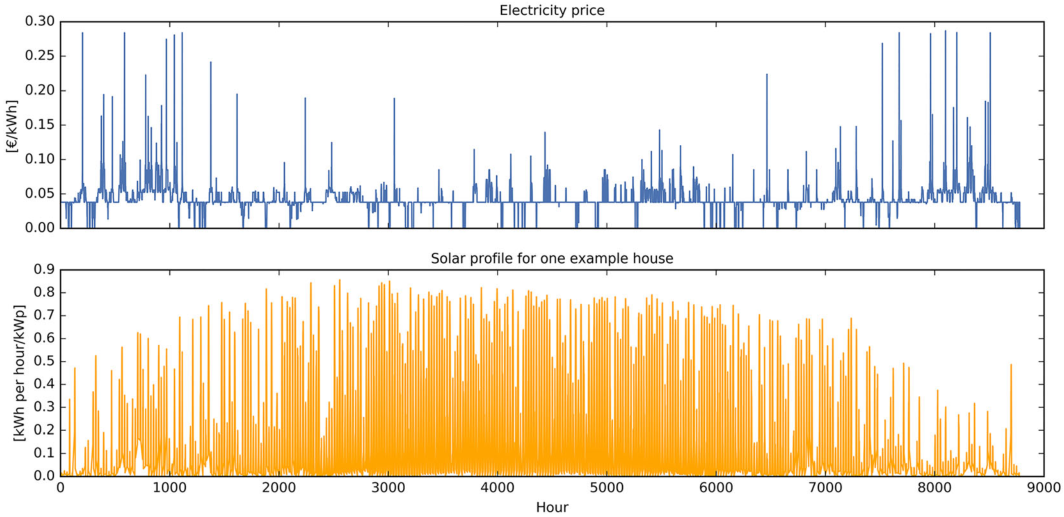

FIGURE 2 Hourly electricity price (excluding the energy tax, grid fees, and VAT that the prosumers have to pay) and the solar profile for one sample household (in the south of Sweden), as utilized in the modeling. [Colour figure can be viewed at wileyonlinelibrary.com]

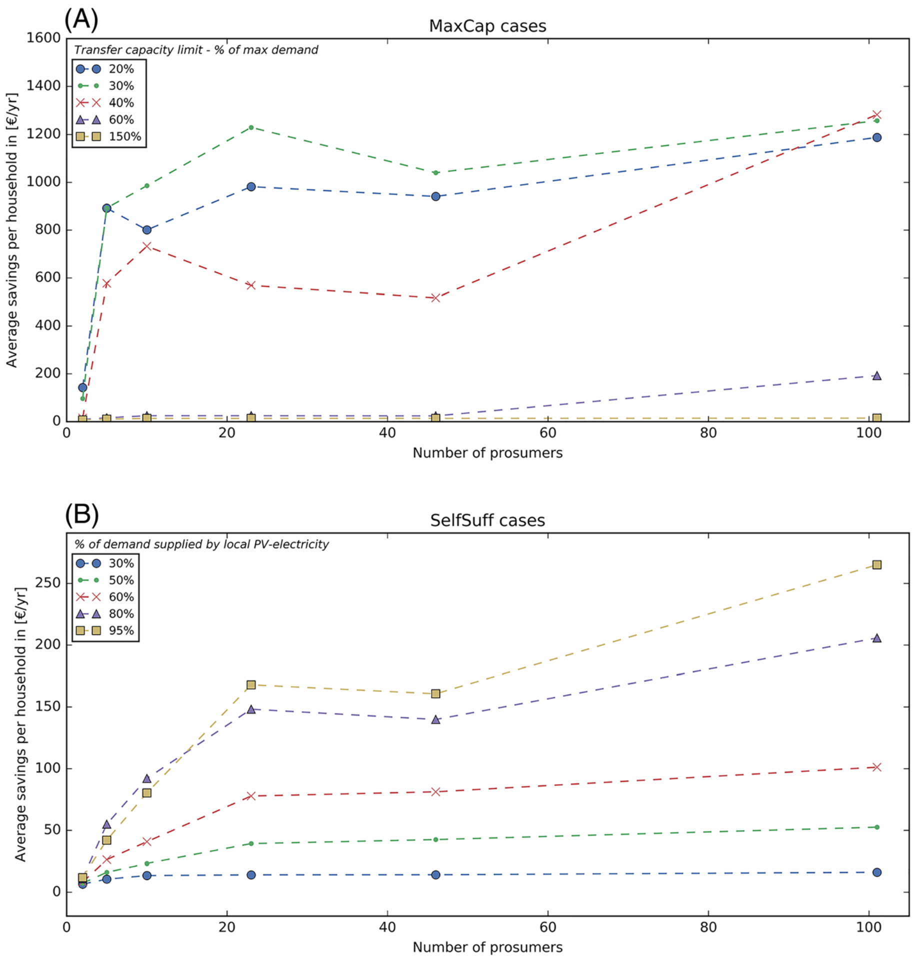

FIGURE 3 Average savings in Euro per household and year from the optimization within a prosumer community, as compared to individual prosumers minimizing their annual costs for electricity. (a) The *MaxCap* cases (where the symbols indicate the limit on transfer capacity in terms of the percentage of the maximum demand). (b) The *SelfSuff* cases (where the symbols indicate the percentage of demand that can be supplied by locally generated PV electricity). [Colour figure can be viewed at wileyonlinelibrary.com]

average prosumer experiences within a prosumer community, as opposed to acting individually, are shown for the *MaxCap* cases (Figure 3a) and the *SelfSuff* cases (Figure 3b) for different numbers of prosumers analyzed in the modeling. In the *MaxCap* case, the results in Figure 3a are given for the various transfer capacity limits, ranging from 10% to 150% of the maximum demand, and in the *SelfSuff* case in Figure 3b for the different requirements for electricity self-sufficiency, i.e., being able to supply 30%–95% of the total demand with locally generated PV electricity. Figure 3 shows that the largest cost savings for prosumers in the *Community* case, as compared to the *Individual* case, are realized in those *MaxCap* cases with a capacity limit of 40%, 30%, or 20% of the maximum load. This can be explained by the households' electricity peak loads. The different measured load profiles used in this study vary in terms of when the maximum loads in the different households occur. In the *MaxCap* cases, the part of the peak load that can no longer be supplied from the centralized system owing to the capacity transfer constraint has to be met with electricity provided by the PV battery systems. The ability to share electricity within a prosumer community gives the prosumer households the possibility to use not only their own PV battery systems but also the electricity generated or stored in other prosumer households. Thus, the limitation imposed on electricity transfer capacity to the centralized grid induces smaller PV battery systems for community prosumers relative to those for individual prosumers. In the *SelfSuff* cases, for which a specific share of electricity is required to be covered by locally generated electricity, the differences in the prosumer household demand peaks have a weak impact on the results, since they represent small amounts of electricity over a short period of time. While the residential load profiles differ with respect to their peak loads, the largest volumes of electricity are used at the same times in all the prosumer households. Therefore, to cover a specific share of this electricity demand using locally generated PV electricity (i.e., to reach a certain level of self-sufficiency) requires very similar PV battery capacities at very similar annual prosumer costs in the cases with and without a prosumer electricity trading community.

For a community of five prosumers in our modeling, it is cheaper by almost 600 € per average prosumer to achieve a *MaxCap* limit of 40% of the maximum demand in a prosumer community, as compared to individual prosumers (Figure 3a). The largest difference in potential savings for prosumers in the *Community* versus the *Individual* cases is seen when increasing the community size from two to five prosumers. For the *SelfSuff* cases in Figure 3b, the possible savings for prosumers in a community, as opposed to individual prosumers, are in the range of 6.5 to 160 € per year per average prosumer.

Table 4 gives more details of the composition of annual prosumer electricity costs in the different cases. The table shows the yearly variable costs of electricity (i.e., buying from and selling to the centralized system) and the annualized investment costs for the average household in modeling runs for 10 prosumer households. We show results for *Community* and *Individual* cases for differently strict *MaxCap* and *SelfSuff* cases. To set the

TABLE 4 Comparison of the yearly costs of electricity and annualized investment costs for the average household (results from modeling runs for 10 households) in EUR/year.

	No PV battery system (all demand supplied by bought electricity):					
Electricity costs	2034.1					
Ann. investment	-					
	***MaxCap* cases:**					
	100%		**60%**		**30%**	
	Community	**Individual**	**Community**	**Individual**	**Community**	**Individual**
Electricity costs	1114.7	1157.6	1137.8	1102.4	3.8	-87.9
Ann. investment	731.4	701.9	711.9	771.9	3491.1	4568.5
	***SelfSuff* cases:**					
	30%		**60%**		**80%**	
	Community	**Individual**	**Community**	**Individual**	**Community**	**Individual**
Electricity costs	1114.7	1157.7	37.5	21.7	-1239.0	-1259.1
Ann. investment	731.4	701.8	2093.1	2149.7	4949.1	5061.3

costs into relation, the yearly costs of electricity for the average prosumer household to supply all their electricity demand by bought electricity (i.e., No PV battery system) has been calculated.

Figure 4 gives the PV (left panels) and battery (right panels) capacities required per average prosumer to reach the different limits (%) on transfer capacity in the *MaxCap* cases, individually and as a prosumer community and for cases with 2, 5, and 23 prosumers. Thus, these are the cases in which the transfer capacity to and from the centralized electricity system is limited. The corresponding plots for the *SelfSuff* cases are presented in Appendix B in Figure A3. With the limit on transfer capacity, the peak demand cannot be fully met any longer by purchasing electricity. Individual prosumers have to supply the remainder of this peak demand by themselves, through PV generation or discharge of their battery systems. The prosumers in a prosumer community can also trade electricity with each other. From Figure 4, it can be seen that for 5 or 23 prosumers and for *MaxCap* limits of 20%, 30%, or 40% of the maximum demand, individual prosumers need larger investments in PV and battery capacities, as compared to prosumers in an electricity trading community. Thus, already when five prosumer households act together, the PV battery capacity required to comply with a transfer capacity limit is substantially lower if the prosumers collaborate in a community rather than act individually. Prosumers in electricity trading communities need up to 35 kWh less battery capacity per average household in the 40% *MaxCap* case as

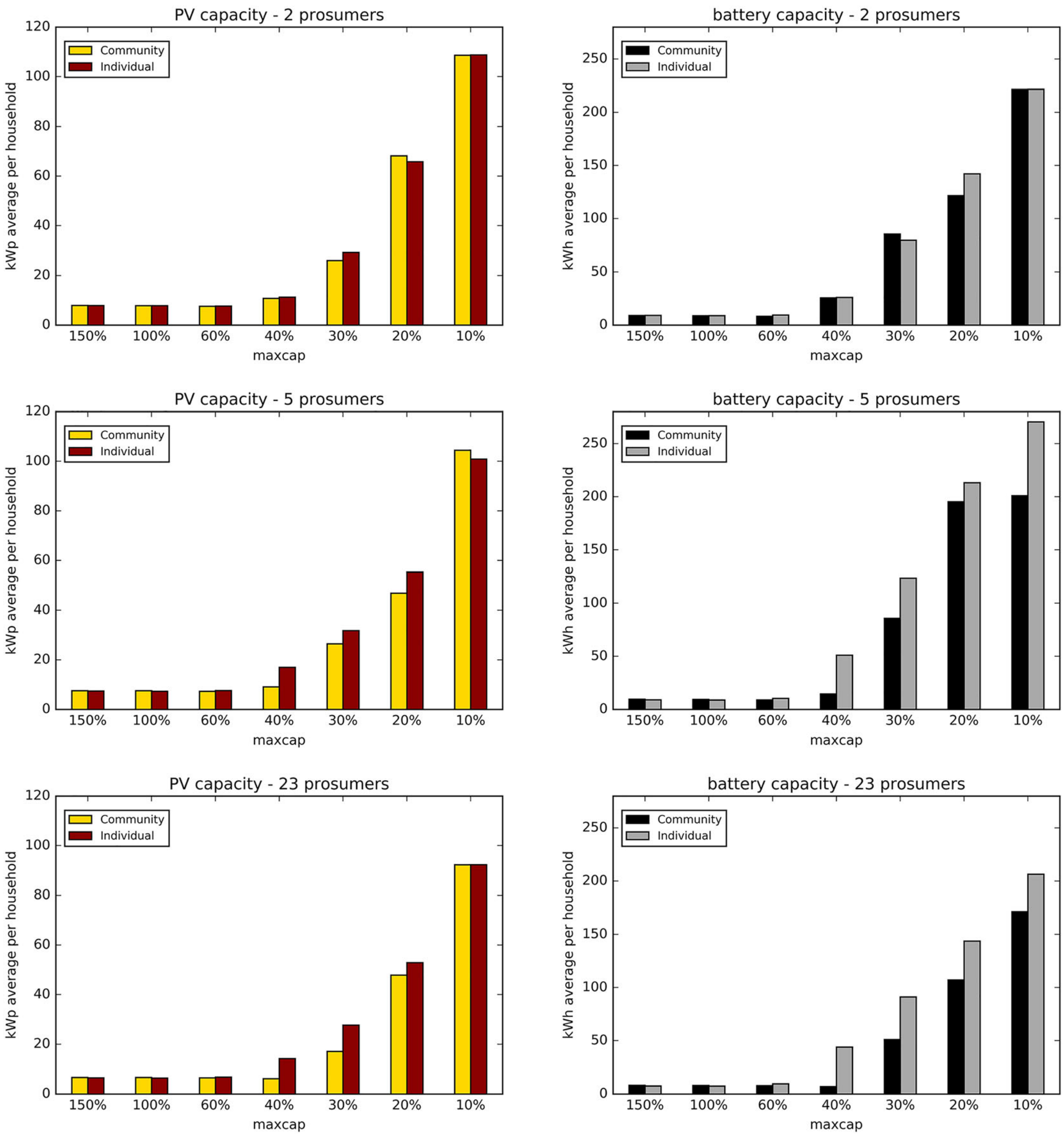

FIGURE 4 PV (left) and battery (right) capacities required per average prosumer to reach the different limits on transfer capacity in the *MaxCap* cases, individually or as a prosumer community, for the modeling of southern Sweden. [Colour figure can be viewed at wileyonlinelibrary.com]

compared to individual prosumers. This is because also other prosumer households' battery capacity can be utilized to supply the highest peaks in electricity demand in the prosumer community.

From Figure 4 it can be seen that the PV battery capacity necessary to comply with the transfer constraint starts to drastically increase at *MaxCap* of 40% for the *Individual* cases but only at a limit of 30% in the *Community* cases (except in the case of only two prosumers). In the cases with a *MaxCap* limit of ≥60%, a prosumer community confers scarcely any additional benefit over individual prosumers. The difference in PV and battery capacities between the *Individual* and *Community* cases is smallest for a size of only two prosumers. This corresponds to the lower cost savings for the cases of only two prosumers shown in Figure 3, since the annual costs for prosumers are partly related to the annualized investment in PV battery capacity and partly related to their operation, i.e., scheduling when to buy and sell electricity. The model runs with groups of 10, 46, and 101 prosumers show the same pattern for the *Individual* and *Community* cases, as shown in this Results section.

3.2 | Patterns of trading to the grid

Figure 5 shows the net duration curve of all the prosumers' trading patterns to and from the centralized grid, for individual prosumers (*Individual*), as well as for prosumers in an electricity trading community (*Community*) for the different *MaxCap* cases. The sold electricity subtracted from the purchased electricity for 10 prosumer households is plotted. Thus, the positive values indicate electricity bought by the prosumers, while the negative values correspond to electricity that was sold by the prosumers. As a reference, the total electricity demand in all 10 prosumer households is plotted as a gray-dotted line. It is evident that prosumers who are operating together in an electricity trading community have a trading pattern to the centralized electricity grid that is different from that of prosumers acting individually and that is very different from the total household electricity demand (dotted line in Figure 5).

For capacity limitations that lie close to the demand (i.e., the 100% and 60% *MaxCap* cases), there is hardly any difference between the duration curve of the trading pattern to the centralized electricity system for individual prosumers and prosumers in an electricity trading community. When the transfer capacity limit is lowered to 40% of the maximum load, the trading pattern duration curves for the *Community* and *Individual* cases start to diverge significantly. In Figure 5, the black-dashed line for 10 prosumers acting individually (*Individual*) is clearly flatter than the red curve for the case of the electricity trading community (*Community*). In contrast, when prosumers are organized into communities, there are more hours without trade between the prosumers and the centralized system. This is again due to the aggregation effect within the prosumer electricity trading community. The modeling gives that during a high number of hours, it is enough for prosumer households to trade electricity among themselves to supply all the households' electricity demands, without any need to buy additional electricity from the outside system and without any surplus to sell. If possible, electricity will always be utilized first within the electricity trading community instead of fed back to the centralized system. Electricity utilized within the electricity trading community can replace electricity that otherwise would have had to be bought from the centralized system with associated taxes and fees. Self-consumption of electricity within the individual households in the *Individual* cases and within the whole prosumer electricity trading community in the *Community* cases is, therefore, under the modeled tariff and tax assumptions, preferred over bought electricity. For comparison, the net trading duration curve for the *SelfSuff* cases is shown in Appendix B in Figure A2.

The results shown in Figure 5 reflect the fact that batteries can be utilized in a more efficient way to enable self-consumption of electricity when prosumers act within an electricity trading community. Instead of selling the surplus electricity from one prosumer household, it can be used to charge the battery of another prosumer household that has a higher demand for electricity during later hours. Therefore, the trading pattern for a community of prosumer households shown in Figure 5 reveals several different plateaus, where prosumers are buying at the maximum capacity allowed (left part of the figure), are not interacting at all with the centralized system (on the zero line), and are selling surplus electricity at the maximum capacity allowed (right side of the figure). As the limit on transfer capacity increases, individual prosumers, as well as prosumers in an electricity trading community, buy electricity during significantly fewer hours per year, thereby shifting the point at which the duration curves meet the zero line to the left of the figure. One reason for this shift is of course the capacity restriction that limits how much electricity can be bought per hour. The other reason is that investment in PV battery systems for a *MaxCap* limit of around 40% for individual prosumers and around 30% for prosumers in a community starts to become sufficiently large to allow for self-consumption of electricity over longer periods of the year and allows surplus electricity to be sold during many hours.

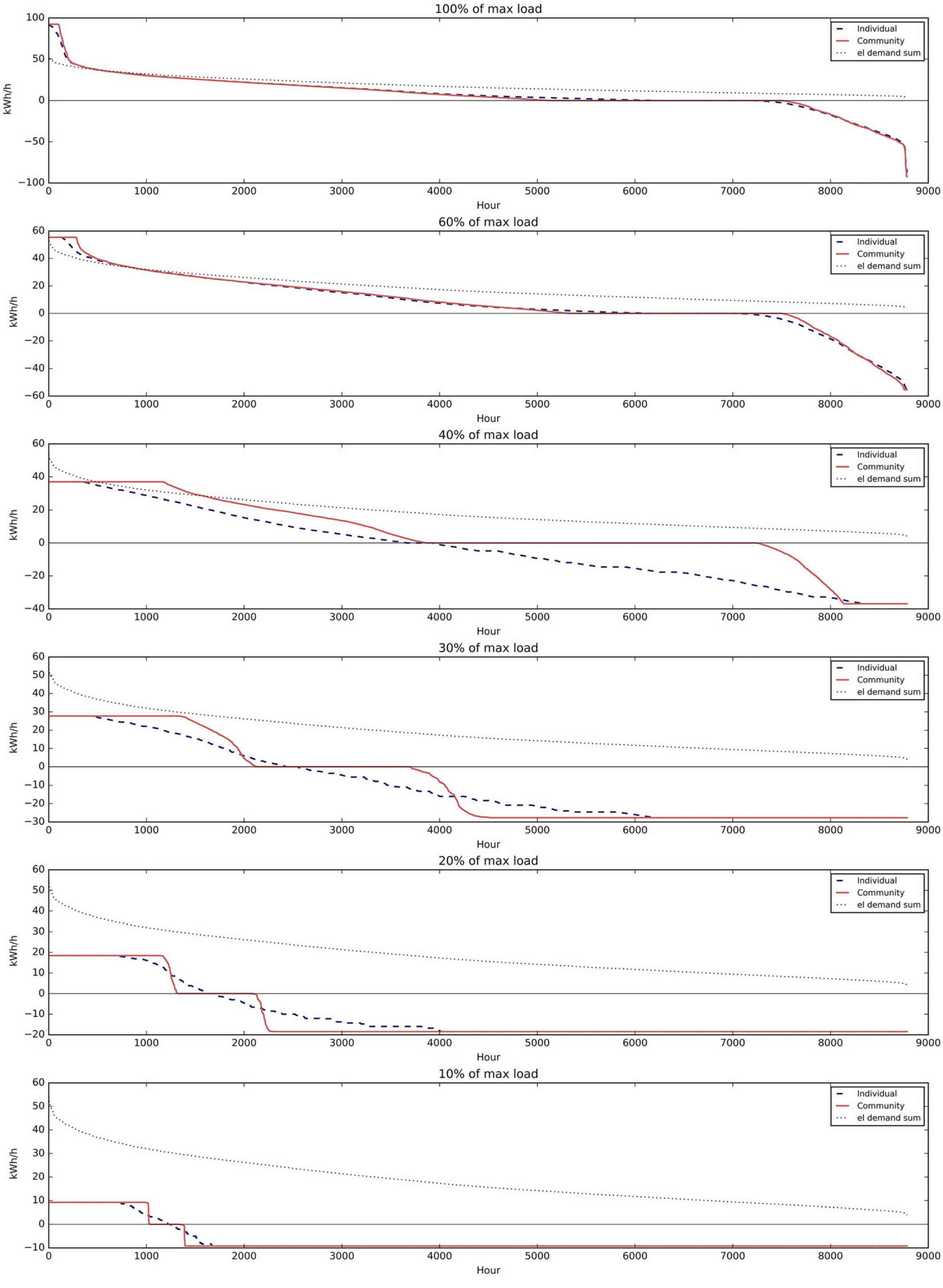

FIGURE 5 Net trading duration curves, comparing individual households (*Individual*) and households that are part of an electricity trading community (*Community*), for the case of 10 households and for different limits on the maximum transfer capacity, ranging from 100% down to 10% of the maximum demand. The plots show the aggregated loads for the two cases, where the modeling for the *Individual* cases is made on an individual household basis, as explained in Section 2. [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Sensitivity analysis: prosumers as net producers of electricity?

In this work, there is no restriction to prevent prosumers from becoming net producers of electricity, i.e., over the course of a year, selling more electricity than they buy from the centralized system. In the modeling, prosumer households are compensated for sold electricity with the hourly spot market price. In the presented results, prosumers are net producers of electricity for a limit on electricity transfer capacity of ≤30% in the *Community* cases and for a limit of ≤40% in the *Individual* cases (modeling runs with five or more prosumers). In cases with requirements on self-sufficiency, prosumers become net producers in cases that have self-sufficiency goals of ≥50% (modeling runs with five or more prosumers). Different countries have different regulations regarding residential households becoming net sellers of electricity to the grid. To test the sensitivity of the results in the present study to this assumption, we ran the model for the case of 10 prosumers with an additional constraint that allows the prosumers to sell only as much electricity over the course of year as they buy from the centralized system (see Section 2.1.4).

It is found that the size of the PV battery system is mainly driven by the requirement to meet the prosumer electricity demand under constraints related to transfer capacity or self-sufficiency. Thus, investments in PV battery systems are scarcely affected by the addition of the constraint. For the *MaxCap* cases, a clear difference in PV battery investment was observed in only one case, the *Community* case with an electricity trading limit of 30%. In this case with the constraint to avoid becoming net producers, the prosumers in an electricity trading community invest in around 13 kW less of PV capacity and around 43 kWh/h more of battery capacity per average prosumer household than in the case without the net producer constraint. For this specific case, it appears to be slightly more advantageous for prosumer households to buy more of their electricity from the centralized system, as compared to the case without the net producer constraint, in which all the surplus electricity from the slightly larger PV panels can be sold. In cases with a less restrictive limit on electricity transfer (≥60%), there is no advantage for prosumer households to become net producers even without the constraint. In cases with an electricity transfer limit <30% of the maximum load, the amount of electricity that can be sold to the centralized system is so small that being a net producer or not does not affect the PV battery investments or prosumer annual costs.

In addition, for the *SelfSuff* cases, constraining net production has a weak impact on the results for the model run with 10 prosumers. The strongest impacts are found at 50% and 60% self-sufficiency, for which cases the constraint that prevents prosumers from becoming net producers induces prosumers to invest in less PV generation capacity (between 0.5 kW and 1.2 kW per average prosumer household in the *Individual* and *Community* cases) and to buy more battery capacity (between 1 kWh/h and 6 kWh/h per average prosumer household in the *Individual* and *Community* cases). As the difference between the *Individual* and *Community* cases remains constant in all the cases of the sensitivity analysis, our conclusions as to the benefits for the prosumer from being in an electricity trading community rather than acting individually still hold with the constraint to avoid the possibility to become net producers of electricity.

4 | DISCUSSION

In the present study, we analyzed the benefits for residential prosumers of organizing themselves into electricity trading communities, providing them with the possibility to share their locally generated electricity for self-consumption. We impose two constraints on the optimization model, a transfer capacity limit and a self-sufficiency requirement, which are the main driving forces for increasing PV battery investments as the imposed constraints become increasingly strict. The benefit that prosumers accrue from being part of a community is, in this work, mainly related to differences between the electricity load profiles of the individual households. We find that there are greater benefits for prosumers to be part of a community in cases with a constraint on transfer capacity to the centralized system (which is mainly influenced by the time distribution of the peaks in electricity demand in different prosumer households) than for the modeled cases that include constraints on electricity self-sufficiency (which is mainly influenced by when the largest volumes of electricity are consumed). Similar results can be expected for other residential prosumers' load curves with similar characteristics. For household load curves such as those utilized in this study, the differences in timing and intensity of the peak load are believed to be influenced to a large extent by occupant behaviors. The hours of utilization of appliances and lighting differ for different prosumer households. However, the demand is of course also governed by typical day–night and morning–evening patterns, which create overlaps in electricity utilization between different households. A considerable share of the electricity consumption is attributed to refrigeration, ventilation, or, in some of the households, heating, which is hardly influenced by occupant behavior and therefore similar in every prosumer household. Including demand-side management (i.e., shifting the heat or electricity load in time) or household load profiles dominated by other types of loads, e.g., cooling loads in countries further south than Sweden, or considerably different occupant behaviors represents an interesting continuation of this study. In addition, the potential for controlled charging of electricity vehicles or dispatch of heat pumps in prosumer households could have interesting effects on prosumer electricity trading communities.

The present study assumes that the same conditions exist in all the prosumer households for placing PV battery systems on their property. Certain households might not have the required space available on their property to install PV panels, which would in turn increase the value of organizing households into electricity trading communities. Community electricity generation and storage systems could consist of one larger installation paid for and utilized by the whole energy community rather than several distributed installations as assumed in this work. Including economies of scale for investments in community-size, as compared to household-size, items of equipment is of particular relevance if thermal generation, as exemplified by local combined heat and power plants, is included in the analysis, potentially making electricity self-sufficiency more beneficial for larger aggregations of residential households, as compared to individual households.[22]

The present study optimizes prosumer PV battery investments and operation so as to minimize the cost for the prosumer. Analyzing a case with a fixed share of solar PV that is already installed (instead of joint optimization of PV and battery capacities as in our study), Barbour et al.[28] have shown that less storage capacity is required for a prosumer community energy storage system than for individual household storage systems, which is in line with the results of our study. In this work the incentive to avoid taxes and fees on bought electricity through local self-consumption of electricity has a greater impact on the optimization and operation of PV battery investments than do the peaks and lows in the hourly electricity price. Without the difference in price (including taxes and fees) paid for bought electricity and the reimbursement for electricity sold to the centralized system, the incentives to self-consume electricity in prosumer households and prosumer communities could be lower in a system with a different tariff system to that modeled for Sweden. For tariff systems where prosumer self-consumption is less incentivized, a PV battery system dispatch that is more adapted to the hourly electricity price is possible. An on average, higher electricity price and solar conditions different from those in Sweden could influence the size of the PV battery investments in both *Individual* and *Community* cases. Generalizations on whether or not prosumer households can benefit from being part of an electricity trading community in a country different to Sweden depend to a large extent on the characteristics and differences in household electricity consumption patterns as discussed in the first paragraph of this section and how well these match with the solar generation profile.

The interaction with the centralized system is an important aspect when analyzing decentralized electricity systems. In our modeling, the centralized system is represented by the hourly varying price curve to which the prosumer households respond. We find clear differences in trading patterns to the centralized system between individual and community prosumers. Further research is needed to investigate these different trading patterns from the perspective of the centralized electricity system. Another interesting aspect for further investigation is the coordination of prosumer households with the goal of providing grid services and value to the electricity system that individual prosumer households cannot provide (see also Morstyn et al[45]).

The strict constraint on the transfer capacity or self-sufficiency requirement in some of the modeling cases leads to results that pertain to large PV battery capacities. We model these cases to investigate whether prosumer electricity trading communities are more relevant for increased independence in terms of transfer capacity from the centralized system or for increased energy independence (self-sufficiency). The results of this study should be seen as a techno-economic maximal benefit to prosumer households, which also is an important information base to design policies for prosumer communities. Further work could investigate aspects as bounded rationality, myopic decision making or forecast instead of perfect foresight for the prosumer households.

As mentioned above, there are currently no regulations or policies for self-consumption within a prosumer electricity trading community in Sweden. To test the impact from the assumptions on taxing, we tested the modeling without any tax on electricity bought or fed into the grid and found no impact on the conclusions drawn from the comparison between individual prosumers and prosumers as part of an electricity trading community.

5 | CONCLUSION

In this work, we develop and apply a cost-minimizing prosumer community model to investigate the benefits of coordinating prosumers within electricity trading communities, applying real-life electricity demand data from 101 households in southern Sweden. The model optimizes investments in and the annual operation of residential PV battery systems. We show that if prosumers desire greater independence from the centralized grid or if the electricity transfer capacity to the centralized system is to be limited, the cost to meet the household demand using more electricity from decentralized PV battery systems is reduced significantly if the prosumers are organized into communities. This cost reduction is possible because not all of the prosumers have their individual hours of maximum load at the same time, which means that surplus electricity from one household can help to supply the peak demand of another household within a prosumer community, without affecting the capacity transfer to the centralized grid. With an electricity transfer capacity limit of 40% of the maximum demand, the cost savings for organizing into a community that comprises at least five households is 600 € per average prosumer and year, as compared to setting the limit on individual prosumers. Limiting the electricity transfer capacity further than 40% of the maximum demand results in even higher savings, whereas the benefit of organizing prosumers into communities at higher electricity transfer capacities or into smaller communities is low.

For the purpose of attaining a certain level of self-sufficiency, i.e., becoming more independent of centralized electricity generation, an aggregation of residential prosumers within an electricity trading community is not advantageous over remaining as individual prosumers. Different residential households have peak demands at different times, but this peak load represents only a small fraction of the total electricity that they utilize. To supply a certain share of this electricity demand locally (i.e., becoming increasingly self-sufficient) therefore requires very similar PV battery capacities at similar annual costs in both cases, for prosumers operating individually or prosumers being able to trade electricity amongst themselves within an electricity trading community.

The net trading pattern to the centralized electricity system differs between individual prosumers and prosumers organized in a community. For the community, the net exchange to the centralized system will result in fewer hours of trade but with a larger amount of electricity being traded during each trading event relative to the individual prosumers. Therefore, it is important to consider how the electricity from distributed generation systems is utilized locally when assessing the effects that a large proportion of prosumers can have on the centralized system.

As a continuation of this work, further analysis of the impact from various types of household loads is suggested, including different conditions for heating and cooling, electric vehicles, and possibilities for demand-side management. The different net trading patterns from prosumer communities, depending on their trading strategy, could be interesting to analyze from the perspective of the centralized electricity system. The option for prosumer communities to provide grid services is also an interesting direction for further research.

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APPENDIX A

Additional equations in the prosumer optimization model

Cost equations:

The annual electricity costs per prosumer households and annualized investment costs for PV battery systems are calculated as follows:

$$c_p^{el} = \sum_h \left(b_{p,h}^{Sys} * P_h^{Buy} - s_{p,h}^{Sys} * P_h^{Sell} + b_{p,h}^{Com} * P^{Com} \right) \quad \text{(A1)}$$

$$c_p^{inv} = pv_p * C^{PV} * a^{PV} + bat_p * C^{bat} * a^{bat} + inv_p * C^{inv} * a^{inv} \quad \text{(A2)}$$

where P_h^{Buy} is the price for prosumers to buy electricity from the centralized system, which is the hourly varying spot market price including VAT, an energy tax, and a distribution grid fee; P_h^{Sell} is the price for prosumers to sell electricity to the centralized grid, which consists of the spot market price and includes a small reimbursement from the distribution grid operator; P^{Com} is a small cost for trading within the electricity trading community, which is 100 times lower than the spot market price for electricity (this is as to avoid 'artificial' circular trading between prosumers in the model); $b_{p,h}^{Com}$ is 0 for the *Individual* cases; pv_p, bat_p, and $inv_p$are the sizes of the PV panels, batteries, and inverters in which the prosumer households invest; and C^{PV}, C^{bat}, and C^{inv} are the investment costs for the PV panels, batteries, and inverters, respectively. The annuity factors a^{PV}, a^{bat}, and a^{inv} are calculated as follows:

$$a = \frac{r}{1 - (1 + r)^{-n}} \quad \text{(A3)}$$

where r is the interest rate and n represents the lifetimes of the PV panels, battery systems, and inverters, respectively.

Household electricity balance equation:

An electricity balance equation ensures that the demand in each hour is met in every prosumer household:

$$Dem_{p,h} \geq pv_{p,h}^{direct} + dch_{p,h}^{internal} * \eta^{dch} + \left(b_{p,h}^{Com} - ch_{p,h}^{Com} \right) + \left(b_{p,h}^{Sys} - ch_{p,h}^{Sys} \right) \quad \text{(A4)}$$

where $b_{p,h}^{Com}$ and $ch_{p,h}^{Com}$ are fixed at 0 in the model runs for the *Individual* cases, $pv_{p,h}^{direct}$ is the part of the PV electricity that is directly utilized to meet the household demand in the same hour, $dch_{p,h}^{internal}$ is the electricity discharged from the household battery to meet the electricity demand in the same hour, and $ch_{p,h}^{Com}$ and $ch_{p,h}^{Sys}$ represent the amounts of electricity bought from the prosumer community or the centralized electricity system, respectively, to charge the prosumer battery.

Battery equations:

The storage levels and the charge and discharge of prosumer batteries are subject to the following equations:

$$st_{p,h} = st_{p,(h-1)} - dch_{p,h} + ch_{p,h} * \eta^{ch} \quad \text{(A5)}$$

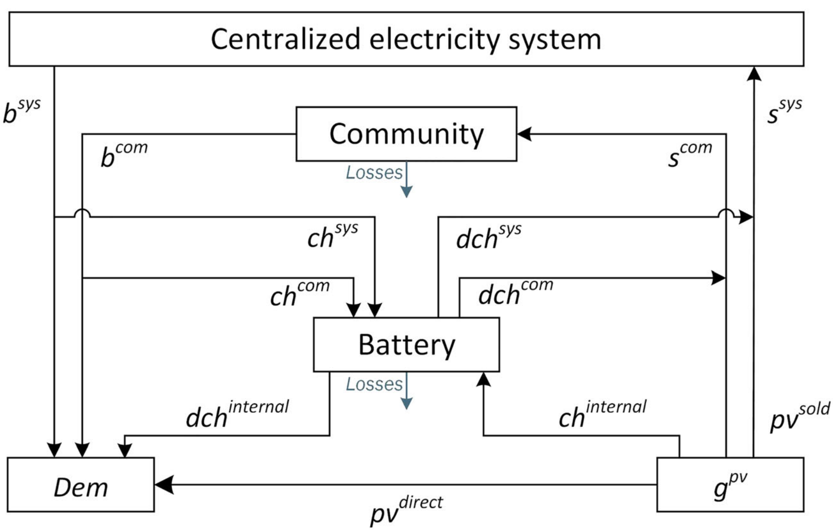

FIGURE A1 Schematic of the variables representing electricity generated in the prosumer households, charged and discharged to and from the battery, and sold and bought to and from the prosumer community (in the *Community* cases) and the centralized electricity system. [Colour figure can be viewed at wileyonlinelibrary.com]

$$st_{p,h} \le bat_p \quad \text{(A6)}$$

$$dch_{p,h} \le st_{p,h} \quad \text{(A7)}$$

$$ch_{p,h} = ch_{p,h}^{Sys} + ch_{p,h}^{Com} + ch_{p,h}^{interal} \quad \text{(A8)}$$

$$dch_{p,h} = dch_{p,h}^{Sys} + dch_{p,h}^{Com} + dch_{p,h}^{interal} \quad \text{(A9)}$$

where $ch_{p,h}^{Com}$ and $dch_{p,h}^{Com}$ are fixed at a value of 0 in the model runs for the *Individual* cases, $st_{p,h}$ is the storage level in the prosumer batteries, and $ch_{p,h}^{interal}$ is the electricity generated from the in-house solar panel and used to charge the household battery.

PV electricity and sell balance:

The electricity generated by the in-house PV panel in this model can be utilized directly within the same prosumer household, charged to the in-house battery, or sold. Electricity can be sold to the centralized electricity system or, in the *Community* cases, to other prosumers in the

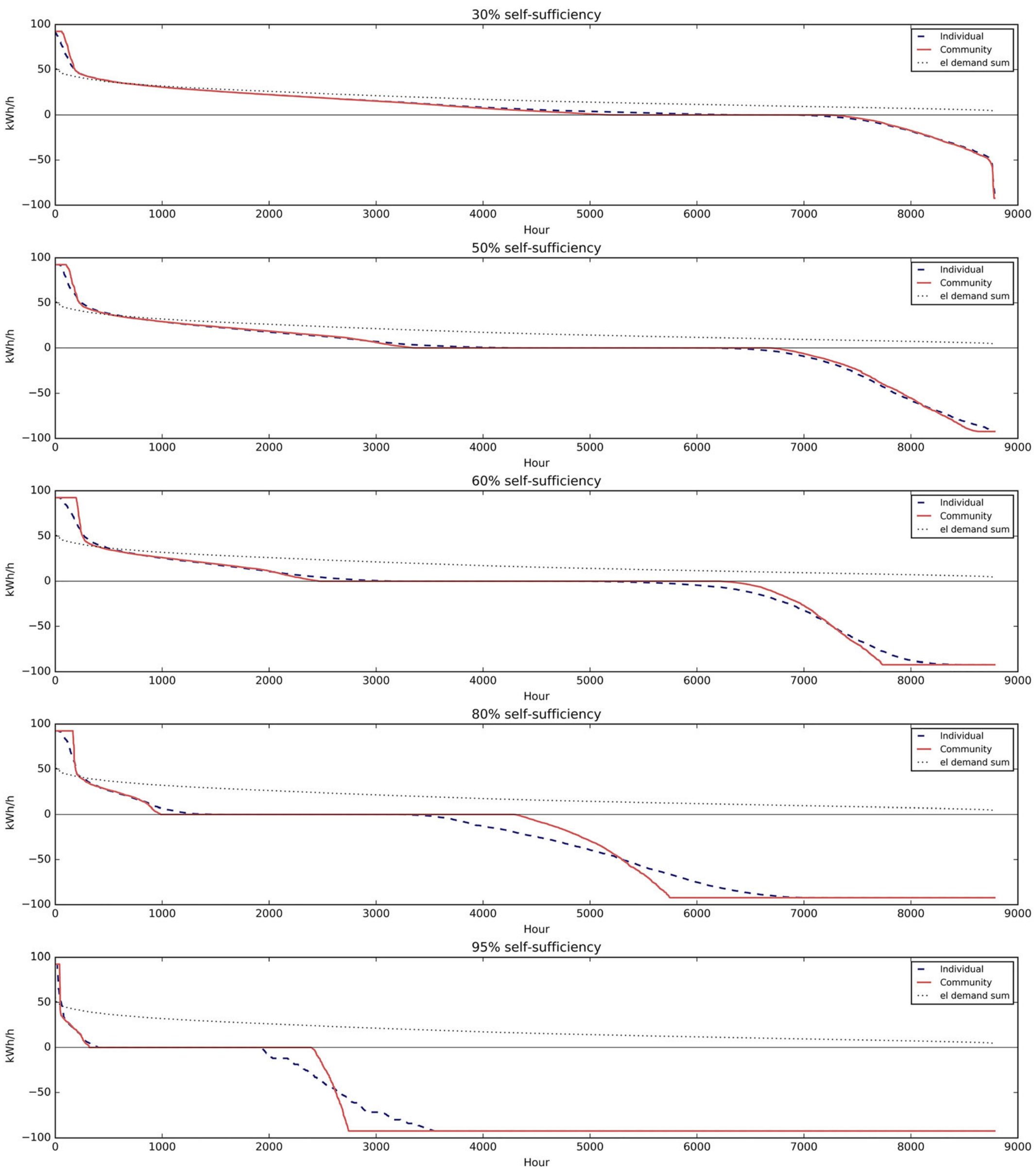

FIGURE A2 Net trading duration curves, comparing individual households (*Individual*) and households that are part of an electricity trading community (*Community*), for the case of 10 households and for different self-sufficiency goals, ranging from 30% to 95% of the total demand supplied by locally generated PV electricity (see Section 2.1.3). Note that a transfer capacity limit of 100% is set also for the *SelfSuff* cases so as to avoid extreme electricity selling peaks durinssg hours of high electricity prices. [Colour figure can be viewed at wileyonlinelibrary.com] electricity trading community. Electricity can also be discharged from the prosumer battery in order to be sold.

$$g^{PV}_{p,h} = pv^{direct}_{p,h} + ch^{internal}_{p,h} + pv^{sold}_{p,h} \quad (A10)$$

$$s^{Sys}_{p,h} + s^{Com}_{p,h} = pv^{sold}_{p,h} + \left(dch^{Sys}_{p,h} + dch^{Com}_{p,h}\right)*\eta^{dch} \quad (A11)$$

Figure A1 gives a schematic of the variables in the modeling, showing the different possibilities to utilize PV-generated electricity, meet the household demand, charge and discharge the prosumer battery, and buy and sell electricity from and to the centralized system or the prosumer community (in the *Community* cases).

APPENDIX B

Additional results for the *SelfSuff* cases

Similar plots as for the *MaxCap* cases (Sections 3.1 and 3.2) are shown in Figures A2 and A3 for the different *SelfSuff* cases.

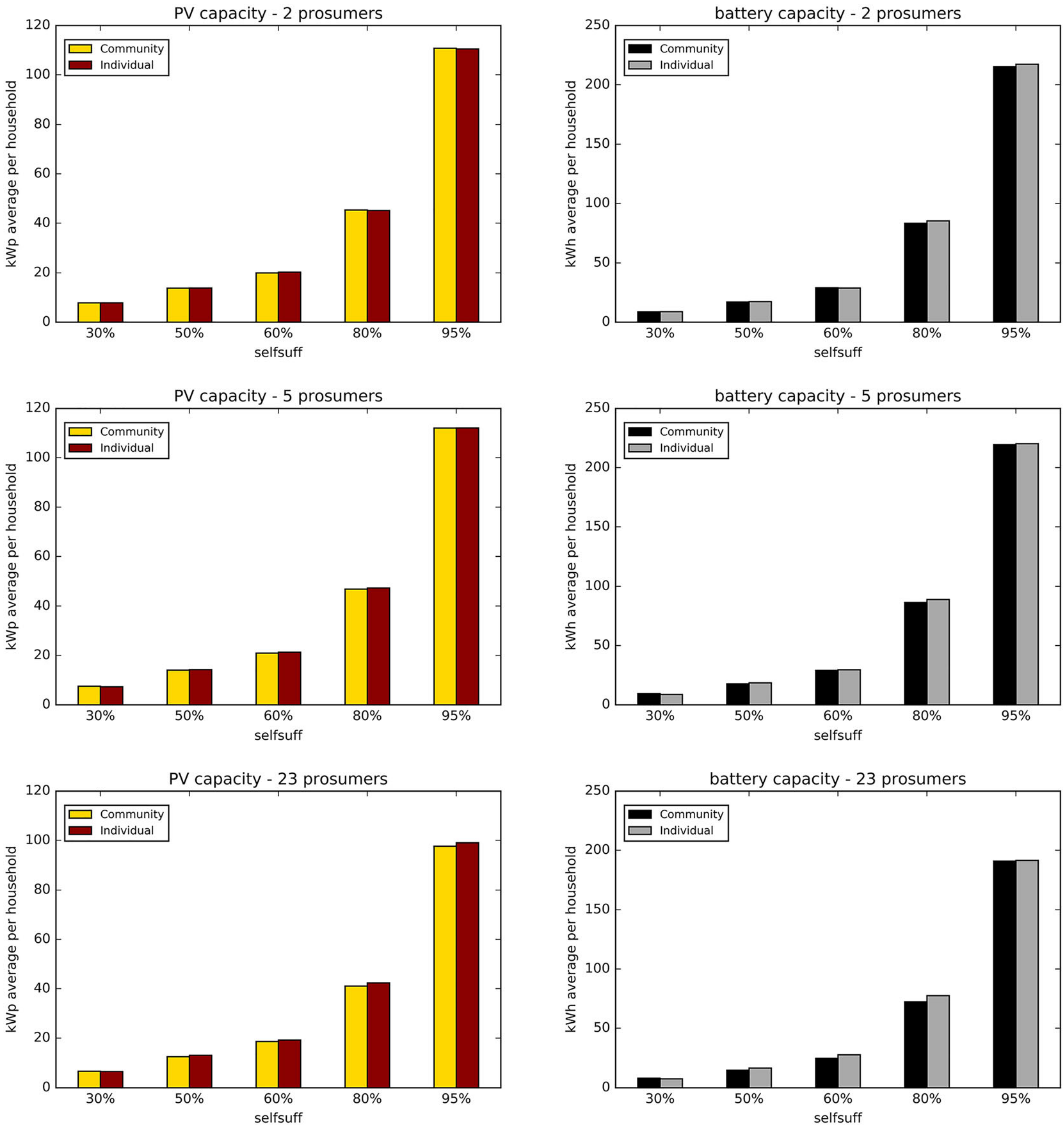

FIGURE A3 PV (left) and battery (right) capacities required per average prosumer to attain the different levels of self-sufficiency in the *SelfSuff* cases, individually or as a prosumer community, for the modeling of southern Sweden. [Colour figure can be viewed at wileyonlinelibrary.com]