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Influence of PV system orientation and design on energy self-consumption and cost savings: A Norwegian case study

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Influence of PV system orientation and design on energy self-consumption and cost savings: A Norwegian case study

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Abstract. This study examines how PV system orientation and design affect energy generation, self-consumption, and cost savings in a Nordic climate. Five different PV systems are analysed from the monitoring data of a Plus-Energy school in Oslo. The analysis shows that roof-mounted systems achieve higher specific electricity generation and cost savings in general. In contrast, façade-mounted systems generate more electricity in spring and autumn. The school's dynamic electricity demand profile aligns well with PV generation, resulting in a 75% self-consumption rate. Demand response strategies, such as heat pump load-shifting, could further enhance the school's self-consumption. These findings provide insights for optimising PV integration in similar buildings and climates.

1. Introduction

The European Union aims to reach nearly 600 GW of solar photovoltaic (PV) capacity by 2030 [1], up from 338 GW in 2024 [2]. 20% of this capacity comes from residential systems (<10 kW), 38% from commercial and industrial installations (10-1000 kW), and 42% from utility-scale systems (>1 MW). Norway has set a target of 8 TWh/year of PV-generated electricity. This necessitates an increase in PV capacity from 762 MW in 2024 to 10 GW by 2030 [3]. Building-mounted PV systems will be important in this growth, where prosumers both consume and generate electricity behind their main meter.

Prosumers in the Nordic countries are economically incentivised to use the electricity they generate directly (self-consumption) [4]. In Norway, prosumers do not pay fixed grid fees on the electricity generated behind their meter. However, self-consumption of solar energy generation can be limited by its significant seasonal variation, peaking during summer [5], whereas electricity demand is highest in the winter because of the high share of electric building heating systems. Furthermore, the cost savings of a PV system with very volatile energy tariffs, such as the spot price on the Nord Pool market, heavily depend on the timing of energy generation and usage throughout the day.

PV tilting angle impacts seasonal production, with façade systems featuring steeper angles of PV array generating more electricity in the spring, autumn, and winter compared to rooftop systems [6]. Orientation also affects daily generation, with east-oriented systems generating more in the morning, south-oriented ones peaking at midday, and west-oriented ones peaking in the afternoon. The daily electricity use in commercial and service-sector buildings, such as offices, schools, and retailers, is typically higher during working hours, which often coincides with the peak periods of PV generation. In residential buildings, unshifted electricity demand typically peaks in the mornings and evenings, which may lead to a mismatch with PV generation.

This study evaluates how PV system orientation and design affect energy generation and cost savings on an hourly and seasonal basis, drawing insights from a case study of a Plus-Energy school in Oslo. The school is equipped with PV systems on façades and roofs. Additionally, the investigation explores PV self-consumption in relation to typical load profiles for buildings in Oslo.

2. Case description

The case study is a school (Voldsløkka school) that is located in Oslo, Norway (see Figure 1). It is one of six demonstration sites in the EU Horizon 2020 project ARV [7]. The school consists of a newly-built building (S-building: 9 267 m^2 of heated floor area for 810 students with a culture hall, a dance hall, and a rehearsal space) and a renovated listed building (H-building: 2 331 m^2 heated floor area; refurbishment of the "Heidenreich" cement factory into a cultural centre). Heat for indoor space conditioning and sanitary hot water production in the S-building is supplied by a ground source heat pump (GSHP) and the local district heating network. The school is the first *Plus-Energy* school in Oslo, built according to the *FutureBuilt* definition from 2014 [8]. The *Plus-Energy* concept applies only to the S-building, as the H-building is under conservation status. According to this concept, the PV installations on the S-building are sized and designed to generate 2 kWh/m^2 per year of electricity more than the total yearly energy use of the building.

Figure 1. View of the S-building west façade (left) and overview of the ARV pilot Voldsløkka school with PV systems on the roofs and facades (right): Image courtesy of Veidekke.

The PV system is designed to generate 230 MWh/year. The school is equipped with five PV systems for a total installed capacity of 337 kW$_p$: two east/west-oriented building-attached photovoltaic (BAPV) systems on the roofs ($BAPV.1_R^{E/W}$ and $BAPV.2_R^{E/W}$), one south- and west-oriented BAPV system on the façade ($BAPV_F^S$), and two south- and west-oriented building-integrated photovoltaic (BIPV) systems on the façades ($BIPV_F^S$ and $BIPV_F^W$). The BIPV modules are both green and black (see $BIPV_F^S$ in Figure 2).

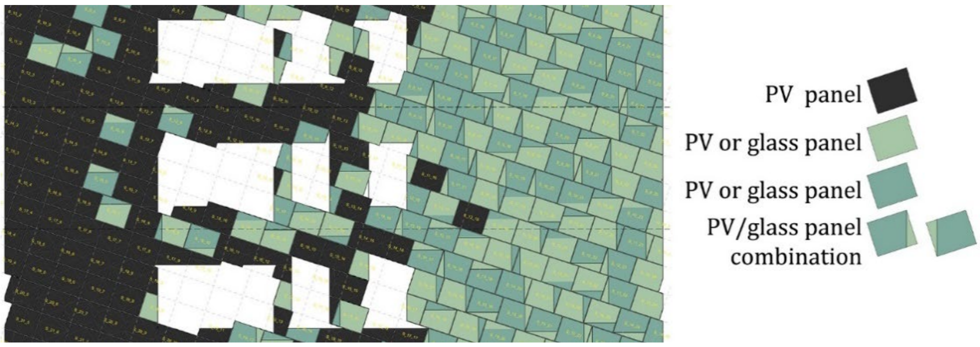

Figure 2. Positioning plan of the PV panel installation on the south façade of the school S-building ($BIPV_F^S$). Original image by KONTUR and SPINN Arkitekter, edited by Nicola Lolli (SINTEF).

The design of the PV module layouts is optimized based on their orientation to the sky, the orientation of the school building's longest façades, and the regulatory provisions regarding the aesthetics of the PV façade. The technical characteristics of the PV systems are presented in Table 1.

Table 1. Technical characteristics of the PV systems.

System	Description	Tilt, Azimuth (N=0°)	Capacity [kW$_p$]	Area [m^2]	Modules
$BAPV.1_R^{E/W}$	BAPV Flat roof	Tilt 10 °, Azimuth 71°/251°	124.8	615.2	320 Trina TSM-390 DE09.08 (20.3% efficiency)
$BAPV.2_R^{E/W}$	BAPV Above technical room	Tilt 10 °, Azimuth 71°/251°	102.4	492.1	256 Trina Vertex S TSM-400 DE09.08 (20.8% efficiency)
$BAPV_F^S$	BAPV Technical room façade	Tilt 90 °, Azimuth 161°/251°	7.2+ 38.4	34.6+ 184.5	96+18 Trina Vertex S TSM-400 DE09.08 (20.8% efficiency)
$BIPV_F^S$	BIPV South façade	Tilt 90 °, Azimuth 161°	26.4	216	216 custom panels 40% black, 60% green
$BIPV_F^W$	BIPV West façade	Tilt 90 °, Azimuth 251°	37.9	311	311 custom panels 25% black, 75% green

3. Results and discussion

The analysis is based on hourly PV production monitoring data from June 2023 to May 2024 along with operational data from the school (energy use), local weather (e.g., Global Horizontal Irradiance: GHI)[9], and electricity spot price from the *NordPool zone NO1* (including VAT) in 2023-2024 [10]. Key performance indicators (KPIs) such as energy generation, self-consumption, and cost savings (PV production multiplied by spot price) are computed for the five PV installations presented above.

3.1 Electricity generation and cost savings for PV systems with different orientations

The annual energy generation from the PV systems in 2024 was 215 MWh, which is close to the estimations of the design phase. The GHI for 2024 is 923.5 MWh, which is about 3% lower than the average GHI for the 2019-2024 period [9]. Table 2 presents the system-specific KPIs computed from June 2023 to May 2024 for the five different PV systems. The total GHI during this period is only 2% higher than that of 2024. The specific energy production varied from 371 to 772 kWh/kW$_p$, with roof-mounted systems $BAPV.1_R^{E/W}$ and $BAPV.2_R^{E/W}$ achieving the highest annual electricity generation. For instance, the roof-mounted, east/west-oriented system $BAPV.2_R^{E/W}$ produced 15% more per installed kW$_p$ than the south-oriented façade system $BAPV_F^S$, despite having similar PV technology.

Table 2. Performance of the different PV systems (average from June 2023 to May 2024).

System	Specific energy production [kWh/kW$_p$]	Specific energy production density [kWh/m^2]	Specific cost savings [NOK/kW$_p$]	Cost savings [NOK/kWh]
$BAPV.1_R^{E/W}$	772	156.6	409	0.53
$BAPV.2_R^{E/W}$	650	135.4	333	0.51
$BAPV_F^S$	567	118.0	321	0.57
$BIPV_F^S$	498	60.7	293	0.59
$BIPV_F^W$	371	45.2	205	0.55

Figure 3 shows the average daily electricity production and electricity spot price profiles for the five PV systems for each month of the year. The roof-mounted systems present a significantly higher production performance in the summer compared to other seasons. In contrast, the façade-installed systems have a flatter profile throughout the year, generating a higher production than roof-mounted systems during spring, autumn, and winter (when the sun is lower in the sky), but a lower production during summer. Orientation also affects daily production profiles: east-oriented systems generate more electricity in the morning, whereas south-facing ones peak around noon, and west-facing systems produce more in the afternoon. Notably, the $BAPV_F^S$ of the technical room's façade generates electricity later in the day because of the large proportion of west-oriented modules in this system. Moreover, the annual specific electricity production of the south- and west-oriented $BAPV_F^S$ is 6% higher than that of the south-oriented-façade $BIPV_F^S$.

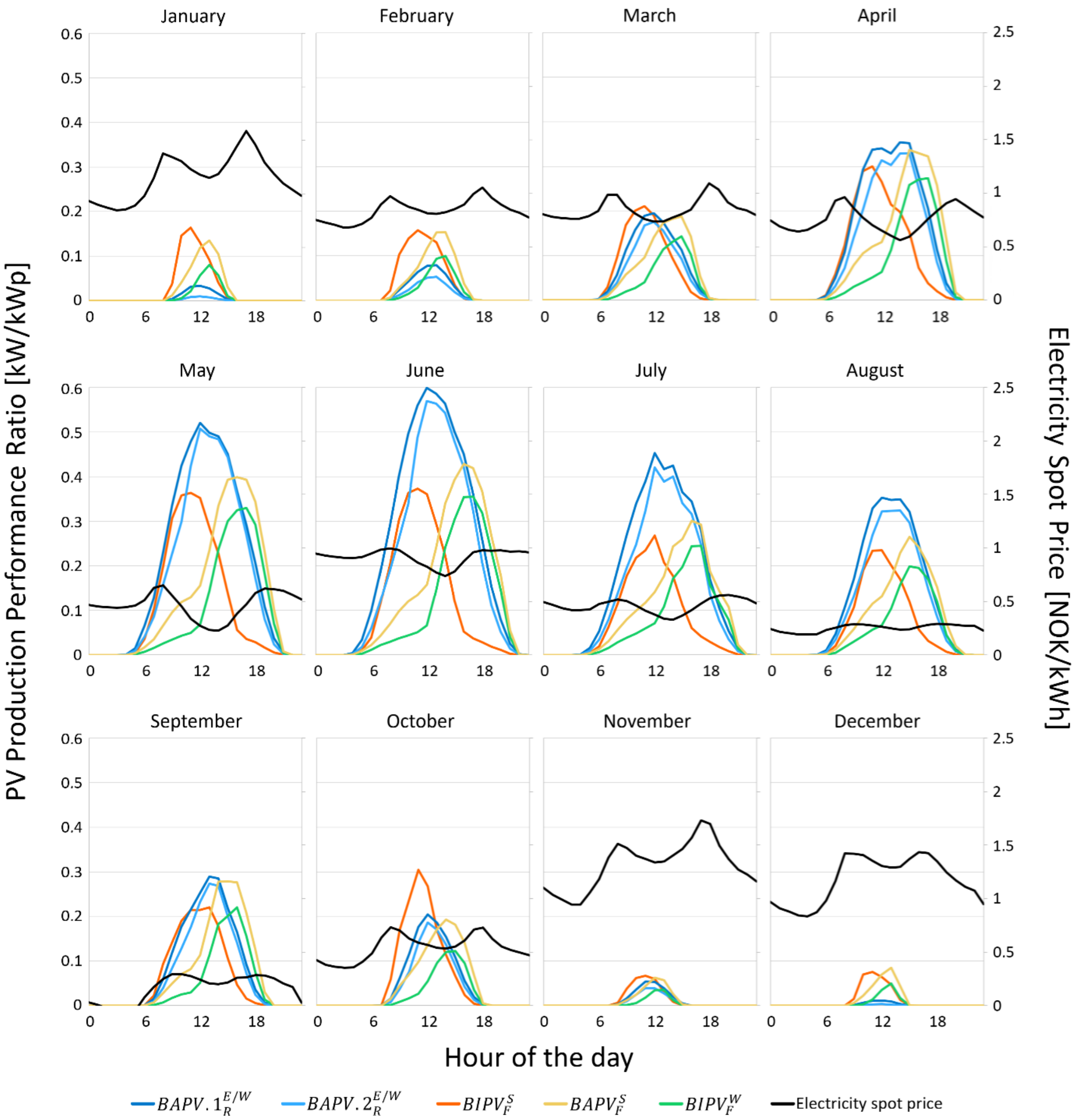

Figure 3. Average daily PV generation profiles for each month across the five different installations and the associated average electricity spot prices (June 2023 – May 2024).

The annual specific cost savings related to dynamic spot price normalized by installed PV capacity is highest for the roof-mounted systems due to their higher specific energy production (see Table 2). Savings range from 409 NOK/kWp for $BAPV.1_R^{E/W}$ to 205 NOK/kWp for $BIPV_F^W$. In addition, daily spot price variations impact both the cost savings from self-consumption and the income from feed-in (electricity export) to the grid. As illustrated in Figure 3, electricity spot prices are higher in the morning and at the end of the afternoon, and typically higher in the colder months. Finally, cost savings per kWh of PV production are higher for the façade systems (0.55-0.59 NOK/kWh) than for the roof-mounted ones (0.51-0.53 NOK/kWh).

3.2 *Electricity self-consumption*

In 2024, the total electricity use of the school is 655 MWh: 494 MWh is imported from the grid, and the on-site PV systems generate 215 MWh. This building has a very low primary energy demand (49 kWh/m^2 per year) compared to other new schools in Oslo, but it remains much larger than the design estimations (19 kWh/m^2 per year). The utilisation factor for electricity loads (ratio of the annual average load to the annual peak load) was 33% (based on hourly values). The annual maximum grid import was 172 kW (January), and the peak export (feed-in) was 143 kW (May). The school buildings used 75% of the on-site PV production (self-consumption). The rest (54 MWh) was exported to the electricity grid. If Norway were to introduce hourly net value metering, 9% of the exported electricity (5 MWh) would have been self-consumed by the buildings within the same hour. The self-sufficiency of the site (the share of total electricity consumption covered by on-site PV generation) is 25%.

The electricity demand of the Voldsløkka school follows the school's schedule, with highest consumption during the daytime. In winter, when PV generation is limited, the school's energy demand profile aligns well with the PV generation curve, even without load-shifting strategies. For example, during the six coldest months of 2024 (October–March), 96% of the 32.4 MWh generated by PVs was used on-site. In contrast, during the warmer period (April–September), hourly self-consumption decreased to 71% of the 182.7 MWh generated by PVs. Figure 4 illustrates the PV generation alongside energy loads in the school buildings during a representative period in May 2024.

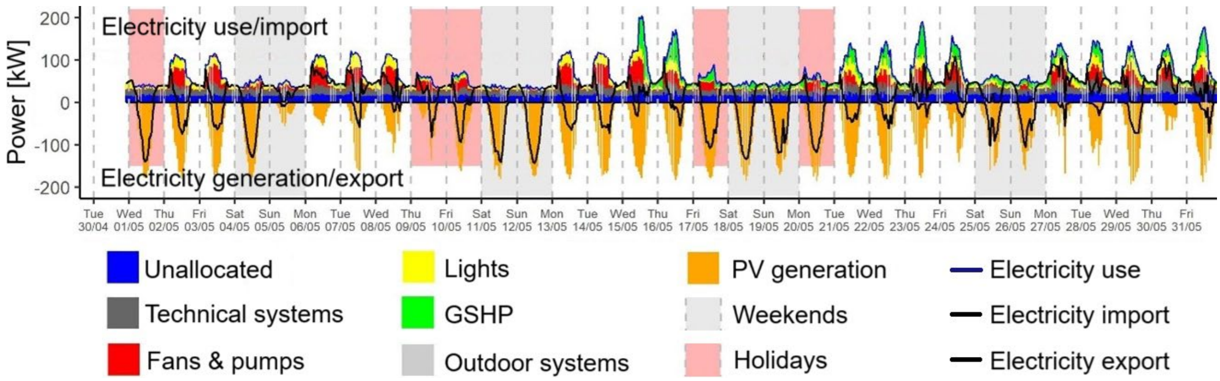

Figure 4. Hourly electricity generation, use, import, and export in May 2024.

The school buildings are equipped with a GSHP for heating and cooling, cold/hot water storage tanks, and thermally-activated building system (TABS) heat emitters. The energy storage of these technical systems, along with the thermal mass of the building, can be leveraged by means of smart control (e.g., Model Predictive Control: MPC) to perform demand response (e.g., shifting heating loads from morning to midday) to reduce peak demand, and increase self-consumption [11].

Figure 5 presents the average daily PV yield profiles (working day or weekend) for the five different systems over the April-September period, alongside electricity use at the Voldsløkka school, the average electricity demand of residential buildings in Oslo (213 apartments) [12], and the electricity demand of 33 other schools in Oslo [13]. One can observe that the Voldsløkka school presents a very typical daily energy demand profile with low energy usage. During working days in the April-September period, the overall timing of the on-site PV generation of the study case matches the daily demand profile of the school. In particular, the roof-mounted PV systems and BIPV systems on the south façade have the best on-site production matching. However, the production of the south façade $BAPV_F^S$ and the west façade $BIPV_F^W$ peaks later in the afternoon, when the electricity demand of the school has already decreased significantly, which is not optimal for the self-consumption of the on-site PV production. Nevertheless, the electricity produced by the $BAPV_F^S$ and the $BIPV_F^W$ systems can be exported to the local electrical grid and be used by the surrounding residential buildings that present an increase of energy demand at the end of the afternoon and beginning of the evening (schools and offices close, and people come home and use appliances/plug electrical vehicles). During the weekend, the energy demand profile of the school is flat and low. Therefore, the roof-mounted PV systems and BIPV systems on the south façade do not match the peak demand. On the other hand, the $BAPV_F^S$ and the $BIPV_F^W$ coincide well with the evening weekend peak of the surrounding residential buildings. These observations can also be made from Figure 6, which presents the contribution of the different PV systems to the school's self-consumption. As expected, the overall self-consumption of the school is significantly higher during the working days than during the weekends, when the electricity export is larger.

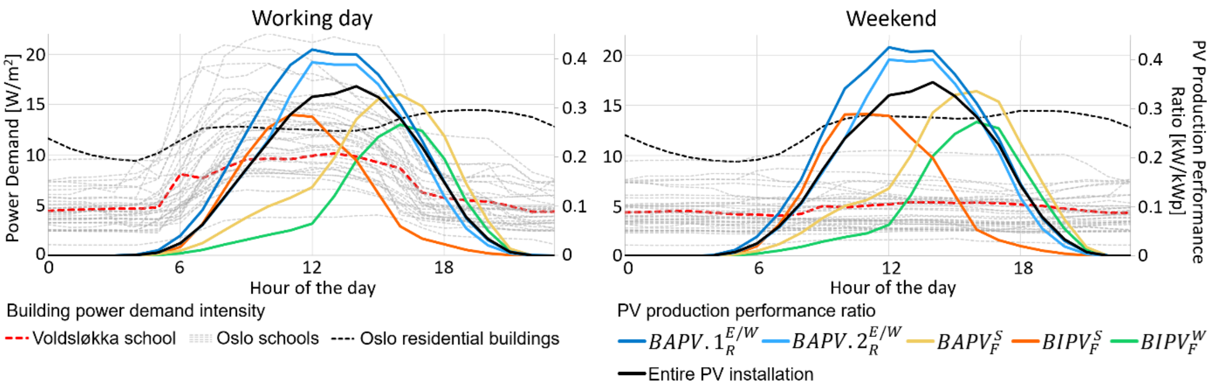

Figure 5. Average daily yield profiles (April-September) for the five PV systems, electricity use in Voldsløkka school, 33 other Oslo schools, and 213 apartment buildings in Oslo.

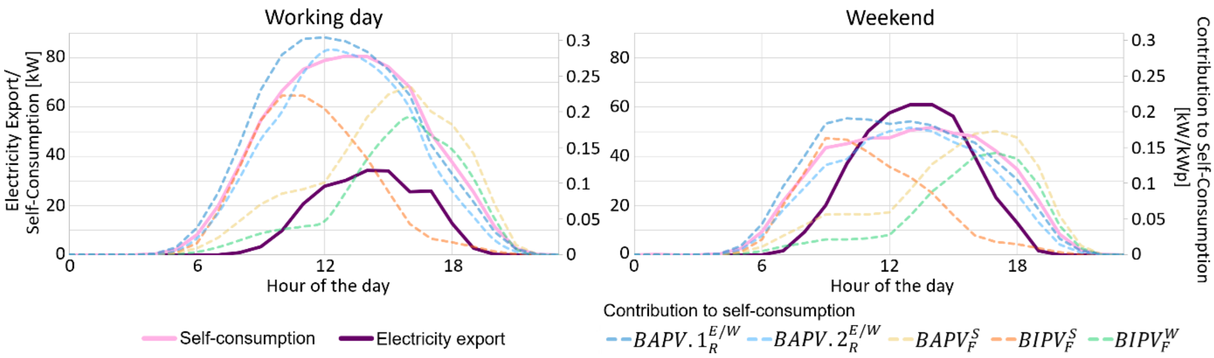

Figure 6. Average daily self-consumption and electricity export profiles (April-September) for the Voldsløkka school, along with the contribution to self-consumption of the five PV systems.

4. Conclusion

This study highlights how PV system orientation and design influence energy generation, self-consumption, and cost savings for a school building in a Nordic climate. Roof-mounted PV systems achieved higher specific energy generation and cost savings, while façade-mounted systems contributed more during spring and autumn. The school's electricity demand aligns well with PV generation, achieving a self-consumption rate of 75%. The roof-mounted PV systems and BIPV systems on the south façade have the best on-site production matching the daily energy demand of the school. Load-shifting strategies, such as optimizing GSHP operation with MPC, could further enhance self-consumption and decrease peak loads. These findings provide insights applicable to other buildings integrating PV systems in similar climates. Future work will focus on energy demand performance gap.

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