Self-consumption enhancement of residential photovoltaics with battery storage and electric vehicles in communities

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Abstract

Grid-connected photovoltaic (PV) systems have been dependent on supporting schemes to be competitive with conventional electricity generation. Selling prices of PV power production are now lower than buying prices in several countries, making it profitable to match generation with household consumption. Self-consumption, calculated as in situ instantaneous consumption of PV power production relative to total power production, can be used to improve the profitability with higher buying than selling prices of electricity. Another measure, self-sufficiency, similar to self-consumption but calculated relative to the yearly consumption, can also be used. Battery storage and electric vehicle (EV) home-charging are interesting alternatives to increase the self-consumption, since the PV power production can be stored for later use. This study uses high-resolution consumption data for 21 single-family houses in Sweden and irradiance data for the year 2008 to examine the potential for battery storage and EV home-charging for communities of single-family houses with PV systems. The aim is to compare how self-consumption and self-sufficiency are affected by individual power grid connections for all households versus one shared grid connection for the whole community. These scenarios are combined with battery storage and EV charging (individual versus centralized). It is found that total consumption profiles level out when several houses are connected together, the self-consumption increases from 52 to 71 % and the self-sufficiency from 12 to 17 %. The size of a centralized storage can be reduced compared to the aggregated size of storages in every house to reach the same level of self-consumption. The potential for EV charging is limited due to mismatch between irradiance and charging patterns. The extra revenue from increased self-consumption with battery storage is too low for all the cases to justify an investment in batteries since the prices are still too high. With dedicated support schemes, higher buying prices of electricity and cheaper battery, PV-battery systems can still be an interesting solution in countries with high solar irradiance throughout the year.

Introduction

Historically, the high costs of electricity generated by photovoltaic (PV) systems made it necessary to have supporting schemes to make PV competitive on the electricity markets (IEA PVPS 2014). This is particularly important for small-scale grid-connected PV systems since they have a higher cost per installed power unit than large-scale centralized PV power stations. A common subsidy is Feed-in Tariffs (FiTs) for which the producer is guaranteed a fixed price per kWh of electricity fed in to the grid for an extended period of time (RES Legal 2012). The FiTs are now lower than the purchase price of electricity in some European countries which makes it more profitable to match periods of high electricity generation with household consumption, instead of selling excess electricity and buying it back when the consumption is higher (IEA PVPS 2014). A common term for in situ consumption of PV generated electricity is self-consumption. This can be used to improve the profitability of grid-connected PV systems, which is an important aspect to increase the number of installations. Increased self-consumption can also lower the stress on the power grid if the peak power from the PV system can be reduced.

The PV power generation often exceeds the power demand during the day, which means that excess electricity production is fed into the grid and sold to an electricity supplier and bought back again in the evening and night. A review of studies covering PV self-consumption showed a spectrum of "natural" self-consumption, i.e. without any energy management or storage, between 15 % and 56 % of the total PV power production (Luthander et al. 2015). The self-consumption is very much dependent on PV system size, location, yearly power consumption and power consumption profile, both over the day and over the year. Self-consumption can be increased with different methods, most commonly energy storage and load shifting. In the latter case, shiftable household appliances such as washing machines are put on when there is excess PV power production. There has been extensive research on battery energy storage combined with distributed generation, such as residential PV, for example in Divya & Østergaard (2009), Hoppmann et al. (2014), Belli et al. (2013) and Kousksou et al. (2014). A Swedish study similar to this one using same consumption and irradiance data was made by Widén & Munkhammar (2013). The study included both load shifting and a simple model of energy storage, but only considered battery storage in individual households. An economic assessment was also performed, which showed a potential of increased revenue on average no more than EUR 12 per year with load shifting and EUR 40 per year with a 5 kWh battery. An economic evaluation of a PV-battery system made by Bruch & Müller (2013) gave a return on the investment of 1.58 % per year with lead acid batteries of 2 kWh. In a compilation of battery storage systems for PV applications from several suppliers for PV made by pv magazine (2013), the lowest price of lead acid batteries was EUR 938 per kWh of usable capacity. It is also stated that a similar PV system without storage achieves a return which is more than twice as high as with storage. However, profitability of both PV- and PV-battery systems is very much dependent on factors such as electricity prices and economic support schemes. Sweden had in 2014 an electricity price significantly lower than several European countries (Statista 2015).

There is also potential for using electrical vehicle (EV) charging as a means for curtailing excess PV power production and thus increasing the hosting capacity of the local electricity grid (Denholm et al. 2013, ElNozahy & Salama 2014, Munkhammar et al. 2013). This is especially interesting since there is a current rapid world-wide expansion of the market for EVs and PHEVs (plug-in hybrid electric vehicle) (Cobb 2014). With a shortage of EV charging data, there is a necessity for obtaining synthetic EV charging data, and many models have been presented in the literature for this purpose (Richardson 2013). EV home-charging is of particular interest because of the proximity with grid-connected PV power production on a residential level (Munkhammar et al. 2013).

When several households share one connection to the power grid, their combined load is subject to random coincidence of the individual loads, which evens out stochastic fluctuations (Luthander et al. 2015). This means that PV power production from a house with excess power production can be consumed in another house with excess consumption. So far, most studies have been made on individual households and therefore, it is interesting to investigate how the smoothing effect affects the PV self-consumption in communities where several PV equipped houses are connected together.

AIM OF THE STUDY

The aim of this study is to determine how the self-consumption from grid-connected residential PV systems in a community is affected by using shared versus individual power grid connections combined with battery energy storages and EV charging. Models of houses with roof-mounted PV systems will be developed using high-resolution measured meteorological and consumption data for one year. The results will be used for a brief economic assessment of PV-battery systems and individual versus shared grid connection for the whole community. The exact values of self-consumption and self-sufficiency for the different configurations are not the main objectives of this study; instead, it is to investigate how self-consumption and self-sufficiency are influenced by different grid connections and storage solutions.

Methodology and material

The methodology section describes the different setups, data, methodology and models used for this study. Simulation models are implemented in MATLAB (2014). Self-consumption and self-sufficiency are defined in the first subsection. The six cases studied in this paper – two reference cases and four extended cases including storage solutions – are thereafter described. Descriptions of the collection of electricity consumption data, modelling of the PV systems and battery storages and simulation of electric vehicle use follow. Finally, a brief economic assessment of PV-battery systems and community versus individual grid connection are presented.

DEFINITION OF SELF-CONSUMPTION AND SELF-SUFFICIENCY

Self-consumption is in this study defined as the share of the PV power production consumed in the house on which it is mounted, compared to the total PV power production. The self-consumption is limited by the lowest value of either the PV power generation, denoted $P(t)$, or total household load, denoted $L(t)$. The length of the time step t is one minute in this study. The instantaneous consumption of the PV power production $M(t)$ can therefore be expressed as

$$M(t) = \min\left\{L(t), P(t)\right\} \tag{1}$$

Excess PV power production, i.e. when $P(t) > L(t)$, can either be fed in to the power grid or stored in a residential energy storage for later use. In the case of energy storage in the building, this can be extended to

$$M(t) = \min\left\{L(t), P(t) + S(t)\right\} \tag{2}$$

where $S(t)$ is the power to and from the storage unit, with $S(t) < 0$ when charging and $S(t) > 0$ when discharging. For both cases, the self-consumption φ_{sc} is defined as

$$\varphi_{sc} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} P(t)dt} \tag{3}$$

Similar to the calculation of self-consumption, another value called self-sufficiency φ_{ss} can be used to evaluate the PV system. Instead of the instantaneous consumed PV power relative to the total PV power production, self-sufficiency is calculated as the instantaneous consumed PV power relative to the total consumption in the household, i.e.

$$\varphi_{SS} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} L(t)dt} \tag{4}$$

In this study, the boundaries for the simulations are set at either household or community level. In the first case, excess power production from one roof-mounted PV system consumed in another household in the community is not counted as self-consumption whereas it is regarded as self-consumption in the latter case. The same is also valid for self-sufficiency. For the community level, self-consumption is based on aggregated load and generation data of the whole community. Local grid losses will be neglected.

STUDIED SYSTEMS

Several configurations of the household loads, batteries, and electric vehicles were used. Most of the houses are equipped with roof-mounted grid-connected PV systems. Each battery energy storage unit has a rated capacity of 4 kWh. For the case with shared battery energy storage, the rated capacity is 21 × 4 = 84 kWh. There are in total 21 EVs with an available battery capacity of 19.2 kWh. The EVs can only be charged. For further information, see following subsections.

Following cases will be simulated, where *case a* and *case b* are reference scenarios and *case c* to *case f* are extended scenarios including storage or EV charging solutions:

- Case a: reference scenario: Detached houses, individual power grid connections (Figure 1a).
- Case b: reference scenario: Detached houses, shared power grid connection (Figure 1b).
- Case c: detached houses, individual battery energy storages and individual grid connections (Figure 1c).
- Case d: detached houses, shared battery energy storage and shared grid connection (Figure 1d).
- Case e: detached houses, individual EV charging and individual grid connections (Figure 1e).
- Case f: detached houses, shared EV charging and shared grid connection (Figure 1f).

ELECTRICITY CONSUMPTION DATA

Consumption data from 21 detached single-family houses in Sweden over one year with a time resolution of 10 minutes were used for this study. The consumption data were collected by the Swedish Energy Agency during a monitoring campaign between 2005 and 2008 and cover approximately 400 households in Sweden, both apartments and detached single-family houses. Most data series are about one month, but 21 series are long-term measurements of roughly one year for detached houses. The measurement process and data processing is described by Zimmermann (2009).

This data set is the most exhaustive data set for electricity consumption in Swedish households available today. The consumption patterns might have changed since the measurements were performed, for example with new lighting sources and heating systems. This is however not crucial, since the focus of the study is the relative impact of different connections and storage solutions and not the exact consumption. Houses with electric heating have in general high annual consumption due to climate conditions in Sweden. In 2008, 31 % of all detached houses in Sweden had electric heating as the only heating source, a number which changed to 28 % in 2013 (Energimyndigheten 2009, Energimyndigheten 2014). The heating systems used in the houses are not specified. However, the total electricity consumption used for heating represent more than 50 % of the total yearly power consumption in 14 of 20 houses included in this study, as presented by Widén & Munkhammar (2013), indicating that electric heating is used in majority of all houses. The average consumption of the 21 detached houses is 14,500 kWh per house and year, which can be compared to

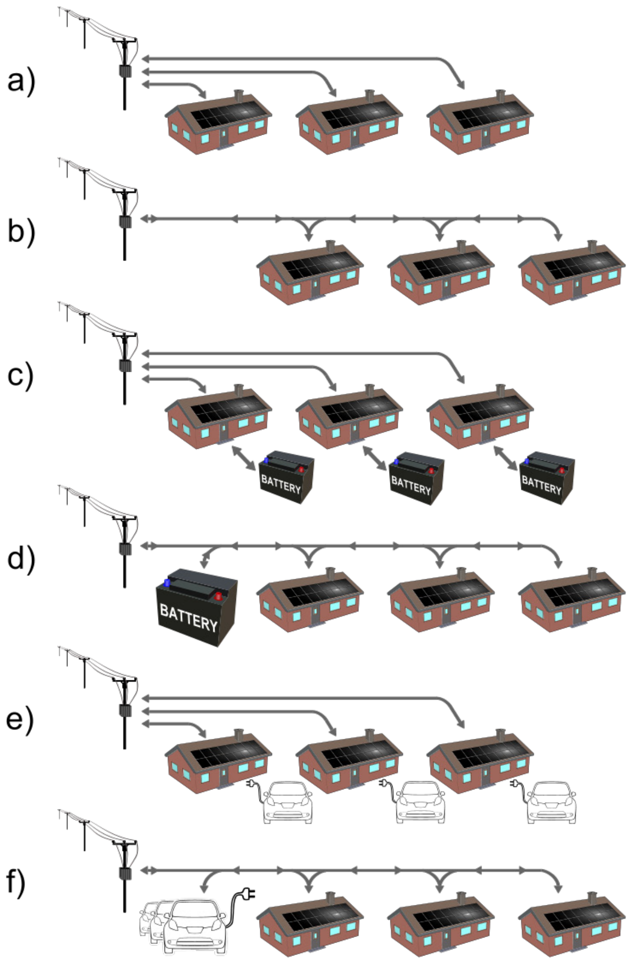

Figure 1. a)–f) Schematic illustration of the different cases. Individual or shared power grid connections and battery energy storage or electric vehicle charging. The arrows represent power flows. EVs can only be charged and do not supply power from the batteries to the houses or the grid.

the average electricity consumption for detached single-family houses in Sweden in 2008 of 15,800 kWh (Energimyndigheten 2009). Since the irradiation data, and thus the PV power production data, as well as the EV charging data are measured and simulated on a one-minute basis, the household consumption data was linearly interpolated to minute basis.

MODELLING OF PHOTOVOLTAIC SYSTEMS

The studied houses are not originally located in a community. Therefore, an example area in Uppsala (59.86 °N, 17.61 °E) with 21 detached houses, the same number as in the consumption data set, was selected to represent the community and to determine the individual azimuth, tilt and rooftop area suitable for PV installations. This area was chosen because high-resolution LiDAR (Light Detection And Ranging) data were available. The PV power production is based on measured high-resolution meteorological data from the Swedish Meteorological and Hydrological Institute (SMHI). The data used for this study were measured in 2008 in a meteorological station in Norrköping (58.58 °N, 16.15 °E) with a resolution of one minute. Missing values made up 0.26 % of the total data series, and were linearly interpolated between the two nearest points with specified values. The PV power production was simulated using a model implemented in MATLAB described by Widén & Munkhammar (2013). Cloud movement would have a smoothing effect on the aggregate PV power production during days with scattered clouds. However, the houses and their PV systems in the community are probably too closely located to have any major effect on aggregate power production on minute basis (Hoff & Perez 2010, Perez et al. 2011, Widén 2012). The same data set of irradiance is therefore used for all houses. With higher time resolution, the smoothing effect due to cloud movements may become significant.

The meteorological station in Norrköping (58.58 °N, 16.15 °E) is the one closest to Uppsala with high-resolution irradiance data and was therefore chosen. The yearly mean solar irradiance on a horizontal plane 2009–2014 for Norrköping was 1,000 kWh/m^2 and for Uppsala 976 kWh/m^2 according to the meteorological database STRÅNG (2015), a difference of 2.4 %. One can assume that this small difference will not influence the selection of roof segments suitable for PV installations.

Figure 2. Aerial LiDAR image of the studied area showing the yearly solar irradiance. The rooftops included in the study are numbered and marked with thick lines.

From the LiDAR data (50 points/m^2), tilt and azimuth angles (cardinal of each grid cell) of the rooftops of the houses were computed in ArcGIS (2013), each grid cell representing 0.4 × 0.4 m. To be able to choose well-suited parts of the rooftops, yearly accumulated global irradiation for each house was calculated in ArcGIS with the built-in tool Area Solar Radiation (Fu & Rich 1999). In this tool the annual solar irradiance is based on the solar path and the typical clearness of the sky at the studied location. Longitude is not needed but the latitude was set according to Uppsala (59.86 °N) and the diffuse fraction of the global normal irradiation was set to 0.52 after validation against a normal year dataset for Uppsala on the horizontal plane (Meteonorm 2015).

A LiDAR image of the housing area with numbered buildings and their annual solar irradiance can be seen in Figure 2. The potential area for solar energy installations was identified based on the annual solar irradiance. Initially the most commonly occurring azimuths were identified by finding the major peaks (>10 % of the height of the maximum peak) in a kernel density estimation, here with a proper bandwidth of 10 °. A kernel density function is a smoothed probabilistic function of a histogram (Rosenblatt 1956). Secondly only grid cells having higher global solar irradiance than 950 kWh/(m^2×yr) were identified. A new histogram of points of high solar irradiance (>950 kWh/(m^2×yr)) were produced ([5] in Figure 3), for which bins of more than 10 % of the maximum bin were assigned the same azimuth as for the nearest peak of the kernel density estimation ([2] in Figure 3). From this an area for each roof segment was computed as the sum of the bins multiplied by the tilted grid cell area. For the 21 houses, 1–3 peaks were identified corresponding to 1–3 possible segments of the roof to install PV on. PV installations were constrained to cover a maximum of 30 m^2 of a roof segment, corresponding to 4.5 kW$_p$ installed capacity, since the module efficiency was set to 15 % at standard test conditions. As a comparison, the mean size of a turnkey PV system for residential application in 2015, offered by the three largest electricity retailers in Sweden, is 4.7 kW$_p$ (Fortum 2015, E.ON 2015, Vattenfall 2015). Only the largest roof segment of each building was considered suitable for a PV installation and it should be at least 10 m^2 but max 30 m^2.

A summary of household consumption, electric vehicle consumption, rooftop orientations, size of PV systems and their power production can be found in Table 1. Optimal tilt for Uppsala is 44 ° and azimuth 0 ° (PVgis Europe 2014). The largest rooftop segment suitable for PV (global solar irradiance ≥ 950 kWh/(m^2×yr)) is also given to show the largest potential for PV installations (1 m^2 PV panel area = 150 W$_p$).

BATTERY MODEL

A model for charging and discharging of batteries was implemented in the simulation programs in MATLAB. The battery banks are only charged when there is excess PV power production and with no more power than the difference in instant production and consumption. The batteries are therefore not charged from the power grid.

The model selected is the kinetic battery model, which is applied on lead-acid batteries (Manwell & McGowan 1993). The kinetic battery model is also used in the software HOMER Energy (2012), which made it simple to verify the MATLAB model of the battery. HOMER Energy can only handle a limited number of loads and could therefore not directly be used for these simulations.

Maximum charge and discharge power is primarily based on instantaneous power production or consumption surplus. Moreover, the maximum charging and discharging power is dependent on the state-of-charge (SOC) of the battery, i.e. the maximum charging power decreases the higher the SOC becomes and vice versa during discharge. The SOC is calculated in a range of 0–100 % and specifies how much energy that is stored in the battery relative to the maximum storage capacity. The maximum charging and discharging current is also dependant on a few constants. Therefore, it might not be possible to store all excess PV power production even though the battery is not fully charged.

In contrast to the battery model used in this study, a simpler one would probably overestimate the improvement of self-consumption and the use of the battery. In a simple model, all surplus PV power production can be stored and consumed when the consumption exceeds the production, as long as the maximum or minimum state of charge is not reached. This would lead to rapid charge and discharge when both over- and underproduction occurs during daylight hours, due to strongly fluctuating PV power production such as in Figure 4. With a more sophisticated battery model, such as the one used in this study, the rate of charge and discharge is slower and cannot fully match large fluctuations. This results in a lower total energy flow into and out from the battery and thus a lower and more accurate estimate of the self-consumption.

The battery banks modelled in this study are only used for short-term storage, i.e. within one day. Weekly or seasonal storage would require either much larger battery banks or another storage technology (Ibrahim et al. 2008). The battery banks

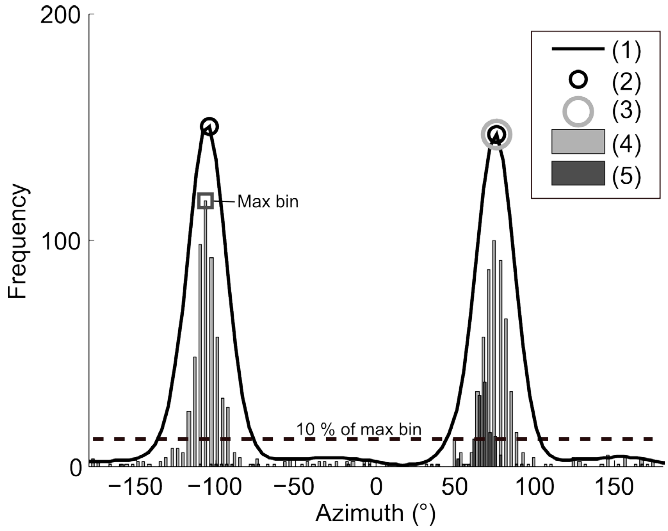

Figure 3. Example of identification of most suitable roof segment for PV installation and its azimuth angle for one house. (1) is the Kernel density estimation of the azimuths of all grid cells of the roof, (2) is the identified azimuths of the (in this case two) roof segments, (3) marks the azimuth of the most suitable roof segment, (4) is a histogram of all the azimuths and (5) only for grid cells with an annual solar irradiance of >950 kWh/m²yr. Bins of (5) reaching above the dashed line (10 % of max bin) are assigned to the nearest azimuth peak along the x-axis.

Table 1. Houses, electricity consumption, orientations and sizes of the rooftops and installed PV power. Definition of azimuth angle: [–90°, 0°, 90°] = [east, south, west], tilt angle: [0°, 90°] = [horizontical, vertical].

House no.	Consumption house (kWh/yr)	Consumption EV (kWh/yr)	Rooftop azimuth (°)	Rooftop tilt (°)	Rooftop area suitable for PV (m^2)	PV system (kW_p)
1	7,297	2,286	-15	27	43.8	4.50
2	9,978	2,041	-19	24	87.0	4.50
3	11,384	2,288	-15	32	42.5	4.50
4	21,365	1,989	-19	31	41.0	4.50
5	20,824	2,154	73	26	32.5	4.50
6	8,189	2,377	75	32	27.0	4.05
7	21,521	2,151	74	30	37.0	4.50
8	22,513	2,039	72	32	21.5	3.23
9	18,610	2,071	–	–	8.5	–
10	13,533	2,668	74	22	42.4	4.50
11	16,941	2,423	-15	32	44.8	4.50
12	17,485	1,952	-17	26	69.5	4.50
13	15,149	2,246	-15	26	69.0	4.50
14	12,384	1,898	–	–	0.2	–
15	12,281	1,998	-19	32	52.6	4.50
16	9,747	2,066	–	–	6.1	–
17	12,580	2,271	-15	42	24.0	3.60
18	12,189	2,062	-16	42	40.4	4.50
19	5,646	2,033	73	30	15.7	2.36
20	4,492	2,374	31	34	71.4	4.50
21	31,222	2,221	76	27	20.3	3.05

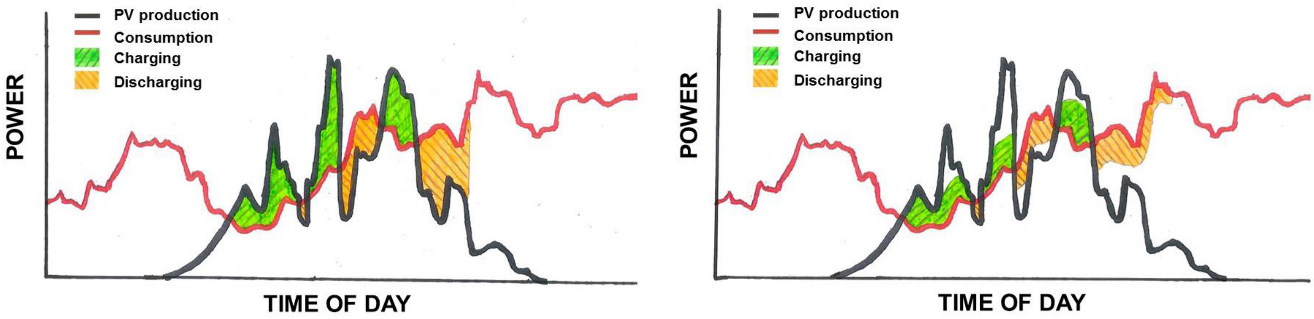

Figure 4. Illustration of different battery models. To the left is a simple model applied where the battery is charged or discharged with the difference between PV power production and consumption, as long the maximum or minimum SOC has not been reached. To the right is a more sophisticated battery model, where the charge and discharge power depends on both the difference in power production and consumption, and the instantaneous SOC and current limitations.

Table 2. Parameters for the EVs.

Probability taking EV when "away from home"	0.2
Available battery capacity	19.2 kWh
Average electricity use when driven	0.2 kWh/km
Charging power	2.3 kW

have installed capacities of 4 kWh each, of which 2.8 kWh is usable capacity since minimum SOC is set to 30 %. This extends the lifetime of the batteries, since frequently occurring low SOC will speed up the decrease of battery capacity. The roundtrip efficiency, i.e. efficiency for charging times efficiency for discharging, was set to 80 %.

No self-discharge and cycle life of the batteries is taken into account in this study. These are aspects that could further improve the model. In a study by Jossen et al. (2004), the self-discharge of lead-acid batteries was found to be 3–4 % per month. This means that the self-discharge is low when using the batteries for daily storage. The cycle life of lead-acid batteries is however rather poor in comparison with lithium-based ones, which is an important aspect for the service life of a residential battery storage system (Krieger et al. 2013).

ELECTRIC VEHICLES

In this study synthetic EV charging patterns on a one-minute basis were generated with a Markov-chain model for EV home-charging developed in Grahn et al. (2013). This model is an extension to the Widén Markov-chain model for generating synthetic household electricity use data (Widén et al. 2009, Widén & Wäckelgård 2010). A Markov-chain model is set up with N predefined states and a certain probability for transitioning from one state to another. This can be used to generate time-series of state-occupancy. In the Widén model each state represents activities for each individual such as "sleeping", "cooking" and "watching TV". The EV home-charging model is based on the assumption that the EV is taken out driving a certain percentage of the times when the Widén model enters the state "away from home". The EV is then assumed to be driven until the state changes to any other state than "away from home", at which time the EV is returned home and plugged in. The assumption was then that the EV was charged until fully charged or taken out driving again. The charging patterns do not depend on PV power production and the vehicles can only be charged, i.e. they cannot be used to store electricity for later consumption in the household. Simulations of vehicle-to-grid (V2G) is not included in this study since the EV model is adapted for charging whenever the EV is at home to minimize range anxiety (since the EV may be taken out driving at any time). However, implementation of V2G could be interesting for future studies.

While driven the EV is assumed to have an average fuel consumption, and if the EV would run out of battery capacity while still "away from home", it is assumed that the EV has stopped during the trip and then depleted the battery upon arrival at home. For simplicity only one individual of each household used the EV. The parameters for this particular study are shown in Table 2. The parameters were setup to mimic an EV similar to Nissan Leaf equipped with estimated typical average fuel consumption, "away probability" and the charging power of a typical Swedish one phase charging station, see (Grahn et al. 2013) for more information.

ECONOMIC ASSESSMENT

This brief economic assessment will only regard PV-battery systems and not PV-EV systems, since EVs are purchased for transportation purposes rather than for maximizing the PV self-consumption. The profitability of a PV-battery system is dependent on several variables, most notably selling and buying price of electricity and initial costs related to the battery and PV system. In this assessment, the cost of the PV system and maintenance or replacement costs of the battery system will not be taken into consideration. The assessment is therefore solely based on buying and selling prices of electricity, self-consumption and PV power production. The four scenarios compared are

- Case a: individual grid connections, no battery (cf. Figure 1a).
- Case b: shared grid connection for the whole community, no battery (cf. Figure 1b).
- Case c: individual grid connections, individual battery storage (cf. Figure 1c).

- Case d: shared grid connection, shared battery storage for the whole community (cf. Figure 1d).

Net present value is often used to evaluate an investment, but will not be calculated in this paper. This is due to the uncertainties of future electricity prices, changes in future consumption patterns and rate of return. The latter is up to the customer, if the investment in a PV or PV-battery system is motivated by for example economic or environmental concerns. Furthermore, degradation of the battery storage has to be considered since it would decrease the self-consumption, as well as the likelihood that the battery storage has to be replaced within the life-length of the PV system.

One way to compare shared versus individual storage is to determine the battery capacities required to reach a certain level of self-consumption. In this study, a self-consumption for the whole community of 75 % has been chosen for the comparison. When using individual batteries, the aggregated self-consumed electricity in kWh for each house has been divided with the total production of all PV systems.

In the simulations, the use of the battery is calculated as well as the losses related to this. Stored electricity, excluding losses, is self-consumed instead of fed into the grid and sold, and therefore increases the value by an amount equal to the difference between buying and selling price of electricity. Losses in the battery due to charging and discharging efficiency have the same value as sold electricity, since they lower the amount of electricity fed in to the power grid, but do not contribute to increased self-consumption. The battery cycle efficiency is set to 80 % and no self-discharge or battery degradation is regarded. If the usable energy stored, i.e. the energy that can be consumed, and the losses are denoted Q_{usable} and Q_{losses}, respectively, and the selling and buying price of electricity R_{sell} and R_{buy}, respectively, the total return $R_{battery}$ due to the battery energy storage can be calculated as

$$R_{battery} = Q_{usable} \times \left(R_{buy} - R_{sell}\right) - Q_{losses} \times R_{sell} \quad (5)$$

The extra revenue Rshared that comes from the increased self-consumption in a community with a shared connection to the power grid in comparison with individual grid connections can be calculated as

$$R_{shared} = \left(\varphi_{sc,shared} - \varphi_{sc,individual}\right) \times \left(R_{buy} - R_{sell}\right) \times P_{total} \quad (6)$$

where $\varphi_{sc,shared}$ and $\varphi_{sc,individual}$ are the self-consumption for a community with shared and individual connections, respectively, and P_{total} is the total PV power production.

The extra revenue due to shared grid connection for the whole community results from the difference in self-consumption between a shared electricity meter and the aggregated self-consumption of electricity meters of every house. Since it is difficult to determine from where the extra revenue comes from; whenever it is the producers or the consumers, one solution is to use the revenue for services which every household benefits from, for example garbage removal or snow clearance. The best way to divide the extra revenue is however out of scope of this study.

The cheapest battery system for PV applications in the compilation made by *pv magazine* (2013) cost approximately EUR 660 per kWh capacity (EUR 938 per useful kWh capacity) with a minimum SOC of 30 %.

The electricity prices for buying and selling can be found in Table 3. The buying and selling prices are based on the mean of monthly spot prices on Nord Pool Spot (2015) between January 2010 and December 2014 to compensate for price fluctuations between single years. Taxes and fees are thereafter added to the buying price. The electricity prices are given in both Swedish krona and Euro, where SEK 1 = EUR 0.105 (status January 14th, 2015). The energy tax is a mean for 2010–2014. The grid fee differs for different locations in Sweden and over time and the value used here is valid for Uppsala in 2014. Producers of renewable energy in Sweden can apply for electricity certificate and the value used in this simulation is a mean for 2010–2014 (CESAR 2015).

Results

In the following subsections, the results of the simulations of self-consumption and self-sufficiency for the 21 houses are presented together with a brief economic assessment of PV-battery systems. Time is presented as UTC + 1 h but without daylight saving time. The section ends with the economic assessment.

PV POWER PRODUCTION AND CONSUMPTION

The calculated yearly PV power production for each household is presented in Figure 5. The total PV power production for all 21 houses is 73,000 kWh/year. One can see that some houses do not have any PV system installed, which is due to

Table 3. Specification of the buying and selling electricity price.

Price specification	SEK per kWh	EUR per kWh	Reference
Spot price (sell & buy)	0.38	0.040	Nord Pool Spot (2015)
Energy tax (buy)	0.29	0.030	Ekonomifakta (2015)
Grid fee (buy)	0.20	0.021	–
Electricity certificate (sell)	0.22	0.023	CESAR (2015)
VAT 25 % (buy)	0.22	0.023	–
Total (R_{buy})	**1.09**	**0.114**	
Total (R_{sell})	**0.60**	**0.063**	

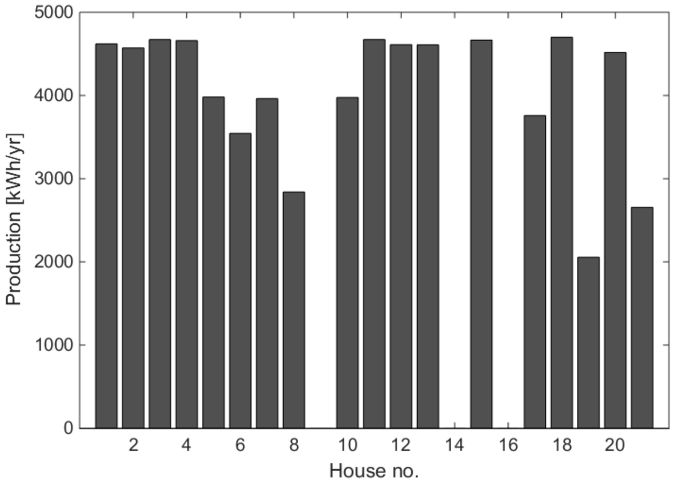

Figure 5. Yearly PV power production for the 21 houses.

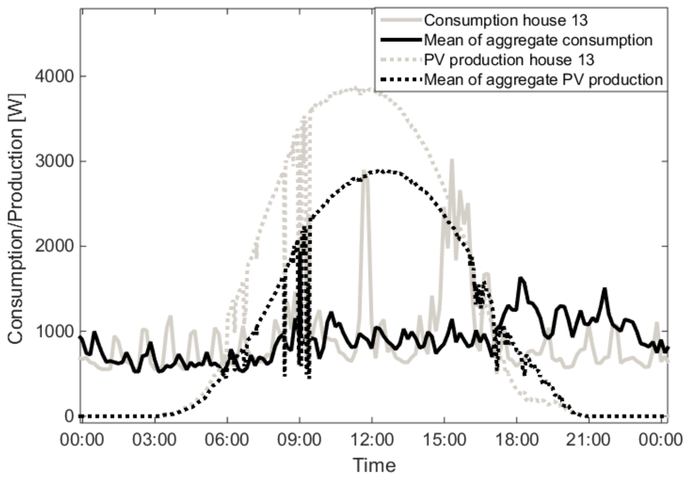

Figure 6. Electricity consumption and PV power production in house 13 and mean of aggregate consumption for all houses on the 9th of July 2008.

too low yearly irradiance of the rooftop segments. The total consumption of the 21 houses over the year was approximately 305,000 kWh and the mean consumption 14,500 kWh, which can be compared to house 13 which had the closest yearly consumption: 15,100 kWh. The smoothing effect of aggregating the consumption for all houses can be seen in Figure 6, where the mean of the aggregate consumption and consumption of house 13 over one day as well as the power production for PV system installed on house 13 and mean of aggregate PV power production are shown. Note that the PV systems differ in installed capacity, tilt and azimuth. PV systems oriented to the east have their maximum power production in the morning and systems oriented to the west in the afternoon. During this period of time, it is clear that the consumption for one house is more fluctuating than the mean consumption for all the houses. The same pattern is also valid for the other houses and for other times of the year.

In Figure 7 the mean daily power consumption and production is shown, both for house 13 and mean of the aggregate consumption and production for all houses. Since each point in the plot represents a mean of 365 values from the whole year, the output curve will be smoother than for a single day. The right picture includes both the household consumption and EV charging. The most significant difference in the consumption profile with and without EV charging is in the evening, since the EVs are mostly charged after working hours. During midday when the irradiance is at its highest, the difference in consumption with and without EVs is very small.

SELF-CONSUMPTION AND SELF-SUFFICIENCY

Simulated self-consumption and self-sufficiency for the different cases (see *Studied systems* in section *Methodology and Material)* is presented in Figure 8. It can be seen that the self-consumption increases remarkably only by setting the boundaries at community level instead of at household level. The increase when using battery storage is slightly higher for the case with individual grid connections than for one shared grid connection. It is obvious that battery storage has a higher potential than EVs of increasing the self-consumption, when using the electric vehicle charging model for home charging as in these simulations.

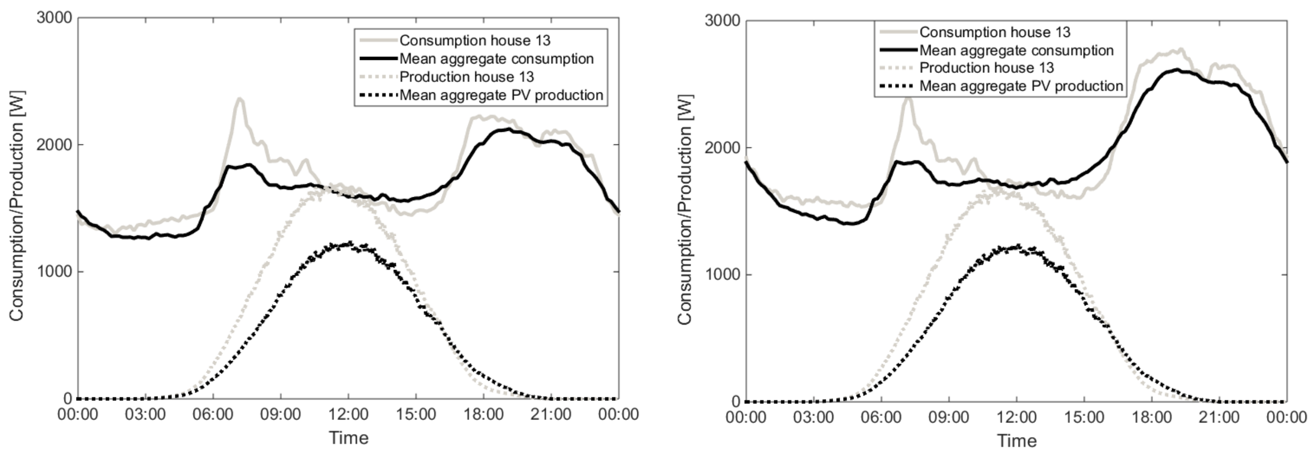

Figure 7. Yearly mean PV power production and consumption over one day. To the left without and to the right with EV charging.

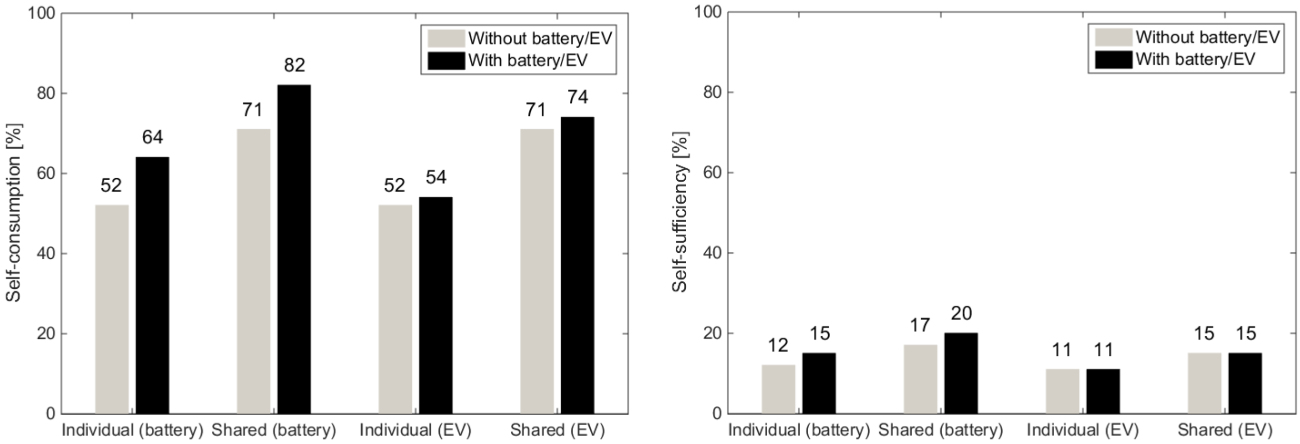

Figure 8. Self-consumption (left) and self-sufficiency (right) for the community with battery storage or EVs. Reference scenarios (case a and case b) in grey. Scenarios with individual (case c and case e) and shared (case d and case f) grid connections separated. Note that self-sufficiency is calculated only relative to the power consumption in the households. The power consumption of the EV charging is not taken into consideration.

Table 4. Size of battery storage needed to reach 75 % self-consumption. Yearly use of battery storage, losses and resulting revenue, both totally and per installed kWh battery capacity.

Grid connection and battery	Storage capacity	Use of storage (excl. losses)	Storage losses	$R_{battery}$	$R_{battery}$ per kWh battery
Individual (case c relative to case a)	144 kWh (8×18)	18,600 kWh	4,700 kWh	EUR 653	EUR 4.6
Shared (case d relative to case b)	17 kWh	3,600 kWh	900 kWh	EUR 127	EUR 7.5

The results for the self-sufficiency show a small contribution of the PV power production to the power consumption in the households and EVs. This is due to two things: either too small PV systems or too high mismatch between electricity production and consumption. The mismatch is particularly high for electric heated houses since the high power consumption in the winter coincides with low PV power production. With EVs, the improvement is only one percentage point. The self-sufficiency is calculated only relative the household power consumption. If the consumption of the EVs would have been taken into consideration, the self-sufficiency would be less in the scenario with EVs than without due to the considerable extra power consumption and the mismatch between PV power production and EV charging.

ECONOMIC ASSESSMENT

The results of the economic assessment of PV-battery systems case c and case d are shown in Table 4, where the revenues are compared with the reference scenarios case a and case b, respectively. To reach a self-consumption of 75 %, which is used as example for the comparison, each house with a PV system needs to have a battery bank of 8 kWh. This means that the aggregate size is 144 kWh for all 18 houses equipped with PV systems, cf. Table 1, when they have individual storages and grid connections. With individual grid connections, houses without a PV system will not use the battery. Three houses were considered to not have any PV system, cf. Table 1, and they are therefore excluded. With a shared battery storage and shared grid connection, the battery capacity is found to be 17 kWh to reach a self-consumption of 75 %. These values are found though an iterative process. Battery system cost has not been taken into account in this economic evaluation. The yearly revenue of using the batteries $R_{battery}$ can now be calculated with Equation 5 and the buying and selling prices specified in subsection *Economic assessment* in section *Methodology and material.*

With revenue of EUR 7.5 per year for the shared storage and a battery price of EUR 660 per kWh capacity, no maintenance and replacement costs and linear payoff, it would take 88 years before the battery solution would be profitable. In this short calculation, the discount rate is set to zero. This price of a complete system suitable for residential PV installations is however higher, since the price of the battery does not include peripheral equipment such as inverter and charge control mechanism.

The increased revenue solely due to higher self-consumption in the community with shared instead of individual grid connections can be calculated using Equation 6. This calculation is valid for a community without battery energy storage (case a and case b). The total PV power production for the community is 73,000 kWh on a yearly basis. The total extra revenue is

$$R_{\text{shared}} = (0.71 - 0.52) \times (0.114 - 0.063) \times 73{,}000 = \text{EUR } 707 \quad (7)$$

for the whole community. If the revenue instead is split up per household, it would be

$$R_{\text{shared,per house}} = \text{EUR } 34. \quad (8)$$

Compared to the total extra revenue R_{battery} of EUR 653 and EUR 127 for shared and individual battery storage, respectively, the increase in yearly revenue solely due to the change from individual to shared grid connection R_{shared} is more profitable with EUR 707 for the whole community.

Discussion

The results show that the self-consumption for a community increases significantly with one shared connection to the power grid instead of individual grid connections. Battery storages are more efficient at the community level, although the storage sizes could be individually sized for each house to optimize the self-consumption. The case with one grid connection and electricity supply contract per home is certainly the most common in the Swedish residential sector. The whole community would profit if households in a community would change to a joint electricity agreement because of the higher aggregated self-consumption. The individual houses can thereafter have their own electricity meters handled by the community. The impact on the power grid would however not change since all houses still use a shared grid connection in the distribution grid. Increased self-consumption and yearly revenue of the community means lower revenue for the power supplier.

The economic assessment indicates that the use of batteries in residential PV is most certainly not profitable with the electricity prices used in this study and with the assumed current cost of batteries when no subsidies are taken into consideration. With prices of residential battery storages in the order of 100 Euro per kWh, grid connected PV-battery systems would be interesting alternatives in Sweden without subsidies, based on the results of this study. The profit of storing electricity is very much dependent on the price difference between the buying and selling price, and it is currently too low to justify the investment of a battery system. Higher price differences between buying and selling prices of electricity combined with dedicated financial support will make PV-battery systems more profitable, but the battery prices must nevertheless be much lower if PV-battery systems shall be an economically viable solution in the future. Another important reason is the difference in power demand during summer and winter. Whereas use of the battery energy storage is high in the summer months, it is very rarely used in the winter due to higher power consumption and significantly lower PV power production. In regions with more stable solar irradiance over the year, for example in southern Europe, use of energy storage would probably be higher and thus increase the yearly revenue.

Driving and charging patterns of electric vehicles and residential PV power production do not coincide well with each other as seen in the *Results* section. This shows that an introduction of home-charged EVs have a negligible effect on PV power self-consumption on both individual and aggregate household level. However, with better synchronization between PV power production and charging, the self-consumption could certainly be increased. This requires probably forecasts of PV power production and smart charging schemes, and puts demand on people to foresee their driving habits.

In future research, the vehicle-to-grid concept could be incorporated in to the model. Also, it would be interesting with simulation models using other types of batteries such as lithium-based ones, since for example efficiency, cycle life and degradation will be improved compared to the models of lead acid batteries used for these simulations. With large fluctuations of the electricity prices over the day, it may also be profitable to store cheap electricity and use it when the price is higher. This would however lead to a rising number of charging cycles, making cycle life and degradation even more important.

A future development of the PV-battery concept is to use "old" batteries from electric vehicles, since the number of electric and plug-in vehicles is rising rapidly. The energy density is much less important for stationary than for mobile applications. Therefore, batteries no longer suitable for vehicles may become accessible for stationary applications at a lower price than for a completely new battery system. A more detailed economic assessment of PV-battery systems also has to be performed.

The method for identifying the best roof segments for PV on each building is promising. The root mean square error (RMSE) of the azimuth is 2.1 ° for the roof segments identified as appropriate for PV systems. Although this method works well for residential houses with 2–4 different roof segments, more complex buildings with several roof segments would require spatial clustering in order to separate roof segments of similar azimuth but different locations. This problem is apparent for house 3 (cf. Figure 2), for which the identified roof area suitable for PV deployment actually should be divided into two roof segments. A refined method could be used for detailed PV potential studies of urban regions for which high resolution LiDAR data are available.

Conclusion

The main conclusions of this study can be summarized as follows: (*i*) The self-consumption of PV systems installed on single-family houses in a community in Sweden rises significantly when all houses use a shared power grid connection instead of one connection per house. (*ii*) The size of battery storage can be considerably reduced when using shared storage and grid connection instead of individual storage and grid connection to reach a certain level of self-consumption. (*iii*) The improvement of self-consumption when using electric vehicle home charging is limited due to mismatch between charging patterns and solar irradiance profile. (*iv*) Battery prices are still too high to motivate installations of battery systems in Sweden without subsidies or higher electricity prices.

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