MATCHING PV PRODUCTION AND ELECTRICITY LOAD ON HOUSEHOLD LEVEL AT HIGH-LATITUDE LOCATIONS

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ABSTRACT: This study analyses the potential for the self-consumption of photovoltaic (PV) electricity for different detached houses and PV systems in Nordic conditions. The aim is to reduce the need for battery energy storage or balancing power generation by fossil fuels to mitigate the high diurnal and weather-dependent variation of PV production. Increasing self-consumption is crucial to increase the usability and economic value of PV electricity on households and to smoothen the grid integration of PV on local and national levels. Three differently oriented monofacial PV systems and one vertically mounted bifacial PV system are compared as clean electricity sources for different detached houses in a high-latitude location. The focus is on total energy production and the potential for self-consumption. For monofacial systems, the self-consumption potential was dominated by the electricity load profile, and the differences in self-consumption between differently oriented systems were small, except when large, flexible loads allowed to utilize high amount of PV electricity at the spot. For vertical bifacial system, the highest overall production and convenient power production profile allowed superior self-consumption compared with monofacial PV systems.

Keywords: Self-consumption, high-latitude location, vertical bifacial PV

1 INTRODUCTION

Solving the challenges arising from imbalance between temporal electricity consumption and variable renewable energy (VRE) production plays a key role for increasing the share of clean energy in future electricity generation. Solar photovoltaics (PV) has extraordinary scalability, allowing all sizes of actors from individual citizens to large power companies to own PV power systems. Thus, PV provides a unique opportunity for individuals and small companies to affect directly how the electricity they consume is produced.

The economic feasibility of a PV system depends on the production capacity, the PV system price, and the local electricity price. The massive drop in the cost of PV over the last decade and the rise in the electricity prices across Europe have increased the feasibility of PV. Thus, PV is now a feasible option even for high-latitude locations, such as the Nordic countries, although the production per kilowatt-peak (kWp) is lower than in southern Europe. Here, we conduct a case study by modelling a detached house with rooftop PV installation located in Turku, Finland (60°N, 22°E). Case studies regarding rooftop PV are common in low- and mid-latitude locations, both for single households [1] and for national-scale analysis on rooftop PV potential [2]. However, at high latitudes, such studies are rare, although some exist [3].

The availability of PV power depends on time of day and weather conditions, making the PV production highly intermittent, creating challenges for the grid integration [4]. With typical, south-facing PV installations on a clear day, PV gives a power production profile which rises rapidly during morning, peaks at solar noon and goes down during afternoon. Orienting panels away from the South increases the production in the morning or evening, at the cost of decreased overall production. Another innovative option is to install vertically mounted bifacial PV (VBPV) panels, which utilize light from both sides and give peak production in the morning and evening when oriented in East-West direction. Low solar elevation favours VBPV over MPV, and thus VBPV is especially attracting option at high latitude locations [5]–[7].

Electricity consumption and supply in the power grid must match temporally and spatially, to ensure reliable electricity delivery. In a typical detached house, the power demand is high during the morning and evening, with a valley between. This leads to a temporal mismatch with a conventional PV production profile. With e.g., East- and West-facing PV systems, the match between production and consumption is better [8]. With VBPV, matching both the morning and evening consumption peaks, and thus allowing high self-consumption, is possible.

The case studies include four different PV power production profiles, representing three differently oriented monofacial systems and one vertical bifacial system. For the electricity load, four profiles are used. Three load profiles, acquired from clustered market data [9], represent Finnish detached houses with different heating solution. The fourth profile adds flexibility to heat demand, allowing the flexible utilization of PV. The aim is to analyse quantitatively the self-consumption and self-sufficiency of different [PV system – Electricity load] combinations, determining the suitability of each PV system for a house with a certain load profile. For MPV, the main interest is to investigate how much the self-consumption of PV electricity can be increased by orienting the PV systems unconventionally, i.e., shifting them from South towards East or West. This orientation shift can be due to the possibility to produce more electricity during the natural peak electricity load hours in the morning and evening, at the cost of decreased total annual production, or by external restrictions, for instance when South-facing roofs are unavailable. For VBPV, that is especially suitable for high-latitude locations [7], the key interest is to compare the total and self-consumed production with the different MPV solutions.

2 METHODS

2.1 PV power production profiles

The global horizontal irradiance (GHI), ambient temperature (T_A), and wind speed (WS) data were acquired from a weather station located in Turku, Finland

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[8]. The GHI values were converted to direct current (DC) power production profiles with a methodology explained in our previous work [10]. The power production was modelled for one year, with the year 2019 weather data. The modelled PV systems, excluding the size sensitivity analysis presented in Section 3.3, were sized to 4.0 kWp, which is a realistic size for a rooftop PV installation.

Four different PV orientations were studied: three monofacial PV (MPV) systems all with 30° tilt and different azimuths and one VBPV system. The tilt of 30° was chosen since it is a typical roof tilt angle for a traditional Finnish house. Azimuth 180° (T30S) represents a conventional installation site for a small-scale PV system: South-facing tilted roof. Azimuths of 90° and 270° in the same system (T30EW) represent a tilted roof which ridge is aligned in South-North direction, resulting in sides facing East and West. Azimuths 135° and 225° in the same system (T30SESW) represent an intermediate scenario, where the main building has a wing or garage, aligned so that there are both Southeast and Southwest facing roofs. The VBPV system is oriented so that sides are facing East and West. Bifaciality of 90% is assumed in calculations, i.e., the power production from the light incident on the rear side is 10% lower compared with the front side due to additional optical losses. The profiles for two example days are shown and analysed in Section 3.1.

Table 1. Summary of the studied PV systems. For the dual-azimuth systems, the percentages show the ratio of the azimuths. Azimuth = 180° is South.

Name	Tilt (°)	Azimuth(s) (°)
T30S	30	180 (100%)
T30SESW	30	135 (50%) and 225 (50%)
T30EW	30	90 (50%) and 270 (50%)
VBPV	90	90* (50%) and 270* (50%)

*Bifaciality 90%

2.2 Electricity loads

The electricity load profiles used here are based on typical electricity consumption behaviour of different Finnish type consumers, defined in literature [9]. The profiles were acquired from clustered data: they represent the averages of many consumers that have similar electricity demand and load profile. Thus, rapid variations in demand, due to such as using a stove, are averaged out.

Three type of user profiles were utilized directly: a detached house without electric heating (EH) (Load1), energy-efficient detached house with direct EH (Load2) and detached house with reserving EH (Load3). These profiles were taken directly from literature [3]. All profiles covered one year and had a resolution of one hour.

A fourth profile, Load3F, was generated based on Load3 and assuming that the heating demand is flexible, based on certain principles as follows: The total consumption (Load3) was divided into consumption used for other purposes than heating (Load1) and consumption due to heating (Load3 – Load1). Then, a flexibility for 24 hours was assumed: if there is any surplus PV power available in a certain hour and expected heat demand within the next 24 hours, the surplus was used to satisfy the heat demand in advance. This profile represents a situation where the surplus PV electricity during a sunny day can be used to satisfy the heat and hot water demand for the following night. The profiles are summarized in **Table 2** and visualized in **Figure 1**.

Table 2. Summary of the used load profiles.

Name	Electric heating	Energy-efficient house	Annual consumption (kWh)
Load1	No	No	5000
Load2	Direct	Yes	10000
Load3	Reserving	No	19000
Load3F	Reserving & flexible	No	19000

Loads1&2 have a very similar diurnal shape due to domestic activities, with Load2 having an additional season-dependent component due to electric heating. Load3, however, has a completely different shape: during daytime, it is close to Load2, but during night, there are high peaks due to heating needs. The high loads are scheduled to night-time due to lower electricity demand and cost. The peaks are the highest during winter due to high heating demand, but they exist throughout the year due to hot water demand. For Load3F, the profile is identical to Load3 during winter, but from spring to autumn the high night peak in Load3 is replaced with a lower and wider day peak in Load3F, representing cases where surplus PV production is used to produce heat. Since Load3F shifts the demand based on PV production, its exact shape depends on the PV system. In **Figure 1**, the PV system is T30S (nominal power 4.0 kWp).

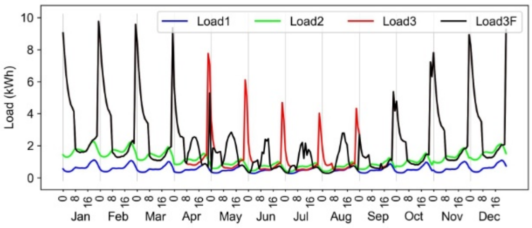

Figure 1. The hourly electricity consumption with the studied load profiles. The consumption is shown for one example day for each month (Tuesday closest to the 15th day of the month).

2.3 Simulations and used metrics

The houses with four different PV profiles and four different load profiles, a total of 16 different combinations, were simulated with one-hour resolution for one year. The dataset for PV production had one-minute resolution and it was converted to one-hour resolution by summing all modelled production within each hour. The nominal power of the PV systems was set to 4.0 kWp (except for the size sensitivity analysis presented in Section 3.3). The quantity and direction of the power flow between the house and the power grid for the hour i was determined based on the quantity of the PV production (E_{PV}) and electricity consumption (E_L):

$$E_{SC,i} = E_{PV,i}, if\, E_{PV,i} \leq E_{L,i} \quad (1a)$$

$$E_{SC,i} = E_{L,i},\ otherwise \quad (1b)$$

For the case (1a), the additional electricity needed to meet the demand is taken from the grid. For the case (1b), the additional PV production is classified as surplus and delivered to the grid. These practices are consistent with Finnish market policies: small-scale PV producers are expected to cover their own demand with PV before delivering to the grid.

For each case, the total absolute self-consumption (E_{SC}), the relative self-consumption (Φ_C), and the relative self-sufficiency (Φ_S) were calculated as follows:

$$E_{SC} = \sum_i E_{SC,i} \quad (2)$$

$$\emptyset_C = \frac{E_{SC}}{\sum_i E_{PV,i}} \quad (3)$$

$$\emptyset_S = \frac{E_{SC}}{\sum_i E_{L,i}} \quad (4)$$

The calculations were done with one-hour resolution due to data availability: both the demand and PV production were assumed to remain constant for one hour. Thus, during a certain hour, only one-directional power flow between the house and the grid is allowed. However, the power may flow to both directions within an hour, due to sudden changes in load (e.g., using a stove) or in production (e.g., cloud movement). This effect is excluded due to resolution of the electricity load data.

For the size sensitivity analysis (Section 3.2), two PV systems (T30S and VBPV) were combined with all four load profiles. The nominal powers of the studied systems are 0.4-8.0 kWp, with an interval of 0.4 kWp.

3 RESULTS

3.1 Self-consumption and self-sufficiency for a single sunny day

To demonstrate the methodology, the E_L, E_{PV}, E_{SC}, Φ_C, and Φ_S were determined for 4.0 kWp PV systems, representing typical single-family house rooftop PV installations. All four PV profiles and one load profile (Load2) were analysed for two example days: Apr 04 (**Figure 2A**) represents an early spring day with varying weather, whereas May 16 (**Figure 2B**) represents a sunny late spring day. The key numbers for the quantitative analysis of the example days are presented in **Table 3**.

When comparing MPV profiles, the E_{PV} is the highest with T30S and lowest with T30EW. However, considering the E_{SC}, the order may be different: for May 16 (**Figure 2B**), the higher production during morning and evening enables higher E_{SC}, and thus higher Φ_S, with T30EW, whereas the majority of the high E_{PV} with T30S is counted as surplus production. This is possible since during daytime (8 am to 6 pm) all systems are producing more electricity than is needed to match the load, and thus the differences in E_{SC} result from the differences in the morning and evening production.

For Apr 04 (**Figure 2A**), the situation is different: since the load is higher and PV production lower, E_{PV} correlates well with E_{SC}. During the period when PV production matches or exceeds the load, T30S is the best-performing MPV system. Actually, the E_{SC} for T30S is higher on Apr 04 than on May 16, since higher load enables the efficient utilization of PV for self-consumption. This phenomenon is especially clear when comparing Φ_C:s for Apr 04 and May 16 (**Table 3**): the Φ_C is higher for Apr 04 with all studied profiles.

For both days, VBPV is superior to all MPV systems when considering the daily E_{PV}, E_{SC}, and Φ_S. These findings highlight the benefits of the higher production and more suitable power production profile with VBPV, which allows to match the load earlier in the morning and later in the evening than it is possible with studied MPV systems.

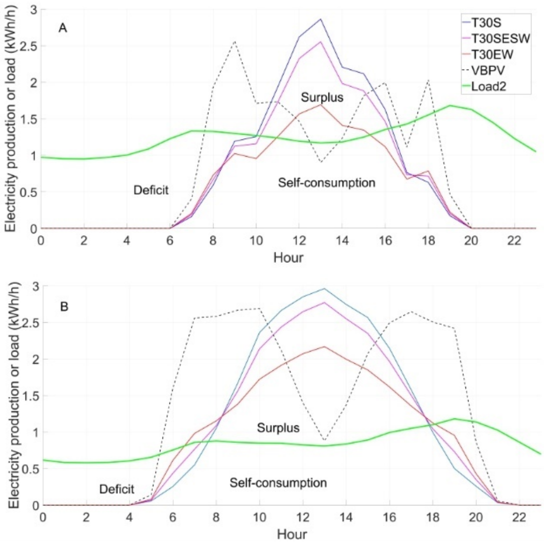

Figure 2. The hourly electricity production and hourly consumption with Load2-profile on (A) a mostly sunny early spring day and (B) on a sunny late spring day. The timestamp of x-axis refers to the start of hour: e.g., values shown for "Hour = 10" are the electricity production and consumption between 10 am and 11 am.

Table 3. The key parameters for different PV profiles on the two example days.

Apr 04: **E_L = 29.8 kWh**	E_{PV} (kWh)	E_{SC} (kWh)	Φ_C (%)	Φ_S (%)
T30S	18.1	12.1	67.0	40.8
T30SESW	16.7	12.2	72.8	40.8
T30EW	13.0	11.7	90.5	39.4
VBPV	19.4	14.6	75.1	48.8
May 16: **E_L = 20.1 kWh**	E_{PV} (kWh)	E_{SC} (kWh)	Φ_C (%)	Φ_S (%)
T30S	25.2	11.5	45.5	57.2
T30SESW	24.4	12.3	50.2	61.1
T30EW	21.5	12.9	60.2	64.3
VBPV	31.1	13.8	44.4	68.7

3.2. Annual self-consumption and self-sufficiency

The annual values for E_{SC}, Φ_C and Φ_S were determined for 4.0 kWp PV system with different production profiles. The key results are summarized visually in **Figure 3** and in numeric form in **Table 4**.

For the MPV systems, the E_{SC} and Φ_S remained practically constant when the orientation was changed for Loads1-3: the significant difference in overall production, especially between T30S and T30EW, went almost entirely to surplus. For Load3F, the Φ_S was significantly lower for T30EW-orientation (15.9%) than for T30SESW (18.3%) and T30S (19.1%), since the Load3F allowed to consume almost all of the produced electricity due to extensive and flexible heat demand.

VBPV had the highest overall production and best match with the typical electricity load, leading to the highest E_{SC} and Φ_S with all load cases. When load is fixed, the differences between the E_{SC}:s of VBPV and the MPV system with the highest E_{SC} varied from 90 kWh (compared with T30SESW) with Load1 to 250 kWh (compared with T30S) with Load3F. However, the increase in total production with VBPV was 380 kWh against T30S and 570 kWh against T30SESW, indicating that despite the improved match between electricity load and PV production, a significant fraction of the additional production with VBPV goes to surplus production.

When comparing different loads with the same PV system, the Load3F had by far the highest E_{SC} (3020-3880 kWh, depending on the PV orientation). Due to flexible heat demand, situations where the own PV power production went to surplus were rare – even during summer. Load2 had reasonable high base load due to direct electric heating, which lead to the second-highest E_{SC} (2170-2460 kWh) and Φ_S. Although Load3 had high E_L, the potential to utilize PV was low, since the reserving heating is used during night-time (**Figure 1**), which would be an optimal solution without PV.

To sum up, the self-consumption potential of PV electricity depended primarily on load flexibility and secondary from the natural base load during daytime from spring to autumn, when the PV production is high. The total overall production was less significant among the case studies: even though the T30EW profile had 19.0% smaller overall production than T30S, it had almost identical E_{SC} than T30S with Loads1-3. This observation is due to the effect shown in **Figure 2**: T30EW system produces more electricity in the morning and evening and extends the period when all consumed electricity is produced by the own PV for a sunny summer day, compared to T30S.

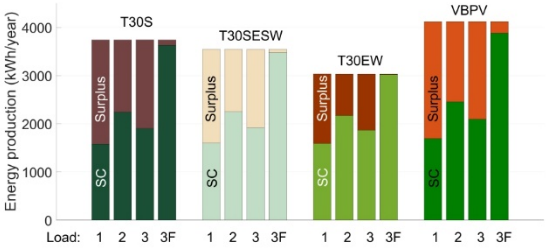

Figure 3. Total annual production and its distribution to the self-consumed and surplus production for each studied [PV system – Electricity load] case.

Table 4. Total annual electricity demand for each Load, the total annual electricity production for each PV system, and the self-consumed PV prodcution, relative self-consumption and relative self-sufficiency for all 16 [PV system – Electricity load] cases.

Load	**1**	**2**	**3**	**3F**
E_L (kWh)	5000	10000	19000	19000
T30S	**E_{PV} = 3740 kWh**			
E_{SC} (kWh)	1580	2240	1900	3630
Φ_C (%)	42.2	59.9	50.9	97.0
Φ_S (%)	31.6	22.4	10.0	19.1
T30SESW	**E_{PV} = 3550 kWh**			
E_{SC} (kWh)	1600	2250	1920	3480
Φ_C (%)	45.1	63.5	54.1	98.0
Φ_S (%)	32.0	22.5	10.1	18.3
T30EW	**E_{PV} = 3030 kWh**			
E_{SC} (kWh)	1590	2170	1870	3020
Φ_C (%)	52.5	71.6	61.7	99.7
Φ_S (%)	31.8	21.7	9.8	15.9
VBPV	**E_{PV} = 4120 kWh**			
E_{SC} (kWh)	1690	2460	2090	3880
Φ_C (%)	41.1	59.7	50.9	94.2
Φ_S (%)	33.9	24.6	11.0	20.4

3.3 Size sensitivity analysis

The effect of PV system size, expressed as nominal power, to the self-consumption is shown in **Figure 4** for T30S and VBPV systems. With very small PV systems, all production is self-consumed. However, with Loads1-3, the point where most of the added production went to surplus was reached between 1 and 2 kWp: as **Figure 2** shows, during a sunny summer day 4.0 kWp system is oversized when compared with base load and thus even significantly smaller systems can provide almost the same amount of self-consumed PV electricity. Although larger systems enable high daily self-sufficiency during early spring and late autumn, when the PV peak production and electricity peak demand are better matched, a large fraction of the added production still goes to summer day surplus production when the system size is increased, since the PV production focuses heavily to summer.

For Load3F, the surplus was close to zero until approximately 4 kWp due to potential for demand flexibility. After that, the overproduction during summer exceeded the summer heat demand and surplus became significant. However, a significant fraction of the added production was self-consumed even at 8.0 kWp, further highlighting the role of demand flexibility.

Overall, the sensitivity analysis shown in **Figure 4** reveals that with Loads1-3, the increase of self-consumption was small after the system size exceeded 2 kWp, whereas with Load3F, the share of the self-consumption from added production was almost 100% still at 4 kWp and remained significant (75.4% with T30S and 70.8% with VBPV) even at the upper limit (8.0 kWp). Thus, the profitability of larger PV systems without potential for load flexibility is strongly dependent on the economic value of the surplus electricity. If the value is high, due to a feed-in tariff or high electricity spot price, the oversized systems are beneficial. However, if the value of surplus electricity is small compared with the self-consumed electricity, small-scale producers' motivation to invest in large PV facilities is low.

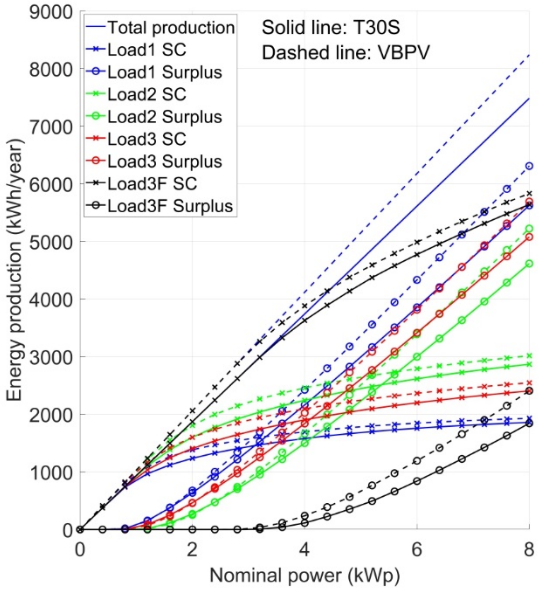

Figure 4. The total (lines overlap for all load cases), the self-consumed, and the surplus production of T30S and VBPV systems with all load profiles, as a function of system size. The full legend is shown only for T30S.

4 CONCLUSIONS

A total of 16 different [PV system – Electricity load] combinations with the nominal PV power of 4.0 kWp were studied in terms of self-consumption and self-sufficiency. VBPV had superior self-consumption potential compared with MPV due to the highest total production and best match between power production and electricity load. When comparing MPV systems with different orientations, the loss of production due to the azimuth shift away from South consisted almost completely of surplus production: the self-consumed productions, and thus the self-sufficiencies, of the MPV systems were very similar, except for the Load3F, which had high flexible demand. This result highlights that PV installations are suitable in Finland for a large variety of differently oriented roofs.

Sensitivity analysis revealed that without load flexibility, the point where the additional production achieved by increasing system size went mostly to surplus, was reached at 1-2 kWp. However, with flexible electric heating, the hot water demand is enough to enable high (75.4% with T30S) self-consumption even for 8.0 kWp PV system. Thus, investing in larger PV systems at detached houses requires either possibility to create value with surplus electricity or high potential for load flexibility. Moreover, high self-consumption enables more PV in the local power grid without the need for massive grid upgrades.

Since the power production is modelled in DC, inverter losses are not included in this study. Moreover, the used electricity load profiles are based on clustered data, representing the average of many similar customers. Thus, for a single house, the actual consumption behaviour may differ significantly from these profiles. However, using clustered profiles allows the easier upscaling of the simulations, to local or national power grid levels.

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