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Self-sufficiency ratio: an insufficient metric for domestic PV-battery systems?

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Abstract

By installing a home battery to accompany rooftop solar PV, grid electricity usage is reduced and self-sufficiency increased. One motivation for pursuing this goal is environmental concern. By modelling domestic PV-battery systems in this work, self-sufficiency is found not to correlate well with CO_2 emissions savings, in some cases even correlating negatively. A system's complexities, such as transmission and distribution losses, are not encapsulated in self-sufficiency. Self-sufficiency should not be considered in isolation when designing PV-battery systems to maximize CO_2 emissions savings.

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Keywords: solar PV; home battery; self-sufficiency; CO_2; techno-economic modeling; environment.

1. Introduction

There is growing consumer interest in home batteries to accompany rooftop solar PV. By storing unused PV generation during the day and using that stored energy within the home at night, home batteries promise an increase in energy self-sufficiency, and a reduced electricity bill. The self-sufficiency ratio (SSR) is defined as the proportion of a household's demand that is served directly by PV generation or discharging the battery onsite, i.e. not by the electricity grid [1]:

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Nomenclature

SSR	Self-sufficiency ratio (%)
$P_g^-(t)$	Electricity import from the grid (kW)
$P_D(t)$	Household electrical demand (kW)
λ_1	Average electrical loss from centralized grid generator to conceptual branch point (%)
λ_2	Average electrical loss from conceptual branch point to house (%)
c_{g0}	Marginal CO_2 intensity of grid generation (kg/kWh)
c_g^-	CO_2 intensity of grid import (kg/kWh)
c_g^+	CO_2 intensity of grid export (kg/kWh)

$$SSR = 100\,\% - \frac{\sum_t P_g^-(t)}{\sum_t P_D(t)}\,. \quad (1)$$

Many design and modelling studies of domestic solar PV and battery systems take SSR maximization as one of the objectives [2-4]. Most take it as given that SSR maximization is a good thing. However, Bertsch et al. have published a critique showing the positive correlation between SSR and internal rate of return (IRR, a measure of financial benefit) exists only up to SSR = 65 % in Ireland and 76 % in Germany [5]. Further increases in SSR can be achieved by larger battery size, but at greater cost than can be recouped by saving on electricity bills during the battery's lifetime.

Simshauser and Nelson have speculated on an adverse consequence of many households trying to maximize SSR, which they term the 'energy market death spiral' [6]. Households increasing their SSR may reduce the income of electricity retailers, who increase their tariffs in response, leading to more households (if they can afford it) increasing their SSR to reduce their exposure to ever higher electricity prices. The pursuit of SSR is not a straightforward good.

Little has been published on the relationship between SSR and environmental benefit. Zhang et al. use SSR as a proxy for environmental benefit in their modelling of a block of flats with PV and battery [7]. They cite Luthander et al.'s paper as justification, though no link between SSR and environmental benefit is claimed therein [1].

Of the 268 residents of Queensland, Australia, that Agnew and Dargusch surveyed on their attitudes towards home batteries, 80 % wished to reduce their greenhouse gas emissions [8]. Although reduction of electricity bills was the most common reason for considering buying home batteries, a link between energy self-sufficiency and environmental benefit has clearly become embedded in many minds. This link must be examined in order that research into the design of domestic PV-battery systems may better serve the environmentally-conscious section of the public.

The method for investigating the link between SSR and environmental benefit through mathematical modelling is described in Section 2. Results are presented in Section 3, followed by conclusions and further work in Section 4.

2. Method

Industry specialists were consulted for this work, to identify potential environmental benefits of home batteries. The claims were examined by developing a Matlab model of a domestic PV-battery system operating an SSR-maximizing 'greedy' algorithm, as used by Weniger et al. [3] and Truong et al. [4]. The battery capacity was varied and its effects on SSR, net present value (NPV), and CO_2 emissions over the 15-year battery lifespan were examined.

One year's rooftop PV generation and six household demand time series in the UK were measured for this work at 2-s and 5-minute resolution respectively. The PV time series was averaged to 5-minute resolution before use. The annual loads range from 2563-8015 kWh. This spans the UK average of 3800 kWh, providing a good range for study. Behavior often changes after installing a home battery [8], but the effect on electrical usage is not modelled here.

A so-called 'greedy algorithm' is mathematically guaranteed to maximize SSR [4]. It serves demand first by PV electricity, then by discharging the battery if this is insufficient. If the discharge power limit is reached or the battery runs empty, power is imported from the grid. If there is more PV electricity generated than needed, the excess is used to charge the battery up to the power limit or until it is full, then any remaining excess is exported to the grid.

SSR is calculated as in equation (1). NPV is calculated by a discounted cash flow analysis, including capital expenditure on PV and batteries, expenditure on electricity import, and income from the Feed-in Tariff (FiT) and export tariff. A similar calculation is made for CO_2 emissions. It includes embodied emissions of PV and battery manufacture, emissions from imported grid electricity, and credits from displacing grid generation when exporting electricity. More details of the model inputs, algorithm and parameter values are given in Appendix A.

3. Results

Consultation with industry specialists identified the following potential environmental benefits of home batteries. These are examined in turn using the model and data described in Section 2.

- Usage of more low-CO_2 electricity,
- Reduction of transmission and distribution losses by consuming more of the electricity generated onsite,
- Reduction of peak import/export and associated losses and inefficiencies,
- Relief of voltage violations on the distribution network, allowing more PV to connect.

'CO_2 arbitrage' (shifting import/export between periods of low/high grid CO_2 intensity), is left to future work.

3.1. Usage of more low-CO_2 electricity

Fig. 1 shows for House 1 (annual electricity consumption 8015 kWh) that SSR is increased by installing larger PV and battery. NPV relative to the case with no PV and no battery is maximized around 11 kW PV and 10.5 kWh battery. CO_2 saved relative to no PV and no battery increases with PV capacity but *de*creases with battery capacity. Kabakian et al.'s finding that installing a battery saves less CO_2 than having PV only [9] is confirmed for all six houses, due simply to the battery's charge/discharge losses and embodied emissions of manufacture. However, Uddin et al.'s conclusion that home batteries are thus bad for the environment [10] is too simplistic, as shown in the next sections.

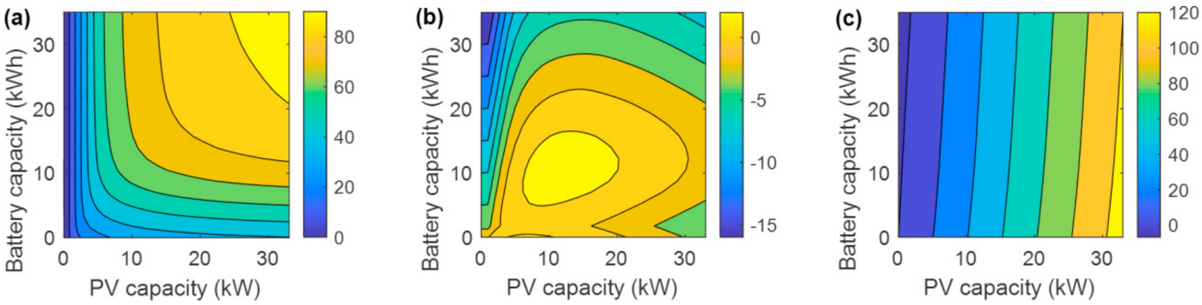

Fig. 1. (a) SSR (%); (b) NPV (k£); (c) CO_2 saved (ton) relative to the case with no PV, no battery, for House 1, vs. PV and battery size.

3.2. Reduction of transmission and distribution losses

The average electrical loss in the UK transmission and distribution networks is 8-9 % [11]. Transmitting PV electricity that goes unused in one house, to one nearby, typically incurs negligible losses. In that case, each kWh exported is credited equally to the burden of each kWh imported. However, if a house is very remote, finite losses in exporting excess PV electricity can reduce the environmental benefit compared to onsite consumption.

To explore this effect, a loss of λ_1 = 8 % is modelled up to a conceptual branch point, and a further λ_2 to the house (Fig. 2). If every kWh of electricity generation causes c_{g0} kg/kWh of CO_2 to be emitted, every kWh imported emits

$$c_g^{\,-} = \frac{c_{g0}}{(1-[\lambda_1+\lambda_2])}\ \text{kg/kWh} \tag{2}$$

when taking account of transmission and distribution losses, while every kWh exported saves

$$c_g^{\,+} = \frac{c_{g0}(1-2\lambda_2)}{(1-[\lambda_1+\lambda_2])}\ \text{kg/kWh.} \tag{3}$$

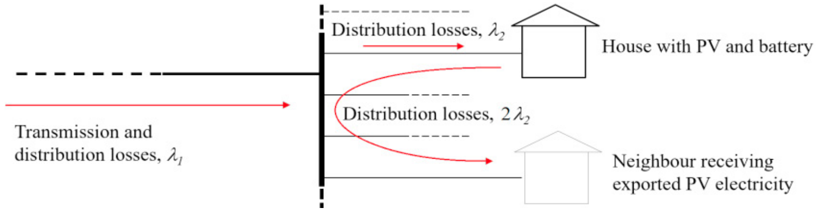

Fig. 2. Abstraction showing transmission and distribution loss of $\lambda_1+\lambda_2$ to each house, and $2\lambda_2$ in exporting from one house to another.

In reality, there is generally not one conceptual branch point and conceptual neighbour: excess PV energy could be transmitted to many neighbours. Local loss λ_2 would vary across the network and throughout the day, with varying network loading. Although the physical characteristics corresponding to specific values of λ_2 have not yet been determined, Fig. 3 (a) and (b) show that for $\lambda_2 \geq 15\%$ and across the range of households, a non-zero battery *can* save CO_2 relative to PV only. This is in contrast to the previous section, when $\lambda_2 = 0$. The extremely unlikely bounding case of $\lambda_2 = 50$ % is included for logical completeness. Varying λ_2 has no effect on SSR nor NPV (Fig. 3 (c), (d)), because λ_2 only affects the CO_2 accounting but neither the other two calculations.

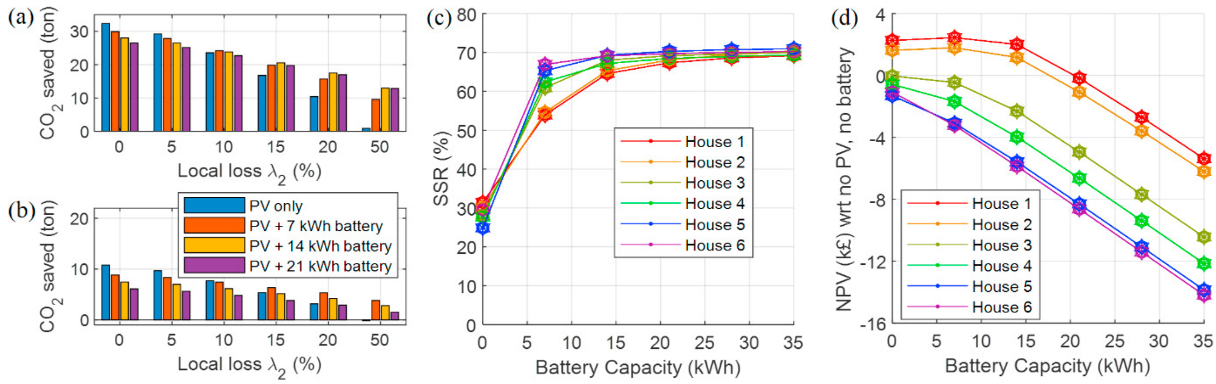

Fig. 3. CO_2 savings of (a) House 1, and; (b) House 6, for varying λ_2 and battery sizes; (c) SSR, and; (d) NPV, showing no change with λ_2.

3.3. Reduction of peak import/export

By reducing peak flows, ohmic losses in power cables are reduced. Furthermore, reduced import peaks mean less need to upgrade electricity network infrastructure such as transformers and new peaker generation plants.

While increasing battery size does reduce peak import across the year (Appendix B, Fig. 4), there is no effect at all on peak export when using the SSR-maximizing greedy algorithm. Solar irradiation at UK latitudes has such wide annual variation that under this algorithm, the battery is empty nearly all the time in winter, and often full before noon in summer, when excess PV generation is highest (Appendix B, Fig. 5).

Unsurprisingly the greedy algorithm is not used when import/export minimization is the goal. Instead, linear programming methods are favoured [12]. With judicious algorithm design, the SSR need not be greatly reduced from the theoretically possible maximum obtained using the greedy algorithm.

3.4. Relief of voltage violations

The increasing penetration of rooftop PV increases the risk of voltage violations on the distribution network. Crossland et al. have modelled this phenomenon in real networks [13]. They recommend placing home batteries in targeted locations to relieve voltage problems, and thus allow more PV to connect and contribute towards decarbonizing the electricity system. Their work relies on the assumption that the batteries are designed to charge during high-risk periods, that is, summer noon-time when domestic demand is low and PV generation high. But as shown in Section 3.3, the greedy algorithm does not achieve this.

4. Conclusions and further work

When exporting electricity to one's neighbors is nearly loss-less, as in most residential areas in the UK, CO_2 savings decrease with battery size. In this case, SSR is *negatively* correlated with environmental benefit. However, when a network is lossy, or PV penetration is high and forces exported energy further away, installing a battery can indeed save CO_2 emissions. This is not reflected in SSR, which has no dependence on local network losses. Finding the level of loss or PV penetration each value of λ_2 corresponds to is left to further work.

Benefits associated with reducing grid import/export and relieving voltage constraints are better achieved through algorithms designed for these aims. They need not sacrifice SSR greatly, but must be designed intelligently.

This may also be true of 'CO_2 arbitrage', whereby electricity is imported from the grid at times of low CO_2 intensity and exported when CO_2 intensity is high. Grid CO_2 intensity has been assumed constant throughout this work, at the level of combined cycle gas turbines (CCGT). In future, the marginal generator may at times be wind, PV or nuclear, rather than always CCGT. The authors are constructing hourly grid CO_2 time series under different generation mix scenarios, to test the impact of CO_2 arbitrage.

Some financial benefit is possible by installing home batteries, as seen for Houses 1 and 2 in Fig. 3 (d). An argument can be made for using the concept of self-sufficiency as a marketing tool, to connect more PV to the grid than otherwise. For researchers however, it should be clear that SSR alone is not an appropriate metric for environmental benefit. The system must be modelled in all its complexity, instead of relying on the apparent objectivity of SSR. Indeed, this work too can be criticized for neglecting human toxicity, resource depletion, ecological damage, and other sustainability indicators. Not only SSR, but CO_2 as well may be an insufficient metric for environmental benefit.

Acknowledgements

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Appendix A. Model details

This comprises a description of the model input data, the operating algorithm programmed into Matlab, the calculation of net present value (NPV) and CO_2 emissions, as indicators of financial benefit and environmental impact respectively, and parameter values used.

A.1. Model input data

The system consists of P_{PV} kW of PV panels (variable, or fixed at values in Table 1), E_B kWh of batteries (variable), and all the household loads, connected behind the meter.

The PV generation time series $P_{gen}(t)$ is given by a 2-s dataset collected by Dickon Hood from a 3.6 kW array on a southeast-facing roof inclined roughly 45˚ from the horizontal, in Berkshire, UK, 2015-12-02 to 2016-11-30.

The household demand time series $P_D(t)$ were taken from six houses in the Midlands, UK, metered at 5-minute resolution from 2012-02-01 to 2013-01-31, by E.ON UK plc. For the simulations with fixed PV capacity, the capacity chosen for each house was such as to cover its electrical demand across the year (Table 1). For Houses 1 and 2, this is larger than a typical UK roof can support. The PV cost structure (Table 2) used in this work may be inaccurate for such cases, so results should be interpreted with caution.

Table 1. Annual loads for each house, and corresponding PV capacity.

House	Annual load, $\Sigma_t P_D(t)\, dt$ (kWh)	PV capacity, P_{PV} (kW)
1	8 015	8.25
2	7 343	7.50
3	4 836	5.00
4	3 845	4.00
5	2 706	2.75
6	2 563	2.75

The PV time series was averaged to 5-minute resolution to match the demand time series. The modelling time step is 5 minutes. All datasets were shifted to begin at 1st January.

A.2. Operating algorithm

Following Weniger et al. [3], Truong et al. [4], and others, the greedy algorithm is used to operate the battery:

- At each time step:
  - If PV generation exceeds demand ($P_{gen}(t) > P_D(t)$):
    - Charge the battery with the excess ($P_{gen}(t) - P_D(t)$), up to the charging power limit P_B, or until the state of charge (SoC) upper limit E_B^+ is reached.
    - Export remaining power to the grid ($P_g^+(t)$).
    - Update battery SoC, $E_{soc}(t)$, taking account of charging efficiency η_c .
  - Else (when $P_{gen}(t) < P_D(t)$):
    - Discharge the battery to meet the net load (at rate $P_D(t) - P_{gen}(t)$), up to the discharging power limit $-P_B$, or until the SoC lower limit E_B^- is reached.
    - Import any power still needed to meet the load from the grid ($P_g^-(t)$).
    - Update battery SoC, $E_{soc}(t)$, taking account of discharging efficiency η_d .

A.3. Calculation of NPV and CO_2

For each case, NPV is calculated from year n = 1 to N, where N = 15 (parameter meanings and values in Table 2):

$$NPV = -CAPEX + \sum_{n=1}^{n=N} \left(REV \left(\frac{1}{1+r_{int}}\right)^{n-1} - SPEND \left(\frac{1+r_{infl}}{1+r_{int}}\right)^{n-1} \right). \tag{4}$$

$$CAPEX = c_{PV,£,v} \cdot P_{PV} + c_{PV,£,f} + c_{B,£,v} \cdot E_B + c_{B,£,f} \, . \tag{5}$$

$$REV = c_{FiT} \cdot \sum_t P_{gen}(t)\, dt + 50\,\% \times c_{exp} \cdot \sum_t P_{gen}(t)\, dt \, . \tag{6}$$

$$SPEND = c_{buy} \cdot \sum_t P_g^{-}(t)\, dt \, . \tag{7}$$

Cash flows are discounted by interest rate r_{int}. Capital expenditure (CAPEX) includes fixed and variable costs for PV and battery, including installation and power electronics. Yearly revenues (REV) comprise feed-in and export tariffs, which are fixed from the beginning of operation. Export is typically not metered but deemed at 50 % of generation. SPEND is yearly expenditure on electricity, buy price c_{buy} increasing at rate r_{infl}. Operations and maintenance are assumed covered by the suppliers. The NPV for the same house with no PV and no battery is then subtracted from (4), as a baseline reference.

The lifetime CO_2 emissions are calculated analogously to (4). Instead of –CAPEX there is embodied CO_2 of manufacture (assumed variable costs only). Instead of –SPEND and +REV there are, respectively, CO_2 emissions, $+c_g^{-} \Sigma_t P_g^{-}(t)\, dt$, and emissions credits, $-c_g^{+} \Sigma_t P_g^{+}(t)\, dt$. There is no inflation associated with CO_2, but a discount rate of $r_{int,CO2}$ is applied. 'CO_2 savings' are –1× CO_2 emissions, and are also considered relative to no PV and no battery.

The parameter values used in the calculations are given in Table 2. The battery parameters are based on the Tesla Powerwall.

Table 2. System parameters, and how they were established.

PV				Interest rates			
$c_{PV,£,v}$	1000	£/kW	Variable cost (a)	r_{int}	4.0	%	NPV discount rate (f)
$c_{PV,£,f}$	2400	£	Fixed cost (a)	$r_{int,CO2}$	1.5	%	CO_2 discount rate (g)
$c_{PV,CO2}$	1590	kg/kW	CO_2 emissions (b)				
Battery				**Grid electricity**			
$c_{B,£,v}$	400	£/kWh	Variable cost (c)	c_{FiT}	0.0378	£/kWh	Feed-in Tariff (h)
$c_{B,£,f}$	2000	£	Fixed cost (c)	c_{exp}	0.0503	£/kWh	Export tariff (h)
$c_{B,CO2}$	193	kg/kWh	CO_2 emissions (d)	c_{buy}	0.163	£/kWh	Retail buy price (i)
$\eta_c \eta_d$	90	%	Round-trip efficiency (e)	c_{g0}	0.378	kg/kWh	CO_2 intensity of grid generation (b)
P_B	0.5	C	Power limit (e)	λ_l	8.0	%	T&D losses to branch point (j)
E_B^{+}	100	%	Upper SoC limit (e)	r_{infl}	5.8	%	Inflation rate (i)
E_B^{-}	5	%	Lower SoC limit (e)				
N	15	years	Lifetime (e)				

(a) https://www.gov.uk/government/statistics/solar-pv-cost-data (accessed 28/06/18) - the 2017/18 median is £1701/kW for 0-4 kW, £1393/kW for 4-10 kW, £1080/kW for 10-50 kW, consistent with a price of roughly £2400 + £1000/kW.

(b) Stamford, Laurence, and Adisa Azapagic. "Life cycle sustainability assessment of electricity options for the UK." *International Journal of Energy Research* 36, no. 14 (2012): 1263-1290. Further breakdown of data kindly supplied by Laurence Stamford. It is assumed that combined cycle gas turbines (CCGT) are the marginal generators at all times, but this may change in future.

(c) https://www.renewableenergyhub.co.uk/product/tesla-powerwall-6-4-kwh-home-battery.html (accessed 28/06/18) - a 7 kWh Tesla Powerwall costs £4800 including power converter, whereas a 14 kWh Powerwall 2 costs £5400 plus £500 for supporting hardware plus £800-2000 for installation – this is consistent with roughly £2000 + £400/kWh.

(d) Hao, Han, Zhexuan Mu, Shuhua Jiang, Zongwei Liu, and Fuquan Zhao. "GHG Emissions from the production of lithium-ion batteries for electric vehicles in China." *Sustainability* 9, no. 4 (2017): 504. Hao et al. found embodied CO_2 emissions of Li-NMC batteries of 36.9-196 kg/kWh reported in the literature.

Hawkins, Troy R., Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman. "Comparative environmental life cycle assessment of conventional and electric vehicles." *Journal of Industrial Ecology* 17, no. 1 (2013): 53-64. Hawkins et al.'s value of 193 kg/kWh is taken, as the embodied emissions of the power converter need to be included.

(e) https://www.tesla.com/en_GB/powerwall?redirect=no (accessed 28/06/18) – although the warranty is 10 years, the battery is likely to keep working for years after that, especially as cycling is low enough not to reach the 7000 cycle limit even by the end of 15 years. Charge efficiency, η_c, is approximated as equal to discharge efficiency, η_d .

(f) 4 % is lower than the return typically asked for from business investments, but it is likely a homeowner will accept less than this. 4 % is still higher than the interest rate on any cash ISA today, which is likely the highest-payoff alternative a homeowner may invest in.

(g) The CO_2 discount rate is a measure of the consideration of future climate-induced suffering relative to suffering in the present. Egalitarians favour lower discount rate, but a rate >0 is advised due to non-zero risk of human extinction by other means.

(h) https://www.ofgem.gov.uk/system/files/docs/2017/10/tariff_table_october_2017_1.pdf (accessed 28/06/18) – rates for installations beginning 01/06/18-30/09/18.

(i) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/695141/table_223.xls (accessed 28/06/18) – price averaged across all regions of the UK, all payment types, 2017. Up 5.8 % from 15.41 p/kWh in 2016.

(j) See [11].

Appendix B. Results: Effect of battery size on peak import and export

Setting $\lambda_2 = 0$ again, the peak import across the year (max($P_g^-(t)$)) was recorded. The effect of battery size on peak import depends on details of the household's demand, not just its annual total. E.g. almost no effect on Houses 1, 3, 4, but large effect on House 6. A 7 kWh battery has no effect on House 2, but the effect becomes sizeable for 14 kWh. Peak import occurs in winter, when there is little PV energy to charge the battery, regardless of its size.

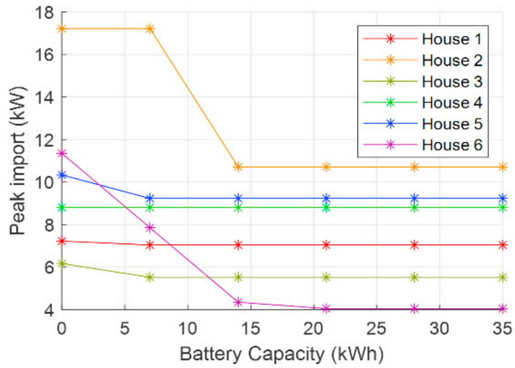

Fig. 4. Peak import power across the year, as a function of battery capacity, for all houses.

The low winter-time PV generation cannot charge the battery as quickly as the household demand drains it every day, resulting in the battery often running empty. The converse is true in summer, resulting in the battery being full nearly all the time. Even for battery capacity as large as 28 kWh, operating a greedy algorithm means the summer-time demand cannot empty the battery sufficiently each night, before the next morning's PV generation completely fills it again, often before noon. The battery then cannot accept more PV energy, at the very time when grid export is highest, and when voltage violations are most likely.

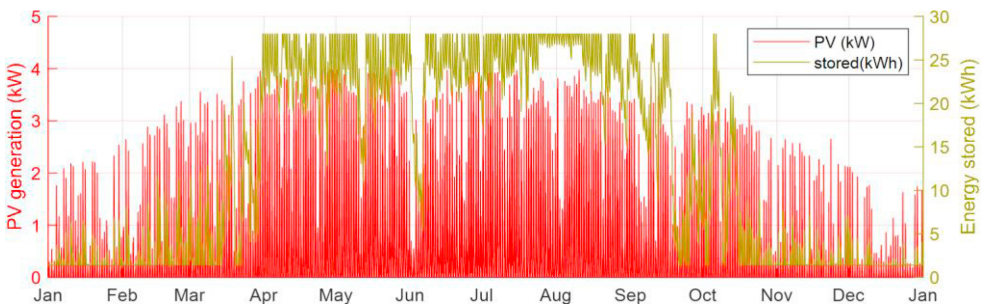

Fig. 5. PV generation and energy stored in a 28 kWh battery, for House 4, whole year.