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Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings

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HIGHLIGHTS

- Self-consumption of PV electricity is studied with detailed monitoring data from 200 Swedish households.
- Optimal daily scheduling of washing machines, clothes dryers and dishwashers is simulated.
- Load shifting increases the self-consumption on average by a few percent of the generation from 3 to 9 kW_p PV systems.
- The potential for PV self-consumption is limited under the studied conditions.

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ABSTRACT

Self-consumption of on-site photovoltaic (PV) electricity in buildings is gaining interest as a way to accommodate high PV penetrations in the power system. On markets where there is no substantial feed-in support for renewables, there is also an economic incentive for PV self-consumption, as selling prices for PV electricity are normally lower than retail electricity prices. One option for improved self-consumption is rescheduling of programmable appliances, typically washing machines, clothes dryers and dishwashers. This paper determines the potential to increase PV self-consumption through scheduling of these appliances in Swedish single-family buildings. Simulations of daily load scheduling were performed to match on-site PV power generation and recent (2008–2012) hourly electricity market prices, using a set of high-resolution (10-min) appliance load profiles from 200 monitored Swedish households. Since these data provide appliance ownership and daily appliance use patterns in a wide range of households, a realistic upper limit to the self-consumption potential is obtained. The conclusions are that load shifting can potentially increase PV self-consumption by around 200 kW h on average, corresponding to a few percent of the total PV power generation for the system sizes studied (3–9 kW_p). The maximum economic benefit over the studied years was 20 EUR per year and household. For the larger PV system sizes that could inject critical peak powers to the distribution grid, the peak hourly PV surplus decreased less than a few percent. The main conclusion is that there is an overall low potential for improved self-consumption through optimal scheduling of the studied appliances, at least with the current Swedish market conditions.

1. Introduction

Grid-connected photovoltaic (PV) capacity is increasing worldwide, with a total cumulative power close to 100 GW_p installed globally by the end of 2012 [1]. Germany, the country with the highest share of PV electricity in the generation mix, had 32 GW_p installed PV capacity [1], generating 4.7% of the national gross electricity consumption in 2012 [2]. Consequently, on the sunniest days in 2013, PV alone contributed to half of the national power generation in Germany during certain hours [3]. On mature PV markets like the German one, with large contributions from PV, it is natural that *self-consumption* of the PV electricity, i.e. using as much of the power generation as possible on-site, is encouraged. For this purpose, the German Renewable Energy Act (EEG) introduced a special premium rate for self-consumed electricity in 2009 [4]. The rate was abandoned in 2012 because feed-in tariffs had then dropped below the retail prices, but a 90% cap on the total generation eligible for feed-in support was introduced for larger systems in order to promote self-consumption [1]. Self-consumption is also encouraged directly in a few other European countries [5], as well as indirectly on all electricity markets

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Nomenclature

t	time interval index
Δt	time interval length (h)
n_t	number of monitored households in time interval t (–)
$P(t)$	PV power generation (W)
$L(t)$	household load (W)
$M(t)$	PV self-consumption (W)
φ	absolute self-consumption (W h)
φ_L	relative self-consumption w.r.t. load (–)
φ_P	relative self-consumption w.r.t. generation (–)
$P_n(t)$	net generation (W)
$L_n(t)$	net load (W)
$L_1(t),\ldots, L_6(t)$	partial loads (W)
$L_{s1}(t),\ldots, L_{s6}(t)$	shifted partial loads (W)
$L_{ij}(t)$	load cycle j of appliance i (W)
$L_{ri}(t)$	residual load of appliance i (W)
τ_{ij}	duration (number of time intervals) of load cycle L_{ij} (–)
T	time interval index for start of rescheduled appliance
$P_{\lim}$	limiting power for identifying individual load cycles (W)
$\Delta L_n(t)$	net load increase after addition of a load cycle (W)
$\Delta M(t)$	self-consumption increase after addition of a load cycle (W)
$C_b(t)$, $C_s(t)$	electricity buying and selling prices (EUR/W h)
C_a	additional fees (EUR/W h)
E	net expenses (electricity purchases minus sales) (EUR)
$G_b(t)$, $G_d(t)$	beam and diffuse solar irradiance on the horizontal plane (W/m^2)
$G_T(t)$	global solar irradiance on the tilted plane (W/m^2)
$P_{dc}(t)$	DC power from the PV array (W)
N	number of PV modules (–)
A	PV module area (m^2)
$\eta(t)$	PV module conversion efficiency (–)
η_{STC}	PV module conversion efficiency at standard test conditions (STC) (–)
q_{add}	additional module and array losses (–)
μ	temperature coefficient of module output power (1/°C)
$T_a(t)$	ambient temperature (°C)
$T_{c,STC}$	cell temperature at STC (°C)
$T_{c,NOCT}$, $T_{a,NOCT}$	cell and ambient temperature at the nominal operating cell temperature (NOCT) (°C)
G_{NOCT}	solar irradiance at NOCT (W/m^2)
P_{ac0}	rated maximum inverter AC power (W)
P_{dc0}	DC power at which the AC rating is achieved (W)
P_{s0}	inverter threshold power (W)

without net metering or feed-in support, where retail prices are higher than wholesale prices.

Because of these altered market and support conditions, the interest in self-consumption has increased, starting in Germany [6], and it is reported that both batteries and energy management systems that help owners of building-applied PV systems increase their self-consumption have become more popular [7]. These energy management systems range from simple relay-based designs, where a load is activated in response to certain PV generation levels, to more advanced systems that provide a variety of options for matching the PV generation with the power demand [8]. One example of the latter is the SMA Sunny Home Manager, which provides monitoring of consumption and generation, appliance scheduling, Bluetooth-controlled power sockets and a battery backup system [9].

Apart from increasing the economic value of the PV generation, these management systems could also help managing electricity distribution grids with high PV penetrations. One major issue when PV systems are introduced in large numbers in distribution grids is that the altered load patterns on the grid may cause voltage rise and component loading to an extent that limiting values are exceeded [10]. Many previous studies have quantified these limiting *hosting capacities* [11] for PV in particular grids [12–17], and currently an important area for research and development is how to allow high PV penetrations while avoiding costly grid reinforcements [18]. Improved PV self-consumption at critical times, i.e. when the PV power overproduction is high, is one such option that has not yet been thoroughly quantified.

How high the default self-consumption of PV power is, without any improvements, depends on the daily electricity consumption patterns of the system owner. These tend to vary heavily between individual residential customers due to differences in both electric equipment and habits [19], but in general, if a single-family residential building is roughly net-zero over the year, self-consumption is around 20–30% of the total PV generation, as observed at different European locations [19–24]. Some of these studies also report substantial self-consumption improvements from demand-side management and battery storage. For example, in [21] both detailed simulations and real experiments were performed on a Spanish building equipped with a 5.55 kW$_p$ PV system, a lead-acid battery bank and a real-time controller for scheduling deferrable loads. One interesting result was that the PV self-consumption over one week, studied in the experiments, was raised from 31% to 57% with load shifting and to 76% with both load shifting and storage, indicating a high impact of these technologies. In another study, annual self-consumption fractions up to 65% were reported for a simulated residential building equipped with a 5.5 kW$_p$ PV and where control of heat pumps, thermal storage and battery storage was optimized [23]. Similar annual fractions were obtained as the maximum theoretically achievable in a Swedish simulated single-family building with a net-zero energy balance [20].

Looking more closely at the load shifting option, the self-consumption increase depends on whether rescheduling of appliances is done spontaneously by the residents or is subject to optimized control by a management system, and on how many of the household's appliances are included in the scheduling. There is evidence that households spontaneously increase their energy awareness and consequently decrease their overall energy use and change the time of electricity use in response to installing a PV system [25,26]. There is also substantial evidence that residential customers alter their energy use in response to advanced metering, billing and different forms of feedback (see e.g. [27]) and that demand response (DR) programs, where electricity use patterns are changed in response to prices or other incentives, have an impact, although their expected effectiveness is often overestimated [28,29]. However, few empirical studies have reported details on the potential for load shifting of individual appliance categories in large, representative sets of residential buildings. Some recent findings have come from a field study where 41 households changed their use of certain smart appliances (washing, drying, ironing and dishwashing) in response to a fictive tariff. The study reports savings up to 30% for the laundry-related appliances and somewhat lower savings for dishwashers [30].