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Photovoltaic self-sufficiency of Belgian households using lithium-ion batteries, and its impact on the grid

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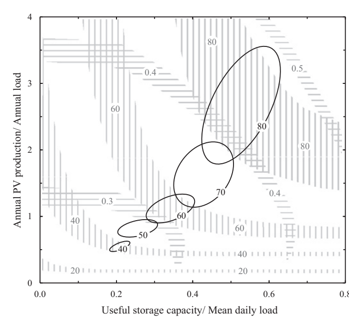
HIGHLIGHTS

- Nearly 30% self-sufficiency is reached close to grid parity using only PV.
- Reaching beyond 40% self-sufficiency requires storage, strongly increasing costs.
- Peak power load remains constant while its variability rises with self-sufficiency.
- Adoption of a capacity-based tariff structure can strongly affect economic viability.
- Limiting feed-in power seems to be a good solution to mitigate grid impact.

GRAPHICAL ABSTRACT



Self-sufficiency (%) [a]

LCOE (€/kWh) [a]

Configuration with lowest LCOE for a given self-sufficiency [b]

[a] For 21 out of 25 profiles (about 80% of the values).
[b] Ellipses are drawn encompassing 80% of the profiles (considering a multivariate normal distribution).

LCOE and self-sufficiency according to PV and storage capacity for a household.

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ABSTRACT

Countries are pushing for the use of local, renewable energy sources in order to reduce the dependence on fossil fuels for energy supply. One of the main problems with several renewable energy sources is their variability, which can be solved with energy storage. With buildings representing an important share of energy consumption, and given the growing capacity of distributed generation, distributed energy storage in buildings is expected to become increasingly present. In this context, the optimal dimensioning of home installations of photovoltaics and lithium-ion batteries, and the impact of such installations on the grid, is of the utmost importance. While there have been developments on this field, some important handicaps remain, notably the independent treatment of installation optimisation and grid impact and the substantial result differences between studies. In this paper, photovoltaics and lithium-ion storage installations are optimised through the use of real, high-resolution data from several individual households, based on realistic cost figures, and through well-defined metrics that correctly grasp the problem at hand. The impact on the grid as well as possible mitigation measures are also analysed. Results show that up to about 30% of electricity self-sufficiency can be obtained using only PV and close to grid parity. Above 40% self-sufficiency, energy storage must be used, strongly increasing the cost of such installations. Economies of scale play an important role suggesting a preferential implementation for larger users or at a community-scale. Feed-in limits seem to be a good solution to attenuate grid impact. On the other hand, a higher share of a capacity-based component on the grid tariff strongly affects the economic viability of such installations for the average household. These results are important for studies on distributed photovoltaics and energy storage as well as for energy policy. Also, the large range of results made available,

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calculated on a free market perspective using a simple control mechanism, provide a much-needed benchmark for further comparable studies.

1. Introduction

To reduce the impact of over-reliance on fossil fuels for energy supply, several countries are pushing for energy efficiency and for the use of local, renewable energy sources [1]. One of the main problems with several renewable energy sources, such as photovoltaics (PV) or wind power, is that their production is variable [2]. To solve this variability, several solutions may be applied. Variable energy sources can be complemented either by controllable ones or by other variable energy sources that present a low correlation in production (such as geographically-scattered photovoltaics [3]). The demand can be adapted according to the available supply, a technique known as demand-side management [4]. Finally, energy can be stored, effectively decoupling energy production from consumption [4].

Several measures have been adopted to promote the use of renewable energy sources, resulting in an increase of the installed capacity and in important cost reductions as manufacturers enjoy on-going learning curves and economies of scale [4–6]. Lower costs, associated with the availability of low power units, are leading to a growing capacity of distributed energy sources effectively disrupting the historical one-way model of power systems [5,6]. With buildings being responsible for a major share of energy consumption [7], and with distributed energy production growing in importance, distributed energy storage in buildings is expected to become increasingly present [5,8].

The injection of PV power on the distribution grid leads to local voltage variation and distortion of current and voltage waveforms (harmonics) that may surpass specified power distribution standards [3]. For large PV penetration values, power flow in the substations can be reversed, affecting the grid's voltage regulators designed for unidirectional power flow, eventually triggering protection mechanisms and disconnecting the load [3]. This is especially important for PV, whose output can quickly change due to atmospheric conditions, leading to flicker effects [3]. At a higher level, the low inertia of PV power affects the ability to keep the grid in balance [3]. All these problems can be solved by limiting the PV power injection on the grid [3,5].

As the cost of distributed energy sources decreases (eventually reaching grid parity), and markets mature, coupled with budgetary constraints, the initial incentives available for distributed generation, such as feed-in tariffs or net-metering, are reduced or even eliminated [9]. At the same time, the growing impact on the grid of distributed generation is leading to stricter access to the grid [9]. As distributed energy sources approach grid parity and feeding-in is strongly limited and/or valueless, distributed producers have the incentive for self-consumption [4,9–11].

Recently, there has been a surge of support policies for distributed energy storage systems. In 2013, Germany introduced an incentive program for distributed installations of PV coupled with storage with the goal of increasing demand for storage devices and bring prices down, as has happened for photovoltaics [12]. The incentives offered have been progressively adjusted to the dropping costs but, initially, consisted of low-interest loan offers and cost rebates, up to 30% of the setup costs or 660 €/kW, for installations up to 30 kW [12]. Sweden has also launched an incentive program for home storage systems by rebating up to 60% of the system cost, to a maximum of SEK50,000, with the goal of enabling a better use of PV while helping to stabilize the grid [13]. In California, the Self-generation incentive program has funded several distributed energy storage projects. For 2017, a first round of a 500USD/kWh rebate will be made available for residential energy storage installations up to 10 kW [14]. Municipalities have also joined the race. In Adelaide, since 2015, rebates up to 50% of the installed system cost, up to a maximum of $5000, are offered for energy storage systems as part of the Sustainability incentives scheme, offering reimbursements for water and energy devices in order to reduce carbon emissions and conserve energy, water, and natural resources [15].

When sizing a PV installation coupled with batteries for increased self-sufficiency in a household, different configurations of PV and battery capacity may provide the same self-sufficiency [16]. Also, the larger the PV and battery capacity, the higher the capital cost of the installation [16]. The goal is to find the PV and battery capacity that reach a predefined self-sufficiency at the minimum cost [16]. This challenge has been approached for some time [16], but recent advances in computational power and access to detailed data have gradually allowed the incorporation of further detailed models, with more variables and higher resolution. Several papers have been published on home photovoltaics coupled with storage [17] and good reviews of the recent literature are provided by Luthander et al. [4] and Hoppmann et al. [18]. Most of these studies focused on simulating specific installations and it is currently known that self-consumption tends to increase with a higher PV and storage capacity although with diminishing returns [4,9,11,19]. Nevertheless, the existing literature suffers from several handicaps [3,4,18]. Although the resolution for such calculations is a trade-off between accuracy and calculation time, the resolution used is frequently below 15 min, usually of 1 h [20–22]. A low resolution smoothes out the consumption profile leading to a reduction of the peak power consumption which, in turn, leads to the under-dimensioning of the required PV and energy storage capacity and, consequently, to optimistic predictions in terms of performance and economics [3,20,22]. The same effect is produced by standardised profiles that are often obtained from the mean of several individual consumers [8]. These standardised profiles can be used for calculations regarding installations that encompass several individual users but not on an individual level. When individual consumption profiles are used, many times they are based on daily or weekly profiles deemed to repeat throughout the year [21]. Again, this can lead to biased results, as PV production and consumption tend to change according to several time scales [8] and in a correlated way [21], namely throughout the year with an increase in consumption during the winter, when there is less PV power available. As more variable inputs are taken into consideration, such as the energy consumption of different appliances for demand-side management, the more important high resolution becomes in order to take into account all the existing correlations [21]. In the literature, there are several results for single cases but these are usually not optimised in terms of both PV and storage capacity [4,18]. Furthermore, cost functions tend to use €/kW or €/kWh mean values which are often optimistic, since they are based on the equipment cost on a market level unavailable to individual households, and do not integrate fixed costs which have a strong impact on small installations. The results themselves are often presented through metrics that are either ill-defined or do not correctly grasp the nature of the problem [4] and are also, many times, calculated based on local subsidies, hiding the real