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Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: A case study from Finland

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Solar PV
Battery energy storage
Virtual battery
Energy measurement
Northern climate conditions

A B S T R A C T
Solar photovoltaic systems have been growing in popularity in prosumer households as a means of increasing the share of renewable energy and decreasing electricity import. The available self-consumption is, however, limited by a temporal supply–demand imbalance. In this paper, options for improving the self-consumption of a prosumer household are studied by using three-year data sets of electricity import and export data from two distinct, real-life cases from Finland. Two separate approaches are analysed: the use of energy storages, physical or monetary, and changing of the electricity metering method. A switch of the electricity metering method from instant phasewise to hourly net metering was found to increase the self-sufficiency by about 3 to 5 percentage points and have an annual monetary benefit of a few tens of euros when a network storage was used. Considering the energy storage methods under study, the network energy storage was found to be more economically feasible than a physical or a virtual battery energy storage, even though a physical battery storage could increase the self-sufficiency as much as by 30 percentage points with a storage capacity of 20 kWh. The studied virtual battery concept was found to limit the profitable solar photovoltaic plant size if high enough storage capacity was not provided. When a physical battery energy storage is used, switching to hourly net metering does not add value to the system. A significant decrease in the system cost is required for a physical battery energy storage to be economically competitive in northern climate conditions.

1. Introduction

The falling prices of solar photovoltaic cells (PV) are increasing the global interest in small-scale end-user solar PV installations as an economical way to reduce one’s carbon footprint of electricity consumption. Installing solar PV capacity to a house transforms its residents from mere electricity consumers into prosumers, who self-produce part of the electricity they consume and may also sell surplus to the electric grid. The intermittent nature of solar energy, however, together with a temporal mismatch between electricity consumption and generation results in limiting the potential for prosumer households to profit from their solar PV installations. Methods and technologies deployed to overcome this imbalance between supply and demand are numerous, and research interest in this field is increasing with the growing popularity of prosumerism.

There are two main options for dealing with the supply–demand imbalance: increasing self-consumption and energy trading. Energy trading is familiar to all consumers of electricity, with or without their own electricity generation, but for prosumers the trading can happen in both ways. If the local legislation allows and there is a defined price for electricity exported to the electric grid, prosumers are able to sell, or export, their excess electricity to their electricity provider and, vice versa, purchase, or import, electricity when the demand exceeds their own electricity generation. Most often, the price for importing electricity is significantly higher than for exporting, which adds interest in increasing energy self-consumption. Absolute self-consumption is defined as the amount of electric energy generated on site that can be directly used by the prosumer [1]. Increasing self-consumption reduces the need for electricity import and export, thus improving the monetary value of the energy system. Absolute self-consumption is not the most convenient metric for comparison because of its dependence on the PV system size. Therefore, self-sufficiency, defined as the absolute self-consumption with respect to the total electricity consumption of the system [2], is used in this paper. There are two common ways of increasing self-consumption in a prosumer household: demand-side management of electricity consumption and energy storages [2]. Demand-side management is used to reschedule peak consumption from nighttime with no sunlight and thus no solar PV electricity generation to the time of day with solar power available. Because of its low cost, demand-side management is widely used and studied, although its ability to increase self-consumption in

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0306-2619/ © 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
the Nordic conditions is considered limited [1]. Not all the electricity consumption can be scheduled to match solar PV generation, however. Examples of non-schedulable loads are lighting, cooking, or use for entertainment devices. Energy storages respond to this limitation by storing electricity produced during daytime for later use. The most common energy storage method for households is the use of thermal energy storages, such as heat-accumulating tanks or structures, which can, for example, enable quick response to peaks in domestic hot water demand or provide a steady, long-lasting heat source for space heating. For prosumer households, however, interest in electrochemical energy storages, such as lithium-ion batteries, has recently been increasing, which has generated growth potential for their supply in the market.

In recent years, investigation of solar PV energy systems with a physical battery energy storage included has attracted widespread interest. Chaianong et al. [3] studied the economic returns for prosumers with solar PV and battery energy storages under decreasing battery prices in Thailand. They found that the upfront costs are currently too high to make the system economically feasible. A cost reduction to 100 USD/kWh at the system level would, however, allow solar PV battery systems to compete with only solar PV-based systems. Ramirez Camargo et al. [4] investigated the requirements for a solarPV battery-powered residential system to be completely grid independent in Germany and the Czech Republic. Their methodology was based on spatiotemporal data sets of electricity consumption, solar PV power generation potential, and long-term weather data, which enabled calculation of solar PV and battery capacity requirements for grid-independent operation based on location by minimising the system cost. Their results show that complete grid independence is challenging with solar PV battery systems because of the intermittency of solar irradiation. Pereira et al. [5] studied the economics of a battery storage system for solar PV-powered households on the island of Madeira, where no grid feed-in is currently allowed. Their analysis shows that although self-consumption can be increased with battery storages, an additional decrease in battery prices is required for economic viability. Reserving some proportion of battery capacity for peak hours only was, however, observed to increase the profitability although simultaneously decreasing self-consumption. O'Shaughnessy et al. [6] conducted a review on research into solar PV systems integrated with batteries and load control, referred to as solar plus. They found that solar plus always increases the value of a solar PV installation. However, batteries, although more effective than load control in increasing self-consumption, are not cost-effective with the current prices. A decrease in the compensation for grid feed-in reduces the value of both solar PV-only and solar plus systems, but, because of having less export and more self-consumption, the reduction is smaller with solar plus. Schopfer et al. [7] investigated the profitability of a solar PV battery system in households using a large set of measured real-world consumption data and different price scenarios for Central European conditions. By using measured data from multiple households, they were able to assess the effects of heterogeneity in load profiles on the results. They found that with the current solar PV and battery prices, the combined system cannot be economically feasible. However, systems with only solar PV would be profitable for households with an annual consumption of more than 7 MWh. Heterogeneity in load profiles added significant variation to the results, which underlined the importance of using real-world data instead of generalised consumption profiles when studying the profitability of household energy systems. Quoilin et al. [8] studied self-sufficiency in solar PV battery residential systems in multiple EU countries. Generalised load profiles from different countries were used with added stochastic noise obtained from a large historical data set to generate realistic yearly consumption time series. Their main findings were that self-sufficiency could be significantly increased with the addition of batteries, but 100% self-sufficiency is not achievable without excessive oversizing of the system. In addition, the current battery cost makes their inclusion in the system infeasible. Furthermore, they found that self-consumption for a given household cannot be predicted deterministically because of the wide variation that depends on the individual load profile.

Some studies on including a battery energy storage in solar PV-powered energy systems have been conducted specifically for northern climate conditions. Earlier work by the authors of this paper [9] considered a physical battery energy storage as part of a solar PV-based off-grid energy system also including a hydrogen seasonal energy storage in a residential house in Finland. A practical limitation of 20kWh for the battery energy storage capacity was set because the increase in self-sufficiency achieved by increasing the battery capacity slowed down significantly after that point. Cao et al. [10] compared the capability of electrochemical batteries with that of domestic hot water storages for reducing the power generation–consumption mismatch in a household in Finland by using either solar PV panels or micro wind turbines. They found that one day’s worth of DHW storage was technically and economically more feasible than larger DHW or electrochemical battery storage options. They also showed that grid feed-in significantly reduces the simple payback time of the system, especially for systems with a larger power generation capacity. Nyholm et al. [11] performed an extensive analysis on the self-consumption and self-sufficiency potential of solar PV battery residential systems for 2104 Swedish households. They found that self-sufficiency can increase up to 12.5 to 30 percentage points and self-consumption by as much as 20 to 50 percentage points, depending on the consumption profile of the household. No economic analysis was performed, however. Salpakari and Lund [12] investigated rule-based and cost-optimal control of a household energy system with solar PV panels, a ground source heat pump, a water tank thermal energy storage, an electrochemical battery, and schedulable loads. The systems were evaluated using real-life energy consumption data, meteorological solar irradiation data from Finland, and hourly SPOT electricity prices. They found the schedulable loads to be the least effective way to provide flexibility for the system. A cost-optimal control enabled a reduction in the electricity cost up to 25% in the best case. Kuleshov et al. [13] analysed the techno-economic feasibility of a LiFePO4-based battery storage system for a Finnish prosumer household with projected battery energy storage investment costs and electricity retail prices between 2018 and 2035. Based on their findings, a battery energy storage system will most likely remain not feasible within the time frame under study. However, with the most optimistic battery cost and electricity price development scenario, the threshold for financial profitability could be reached in the first half of the 2030s.

Although the research presented above agrees on that the prices of battery energy storages are still too high for economically viable systems, opposing voices are also heard. Comello et al. [14] argue that in some market areas, for example in Germany, low feed-in tariffs compared with electricity prices make battery storage systems an economically feasible energy storage method for prosumers. Bertsch et al. [15] also find that combined solar PV and battery energy storage is profitable in Germany. The internal rate of return for stand-alone solar PV is, however, still higher than for the combination of solar PV and storage. Koskela et al. [16] conclude that the combined solar PV and battery energy storage could be even more profitable than solar PV alone for residential customers in apartment buildings in Finland. The presumption for the profitability is that the household belongs to an energy community and the battery prices are on the lower edge of the current price estimations.

The other option for the prosumer to overcome the energy supply–demand imbalance, besides by increasing self-consumption, is energy trading. Most often, the trading is based on a contract between the prosumer and their electricity provider to trade through the electric grid, but the contents of the contract may vary. In practice, the trading can be compared to an energy storage where the energy is stored in monetary form and, therefore, the two contract types studied in this paper are referred to as a network storage and a virtual battery storage.
A network storage, on one hand, is based on selling excess solar PV-generated electricity and purchasing electricity back when the local power generation is not sufficient to meet the demand. Energy is thus stored in monetary form as the income from sold electricity, which is later used for buying electricity back. The term network storage is used here to emphasise the comparability with other energy storage options under study. In effect, a network storage is equal to a two-way electricity market, where prosumers can sell their surplus electricity. The market price is used for both import and export of electricity, and the price in both directions includes a margin set for the benefit of the service provider. There is no mechanism preventing the usage of a physical battery storage simultaneously with a network storage, and in this paper, they are always used in tandem when a physical battery storage is included in the system. A network storage is the default option for a prosumer if selling of electricity is allowed by the local legislation.

A virtual battery storage, on the other hand, is not as established a concept. The term can easily be mixed with multiple similar terms from previous literature. For instance, Amini and Almassalkhi [17] and Jin et al. [18] studied the concept of virtual energy storage, which means the use of schedulable loads for grid stability control. Another closely related concept is the sharing of prosumer-owned physical battery storage capacity, i.e., cloud energy storage studied by Liu et al. [19], and Rapaport and Miles [20]. Furthermore, the usage of a larger, centralised physical battery as a shared energy storage, also called a virtual energy storage, was studied by Zhao et al. [21]. In this paper, a virtual battery is defined as a type of service for electricity trading between prosumers and their electricity providers. These kinds of services are delivered at least by some Finnish [22,23] and German [24] electricity providers. The capacity of a virtual battery is limited within a set billing period, and electricity exported to the grid is not compensated. However, the stored electricity that is retrieved from the storage is compensated with a fixed price, which equals the average electricity purchase price. Because of the novelty of such a trading mechanism, the literature on the topic is scarce.

Energy trading provides a third approach, in addition to demand-side management and energy storages, to increase self-consumption from the viewpoint of reducing the electricity cost for the prosumer: by changing the method and time resolution of the electricity export-import balance measurement. Extending the measurement time allows the prosumer to circulate the produced electricity through the electric grid within the measurement time, thereby virtually enabling more of the produced electricity to be consumed on site. For household electric systems consisting of more than one separate phase, also the order between summation of the phase powers, determining whether there is export or import, and integration over the measurement time have an impact on the end result. Changing the measurement methods is, of course, not in the hands of the prosumer but has to be achieved either through regulation or through the policy of the electric grid operator.

Ayala-Gilardon et al. [25] studied the effect of time resolution of electricity measurement on the self-consumption and self-sufficiency of a prosumer household. Their study clearly shows that a higher measurement resolution results in decreasing self-consumption, and longer measurement times increase it because of the loss of high-accuracy information. The largest changes are observed in longer than one-hour measurement times where daily, monthly, or annual variations in the power generation start to get blurred. Nyholm et al. [26] analysed how different pricing schemes affect the attractiveness of solar PV investment for Swedish households. Based on their results, longer energy integration periods improve the economics of larger solar PV plants. However, the improvement in profitability reduces the economic benefit of improving demand response. Kraus et al. [27] identified and analysed the significance of electricity measurement methods for subjects with both power consumption and generation in three-phase electric networks. De Boeck et al. [28] compared the support policies for consumer solar PV generation in multiple European countries. As to the electricity metering methods, they consider annual net metering as a subsidy. Unlike in the paper of De Boeck et al. in our study the time step for net metering is shorter, equalling the time step length of the electricity market. In this paper, metering methods are thus not considered subsidies.

The objective of this study is to analyse by time-step-based simulations the effects of both energy measurement and electric energy storage methods on the self-sufficiency and system value of a residential solar PV energy system. Simulations are performed using real-life combined hourly grid export and import data from two prosumer households with rooftop solar PV installations in southeastern Finland recorded during years 2017–2019. Hourly Nord Pool Finnish SPOT electricity market prices from the same time period and the present electricity contracts of the households are used to determine the annual mean price for electricity, which is used to enhance comparability between the houses. The two houses differ in their amount of solar PV capacity utilised and their method of heating, one belonging to the district heating network, the other using a ground source heat pump, which is scheduled to operate in synchronisation with the solar PV power generation. This difference in the heating method affects the consumption profile of the houses and their initial self-sufficiency. A case comparison between the subjects provides information on how the different consumption profiles affect the value increase potential of an energy storage included in the system. Studying cases for three operational years, instead of statistical sets of houses, enables more in detail analysis of the effects of storage capacity, solar PV capacity and electricity prices with real-life combinations of solar PV generation and electricity consumption data.

In this study, three different energy measurement methods are compared, termed instant phasewise metering, instant net metering, and hourly net metering. Their effects on the electricity import and export are illustrated by using a short four-hour measured data set of three-phase power with five-minute intervals. Instant phasewise metering and hourly net metering methods are also used in combination with the studied energy storage methods.

One physical energy storage method, namely electrochemical battery storage, and two monetary storage options, network storage and virtual battery storage, are analysed as the energy storage methods. The analysis is carried out on the effects of changing the solar PV peak power capacity, battery storage capacities (when applicable), and electricity prices on the self-sufficiency and value of the energy systems under study. Network storage is considered a reference with which the two battery options are compared.

The novelty of the paper lies in the following three aspects: First, the use of combined electricity import and export data from actual prosumer households represents real-world systems with their non-optimal characteristics more accurately than generated data. Combining simultaneously measured solar PV power generation, electricity consumption and electricity market price data in the simulations integrates their real-life correlations in the results. These correlations would be lost with meteorologically created solar PV data or generalised consumption profiles. Second, the definition of energy storage is extended to consider monetary options on a par with physical storage options highlighting their comparability from the prosumer’s perspective. Few research has been conducted earlier about virtual battery concepts offered for prosumer households. The different storage options are analysed in this paper together with the dimensioning of solar PV capacity. Third, as the monetary storage options are included, the emerging question about the meaning of energy measurement from the prosumer’s viewpoint is assessed, which has had little attention in the existing literature. Although the results are regional because of the nature of solar insolation and climate conditions, the findings of this study are presented as comparable as possible also for other locations. The applicability of the results is highest inside the Nord Pool market area, but also other high-latitude regions are within the range of this study if the characteristics of local electricity markets are taken into account.
The topic of this study is approached from the perspective of residential prosumer households, and the results give valuable information by comparing different energy storage options that are easily accessible. The results are, therefore, directly applicable to decision-making when a prosumer is looking for options for using their surplus generated electricity. Furthermore, the results of electricity metering methods are directly applicable to policymaking, giving information on how effective a switch of the metering method would be in increasing the prosumer self-sufficiency.

This paper is organised as follows. Section 2 provides the description of the two prosumer energy systems whose data are used for simulations in this paper. The energy measurement methods and their effect on electricity import and export are presented in Section 3. Section 4 introduces the studied energy storage methods in more detail and presents their analysis results. In Section 5, the results are summarised and their further significance discussed.

2. System description

Two residential detached houses from southeastern Finland are studied: a zero-energy log house (House A) and a house with district heating (House B). Both the houses have solar PV installations in service and electricity import–export data collected for three years. The houses differ, however, in their method of heating, which affects their electricity consumption profile. The grid connections of both houses are dimensioned at 3×25 A, but the houses are located in areas of different distribution grid companies, which is seen as different pricing of electricity distribution. The electricity purchase and sales contracts are tied to the Nordpool SPOT Finland area price. The electricity purchase and sales contracts have also been made with separate energy companies. Surplus electricity is exported to the electric grid and imported back when there is not enough power generation. The annual amounts of electricity import and export for both the houses, and the respective cash flows are presented in Table 1. Electricity measurements are performed with smart meters, whose allowed uncertainty is regulated in the Directive 2014/32/EU of the European Parliament and of the Council [29].

House A is the first zero-energy log house in Finland; it is a zero plus-energy house at the net level [30]. It is a detached house whose main heating system is based on a ground source heat pump (GSHP) with fireplaces for supplementary heating. The solar PV installation capacity of the house is 21.1 kWp with 10.40 kWp directed to south and 5.35 kWp to both east and west. Heating with GSHP enables the control of the time of heating to match solar PV generation when possible, which leads to a high self-sufficiency of 36.27%. A combination of average hourly power generation and consumption profiles from March to October is presented in Fig. 1, showing a good match between their timing. A more in detail description of the house can be found in Appendix A.

The second house studied in this paper, House B, is also a single-family house in Finland, whose main heating system is district heating. Supplementary heat is provided with a fireplace and an air source heat pump installed in December 2018. The house has a 8.8 kWp rooftop solar PV system aligned south-west. As the heating method is non-schedulable, the consumption of House B is not as well aligned with the power generation from the solar PV as it is with House A. The case is demonstrated in Fig. 1(b). Therefore, the self-sufficiency of House B is only 18.29%. More details of the house can be found in Appendix A.

3. Energy measurement

The Nordic electricity market was deregulated in 1995 by unbundling the electricity distribution and trade. Since 2010, smart remotely read electricity meters, able to measure both electricity consumption and generation at an hour level, have been installed to all electricity consumers. Each electricity consumer is free to select the electricity provider and the type of electricity contract. Almost all electricity providers buy solar PV electricity with an hourly system price, although other contract types are also available. The hourly system price of electricity is formed day-ahead based on supply and demand in the Nordic Power market Nord Pool [31]. Owing to bottlenecks in power transmission capacities, there are several price areas in the Nordic countries.

Both the electric energy exported to and imported from the grid are measured with a smart electricity meter and recorded on an hourly basis. The measurement is based on integrating instant phasewise

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**Table 1** Amounts of surplus solar PV power generation exported to and electricity imported from the electric grid, and the annual costs for these two transactions.

<table>
<thead>
<tr>
<th></th>
<th>House A</th>
<th>House B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Import MWh/a</td>
<td>4.835</td>
<td>4.528</td>
</tr>
<tr>
<td>Export MWh/a</td>
<td>13.976</td>
<td>15.485</td>
</tr>
<tr>
<td>Import €/a</td>
<td>655.24</td>
<td>725.28</td>
</tr>
<tr>
<td>Export €/a</td>
<td>478.98</td>
<td>779.67</td>
</tr>
<tr>
<td>Total</td>
<td>176.26</td>
<td>53.39</td>
</tr>
</tbody>
</table>

---

**Fig. 1.** Average distribution of power consumption and generation throughout the day from March to October for (a) House A and (b) House B.
power within each hour. The result, however, is dependent on the order of applying three mathematical operations: summation of phases, division between export and import, and integration over the one-hour time period to obtain the hourly flow of energy. Three distinct methods for energy measurement are presented in this paper, referred to as instant phasewise metering, instant net metering, and hourly net metering. The power measurement of instant phasewise metering and instant net metering are comparable to the methods V1 and V2 in [27], respectively, but an additional integration step over an hour is needed in order of applying three mathematical operations: summation of phases, division between export and import, and integration over the one-hour time period to obtain the hourly flow of energy.

3.1. Descriptions of the energy measurement methods

3.1.1. Instant phasewise metering

Instant phasewise metering is the currently used metering method for both the houses studied in this paper. The method is based on first determining the direction of power \( P_i(t) \) in each phase \( i \) and time instance \( t \). Here, the direction from the grid is defined as positive and to the grid as negative. The exported power \( P_e \) is found by summing all \( P_i(t) \) going to the grid and the power imported from the grid \( P_i \) by summing the ones coming from the grid at the time instance \( t \):

\[
P_e(t) = \sum_{i=1}^{3} P_i(t), \quad \text{if } P_i(t) < 0
\]

\[
P_i(t) = 0, \quad \text{otherwise},
\]

\[
P_e(t) = \sum_{i=1}^{3} P_i(t), \quad \text{if } P_i(t) > 0
\]

\[
P_i(t) = 0, \quad \text{otherwise}.
\]

\[
P_e(t) \quad \text{and } P_i(t) \quad \text{for the four-hour test period are shown in Fig. 3(a). After summation over the phases, both the exported and imported power are integrated over the period of one hour to find the values for the exported energy \( E_e \) and the energy imported from the grid \( E_i \),}

\[
E_e(t) = \int_{t-1}^{t} P_e(t) \, dt.
\]

\[
E_i(t) = \int_{t-1}^{t} P_i(t) \, dt.
\]

3.1.2. Instant net metering

Instant net metering relies on first summing the phase power values to find the direction of net power:

\[
P_{\text{net}}(t) = \sum_{i=1}^{3} P_i(t),
\]

which is then divided into either the exported power \( P_e \) or the imported power \( P_i \) for each instant of time:

\[
P_e(t) = \begin{cases} P_{\text{net}}(t), & \text{if } P_{\text{net}}(t) < 0 \\ 0, & \text{otherwise,} \end{cases}
\]

\[
P_i(t) = \begin{cases} P_{\text{net}}(t), & \text{if } P_{\text{net}}(t) > 0 \\ 0, & \text{otherwise.} \end{cases}
\]

\[P_e(t) \quad \text{and } P_i(t) \quad \text{for the four-hour test period are shown in Fig. 3(b). The amounts of exported and imported energy are again obtained by integrating the respective power values over the period of one hour with Eqs. (3) and (4).}

3.1.3. Hourly net metering

With hourly net metering, the net energy flow for each hour is calculated first by integrating the net power:

\[
E_{\text{net}}(t) = \int_{t-1}^{t} P_{\text{net}}(t) \, dt.
\]

\[E_{\text{net}}(t) \quad \text{could also be calculated by adding the imported and exported energy from Eqs. (3) and (4). Export takes place only when the net energy is negative and import when the net energy is positive:}

\[
E_e(t) = \begin{cases} E_{\text{net}}(t), & \text{if } E_{\text{net}}(t) < 0 \\ 0, & \text{otherwise,} \end{cases}
\]

\[
E_i(t) = \begin{cases} E_{\text{net}}(t), & \text{if } E_{\text{net}}(t) > 0 \\ 0, & \text{otherwise.} \end{cases}
\]

3.2. Metering comparison results

The hourly exported and imported energy for each metering method over the test period are shown in Fig. 4. Both the instant phasewise metering and the instant net metering enable export and import to take place within a single hour, whereas with the hourly net metering only export or import is possible. There are two possible ways for simultaneous export and import to take place:

1. Unsymmetrical loading. Simultaneous export from some of the three phases and import from the others; this is a result of unsymmetrical loading of the phases.
2. Balance fluctuations. Changing the sign of balance between import and export within an hour; this results from temporal changes in power generation and consumption within a single measurement period.

Instant phasewise metering is prone to both phenomena, whereas instant net metering is only liable to the second one. This difference is clearly visible in Fig. 3(a) and Fig. 3(b) for instant phasewise and instant net metering, respectively.

Removing simultaneous export and import when changing the metering methods reduces both \( E_e(t) \) and \( E_i(t) \) with the same amount because of conservation of energy. This phenomenon is clearly visible in Table 2, which shows the imported and exported energy and their difference compared with the values from instant phasewise metering for the four-hour test period. The effect on the electricity bill is, however, beneficial for the end-user as the price for imported energy is higher than the price for exported energy.

In addition to the monetary benefit, the decrease in energy transactions can also be seen as an effective increase in self-consumption. To observe this phenomenon, the definition of self-consumption is extended in this study from the definition found in the literature [2].
Fig. 3. Exported and imported power with 5 s time intervals for instant phasewise and instant net metering methods.

The definition used here is based on the difference between generated and exported energy within each hour, which also includes the electricity that is circulated through the grid within each hour. Total self-consumption is now defined as:

\[ E_{\text{self}}(t) = \int_{t-1}^{t} P_{\text{prod}}(\tau) \, d\tau - E_{-}(t). \]  

(11)

Often, self-sufficiency is more useful for assessing the ability of a system to produce the energy it consumes. It is defined as the ratio between self-consumption and total energy consumption [2]:

\[ S = \frac{\sum_{t=0}^{T} E_{\text{self}}(t)}{\int_{0}^{T} P_{\text{cons}}(\tau) \, d\tau}. \]  

(12)

The growth in effective self-consumption and thus self-sufficiency is based on the ability of the end-user to use more self-produced energy during an hour by circulating it through the grid without affecting the energy export and import values.

### Table 2

<table>
<thead>
<tr>
<th>Method</th>
<th>Order</th>
<th>Import (kWh)</th>
<th>Export (kWh)</th>
<th>Change from phasewise metering (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instant phasewise</td>
<td>DSI</td>
<td>0.885</td>
<td>9.071</td>
<td>–</td>
</tr>
<tr>
<td>Instant net</td>
<td>SDI</td>
<td>0.725</td>
<td>8.911</td>
<td>–0.160</td>
</tr>
<tr>
<td>Hourly net</td>
<td>SID</td>
<td>0.628</td>
<td>8.816</td>
<td>–0.256</td>
</tr>
</tbody>
</table>

4. Storage options

Because of the highly intermittent nature of solar PV power generation, some form of energy storage is needed to maximise the benefit of the solar PV installation. Usually, the definition of an energy storage only includes physical storage options that bind electrical energy to some other form of energy, such as kinetic, potential, electrochemical, chemical, or thermal energy [32]. These kinds of storages aim to minimise energy loss during the storage period and release energy when needed, mostly in either electrical or thermal form. A common example of a physical storage option is the electrochemical battery.

In this study, however, the aim is to investigate how prosumers can better benefit from their investment. Therefore, in this context, also monetary storage options can be defined and regarded as an energy storage. Monetary storages are based on using the electric grid connection to transfer surplus solar PV-generated electricity to the grid and recover it when needed, effectively using the grid as an energy storage. The storage capacity and cost are, therefore, dependent on the contract signed between the end-user and the electricity provider.

Two examples of the monetary storage options studied here are a network storage and a virtual battery storage. A network storage is based on exporting surplus generated electricity to the grid and buying electricity back when consumption exceeds power generation. A virtual battery storage, in turn, includes a set amount of energy capacity that the end-user is able to store to the grid for later use with a fixed fee. Usually, there is no additional benefit for the end-user of the energy exceeding the virtual battery limit, although the content of the contract may vary. In this study, a physical and a virtual battery storage are compared with a network storage using three-year hourly exported and imported energy data from the two houses described in Section 2. Both the houses had a network storage in use with instant
prices with margins, fixed costs, and taxes. Hourly electricity price for electricity transmitted in either way is built on the SPOT electricity use, the power generation, and the prices agreed with the on two-way electricity trading. The final storage cost depends on the used always when a prosumer and an electricity provider have agreed.

4.1. Network storage

4.1.1. Description

A network storage is a monetary energy storage method that is used always when a prosumer and an electricity provider have agreed on two-way electricity trading. The final storage cost depends on the electricity use, the power generation, and the prices agreed with the electricity provider. Within the Nord Pool electricity market, the total price for electricity transmitted in either way is built on the SPOT market price with margins, fixed costs, and taxes. Hourly electricity prices \( p(t) \) are calculated as:

\[
p_+ (t) = \epsilon_{\text{spot}} (t) \cdot (1 + \text{VAT}) + m_+
\]

\[
p_- (t) = \epsilon_{\text{spot}} (t) - m_-
\]

where \( \epsilon_{\text{spot}} (t) \) denotes the hourly market price for electricity and \( m \) the total price margins. Differentiation between prices for export and import is indicated by subscripts \(-\) and \(+\), respectively. Value-Added Tax (VAT) is paid only when buying electricity. Fixed fees are in units \( \text{€/month} \), whereas consumption-based prices are in \( \text{c/kWh} \). In this paper, the real SPOT price data and electricity contracts of the two houses studied are used for estimating electricity prices. The SPOT price varied between 0.012 \( \text{c/kWh} \) and 25.502 \( \text{c/kWh} \) during the measurement period, having a mean at 4.134 \( \text{c/kWh} \) with a standard deviation of 1.481 \( \text{c/kWh} \). All the required price elements used in this paper are presented in Table 3, whereas the realised prices, which combine the electricity flow data with the SPOT price data, are given in Table 4. Mean SPOT margins, listed in Table 5, are used in simulations to enhance comparability between the houses.

The annual monetary value of a system \( v \) is used in this paper to compare the economics of separate systems. The benefit of using

\[
v = \sum_{t=0}^{n_{\text{years}}} E_- (t) p_-(t) + E_{\text{self}} (t) p_+ (t)
\]

where \( n_{\text{years}} \) is the number of years. In this study, both the houses had only network batteries in use during the data collection period. The network battery is, therefore, used as a reference energy storage method with which other methods are compared. However, using other energy storages does not necessarily prevent the use of a network battery in parallel. In this study, a network battery is also used along with physical batteries.

4.1.2. Analysis

The network storage was analysed as a function of installed solar PV peak power capacity using hourly net metering. Self-sufficiency results of this analysis are presented in Fig. 5(a) and Fig. 5(b) for House A and House B, respectively. Although the solar PV power generation grows steadily with the increasing solar PV peak power capacity, the growth of self-sufficiency slows down to meet an asymptotic limit. This limit is found to be 51.0% for House A and 41.5% for House B.

The increase in the value for House A as a function of solar PV peak power capacity is shown in Fig. 6. The total value grows slightly faster with smaller power plant sizes with a stronger emphasis on the more valuable self-consumption. However, the overall increase is close to linear.

4.2. Physical battery storage

4.2.1. Description

In this study, physical battery modelling is performed by both instant phasewise metering and hourly net metering. When using instant phasewise metering with a physical battery, the battery itself is used to balance interhour variations in imported and exported electricity. This balancing is assumed to be perfect, thus having no effect on the battery SOC. In real applications, a downside of this approach is the need for a three-phase battery inverter capable of unsymmetrical load control; inverters of this kind are not widely available. Hourly net metering, on the other hand, levels out interhour variations caused by both unsymmetrical loading and interhour balance fluctuations. Simulated hourly net metering with a physical battery, therefore, slightly underestimates the use of the battery.

A simple battery model with a limited storage capacity \( \epsilon_{\text{bat}} \) but unlimited power ratings for both charge and discharge is used in

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Three-year electricity contract fixed costs and SPOT margins (containing electricity, transmission, and taxes) for purchase (import) and sales (export) for the houses under study. When purchasing electricity, 24% VAT is added to the SPOT price.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price element</td>
<td>House A</td>
</tr>
<tr>
<td>Purchasing, margin on SPOT</td>
<td>m_+</td>
</tr>
<tr>
<td>Selling, margin on SPOT</td>
<td>m_-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Annual and three-year average realised import and export prices that take into account the energy flow and the SPOT price at each time point. Fixed fees are not considered.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realised price</td>
<td>House A</td>
</tr>
<tr>
<td>Import</td>
<td>c/kWh</td>
</tr>
<tr>
<td>Export</td>
<td>c/kWh</td>
</tr>
<tr>
<td>Difference</td>
<td>c/kWh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Mean SPOT margin prices, transmission prices, and electricity tax between House A and House B calculated from individual prices in Table 3. The mean prices are used to improve the comparability of system values.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean price element</td>
<td>2017</td>
</tr>
<tr>
<td>Purchasing, margin on SPOT</td>
<td>c/kWh</td>
</tr>
<tr>
<td>Selling, margin on SPOT</td>
<td>c/kWh</td>
</tr>
</tbody>
</table>
Fig. 5. Total annual solar PV power generation, total annual consumption, and self-sufficiency for (a) House A and (b) House B as a function of scaled solar PV peak power. Hourly net metering is employed for simulations with the scaled solar PV peak power capacity. The current plant capacity is indicated by a vertical line.

Fig. 6. Solar PV system value annually with a network battery for House A and House B. The value is calculated as a sum of the income from exported electricity and the saving from self-consumption, both of which are also shown in the figure. The dashed line represents the solar PV capacity of the current system.

this study. The same model was used previously in [9]. A symmetric efficiency of $\eta = 0.92$ is assumed for both charging and discharging, which is a realistic estimation for lithium-ion batteries taking into account any required power electronics [33,34]. Battery state of charge (SOC) as a proportion of the total capacity is used to monitor the amount of energy charged to the battery. Self-discharge is assumed to be negligible, and the depth of discharge and the number of cycles unlimited. Capacity degradation observed in real Li-ion batteries is also omitted to maintain simplicity of the model, and the battery is expected to stay unchanged during the simulation time of three years. Thus, the resulting operational value of the battery energy storage represents an upper limit for the possible annual value. Details of the battery modelling are presented in Appendix B including equations for the determination of self-consumption and operational value, $v_{\text{bat}}$, of the battery storage system.

4.2.2. Comparison between physical battery storage and network storage options

The characteristics of the physical batteries incorporated in the systems were analysed with two cases: first using instant phasewise metering with only the battery capacity as a variable for the current solar PV peak power capacity, and second using hourly net metering with both the battery capacity and the solar PV peak power as variables. When the solar PV peak power was varied, only hourly net metering could be used as the hourly data resolution prevented calculation of interhour changes in the electricity generation–consumption balance with a changing solar PV peak power.

Two resulting values were obtained from the simulations: the system self-sufficiency and the battery relative monetary value calculated as the value of the battery in relation to its capacity. Mean price elements, listed in Table 5, were used instead of individual price elements to allow a better comparison between the houses.

Self-sufficiency as a function of battery capacity is shown in Fig. 7(a) and Fig. 7(b) for House A and House B, respectively. The increase in self-sufficiency obtained from the inclusion of a battery storage is shown in Fig. 8(a) for House A and in Fig. 8(b) for House B. The greatest benefit in self-consumption is found with moderate battery capacities below 20 kWh, after which the growth with the increasing battery capacity slows down significantly. In the case of House A, the increase in self-sufficiency below the capacity limit is not as profound as in the case of House B because of the higher self-sufficiency to begin with. However, for both the houses, the level to which self-sufficiency settles after its growth has slowed down is nearly equal when systems with equal solar PV peak power capacities are compared.
Fig. 7. Self-sufficiency for systems with different values of solar PV peak power capacity as a function of physical battery capacity. House A and House B are used as the starting point for (a) and (b), respectively. Hourly net metering is employed when the solar PV peak power is scaled from the original.

Fig. 8. Increase in self-sufficiency obtained by the inclusion of a physical battery storage in the system. House A and House B are used as the starting point for (a) and (b), respectively. The basic self-sufficiency levels for the houses without a battery storage were presented in Fig. 5(a) and Fig. 5(b). Hourly net metering is employed when the solar PV peak power is scaled from the original.

The battery value relative to its capacity using different solar PV peak power capacities with hourly net metering is shown for House A in Fig. 9(a) and for House B in Fig. 9(b). For comparison, the same relative value for both houses with instant phasewise metering is illustrated in Fig. 10. House A can be seen to benefit more from smaller battery capacities with the value declining rapidly as the capacity increases. In contrast with House B, the decrease in battery value is not as profound thus making larger battery capacities more beneficial. If instant phasewise metering is used, the battery relative value increases by about 70% for House A and nearly by 300% for House B when the smallest battery capacity of 1 kWh is used. The value remains higher in both cases with an increasing battery capacity, when comparing with the same system with hourly net metering. The higher battery value observed with instant phasewise metering is a result of the usage of the battery for balancing interhour power fluctuations. With hourly net metering, this interhour balancing is, instead, carried out by using the grid, which decreases the battery usage and thus decreases its monetary value.

One problem has to be considered, however, when simulating the battery usage with data from hourly net metering or instant phasewise metering methods. On one hand, the battery cannot wait until the energy integration over the hour has been completed and only then charge or discharge with the remaining energy or demand from the past hour. Therefore, data from hourly net metering cannot be used to control battery charging and discharging in actual systems, where the battery has to respond instantly to power fluctuations. On the other hand, using data from instant phasewise metering to control battery usage would require unsymmetrical loading capability from the battery inverter. Otherwise, the battery may end up importing energy for the charging purpose or discharging to export in situations where there is unsymmetrical loading of phases. Battery control simulations would therefore have to be performed with instant power measurements regardless of the method of grid interface energy metering used, requiring higher than hourly data resolution.

Sensitivity of the relative monetary value of the battery storage system to changing SPOT margin for export, $m_e$, was also analysed. Current solar PV peak power capacities of the houses and variable battery capacities were used for this sensitivity analysis. The results of this analysis are shown in Fig. 11(a) and Fig. 11(b) for House A and House B, respectively. The relative value is found to increase linearly as a function of SPOT price margin with the battery capacity determining its slope and zero crossing value.
4.2.3. Comparison of battery value and current purchase prices

The installation costs of a lithium-ion battery energy storage were estimated to be in the range of 150 $/kWh to 1000 $/kWh in 2020 based on a Cost-of-Service tool by the International Renewable Energy Agency (IRENA) [35]. The average relative installation cost of a battery storage is compared with the relative value increase resulting from its utilisation as a function of battery capacity in Fig. 12. The relative cost comprises the sum of the energy installation cost of the storage divided by its expected lifetime and the power installation cost of the required inverter. The power installation cost is obtained by using the simulated maximum power requirement of the system and dividing it by the expected calendar life of the inverter. The calendar and cyclic life expectations are obtained from the IRENA tool and used to estimate the expected lifetime of the storage system. Although the energy installation cost of the storage varies considerably between battery chemistries and even within each type of chemistry, it can be seen that the cost is still much higher than the value addition a battery storage is able to provide. Operating costs are not taken into account; they would increase the total storage cost even further.

In addition to self-sufficiency and monetary value, also information of the number of battery cycles annually with the depth of discharge of 80% was collected from the results of the sensitivity analysis. Even with the smallest battery capacities, the number of cycles stayed below 350 annually. Assuming an expected battery lifetime of 15 years, the total number of cycles would still stay below 10,000, which is the average cyclic life of lithium-ion batteries [34]. Therefore, the battery can be expected to last through its whole calendar life when installed to the system studied in this paper.

In a real system, the battery capacity would degrade during its usage [36]. The degradation rate is increased by multiple parameters, including cycle rate, depth of discharge, and charge/discharge rate [37]. All of these parameters are higher for smaller battery capacities, making their capacity degradation faster. As the simulation time in this paper is only three years, however, most of the degradation during the lifetime of a battery storage would take place outside the simulation frame. Taking this into account in the current simulation would be difficult and, therefore, battery degradation is omitted in this study. As a result, the simulations provide an upper limit for both the self-sufficiency and operational value of the battery. Considering degradation phenomena would only further decrease the profitability of a battery energy storage system.

4.2.4. Single-case comparison between physical battery storage and network storage options

Addition of a 20 kWh physical battery to both the studied energy systems was analysed in more detail as a single-case example, the results of which are presented in Table 6. Both instant phasewise metering and hourly net metering were considered. With both the houses, the use of a battery storage increases self-consumption by 20 to 30 percentage points and reduces the total cost for electricity between €90 and €170 annually. For House A, the average annual electricity bill would turn negative after installing a battery storage of this size, but the value increase from the installation would be less than with House B, as discussed above. Hourly net metering decreases the total cost of electricity in both cases, with or without a physical battery storage, but it is also found to decrease the value of the battery storage. This decrease in value is caused by the metering method taking over interhour import–export balancing from the battery storage, thus reducing the battery usage.
Fig. 11. Annual monetary value of a physical battery relative to the battery capacity with variable three-year mean SPOT margins. Original solar PV peak powers and electricity data from House A and House B are used as the starting point for (a) and (b), respectively. Hourly net metering is employed and the value of the current system (indicated by a black line) is calculated with individual prices from Table 3.

Table 6
Three-year average cost and value for the system annually and energy imported from the grid, exported surplus energy, and self-consumption for both House A and House B. The network energy storage and the 20 kWh physical battery storage are compared employing both the instant phasewise metering and hourly net metering methods. Average prices from Table 3 are used.

<table>
<thead>
<tr>
<th></th>
<th>Network storage</th>
<th>Physical battery storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instant</td>
<td>Hourly</td>
</tr>
<tr>
<td>MWh/a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Import</td>
<td>4.595</td>
<td>4.415</td>
</tr>
<tr>
<td>Self-consumption</td>
<td>−2.615</td>
<td>−2.854</td>
</tr>
<tr>
<td>Self-sufficiency</td>
<td>36.27 %</td>
<td>39.27 %</td>
</tr>
<tr>
<td>€/a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Import</td>
<td>715.00</td>
<td>694.79</td>
</tr>
<tr>
<td>Export</td>
<td>−642.90</td>
<td>−636.02</td>
</tr>
<tr>
<td>Self-consumption</td>
<td>−302.47</td>
<td>−330.21</td>
</tr>
<tr>
<td>Total cost</td>
<td>72.10</td>
<td>58.78</td>
</tr>
<tr>
<td>solar PV value</td>
<td>945.36</td>
<td>966.23</td>
</tr>
<tr>
<td>Physical battery value</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

4.3. Virtual battery storage

4.3.1. Description

A virtual battery is a monetary energy storage service, whose content may vary depending on the contract. A version of a virtual battery found in the Finnish market provides the end-user with a set amount of available energy storage capacity in a given storage period with a periodic fee. In effect, the end-user can then store surplus energy using the grid and retrieve the stored amount of energy within the same storage period. The amount of imported and exported electricity will be equal regardless of whether a virtual battery or a network storage is used, but when using a virtual battery, the amount of energy retrieved from the virtual battery, instead of the energy exported to the grid, is compensated for the end-user in their electricity bill by using a fixed price. Surplus energy exceeding the storage capacity is not compensated in any way.

The contracts governing virtual battery services vary in periodic fees, compensation for stored electricity, storage capacities, and lengths of the storage periods. Simulations are carried out for the two houses, House A and House B, to find the increase in value when using a virtual battery compared with a network storage as a function of battery capacity, compensation for stored electricity, and the solar PV capacity used. Storage periods of a year are employed. Calculation of the value increase from the viewpoint of the end-user enables estimation of the maximum monthly fee allowable by the end-user without pinpointing
which, in turn, is calculated from the minimum between exported
sation during each storage period is determined from battery usage,
Hourly net metering is employed for both the houses under study.
of expected operation compared with the annual relative monetary value of the system.
Relative cost of the investment in a battery storage system divided by 15 years
side is shifted toward smaller solar PV capacities. This shift reduces
amount of export, the envelope edge on the larger solar PV capacity
side by the electricity import limit. The monthly fee for a virtual battery

*Fig. 12. Relative cost of the investment in a battery storage system divided by 15 years of expected operation compared with the annual relative monetary value of the system. Hourly net metering is employed for both the houses under study.*

to any existing companies and their products. The amount of compensa-
tion during each storage period is determined from battery usage, which, in turn, is calculated from the minimum between exported electricity, electricity imported from the grid, and the battery capacity.

\[ U_{\text{virt}}(t) = \min\{E_s(t), E_e(t), C_{\text{virt}}\} \quad \text{(16)} \]

The value of the virtual battery is found by comparing its total annual cost with the cost of a network storage, excluding periodic fees in both cases.

### 4.3.2. Comparison between virtual battery storage and network storage options

The value of a virtual battery storage with a battery capacity range of 0 kWh to 6000 kWh and a price range of 0–20 c/kWh compared with a network storage are shown in Fig. 13(a) and Fig. 13(b) for House A and House B, respectively. When the storage capacity is smaller than either energy export or import within the storage period, the storage capacity limits the value of the system resulting in a linearly increasing value. As the storage capacity increases above either export or import, the smaller of them sets the limit for the value of the virtual battery. As both the import and export are independent of the storage capacity, increasing the capacity further does not add value.

The method of calculating virtual battery usage, described in Eq. (16), introduces three limiting factors for the value available from such a storage: storage capacity, exported electricity, and imported electricity. The best way to visualise their impact on the system value is to plot the difference in values between virtual battery and network storage options as a function of solar PV capacity for multiple virtual battery storage capacities, shown in Fig. 14(a) and Fig. 14(b) for House A and House B, respectively. The value of the system is limited by a triangular envelope, whose edge on the smaller solar PV capacity side is caused by the electricity export limit and on the larger solar PV capacity side by the electricity import limit. The monthly fee for a virtual battery storage would have to be limited below this triangular envelope for the concept to be beneficial for a prosumer. The peak value potential is achieved when both the import and export are equal. However, if the storage capacity is limited below either the amount of import or the amount of export, the envelope edge on the larger solar PV capacity side is shifted toward smaller solar PV capacities. This shift reduces both the maximum value achievable from the system and the solar PV capacity at which the maximum is reached. In a sense, the virtual battery ends up limiting the optimal solar PV capacity and direct self-consumption, especially if the storage capacity provided is insufficient to meet the total consumption.

In addition to the amounts of exported and imported electricity and storage capacity, the value of a system with a virtual battery is also affected by the level of compensation paid for the stored electricity and the length of the storage period. As can be seen from Fig. 13(a) and Fig. 13(b), the amount of compensation paid for the storage use can have a significant impact on the value of the system. However, the compensation for stored electricity can be expected to be dependent on the overall electricity price, and therefore, independent changes in compensations are not likely. The average electricity import price calculated from Table 4 is used as an educated guess for realistic compensation for stored electricity in Fig. 14(a) and Fig. 14(b). A storage period of a full year is found to maximise the value for the end-user. Shortening the period to a month, for example, prevents using excess generation from summer during winter when it would be needed the most, whereas lengthening it to span multiple years would not bring additional benefit owing to the annually cyclic nature of power generation and consumption. In addition, a longer storage period would be impractical because of extended billing periods.

### 5. Discussion

#### 5.1. Discussion on the key findings and their implications

When using measured electricity import and export data sets with hourly resolution, the monetary benefit of switching from instant phase-wise metering to hourly net metering was found to be about €14 and €35 annually for House A and House B, respectively. Yet, the absolute value for a prosumer from switching the metering method was found to be unpredictable because of its dependence on the amount of interhour balance fluctuation and the level of unsymmetrical loading. These values are highly random in nature, and they are only indirectly dependent on the system configuration. The direction of change in the system value from switching to hourly net metering is, however, always positive for the prosumer.

Switching the energy measurement method is not up to the end-user, and for that reason, legislative changes have to be made in order to allow the change. This kind of legislation is a potential way to increase the value of a solar PV installation without additional costs for the prosumer and could thus increase the attractiveness of investing in domestic solar PV energy systems. At the time of writing this paper, a decree on electricity measurement methods to implement hourly net metering, among other subjects, was issued in Finland. The aim of the decree is to enable prosumers to use a larger portion of their electricity generation on site. Based on the results presented in this paper, improvement in self-sufficiency on a scale of 3 to 5 percentage points can be expected, resulting in monetary savings of a few tens of euros annually.

Even though its deployment will require legislative changes, hourly net metering is not seen as a method of subsidy in this paper because of the integration time being equal to one time step of the electricity market. Instead, the change is seen as a means to standardise the treatment of different operators in the market. In previous research on net metering, the integration period has been extended, thus justifying the categorisation of the method as a subsidy [26,28].

Addition of a physical battery energy storage to the energy system was found to increase self-sufficiency from 20 to 30 percentage points for the houses under study. The peak power capacity of the solar PV installation was observed to be a significant factor for determining the amount of self-sufficiency increase obtained by the use of a battery energy storage, with the increase being higher for larger solar PV installations. House B, with a lower initial self-sufficiency resulting from less optimal consumption scheduling, had a greater increase in self-consumption with lower battery capacities than House A, when
Fig. 13. Annual value of the solar PV system with a virtual battery, compared with a system with a network storage, using an annual storage period for (a) House A and (b) House B. No monthly fees are included for either the virtual battery or the network storage.

Comparing systems with equal solar PV capacities. After the battery capacity had exceeded 20 kWh, the self-sufficiency saturated to nearly equal values for both the houses. It has been shown previously that the 20 kWh battery capacity is enough to maintain House A off-grid during summer months, given that sufficient solar PV capacity is provided [9]. The results of this study indicate that it may be possible to find a general upper limit for useful battery capacity based on easily obtained parameters, such as location and type of housing. More research with a larger sample size is needed, however, to establish such a generalisation.

An increase in the system value relative to the battery capacity is found to be limited below 25 €/kWh per year for both the houses under study when using hourly net metering, and falling steadily with increasing battery capacities. House A benefits slightly more with smaller battery capacities than House B, but the relative battery value decreases slower for House B with an increasing battery capacity because of the greater increase in self-sufficiency. Increasing the solar PV peak power capacity also increases the relative value of the battery in addition to the value increase from the solar PV plant itself. The growth is, however, minimal compared with the value increase from the solar PV alone.

With the current electricity prices in Finland and the lithium-ion battery prices, it is clear that physical battery storages are not yet economically feasible for either of the houses studied in this paper. An increase in price for electricity import, of which the price of transmission is the most significant and prone to rise, would improve the profitability of an investment in a physical battery storage. However, the increase in price would have to be significant in order for the relative value increase to approach the mean relative cost for such a storage. For the battery operational value to reach the average battery prices, the realised electricity price, which includes SPOT price at the time of electricity import, taxes, and the margin of the electricity provider, should be 2 to 5 times the current three-year average realised electricity import prices (see Table 4). The required price increase depends on battery capacity, being greater for larger installations. A further decrease in battery prices is, therefore, also needed. For the purposes of increasing self-sufficiency and allowing time periods of full reliance on only self-generated electricity, battery energy storages would perform well.

When comparing the two monetary storage options, a virtual battery storage and a network storage, it was clear that the virtual battery concept under consideration is hardly profitable for House A because of the large excess solar PV power generation and large amounts of electricity export. House B was able to exceed the profitability limit because of the lower amount of electricity export and thereby a lower
value for the sold electricity in the reference case with a network storage. It was found that the maximum benefit from a virtual battery is achieved for systems with equal electricity import and export with the virtual battery having enough capacity to entirely cover them. For both the houses under study, a solar PV capacity of about 8 kWp would result in this optimal import–export balance providing an annual value of roughly €400. However, if a large enough virtual battery capacity is not provided by the contract, the most profitable solar PV capacity will decrease. Increasing solar PV capacity further is not preferred as there is no compensation for excess export when using a virtual battery. The annual value sets the maximum for the annual fee justifiable for the virtual battery service.

In an ideal case, the concept of a virtual battery could allow a prosumer to remain, at least virtually, fully self-sufficient throughout the year, assuming that large enough virtual battery capacities were provided. If, however, the capacity is limited, the virtual battery only ends up limiting the profitability of increasing the solar PV peak power capacity. The compensation for electricity stored in a virtual battery is presumably related to the general electricity prices and, therefore, an increase in profitability cannot be expected based on changes in electricity pricing. The use of hourly net metering instead of instantaneous phasewise metering will further decrease the benefit of a virtual battery based on the increased value of a network storage and the lower amount of electricity export and import. It can thus be concluded that the virtual battery concept studied in this paper can be beneficial for the prosumer only in a limited set of cases assuming that a sufficient storage capacity is provided.

5.2. Limitations and outlook

The results presented in this study are subject to some limitations. Data resolution of an hour is long when considering the rapidly alternating demand patterns of domestic households and variation in cloudiness, for example. Shorter time steps would not only provide a more realistic measure for self-consumption [25] but also enable a higher accuracy in the simulation of battery control in combination with different electricity metering methods. The number of prosumer households studied should also be increased for further research to obtain statistical results, as there is known to be considerable heterogeneity in individual load profiles [7].

As the solar PV generation, consumption, and price data for this research were collected in Finland, the results of this study are not directly applicable to other areas. The same holds for all research on solar energy with measured data. The findings considering electricity measurement methods are, however, universal. The results and methodology on self-sufficiency with solar PV and physical batteries can be easily applied to other northern or southern locations having a clear difference between summer months with high solar radiation and cold and dark winters. The economic results are comparable within the Nord Pool electricity market when local market characteristics are taken into account. Further research should be carried out with a larger set of households across the Nord Pool market area.

A way to further optimise the physical battery storage usage in future research could be to enable its usage during winter months to shift electricity consumption from high price peaks to lower electricity prices as SPOT prices are known for 24 h in advance. Finding an optimal control mechanism to combine these two functions for the battery energy storage, namely storing excess solar PV-generated electricity and shifting consumption to times of cheaper electricity, would be a topic worthy of further research.

6. Conclusions

In this study, two distinct ways to increase the self-sufficiency of grid-connected households with solar photovoltaic installations were investigated using three-year data sets from two separate prosumer households. First, the significance of the electric energy flow measurement method applied for the amounts of grid export and import and thus, the monetary value of the system, were analysed. Second, the effects of different electric energy storage methods on the self-sufficiency and monetary value of the system were investigated. In addition to a physical battery storage, the studied energy storage methods included two methods that are based on monetary transactions, namely a network storage and a virtual battery storage, enabled by the grid connection. These monetary storage methods, although not actual energy storages from the viewpoint of the whole electricity network, act like one from the prosumer’s perspective. Thus, in this paper, the issue was approached from the prosumer’s viewpoint, and the definition of self-consumption was extended to include all the solar PV-generated electricity consumed on site within each one-hour metering period.

The switch of the electricity measurement method from instantaneous phasewise metering to hourly net metering was observed to induce a small increase of 3 to 5 percentage points in self-sufficiency. The monetary savings for the prosumer would thus be on the scale of a few tens of euros annually. The amount of increase in self-consumption was found to be highly random, depending on the amount of interhour fluctuations of the import–export balance and the occurrence of unsymmetrical loading. Although the monetary benefit for the prosumer is small, the psychological advantage of being able to use the best out of one’s solar photovoltaic installation can be a factor increasing the attractiveness of the investment.

A comparison of the two monetary energy storage methods and the physical battery energy storage indicated that neither physical batteries nor virtual batteries are economically viable for the houses under study. A physical battery storage, although capable of inducing a significant increase in self-consumption, would require battery prices half the current ones or the electricity purchasing margins two- to fivefold greater than the current ones to be feasible. Virtual batteries, on the other hand, end up limiting the profitable solar photovoltaic capacity especially if their storage capacity is restricted under the amount of annual electricity importation. The results indicate that although the revenue from selling exported electricity is low compared with the cost of imported electricity, a network storage is still the most viable option for residential prosumer households to use their excess solar PV generation.

The results of this study give a comprehensive picture of different options for prosumers to use their excess electricity. The benefit of different options is not always clear, and therefore, to facilitate a comparison between options, this paper provides tools for critically assessing them. The results are specifically applicable to the Nord Pool electricity market area, but can be extended to other high-latitude countries when the local market characteristics are accounted for.

CRediT authorship contribution statement

Pietari Puranen: Term, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration. Antti Kosonen: Term, Conceptualization, Data curation, Investigation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. Jero Ahola: Term, Conceptualization, Data curation, Investigation, Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Subject description


The house is the first zero-energy log house in Finland; it is a zero plus-energy house at the net level and connected to the electric grid [30]. The house has two floors, of which the first floor is half underground. It was constructed in 2017, and the building envelope was built according to the National Building Code of Finland. The net heated space area is 183 m² occupied by two adults during the recorded period.

The main heating system is based on a ground source heat pump (GSHP) with a 150 m vertical borehole that enables also precooling of the incoming air. The heat is transferred by water that is circulated under the floor. Part of the rooms are equipped with room thermostats to control the temperature. The indoor temperature setpoint for heating is adjusted to be about 20 °C. The heat can be stored to a 750 l two-layer water hybrid boiler, in which the upper layer is intended for domestic hot water (DHW) and the lower layer for buffering (storage) of the space heating and preheating of DHW. The heat pump is controlled to prefer producing heat during solar PV power generation in order to increase self-consumption. There are fireplaces as supporting heat sources on both floors. The sauna has two stoves; a wood-burning and an electric one. The wood-burning stove is mainly used when solar PV electricity is not available. The annual firewood consumption in the fireplace is around 3 m³ to 7 m³, of which the main part is consumed by the sauna. Mechanical balanced ventilation is used with a heat recovery unit of 75% annual efficiency. The monthly levels of consumed electricity for the last three years are presented in Fig. A.1(a). The total annual electricity consumption was 7.5 MWh, 7.2 MWh, and 7.1 MWh for the years 2017, 2018, and 2019, respectively. More accurate data are available in [38].

The main building has a south-facing and the garage an east-west-facing solar PV installation, including a total of 21.1 kWp modules and 16 kW of inverter power with two string inverters and four separate maximum power point trackers (MPPT) in total. The buildings on the site, including the main building itself and the garage, are positioned to avoid shade on the roofs to maximise solar PV power generation. The main building has 40 panels (260 Wp multicrystalline modules, 10.4 kWp in total) facing south, and the garage has 42 panels (255 Wp multicrystalline modules, 10.7 kWp in total) facing east and west, 5.35 kWp in both directions. The peak generation hours during summer (in standard time) for the installations facing east, south, and west are 9 a.m., 12 p.m., and 3 p.m., respectively [38]. Both the southern and the east-western installations are further divided into two identical strings with individual MPPTs. The monthly energy yields for the three years under study are presented in Fig. A.1(b). The annual amount of electrical energy generated was 16.6 MWh, 18.1 MWh, and 17.3 MWh for the years 2017, 2018, and 2019, respectively.

The solar PV peak power capacity was designed to maximise the system self-sufficiency while maintaining a manageable plant size. As can be seen from Fig. 5(a), this approach leads to a large amount of excess power to be exported to the grid. The off-grid potential of the house has been studied previously in [9].

Incorporation of the heating demand into the electricity consumption by using a heat pump is another factor enabling a high self-sufficiency. The average distribution of electricity consumption and solar PV power generation throughout the day from March to October is shown in Fig. 1(a). Controlling the time of use of the heat pump to match solar PV generation, when possible, minimises the need for electricity import during months of sunlight.

A.2. House B: House with district heating

The second house studied in this paper is a single-floor house constructed in 2010 from wood and insulated with glass wool with a thickness of 25 cm in the walls and 50 cm on the attic. The living area of the house is 133 m², and it is occupied by a four-person family with two adults and two children. The main heating system is district heating for a net heated area of 148 m². The secondary heating systems are a fireplace and an air source heat pump installed in December 2018. The annual firewood consumption in the fireplace is around 3 m³, and it is used mainly to produce heat for comfort. The heat pump also produces comfort heat as well as cooling in the summertime. The mechanical ventilation system of the house is equipped with a heat recovery unit of 75% annual efficiency.

Monthly levels of electricity consumption for House B for the last three years are presented in Fig. A.2(a). The total annual electricity consumption was 6.5 MWh, 7.1 MWh, and 8.5 MWh for the years 2017, 2018, and 2019, respectively. The total consumption in 2017 was lower than expected because the house residents were absent during the summer months from May to July. As the missing consumption would have been met mostly with surplus PV generation in the summer, its significance for the results is minimal. Additionally, the total consumption increased after the installation of an air source heat pump in December 2018.

The house has a 8 kWp rooftop solar PV system installed in 2014. It is aligned to south-west in a shadowless position. The solar PV system consists of 32 panels (250 Wp multicrystalline modules, 8.00 kWp in total), which are divided into two identical strings with individual MPPTs. The monthly energy yields for the last three years are presented in Fig. A.2(b). The annual amount of electrical energy generated was 6.8 MWh, 7.2 MWh, and 7.0 MWh for the years 2017, 2018, and 2019, respectively.

The solar PV plant capacity for this house is designed so that the annual electricity generation would be equal to the annual electricity consumption. Therefore, the self-sufficiency is not optimised like with House A, as can be seen in Fig. 5(b). The use of district heating instead of a heat pump decreases the self-sufficiency even further compared with House A. The average hourly power generation and consumption profiles from March to October in Fig. 1(b) show that the highest consumption peak is found just outside the hours of most PV power generation, which differs from that observed with House A. The difference in the consumption profile follows from the use of a non-schedulable heating method.

Appendix B. Physical battery storage modelling

In the simulations, battery usage is determined from the net surplus energy $E_{\text{surplus}}(t)$ and the additional energy demand $E_{\text{demand}}(t)$ for each hour, which are calculated from the exported and imported energy:

$$E_{\text{surplus}}(t) = \max \left\{ E_{\text{in}}(t) - E_{\text{out}}(t), 0 \right\}$$

and

$$E_{\text{demand}}(t) = \max \left\{ E_{\text{in}}(t) - \eta E_{\text{out}}(t), 0 \right\}.$$  \hspace{1cm} (B.1)

This results in either the surplus energy or the additional energy being zero. For instant phasewise metering, the exported and imported energy $E_{\text{in}}(t)$ and $E_{\text{out}}(t)$ are given by Eq. (3) and Eq. (4), respectively. For hourly net metering, they are given by Eqs. (9) and (10).

In the case of surplus energy ($E_{\text{surplus}} > 0$), the battery is in the charging mode, and it is charged with an energy input proportional to the hourly surplus energy. The energy charged to the battery is determined as the smaller value between the input energy and the available battery capacity:

$$E_{\text{bat, in}}(t) = \min \{ \eta E_{\text{surplus}}(t), (1 - \text{SOC}(t)) C_{\text{bat}} \}.$$  \hspace{1cm} (B.2)
Battery SOC after charging is determined by:

$$\text{SOC}(t + 1) = \text{SOC}(t) + \frac{E_{\text{bat,in}}(t)}{C_{\text{bat}}},$$

and the energy that could not be charged to the battery, which is then exported to the grid, is now calculated as:

$$E_{-\text{bat}}(t) = E_{\text{surplus}}(t) - \frac{E_{\text{bat,in}}(t)}{\eta}.$$  

(B.5)

When there is too little solar PV generation to cover consumption ($E_{\text{demand}}(t) > 0$), the battery is in the discharging mode, and the energy output by the battery is determined as the smaller one between the energy demand and the available battery charge:

$$E_{\text{bat,out}}(t) = \min \{ E_{\text{demand}}(t), \text{SOC}(t)\eta C_{\text{bat}} \}.$$  

(B.6)

The SOC after discharging is calculated by:

$$\text{SOC}(t + 1) = \frac{E_{\text{bat,out}}(t)}{\eta C_{\text{bat}}},$$

(B.7)

and the unmet power demand after battery discharge, which is then imported from the grid, is determined as:

$$E_{+\text{bat}}(t) = E_{\text{demand}}(t) - E_{\text{bat,out}}(t).$$  

(B.8)

In this paper, the definition of annual self-consumption includes also energy stored and returned from the battery. Self-consumption for systems with a battery storage is thus calculated as:

$$E_{\text{self, bat}}(t) = E_{\text{self}}(t) + E_{\text{bat,out}}(t).$$  

(B.9)

Self-sufficiency is calculated similar to Eq. (12) using $E_{\text{self, bat}}$ instead of $E_{\text{self}}$. The monetary value increase from including a battery storage in the system is now determined as:

$$v_{\text{bat}} = \sum_{t=0}^{T} \left( \frac{E_{-\text{bat}}(t)\eta(t) + E_{\text{self, bat}}(t)\eta(t)}{\eta_{\text{years}}} + v \right).$$  

(B.10)

References


