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Effects on the self-consumption and self-sufficiency for household solar producers when introducing an electric vehicle

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Summary

The aim of this study is to analyse how an introduction of an EV affect the self-consumption and self-sufficiency for households with in-house electricity generation from solar PV. The model results shows that there is a possibility to use the EV battery instead of a stationary battery and still reach the same levels of self-consumption and self-sufficiency for households with solar PV and an EV. The possibility for the EV to discharge electricity back to the household by V2H technology is proven to be necessary for the ability to use the EV as storage instead of a stationary battery.

Keywords: photovoltaic, solar energy, modelling, energy storage, V2H (vehicle-to-home)

1 Introduction

The acquisition of an EV to a household with solar PV electricity generation can have effects on the levels of self-consumption and self-sufficiency for that household. Self-consumption of PV-generated electricity has been defined by Luthander et al. [1] as the share of locally generated electricity that is being consumed in-house, while self-sufficiency is defined as the share of total demand that is being supplied by in-house-generated electricity. As self-consumption of the generated electricity is economically advantageous for households that have solar PV, since other costs (e.g., electricity taxes and grid fees) that are added to the end-user price for electricity can be avoided, ways of increasing self-consumption are of interest [2].

Studies investigating the introduction of an EV to a household with solar PVs have shown that it can result in a lowering of the households self-sufficiency, primarily due to the mismatch between EV charging demand and solar PV generation [2, 3]. Other studies looking at the economics of optimised charging strategies have shown that such strategies can be economically beneficial for the household [4-8]. Furthermore, the inclusion of vehicle-to-home (V2H) technology has been shown to further increase the economic value of a charging strategy, as compared to unidirectional charging [5, 7].

The majority the studies mentioned above (e.g., [2, 4-6]) have used real-life data regarding the households' electricity consumption (excluding EV charging demand) and solar PV generation levels. However, none of these studies used real-life data, e.g., Global Positioning System (GPS) measurements, as the basis for EV driving patterns. Instead the studies assume either a fixed time period during which the vehicle is at home, or use a stochastic modelling approach to generate different driving patterns depending on lifestyle [2, 4-7]. The driving patterns in these studies are most likely based on general travelling patterns with different travel surveys used as background, even though none of the studies refers to any specific survey.

Data from self-reported travelling surveys often under-estimate the frequency of trips and focus on the travel behaviours of persons during a single day rather than the movement patterns of cars over longer time periods [9]. Elango et al. [10] have shown that individual car movements vary considerably from day to day. Such behaviour could be of importance when estimating the impacts on self-sufficiency and self-consumption, not only for an average day but for a longer time span, such as one year. A more detailed measurement of individual car movement patterns can be achieved by measuring the time of travel and position with a GPS over a longer time period. However, a limited number of representative GPS-measured data-sets is available for passenger vehicles in which the data have been gathered and made available for scientific purposes, with most having been collected over a short time period and/or for a smaller geographical area [11-15]. There are only a few studies that have focused on the charging patterns of EVs based on GPS travel data (e.g., [16]). However, the study carried out by Wu [16] does not consider electricity management in households specifically, instead focusing on the role of work-place EV charging.

As shown, there is a lack of studies that have investigated self-sufficiency and self-consumption using real-time driving data. The present study addresses this gap in the literature by employing real-time GPS measurements of vehicles' driving patterns in combination with measured data for household electricity consumption and modelled PV electricity generation profiles, as applied to Swedish households. In contrast to the previous studies, the present study uses 400 combinations of unique households and vehicles. The aim of this study was to answer two main questions:

- How does the introduction of an EV affect the self-consumption and self-sufficiency levels of households with in-house electricity generation from solar PV?
- Can an EV complement or alternatively replace a stationary battery for storage of electricity in households with in-house electricity generation from solar PV?

2 Modelling

This study uses an optimisation model for the electricity system in a household. The model covers the electricity load for the household and charging of the EV, a stationary battery, and PV electricity generation. Optimisation is carried out with respect to maximising the households' self-sufficiency, and thereby, also the level of self-consumption of in-house generated electricity. Thus, no economic factors are taken into account in this study. The model is optimised for 400 combinations of households and EVs, for 30 different combinations of sizes of the PV system and stationary battery for households without an EV, and for 120 different combinations of sizes of the PV system, stationary battery, and EV battery for households with an EV. A temporal resolution of one hour is used, and the optimisation is performed with perfect foresight over one year. Fig. 1 illustrates the structure of the model and the main input and output parameters.

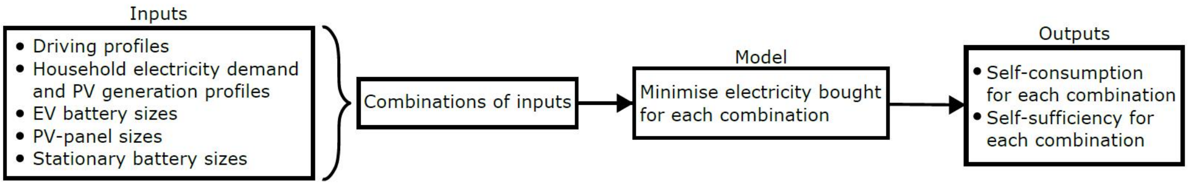

Figure1: Schematic of the main modelling elements applied in this work including input and output parameters

2.1 The model

In the model formulation, the amount of electricity imported from the grid to a household is minimised. As a result of the formulation, the dispatch of the EV battery and the stationary battery (in the scenarios when these batteries are available for the household) is optimised so that the levels of self-consumption and self-sufficiency of the household are maximised.

Equations 1-11 describe the model used in this study. Bold letters in Equations 1-11 indicate decision variables in the optimisation process. When leaving home, the EV battery must have a sufficient SOC level to allow completion of all trips until the EV returns home again. In case this is not possible, i.e., if the assumed driving distance between stops at home location is too long for the investigated EV battery capacity, recharging is assumed to be possible outside the home although only so much as it covers the energy needed to return home. To the greatest extent possible, the model minimises charging outside the household. Thus, the objective function (Eq. 1) for the model includes both electricity drawn from the grid to the households and any eventual charging of vehicles outside the household. The charging outside the household is multiplied by a factor two to avoid such charging and will thereby only be used when necessary to meet the driving demand. Each household is modelled individually and does not influence the other households in the model.

$$\min \left[E_{tot} = \sum_{h\in H}\sum_{v\in V}\sum_{t\in T} \boldsymbol{e}^{bot}_{h,v,t} + 2 * \boldsymbol{b}^{out}_{h,v,t}\right] \quad (1)$$

$$d_{h,t} + \boldsymbol{e}^{sold}_{h,v,t} + \boldsymbol{s}^{add}_{h,v,t} + \boldsymbol{b}^{add}_{h,v,t} \times u_{v,t} = \boldsymbol{e}^{bot}_{h,v,t} + p_{h,t} + \left(\boldsymbol{s}^{rem}_{h,v,t} + \boldsymbol{b}^{rem}_{h,v,t} \times u_{v,t}\right) \times \eta^{bat} \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (2)$$

$$\boldsymbol{k}_{h,v,t} = \boldsymbol{k}_{h,v,t-1} + \boldsymbol{b}^{out}_{h,v,t} + u_{v,t} \times \left(\boldsymbol{b}^{add}_{h,v,t} \times \eta^{bat} - \boldsymbol{b}^{rem}_{h,v,t}\right) - d_{v,t} \times \mathrm{c} \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (3)$$

$$\boldsymbol{l}_{h,v,t} = \boldsymbol{l}_{h,v,t-1} - \boldsymbol{s}^{rem}_{h,v,t} + \boldsymbol{s}^{add}_{h,v,t} \times \eta^{bat} \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (4)$$

$$\boldsymbol{b}^{rem}_{h,v,t} \leq g \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (5)$$

$$\boldsymbol{b}^{add}_{h,v,t} \leq g \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (6)$$

$$\boldsymbol{k}_{h,v,t} \leq f_v \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (7)$$

$$\boldsymbol{s}^{rem}_{h,v,t} \leq w_h \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (8)$$

$$\boldsymbol{s}^{add}_{h,v,t} \leq w_h \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (9)$$

$$\boldsymbol{l}_{h,v,t} \leq n_h \quad \forall h \in H, \forall v \in V, \forall t \in T \quad (10)$$

$$\boldsymbol{e}^{bot}_{h,v,t};\ \boldsymbol{e}^{sold}_{h,v,t};\ \boldsymbol{s}^{add}_{h,v,t};\ \boldsymbol{s}^{rem}_{h,v,t};\ \boldsymbol{b}^{add}_{h,v,t};\ \boldsymbol{b}^{rem}_{h,v,t};\ \boldsymbol{b}^{out}_{h,v,t};\ \boldsymbol{l}_{h,v,t};\ \boldsymbol{k}_{h,v,t} \geq 0 \quad (11)$$

Notation	Description
H	set of modelled households
V	set of modelled EVs
T	set of modelled time-steps
$d_{h,t}$	demand for electricity in household *h* at time *t*
$p_{h,t}$	electricity generated by the PV panel in household *h* at time-step *t*
$u_{v,t}$	binary parameter indicating whether EV *v* is plugged in at home at time-step *t* (value 1) or not (value 0)
η^{bat}	battery efficiency
$d_{v,t}$	hourly distance driven for EV *v* at time-step *t*
c	EV energy consumption at the wheels
g	maximum charging and discharging capacities of the EV battery
f_v	maximum energy level in the battery for EV *v*
w_h	charging power capacity of the stationary battery
n_h	Energy capacity of the stationary battery
$\boldsymbol{e}^{bot}_{h,v,t}$	electricity transmitted from the grid to household *h* in combination with EV *v* at time-step *t*
$\boldsymbol{e}^{sold}_{h,v,t}$	electricity transmitted to the grid from household *h* in combination with EV *v* at time-step *t*
$\boldsymbol{s}^{add}_{h,v,t}$	energy added to the stationary battery in household *h* in combination with EV *v* at time *t*
$\boldsymbol{s}^{rem}_{h,v,t}$	energy removed from the stationary battery in household *h* in combination with EV *v* at time *t*
$\boldsymbol{b}^{add}_{h,v,t}$	energy added to the EV battery for EV *v* in combination with household *h* at time-step *t*
$\boldsymbol{b}^{rem}_{h,v,t}$	energy removed from the EV battery to the household for EV *v* in combination with household *h* at time-step *t*
$\boldsymbol{k}_{h,v,t}$	storage level of EV battery belonging to EV *v* in combination with household *h* at time-step *t*
$\boldsymbol{l}_{h,v,t}$	storage level of stationary battery belonging to household *h* in combination with EV *v* at time-step *t*
$\boldsymbol{b}^{out}_{h,v,t}$	charging conducted outside the home for EV *v* in combination with household *h* at time-step *t*

2.2 Definition of PV electricity self-consumption and self-sufficiency

The level of self-consumption of in-house PV electricity generation and the level of self-sufficiency of the household are calculated using the definitions proposed by Luthander et al. [1]. Self-consumption is expressed as:

$$\varphi_{h,v}^{sc} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} P(t)dt} \quad (8)$$

where *M(t)* is the electricity generated from PV panels that is being used in-house in every instance, either immediately or later in the household after storage in a stationary or EV battery. The energy lost as heat during charging/discharging is not considered as self-consumed, and therefore, is not included in *M(t)*. *P(t)* is the instantaneous PV electricity generation within the household. To capture seasonal variations in load and PV generation, Eq. 8 is integrated over the time period of 1 year.

By replacing the PV generation (*P(t)*) from Eq. 8 with the load from the household that includes EV charging, *L(t)*, the self-sufficiency for households, both with and without an EV, is calculated as:

$$\varphi_{h,v}^{ss} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} L(t)dt} \quad (9)$$

The integration is performed with respect to the discrete input data with an hourly resolution, despite the fact that the above formulations call for continuous integration over the investigated time-period.

2.3 Sizing of the PV system, stationary battery, and EV battery

The sizes of the PV panel system and stationary battery for each household are related to the electricity load in the household, before the introduction of an EV. The sizes of the PV panel systems and stationary batteries are related to the load of each household to facilitate comparisons of the results between households. The installed PV capacity is expressed using the array-to-load ratio (ALR), defined by Widen et al. [17] as:

$$ALR = \frac{\text{array size } (W_p)}{\text{average annual household load, excluding EV } (W)} \quad (10)$$

In the same way, the size of the stationary battery is related to the demand by the battery-to-demand ratio (BDR), as defined by Nyholm et al. [18].

$$BDR = \frac{\text{battery energy capacity } (Wh)}{\text{average annual hourly household demand, excluding EV } (Wh)} \quad (11)$$

The battery capacity in the model is the usable share of the battery, so it is assumed that the battery can be fully charged and discharged. The size of the EV battery is varied independently of the electricity load of the household.

3 Data

The data for the households' electricity consumption is taken from a data-set consisting of the hourly load profiles of 2,221 Swedish single-family households for one year. For additional information about this data-set, see Nyholm et al. [18]. The data regarding the driving patterns of vehicles are taken from *The Swedish Car Movement Data Project* [19]. The data used as input for this study are from 426 vehicles measured during 30-73 days extrapolated to one year of driving. For a description of treatment of the driving data, see Gudmunds [20].

Of the 2,221 available households, 20 were selected based on their levels of annual electricity consumption (ranging from 2,779 kWh/year up to 44,674 kWh/year) and potential PV electricity generation. This selection was performed to obtain as large a variation as possible among the selected households with respect to both electricity demand and PV electricity generation. Similarly, 20 EVs were selected to obtain as large variations as possible based on the number of hours parked at home location and the total driving distance over the year. The total number of hours that the EV was at the home locations was in the range of 2,002–7,946 hours, with a median of 5,151 hours for all 20 vehicles. In total 400 combinations of households and EVs were used as an input to the model.

Table 1 shows the model input data for the PV system, stationary battery, and EV. The maximum charging/discharging power of the stationary battery is 1*E, where E is the capacity of the battery. Thus, a battery with capacity of 2 kWh has a maximum charging power of 2 kW.

Table 1: Input parameters and values for the PV system, stationary battery, and EV used in the model. Abbreviations: EV, electric vehicle; PV, photovoltaics.

Input parameter	**Input value**
Inverter efficiency	0.95 [21]
PV panel orientation	Due south
PV panel tilt	31° [22]
PV panel degradation	0.98 [23]
Annual level of generated PV electricity (the range represents the different locations)	839–1150 kWh/kW_P [24, 25]
Battery efficiency (round-trip)	0.95 (0.90) [26]
EV energy consumption at the wheels (mixed driving)	0.18 kWh/km [27]
EV battery maximum charging/discharging power (230 volts, three-phase, 16 Amperes)	11 kW

3.1 Varied model input parameters

The range of combinations of ALR, BDR, and size of EV battery investigated are presented in Table 2. The PV sizes and battery sizes correspond to a range of 0.32 kW_P to 40.69 kW_P and 0.32 kWh up to 20.34 kWh, respectively, depending on the household electricity demand. The households were also modelled without a stationary battery (BDR = 0) as a reference case. The size of the EV battery was varied independent of the electricity demand of the household or EV, from 15 kWh up to 75 kWh. These input values for sizing the PV panel, stationary battery, and EV battery results in 120 combinations modelled. In a sensitivity analyses, some more model runs without V2H, with a minimum level of energy in the EV battery (to allow at least 50 km of driving), and with charging power of the EV battery reduced to 3.7 kW has been performed.

Table 2: Input parameters used for the PV panel, stationary battery, and EV battery in the different model runs. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics.

Input parameter	**Input value**
PV panel ALR	1, 2, 3, 4, 5 or 8
Stationary battery BDR	0, 1, 2, 3 or 4
EV battery (kWh)	15, 25, 50 or 75

4 Results

The self-consumption and self-sufficiency outcomes are presented and compared for the different combinations of PV system size, stationary battery size, and EV battery size. The results for all 400 combinations of households and EVs modelled are presented. The data used for the households and vehicles are selected to include as large variations as possible, which means that they are not representative of a normal distribution. To assign a lower impact to the extreme data-points, median values are presented. For all the results, unless stated otherwise, the EVs have the possibility to discharge electricity back to the households (V2H) during all the hours that the EV is parked at the home location.

4.1 Self-consumption and self-sufficiency

Fig. 2 shows the median levels of self-consumption (2a) and self-sufficiency (2b) for households with an EV (blue lines), households with a stationary battery (red lines), households with both an EV and a stationary battery (grey line), and households without any storage (black dashed line). Fig. 2a shows that with increased installed PV capacity in the households (i.e., higher ALR), the degree of self-consumption is decreased in all cases. At an ALR of 1, comparing the EVs to the stationary batteries, all model runs with EVs performed worse. The worse performance of the EVs at lower ALRs, despite larger storage capacities than the stationary battery, is due to lower availability of the EVs (i.e., EVs have a risk of not being available for charging at moments of surplus electricity generation from PVs). In addition, there is little benefit in the larger storage capacities of the EVs batteries if the surplus generation is low. However, as the ALR increases, the decrease in self-consumption is smaller for the EVs compared the stationary battery. At an ALR > 5, the EVs are becoming better (50 and 75 kWh) or comparable (15 and 25 kWh) to the stationary batteries. When ALR increases the number of hours with surplus generation increase, and thereby also the amount of surplus electricity, resulting in an increased possibility to charge the EV with surplus electricity. Furthermore, the extra demand created when introducing the EV also helps in increasing the self-consumption.

In Fig. 2b the same trend as above can be observed for self-sufficiency as for Fig. 2a self-consumption. The impact of the increased demand due to the introduction of an EV, however, results in a lowering of the self-sufficiency, i.e. the opposite to the impact on self-consumption. As a result of this the impact of the EVs on self-sufficiency is not as great as for self-consumption. As can be seen in Fig. 2b the median level of self-sufficiency with an EV never reaches the level obtained with the largest stationary battery investigated. Thus, despite the larger storage capacity provided by an EV battery, it cannot replace the largest investigated stationary battery with regards to self-sufficiency. Furthermore, at an ALR of 1 the introduction of an EV results in a lower self-sufficiency for the median household when compared to a household without any storage at all.

In both Fig. 2a and 2b it can be seen that combination of a stationary battery and EV (grey line) results in an improvement in both self-consumption and self-sufficiency compared to only an EV. This behaviour indicates that the benefits of both storage solutions can be exploited. It should be noted, however, that when introducing an additional storage option, the increase in electricity self-consumption is never as large as when the first option is offered to a household without any previous storage technology (i.e., the effects are not additive).

An additional observation is that the marginal effect on self-consumption and self-sufficiency of increasing the EVs battery size is diminishing, e.g., the change in self-consumption and self-sufficiency from going from an EV battery of 25 kWh to 50 kWh is larger than going from 50 kWh to 75 kWh (Fig.2).

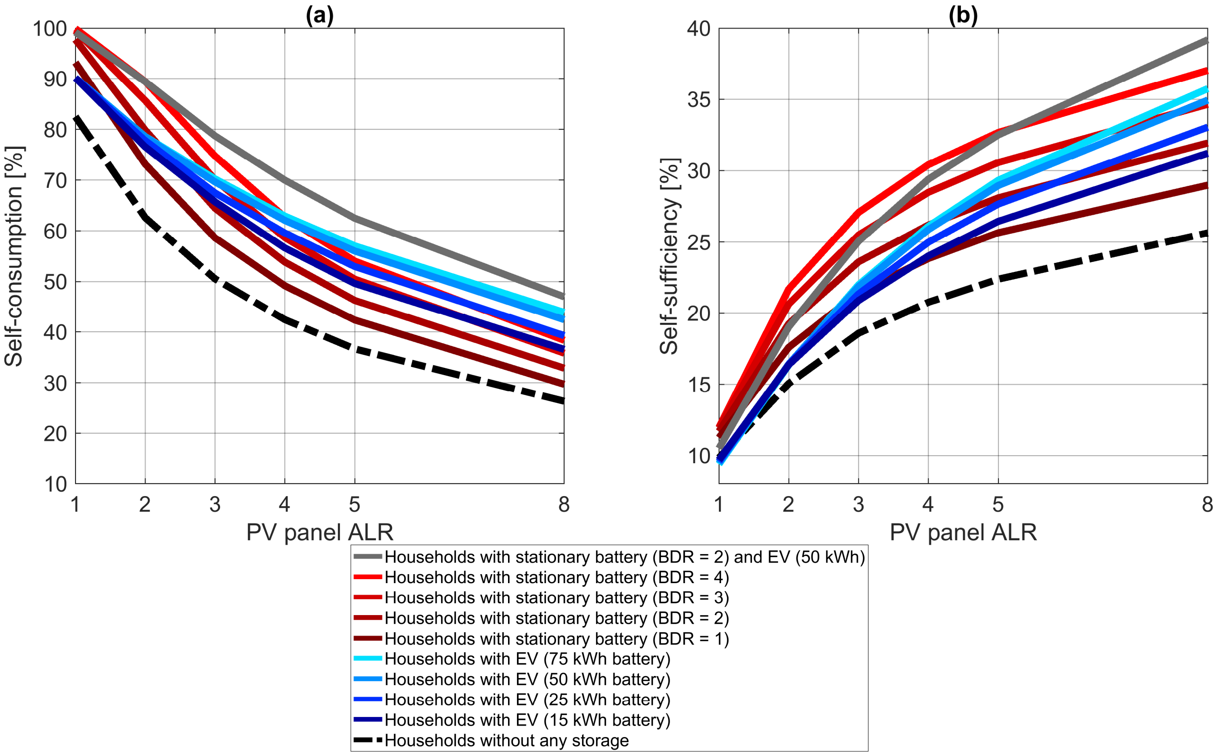

Figure 2a: Median levels of (a) self-consumption and (b) self-sufficiency of electricity for households without a storage option, households with a stationary battery, households with an EV, and households with both a stationary battery and an EV. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics.

The trends depicted in Fig. 2 are median trends, whereas the variations seen between different combinations of households and EVs are large. In Fig. 3a and b, the variations in self-consumption and self-sufficiency, respectively, for households without any storage (white boxes), households with a stationary battery (red boxes), households with an EV (blue boxes), and households with both an EV and stationary battery (grey boxes) are shown. As can be seen in Fig. 3, there are considerable variations between different households without any storage for all the investigated PV sizes and BDR values, for both self-consumption and self-sufficiency. However, the variation drastically increases if one includes an EV, as seen in Fig. 3a and b. As an example, the difference between the maximum and minimum levels of self-consumption for households with a PV panel with an ALR of 4 is 26 percentage points without any storage, 31 percentage points with a stationary battery (BDR of 2), 59 percentage points with an EV (50 kWh), and 54 percentage points with both an EV (50 kWh) and a stationary battery (BDR of 2). The fact that EV batteries have a higher capacity than stationary batteries, which is not related to the magnitude of the electricity load in the households, and the variations in driving profiles between EVs, are contributing factors to the larger spread in self-consumption and self-sufficiency levels for households with an EV.

An additional observation in Fig. 3b is that for some household-PV combinations the self-sufficiency is larger without any storage compared to when an EV is included, i.e., comparing the white and blue boxes and their outliers. This can occur when the demand from the introduced EV constitutes a large share of the households' total demand. For example, if the EV accounts for a larger share of the total electricity demand in the household (>26.7% at an ALR of 3, for households without a stationary battery and an EV with a 50-kWh battery), the EV has a negative impact on self-sufficiency for a large fraction of the households. As ALR increases, however, the number of combinations that results in a lower self-sufficiency decreases, although there are still combinations that are worse at an ALR of 8.

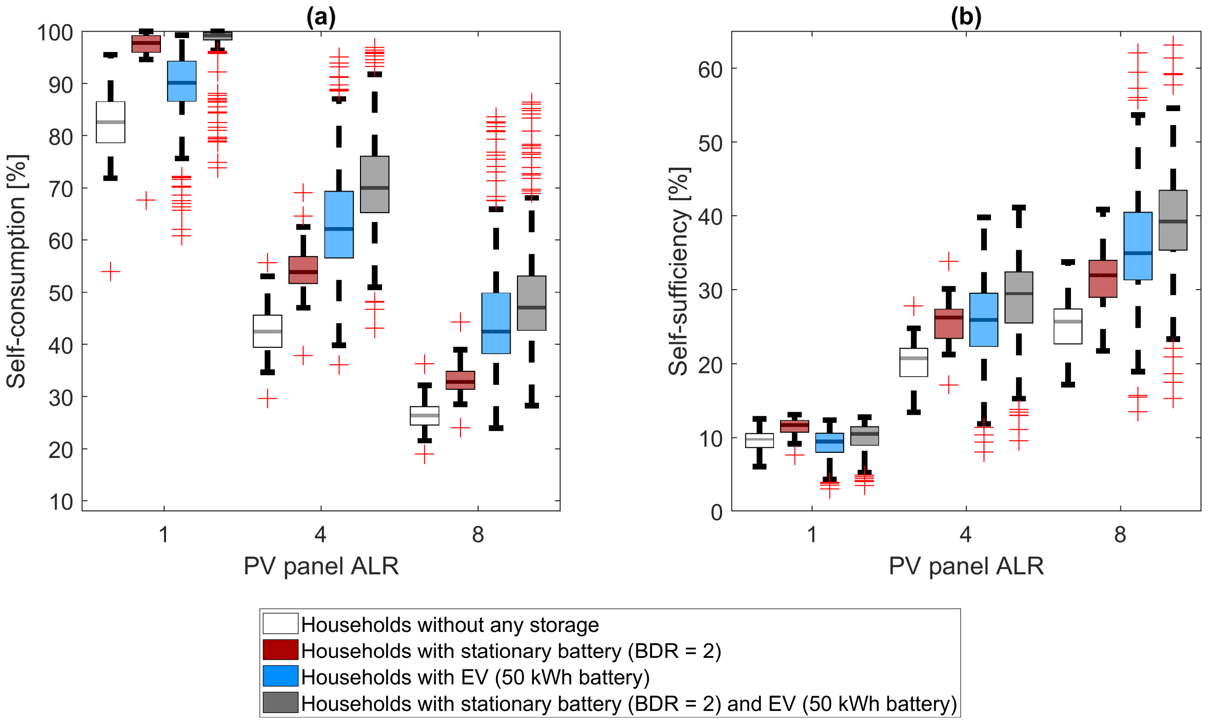

Figure 3a: Variations in the percentages of electricity (a) self-consumption and (b) self-sufficiency for households without any storage, households with a stationary battery, households with an EV, and households with both an EV and stationary battery, for households that generate electricity using PV panels with different ALRs. For households without an EV, the variation is shown for the 20 modelled households. For households with an EV, the variation for 400 combinations of households and vehicles is modelled. The central line in each box indicates the median value, while the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. Values considered as outliers are indicated by red crosses, while the whiskers are extended to the most extreme data-point not considered to be an outlier. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics.

4.2 Impact of the V2H technology

Fig. 4 shows the median self-consumption (4a) and the median self-sufficiency (4b) for: households with EV without V2H (green line); households with EV with V2H (blue line); households with only a stationary battery (red lines); and households without any storage (black dashed line). With the V2H technology, the median level of self-consumption with an EV that is equipped with a 50-kWh battery is higher than with the investigated stationary battery sizes for ALRs >4. The median level of self-consumption with an EV that has a 50-kWh battery without V2H at most show similar performances to a stationary battery with BDR of 2. The difference in self-consumption levels for households with an EV with or without the V2H technology is greater for those households that have larger installed PV panel capacities (Fig. 4a).

However, in the case of self-sufficiency, removing the possibility for V2H results in a lower self-sufficiency, as compared to cases with a stationary battery for all ALRs <8 (Fig. 4b). Thus, the ability of an EV to replace a stationary battery and obtain the same level of self-sufficiency is strongly affected by the V2H technology.

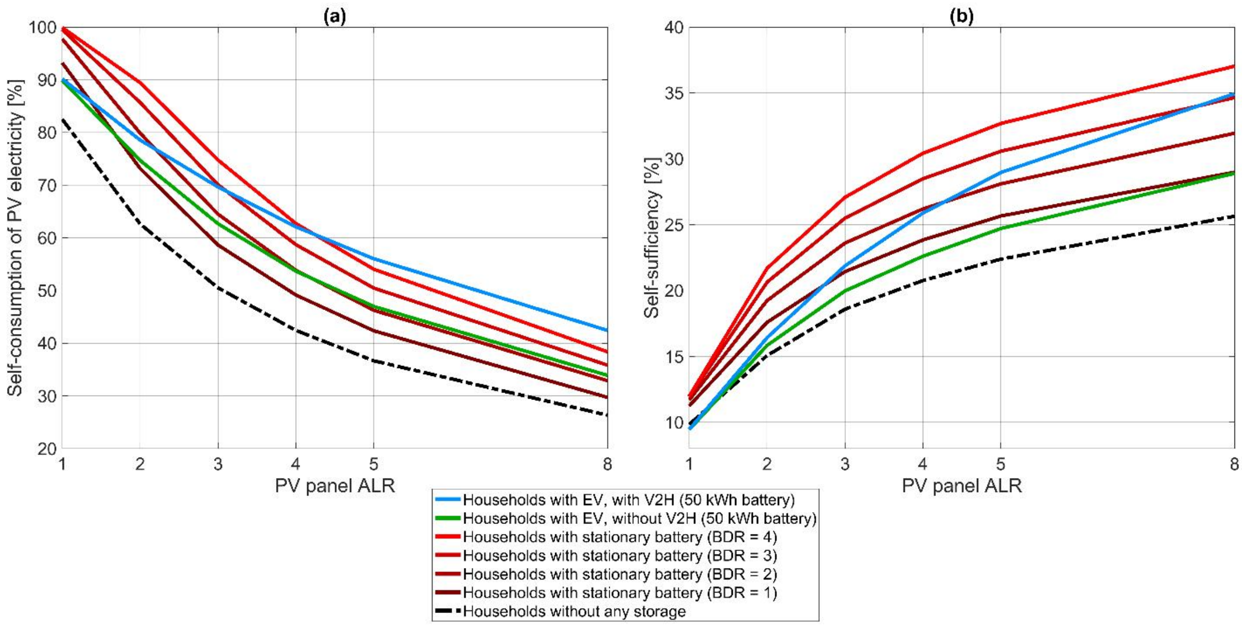

Figure 4: Self-consumption (a) and self-sufficiency (b) levels for households without storage, households with a stationary battery, and households with EV, with or without V2H. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics, V2H, vehicle-to-home technology.

Fig. 5 shows the median amount of electricity discharged from the EVs to the households relative to the amount of electricity used for driving the EVs. Fig. 5b shows instead the median amount of amount of cycles per year for the EVs due to both V2G and driving. The number of cycles are calculated by dividing the amount of EV charging for a specific vehicle with the EV battery capacity.

For specific combinations of households and EVs (not shown in Fig. 5) the amount of discharged electricity from the EV to the household can be higher than the amount of electricity that is needed to meet the driving demand. For such cases, the EV batteries act more as batteries for the household than for the EV, since the largest share of the electricity charged into the EV battery is discharged back to the household. However, the median amount of discharged electricity from the EVs is never higher than the electricity demand for driving when all combinations of households and EVs are summarised (Fig. 5). Utilisation of the EV battery as an energy storage unit for the households is executed to a greater extent for households with larger PV capacities, as shown in Fig. 5.

Fig. 6 shows the variation in number of battery cycles per year (here defined as the "total energy charged during a year" divided by "total battery capacity") for households with an EV without V2H (50 kWh), EVs with different battery sizes (25, 50 and 75 kWh), and households with both an EV (50 kWh) and stationary battery (BDR 2) at different ALRs. The impact of V2H on the number of cycles at low ALRs seem to be low, i.e., the boxes for the 50 kWh EVs without V2G (white) and with V2G (red) are almost identical at ALR 1.

As ALR increases the impact of V2H increases, with a doubling of the median number of cycles, from 50 to 100, for a 50 kWh EV between ALR 1 and ALR 8. For some EV-household combinations, however, there is almost no increase in cycles at all with increasing ALR. This is due to the low availability of the EV, i.e., it is seldom parked at home. As to be expected a smaller EV battery size (25 kWh, yellow) results in a higher amount of cycles and larger EV battery size (75 kWh, grey) results in a lower amount of cycles compared to the 50 kWh EV. However, the percentage increase in cycles as ALR increase is lower for both the 25 kWh and the 75 kWh EV compared to the 50 kWh. It should also be noted that the inclusion of a stationary battery to the households with a 50 kWh EV (blue) only results in a minor reduction of the number of cycles.

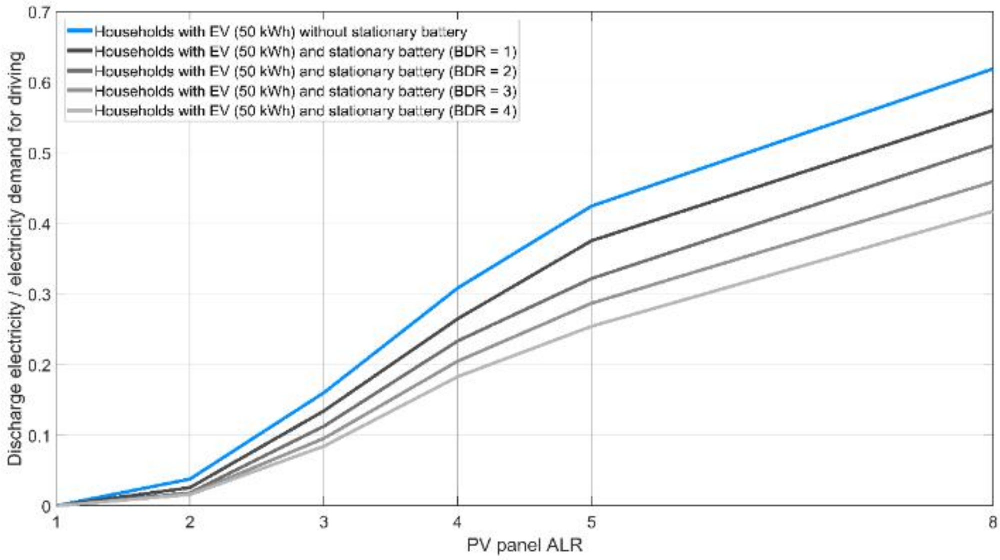

Figure 5: Usage of the vehicle-to-home technology to discharge electricity from the EVs to the households. Shown are the median amounts of electricity discharged from the EV to the household relative to the amount of electricity needed for driving, summarised over a full year for households that generate electricity using PV panels with different ALRs. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics.

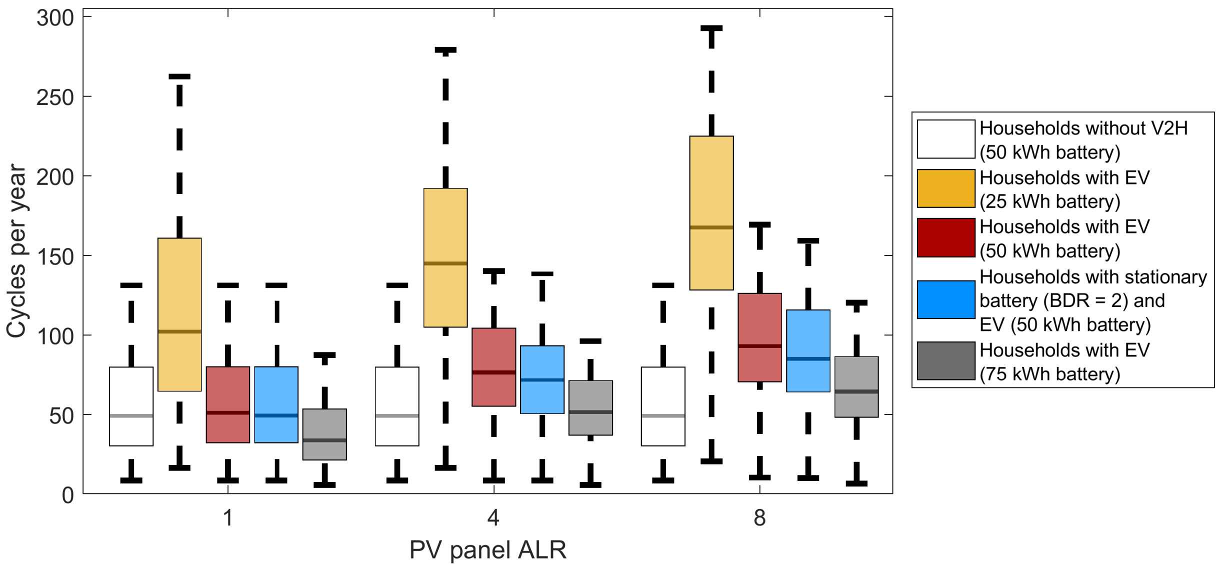

Figure 6: Variations in number of battery cycles per year for households with an EV without V2H (50 kWh), EVs with different battery sizes (25, 50 and 75 kWh), and households with both an EV and stationary battery at different ALRs. The central line in each box indicates the median value, while the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively, and the whiskers represents the values outside of this range. Abbreviations: ALR, array-to-load ratio; BDR, battery-to-demand ratio; EV, electric vehicle; PV, photovoltaics.

5 Discussion and Conclusion

The results shows that there is a possibility to use the EV battery instead of a stationary battery and still reach the same levels of self-consumption and self-sufficiency for residential households with solar PV and an EV. The combination of a stationary battery and an EV battery for storage are found to be able to complement each other. The possibility for the EV to discharge electricity back to the household by V2H technology is proven to be necessary for the ability to use the EV as storage and completely replace a stationary battery. The V2H technology are shown in study to substantially increase the amount of battery cycling for most model runs in order to maximise the self-consumption and self-sufficiency compared to only using the EVs for driving. However, the impact on the battery health status due to V2H has not been included in the modelling of this work.

The possibility for EVs to contribute to increased electricity self-consumption and self-sufficiency for households is strongly affected by when and for how long the EVs are plugged in at home. The large variations seen between the vehicles shows that it is important to include individual driving profiles in these types of studies. The real measurements of vehicle driving used in this study differ from the driving patterns used in previous studies regarding for example the magnitude of the increase in electricity demand for households that the introduction of an EV implies. A drawback with also measured driving patterns, as well as traveling surveys, is that it is not possible to tell the willingness to use the EV battery as an electricity storage system for the household. In a sensitivity analysis, we have also checked the results using a “security margin” for unplanned trips (i.e., a minimum SOC-level as a model constrain). The results shows that it is mainly in the case of smaller EV battery size (15 kWh) that impacts the results.

The input data regarding solar PV generation are representative only for the northern latitudes. There is for example a negative correlation between electricity generation from solar PV and residential power demand, both on a daily and an annual basis on these latitudes [2]. For such circumstances, a storage solution is useful only during the months with excess PV generation. In regions with a more even electricity generation from solar PV on an annual basis, a storage solution, such as an EV battery, can be used as storage for households during a higher number of days over the year, due to the greater number of hours with excess PV generation.

Finally, the results of this study should be regarded as the technical potential to use an EV battery as a power storage unit for a residential household, not as an economic evaluation, and not in terms of any future predictions.

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