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Solar energy for multi-story apartment buildings – Innovative façade solutions and energy sharing enable load-matching

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ABSTRACT

This study provides novel insights on increasing the profitability of solar photovoltaic (PV) systems in Nordic urban areas via innovative façade solutions and internal electricity trade in a multi-story apartment building. Nordic PV is growing fast, and the low solar elevation makes various facade installations attractive, but the insight on their impacts on energy economics of apartment buildings is lacking, and this research gap is addressed in this study. Besides conventional rooftop PV, this work investigates innovative vertical bifacial PV (VBPV) façade solutions that allow improved load-matching. Such matching of daily PV profile to load is an unusual approach compared with demand response and energy storage. Investigating the economic value of PV generation with real electricity price data and a large set of real apartment consumption profiles from south-western Finland and different energy sharing scenarios in building- and apartment-levels provide additional novelty. In addition, investigating different real shading scenarios as well as the impact of exact building orientation provides robustness. The key results show that energy sharing corresponds to 13–14% of the total PV production and provides a 10–12% increase in the value of the produced PV electricity with a small (12-panels, 5.28 kW) rooftop PV system and different façade systems. Buying electricity from the intra-building market is beneficial for the apartment owner. The shading reduced PV production by 5.6–8.3% with minor shading, whereas non-optimal building orientation had a limited impact on the PV electricity value giving freedom to the practical building design.

1. Introduction

This work investigates two knowledge gaps: what kind of solar photovoltaic (PV) systems are profitable for multi-story buildings in the Nordic urban areas, and what ownership and energy sharing policies support the profitability of urban PV electricity generation. Dedicating a large area of land to PV is challenging in urban areas due to high land use costs and low energy output of PV per area that the PV panels occupy. Therefore, integrating PV with buildings and other urban infrastructure is crucial to enable PV production in cities. The profitability of PV has increased so that PV has reached grid parity even in high latitude locations leading to significant interest and growth in applying PV, e.g., in Nordics. High latitude locations benefit from long summer days and low sun elevation angle, which has a major impact on which type of PV systems are profitable in these conditions, requiring novel analysis. Since the popularity of Nordic PV is very recent, there is a major lack of insight in this field. The scalability of PV makes the building-applied and building-integrated PV (BAPV and BIPV) attractive solutions to power urban areas with locally produced, green electricity.

Insights into optimization of apartment-level PV-sharing are scarce, especially for high-latitude locations. This gap is addressed within this work. For detached houses, the owner can decide on building a small PV system installed on a rooftop. These installations are owned by individuals, and their economic profitability depends primarily on the ability to self-consume the produced electricity at the spot [1]. Self-consumed electricity avoids transmission fees and taxes, which can consist over half of the total price that a residential consumer pays for the electricity bought from the grid (55–56% on average in Finland in 2023 for consumers with 1–5 MWh annual consumption [2]).

In multi-story buildings, the roof area to electricity consumption –ratio is lower and the ownership structure often more complicated than in detached houses. These factors create challenges for PV

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installations, creating the need for research on this topic. Surface area on the façades of buildings increases with the number of floors, while roof area is limited by the building footprint, making façade-mounted PV relevant [3]. Liu et al. studied the urban building layout's impact on PV production in the building facades, in terms of annual electricity production [4]. In the Netherlands, façade solutions offered higher self-consumption and value factor than optimally oriented rooftop installation, as PV production increases [5]. In Adelaide, Australia, the building facades have significant PV generation potential, shown by Zhao and Gou [6]. Aesthetics of façade-PV solutions are important to ensure public acceptability and to maintain architectural values. Comprehensive reviews on BIPV are reported elsewhere [7,8].

This work address façade-mounted PV together with conventional rooftop PV to study PV generation and its match with the electricity load in building-level in a high-latitude location. Investigating load-matching and architectural aspects of vertical bifacial PV (VBPV) façade solutions provides a novel contribution to this field. The opportunities and challenges of high-latitude VBPV, and its different installation options in urban settings are summarized in our previous work [9]. In the Nordics, the low solar elevation makes vertical installations on façades more favorable to their counterparts in lower latitudes, differing significantly from locations studied in the literature. As there are only a few studies on Nordic BIPV and BAPV, this work contributes to filling the particular research gap by providing novel insight on energy production and sharing in these conditions.

Multi-story buildings offer possibilities to increase the value of PV production via internal energy sharing, a relevant topic with limited research, particularly in Nordics. Peer-to-peer renewable energy communities (RECs) allow individuals to access green PV electricity in a profitable way [10] and provide opportunities to use the distributed PV generation to power up small communities [11]. If the grid electricity is billed on the building-level, the internal net metering improves the self-consumption rate and the value of the generated PV electricity [12]. The energy sharing potential inside a building or REC depends on multiple factors, including PV system size, location, and possibility to store electricity [13]. Here, our primary goal is to improve the self-consumption of the building, which was found to create the highest savings for a REC in a Canadian study [14]. Supporting metrics, such as self-sufficiency, are calculated, but since PV has major seasonality in Nordics, aiming for a net-zero energy building [15] with only PV is challenging. Other metrics, such as self-production and grid-liability, have been suggested to analyze residential PV [16], but here we focus on self-consumption.

Analyzing the benefits of VBPV and energy sharing in a high-latitude REC is a literature gap with high potential for research output. A study analyzing BIPV in RECs with climatic data from Brussels, Rome, and Vienna showed an increase in the BIPV capacity in the modelled building due to energy sharing [17], but high latitudes were excluded. In Sweden [18], a high-latitude location, aggregating normalized load curves for residential and commercial end-users increased the self-sufficiency by 7% (up to 70%) when compared with normalized PV production curve. However, the use of normalized load and PV production may bias the results. In Finland, electricity sharing led to self-consumption rate improvements by 6–17 percentage points [19], benchmarking the potential of this approach. Compared with state-of-the-art literature, our novel approach improves the load-matching via innovative panel orientations and internal electricity sharing in the building, instead of demand response and energy storage. Demand response, i.e., consumers scheduling their electricity demand based on the price signal, became more popular in Finland during the recent energy crisis [20] even in residential houses. In a REC, a coordinated demand response increases the benefits for PV self-consumption [21]. However, in this work, the focus is to investigate the potential of energy sharing and load-matching alone. Therefore, demand response was excluded from the scope and this work differentiates from state-of-the-art literature by improving load-matching via VBPV and internal electricity sharing in the building. Each apartment owns a share of the common PV system, and they can trade electricity in the intra-building market to increase the building-level self-consumption. Moreover, analyzing the impact of shading and orientation of the building on the PV production value provides a robust sensitivity analysis on energy sharing.

REC topology with respect to the distribution system operator affects its economics. Several alternative topologies are described in [22]. This work focuses on a single building located in an urban area with a grid connection, and thus, the studied topologies are in-front-of-meter and behind-the-meter. In the former option, all apartments have their own electricity retail contract, while in the latter option the building is acting as one end-user. For PV, similar to most power production methods, the initial investment cost is high. The investment can be financed by distributing the costs to REC members (self-investment) or by making an agreement with a third party, who then owns the system and sells electricity to REC members. The third party has a higher possibility of making profits with REC [23], but self-investment ensures that the profits stay within the community, if REC has clear and fair rules for electricity sharing [24].

REC can improve the self-consumption rate of the produced PV electricity with energy storage. An Italian study observed that REC consisting of a university campus and neighboring communities could achieve a levelized cost of electricity of 3.9c$/kWh with a system consisting of distributed PV production, local electricity sharing, and batteries with optimized operational strategy [25]. However, in Finnish conditions the low electricity price reduces the potential of batteries and therefore, the batteries are far from profitability [26]. In cold climates, thermal energy storages provide added flexibility due to high heat demand, as showed in Norway [27]. Heat pumps and charging electric vehicles allow improving the self-consumption even further [28], whereas expanding the optimization outside only electricity further increases the benefits [29]. However, as this work focuses on matching PV production and electricity load with VBPV façade solutions, using this freely available load-matching potential, energy storage that causes additional costs is excluded.

The two main ownership structures of multi-story buildings in Finland are 1) housing cooperatives, where individuals owning the single apartments own the cooperative shares and; 2) company-based ownership, where a company owns the entire building and rents the apartments. In housing cooperatives, the challenges for advancing PV production include the potential disagreements between the shareholders on how the benefits of PV should be divided. Addressing the division of the benefits, and especially, avoiding unfair situations between the apartment owners, is critical to mitigate resistance towards PV deployment in buildings and to advance just green transition. A blockchain-based ledger with commonly agreed rules was suggested as an energy sharing algorithm in a Finnish context [30]. In company-based ownership, the interest of the company in investing in PV is the factor deciding whether PV systems will be installed. Since the direct benefit of PV self-consumption in rental apartments goes to the tenants instead of the owner, investing in PV is feasible only if the own PV system in the building has an impact on the rent.

This work studies a multi-story building in Turku, Finland. The aim is to study how different façade PV solutions and energy sharing affect the value of the produced electricity and link this value to the self-consumption of the building. Compared with existing literature, with insights on energy storage and demand response, the key novelty is identifying how VBPV façade solutions combined with intra-building energy sharing improve the value of the generated PV electricity. The studied PV systems have a sufficient physical size compared with the building while maintaining high self-consumption, since the building lacks energy storage. A commercial software, PVsyst [31], is used to model PV production, whereas real electricity consumption data from the Finnish residential end-users from the year 2023 is used. The aim is to define the economic value that PV production creates for the residents with different PV systems, their ownership structures, and energy sharing policies. The impacts of the electricity contract type, shading, and building orientation on the value created by energy sharing are investigated. Completing detailed apartment-level analysis provides insight on how the benefits of electricity sharing are distributed among individual apartment owners. The comprehensive analysis reveals the potential of intra-building energy sharing in the Finnish conditions and its sensitivity considering the surroundings and orientation of the building and provides insight into how the benefits are divided, thus filling this identified research gap.

2. Methodology

2.1. Case study building, PV systems, and residential electricity load

A building from a development project "Make 2.0", funded by City of Helsinki [32] and designed by Harris-Kjisik Oy [33], was used as a case study. The building is a modern wooden building with five stories and 18 apartments. The building is implemented as a 3D model in PVsyst. The annual power production of the studied PV systems is modelled with PVsyst, using the year 2023 weather data. Our analysis is confined to the year 2023 since the residential electricity consumption data set that we used is from that year. This choice allows us to include the impact of weather on the electricity consumption to our analysis, although it excludes the impact of year-to-year variation of the PV production. An hourly satellite weather data from Copernicus Atmosphere Monitoring Service (CAMS) for the year 2023 was used to create PVsyst profiles. Specifically, global horizontal irradiance, diffuse horizontal irradiance and ambient temperature along with a monthly average albedo was used for three locations in Turku, described further in this section. For the unshaded base scenario, the weather data used was the same as for the "minor shading" scenario. The method to model VBPV with PVsyst is validated against experimental data in our previous study [34], in context of agricultural PV installations.

The reference case is a building model reported in our initial study [3], which provides a tilted, south-facing roof (22° tilt for the south-facing slope) and a south-facing façade as platforms for PV installations, shown in Fig. 1. The choice of PV systems is based on balancing energy yield, load-matching, building requirements, and aesthetic values. All of these factors need to be considered to enable profitable and acceptable PV production. The aim is to design systems that could be applied to real buildings with the applicable locations and ownership structures. More discussion on this topic is available in [3].

For the rooftop, two PV systems, a 45-panel system (MPV$_{45}$, Fig. 1a) and a 12-panel system (MPV$_{12}$, Fig. 1b) are studied. The former utilizes almost whole roof for PV (Fig. 1a), leaving only small areas for other building infrastructure, whereas the latter covers only a small part of the roof (Fig. 1b), avoiding over-generation of PV around noon. For the façade, this work investigates four different options. A monofacial parallel-to-façade system (MPV$_{F}$, Fig. 1a) provided a reference. Load-matching improvements are sought with three different VPBV options, VBPV$_{L}$, VBPV$_{S}$, and VBPV$_{H}$, shown in Fig. 1b-d. Enlargements of each subfigure are shown in Supplementary Information, Section 1, Figs. S1-S4. The VBPV façade systems differ considering the number, size, and placement of the panels on the façade. The main design criteria with VBPV were avoiding high row-to-row shading and leaving sufficient space for windows and balconies. The MPV$_{F}$ façade system was sized to have identical number of panels than the VBPV$_{L}$ system. The peak powers and annual electricity yields of PV systems are shown in Table 1. For bifacial panels, the bifaciality was 90% and the side with higher expected production was chosen as a front-side (rear side is indicated with black color in Fig. 1). The overall PV systems are combinations of rooftop and façade PV systems: any rooftop system can be combined with any façade system. The overall systems are notated as 'Roof_Facade', e.g., MPV$_{12}$_VBPV$_{L}$.

The building is studied in four different shading scenarios. The 'ideal' scenario excludes shading, whereas the other three shading scenarios, 'minor' (60.4363° N, 22.2310°E), 'medium' (60.4451°N, 22.2815°E), and 'heavy' (60.4476°N, 22.2647°E) are based on real locations in Turku, Finland (Fig. 2). Direction and distance to the nearby objects defines the severity of shading. The self-shading between VBPV panels exists in all scenarios, including 'ideal'.

The residential electricity loads are covered with the real 2023 residential electricity consumption data provided by Vakka-Suomen Voima Oy (VSV), a distribution system operator in the southwestern Finland. The model building consists of a ground floor (two 1-room apartments) and four upper floors. There are two alternative designs for the upper floors, one with two 1-room and two 2-room apartments (smaller and larger), another with one studio, 1-room, 2-room (small) and 3-room apartments. Alternative floor designs can be used in the same building. This model building has two floors of both upper floor types. The electricity consumption of the building composed of different apartments is presented in Table 2. The annual consumption estimates are based upon [35]. A hundred different versions of the case study building electricity consumption are created with Monte Carlo method: a consumption profile for each apartment is chosen by random from the VSV-dataset, as explained in Supplementary Information, Section 2.

2.2. Electricity price

Three different electricity price contracts were used, based on the

Table 1
Annual yields and peak powers of the studied PV systems.

System	Yield (kWh/year)	Peak power (kW)	Type
MPV$_{12}$	5,430	5.28	Roof
MPV$_{45}$	20,500	19.8	Roof
MPV$_{F}$	7,110	9.24	Facade
VBPV$_{L}$	7,770	9.24	Facade
VBPV$_{S}$	2,600	4.58	Facade
VBPV$_{H}$	6,350	7.67	Facade

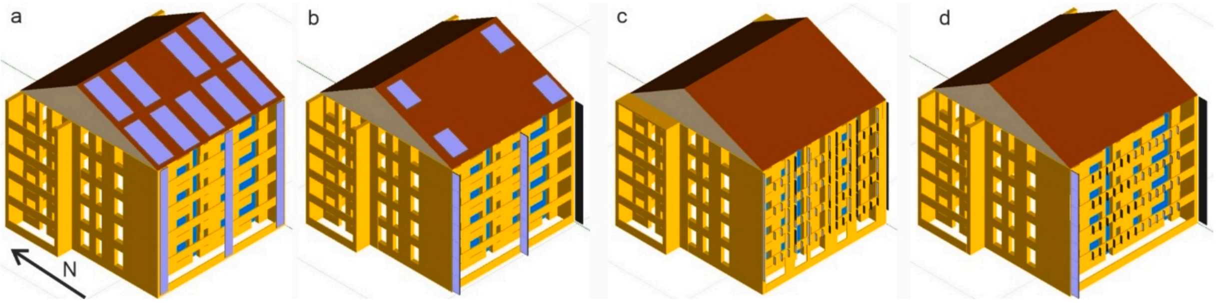

Fig. 1. A 3D-model of Make 2.0 building with the studied PV systems: MPV$_{45}$ and MPV$_{F}$ (a), MPV$_{12}$ and VBPV$_{L}$ (b), VBPV$_{S}$ (c), and VBPV$_{H}$ (d). Any rooftop system can be combined with any façade system. Figure created with PVsyst. Larger figures are shown in Supplementary Information, Section 1, Figs. S1-S4.

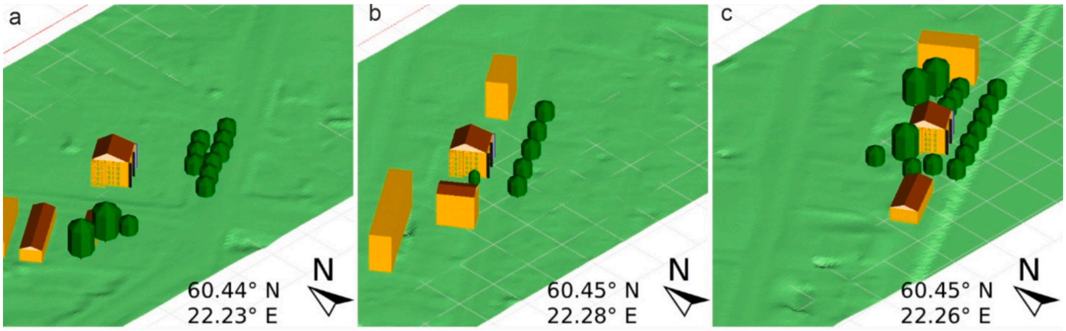

Fig. 2. Surroundings of the studied building with a) minor, b) medium, and c) heavy shading scenario. Figure created with PVsyst.

Table 2
The flat types, their amounts, areas, and electricity consumptions of the model building.

Apartment	n	Floor area (m^2)	Consumption (kWh)
Studio	2	34	1,500 ± 100
1-room	8	47	2,500 ± 100
2-room-S	4	65	3,500 ± 200
2-room-L	2	74.5	3,500 ± 200
3-room	2	86.5	4,500 ± 300

Finnish electricity retail market standards. Spot-price contract contains the Nord Pool hourly spot price, and a margin charged by electricity company (here 0.40c/kWh). Fixed-term contract locks the price for a fixed period, typically 12 or 24 months, whereas with until further notice (ufn) –contract the price per kWh is constant, but the electricity company can change the price with one-month announcement time. The exact prices were for the Finnish type consumer ‘K1′, which stands for a typical apartment in a multi-story building without an electric sauna.

The fixed-price contracts represent the mean value of 24-month fixed-term contracts made during the year 2021 (7.86c/kWh [36]). For ufn-contract type, the prices are monthly averages from the year 2021 (7.84–9.78c/kWh, depending on month [36]). The justification for using old electricity price data is the energy crisis that occurred in 2022 due to Russia’s attack on Ukraine. Ufn-prices in Finland rose rapidly and were still at an extremely elevated level in 2023 and thus, using the 2023 prices for ufn-contract would represent a crisis situation and make the comparison to other contract types biased. Therefore, the values in prior to the energy crisis were used to enable reasonable comparison of the contract types.

This work used Monte Carlo method for setting the default electricity purchase contracts for each apartment, based on the shares of different contract types in the Finnish markets at the end of the year 2023 [37]. The electricity spot price is acquired from Nord Pool [38], and the fixed and ufn-prices are based on the average statistics provided by the Finnish Energy Authority [36]. Table 3 summarizes the key properties of the used electricity contracts. The mean daily profiles for each month during April – September are shown in Fig. 3, showing that the spot price purchase contract had lower price for the bought electricity than the fixed and ufn-contracts during the best PV production times. Moreover, the sell price for PV was low during the summer, highlighting the role of self-consumption in value creation.

Table 3
The electricity purchase and sell contracts and the mean price (inc. transmission fee and taxes) used in this work. The probabilities for the apartment default purchase contracts are based on the shares of each contract type at the end of 2023 [37].

Contract	Type	Mean price (c/kWh)	Probability (%)
Spot	Purchase	15.81	31
Fixed	Purchase	16.30	45
Ufn	Purchase	17.00	24
Spot	Sell	5.25	100

In addition to the electricity cost, the Finnish retail price includes a transmission fee and electricity tax, which are charged as a fixed price per kWh. We use the real 2023 values for the Finnish type consumer ‘K1′, 8.73c/kWh [36]. The monthly fixed prices that are independent of the consumption for the electricity purchase and transmission fee are neglected since they are realized regardless of the use of PV. The surplus (production exceeding consumption) PV electricity is sold with the tax-free spot price deducted by a margin. This contract is typically only available option for a Finnish small-scale producer, and it is highly unfavorable for them due to low revenue compared with the savings for self-consuming PV electricity.

To support households during the energy crisis, the Finnish government deducted VAT for electricity from 24% to 10% from Dec 2022 to Apr 2023. Thus, the electricity prices from Jan-Apr are scaled to account for this VAT deduction. The deduction affects only the electricity price itself, while the transmission fee and electricity tax remain constant.

2.3. Economic analysis

The economic analysis investigates a housing cooperative –based PV system ownership structure, where each individual apartment owner owns a share (defined by the floor area of the apartment) of the PV system. The options for the energy sharing are:

1) Disabled (D): Each apartment owner has an individual electricity contract (Table 3), and the surplus PV is always sold to the grid. This is a theoretical case, which provides a reference for multi-story apartment PV production without the benefits of energy sharing.
2) Unconstrained (U): Building has an intra-building electricity market, where apartments can sell PV electricity that exceeds their consumption and buy PV electricity from other apartments for their own use. The electricity price in the intra-building market is the tax-free spot price.

The U-scenario is investigated in building-level in Sections 3.1 – 3.3, which represents an energy community with behind-the-meter monitoring. In this case, the EC has a joint electricity contract and handles independently the energy sharing within the building. This concept is allowed by the current Finnish legislation, although formation of a such community requires agreement of all shareholders. In Section 3.4, the apartment-level analysis is done with reimbursement calculation, possible in Finland since 2021, where each apartment has its own electricity contract and the housing cooperative is responsible for sharing the electricity according to the floor area and intra-building electricity market rules and selling the surplus electricity to the grid. The intra-building market is clarified in Supplementary Information, Section 3.

The energy management of each apartment works as follows. For

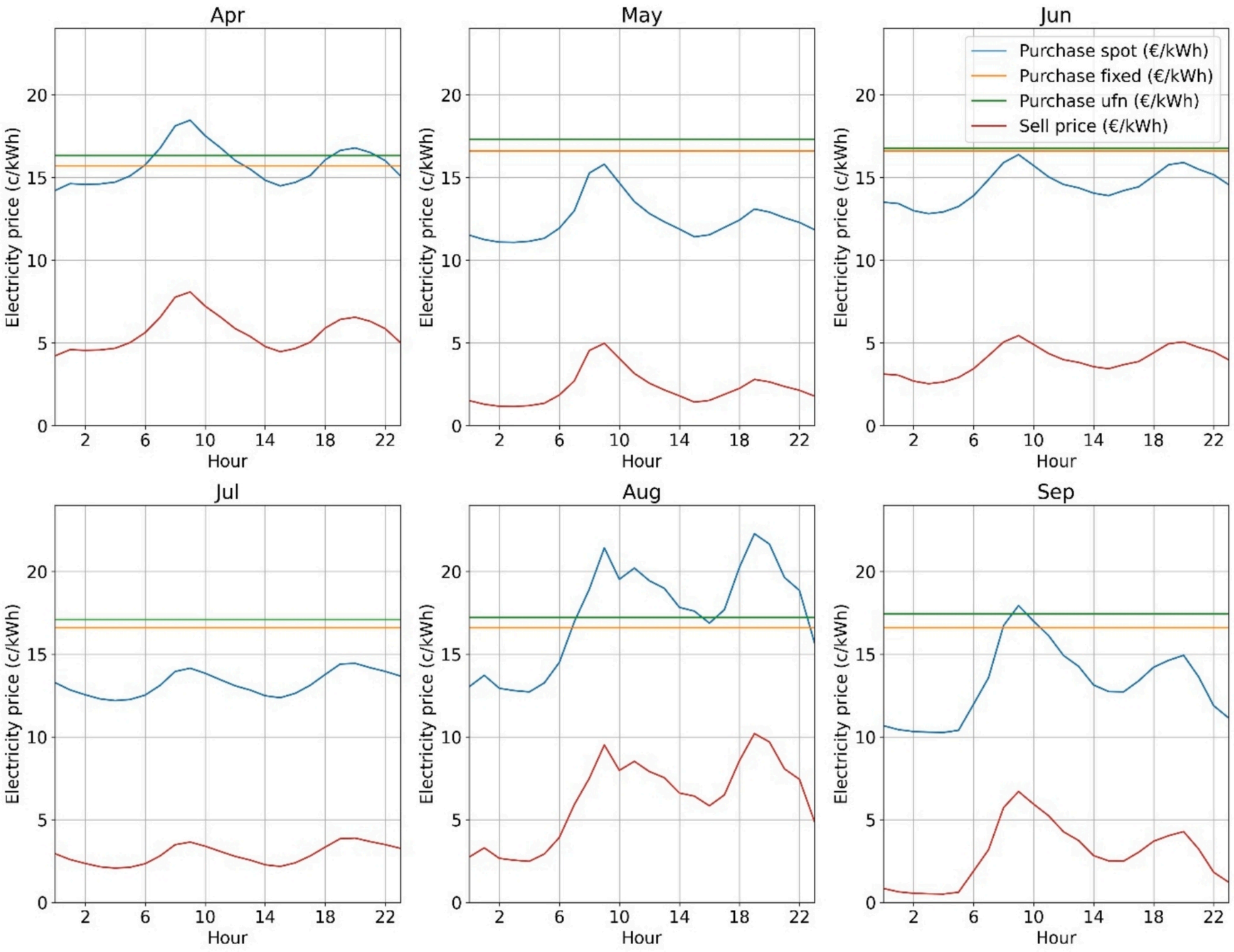

Fig. 3. The hourly mean electricity price for the contract types used in this work. The mean daily profile is shown for every month separately. The prices for the purchase contracts include the transfer fee and taxes.

acquiring electricity, the primary source is the own share of PV production, the secondary source is the intra-building electricity market (only for U-scenario), and the tertiary source is buying from the power grid. For using PV electricity, the primary option is self-consumption, the secondary option is the intra-building electricity market (only for U-scenario), and the tertiary option is selling the electricity to the power grid. As an exception, apartments with a fixed- or ufn-price contract buy from the grid when the electricity price in the intra-building market is higher than their total purchase cost from the grid. If the electricity supply exceeds demand in the intra-building market, all additional consumption is satisfied with surplus PV from other apartments, and the surplus production is sold in proportion to the flat floor area. Vice versa, if the building consumes more electricity than it produces, all the surplus PV is sold in-house and the maximum allowed electricity purchase amount is defined by the apartment floor area. The computational load of this algorithm is low: a full year simulation (8760 h) for one building took approximately three minutes on a typical laptop (Dell Latitude 5450, with 13th Gen Intel(R) Core(TM) i3-1315U (1.20 GHz) processor).

The key objective is to define the annual value of the produced PV electricity in the year 2023. The value is calculated with our previous methodology [1], shown in Eq. (1):

$$VAL_{PV} = \sum_{i=1}^{8760} (E_{SC,\,i} \bullet C_{purchase,\,i} + E_{sur,\,i} \bullet C_{sell,\,i}), \tag{1}$$

where $E_{SC,i}$ and $E_{sur,i}$ are the self-consumed and surplus PV production (kWh), $C_{purchase,i}$ is the total cost of buying electricity from the grid (including transfer fee and taxes), and $C_{sell,i}$ is the revenue for selling PV electricity to the grid during the hour *i*.

The intra-building electricity trade is quantified based on the trade volume and balance in the apartment-level, defined by the following equations:

$$V_{trade} = \sum_{i=1}^{8760} (E_{PV,sold,i} + E_{PV,bought,i}) \tag{2a}$$

$$B_{trade} = \sum_{i=1}^{8760} (E_{PV,sold,i} - E_{PV,bought,i} \tag{2b}$$

where $E_{PV,\ sold}$ is the sold PV electricity and $E_{PV,\ bought}$ is the bought PV electricity during the hour *i*.

The created value for the share owners is then compared with a threshold value needed to achieve a zero net present value, i.e., the threshold for economic profitability. This methodology enables us to provide suggestions and recommendations for installing profitable PV systems in housing cooperatives.

Levelized cost of electricity (LCOE), net present value (NPV) and payback time are common indicators for economic analysis of PV. They are defined with equations:

$$LCOE = \frac{C_0 + \sum_{i=1}^{n}\left(C_i \bullet (1+r)^{-i}\right)}{\sum_{i=1}^{n}\left(E_i \bullet (1+r)^{-i}\right)} \tag{3}$$

$$NPV = \sum_{i=1}^{n}\left(\frac{VAL_{PV,i} - C_i}{(1+r)^i}\right) - C_0 \tag{4}$$

$$NPV(i = paybacktime) = 0 \tag{5}$$

where C_i is the cost and E_i the PV production (including degradation) during the year i, and r is the discount rate.

2.4. Case studies

This work is divided into four case studies. The base-study investigates the impact of PV systems and electricity contract on the benefits of energy sharing. The shading-study considers the impact of shading scenario on the economic value. The rotation-study investigates how the orientation of the building impacts on the market-based value of the produced PV electricity. Finally, apartment-study defines how the economic profits of energy sharing are distributed among the apartment owners. A summary of case studies is shown in Table 4. In all studies, the modelling is done for the year 2023 with one hour time step. All simulations are done for one building at time (i.e., neighborhood-level electricity sharing was excluded), but to create statistical representativeness, we used Monte Carlo method to repeat the simulations with different electricity consumption profiles and electricity contract types (apartment-level analysis only).

3. Results and discussion

3.1. Base scenario and key variables

The total annual production of the systems ranged from 8,030 ($MPV_{12}\_VBPV_S$) to 28,200 ($MPV_{45}\_VBPV_L$) kWh/year (Table 5 and Table 6). Here, the smaller rooftop system (MPV_{12}) led to high self-consumption rates: 84.6–98.0% and 71.8–84.6% for U- and D-scenarios, respectively. With MPV_{45} rooftop system, the corresponding values dropped to 55.5–62.6% and 49.0–54.5% for U- and D-scenarios, respectively. Since the production increase when changing from MPV_{12} to MPV_{45} rooftop system corresponds to 27.8% of the total annual consumption, most of the additional generation is sold to the grid. In our previous work [39], the annual electricity production value of 81 €/kW was found as a threshold value that covers the initial investment costs for a residential 4 kW system during the system lifetime with reasonable economic assumptions (e.g., 1.25 €/W investment cost). In reality, the investment cost of small PV systems in Finland depends strongly on the market situation and in this case the added structures of VBPV façade systems are likely to increase the costs. Due to high uncertainties related to these costs, we chose the annual value of electricity production as the key economic indicator when comparing the systems. Since all values are between 97–136 €/kW (Table 5 and Table 6), the model building shows potential for profitable energy production even without energy sharing.

As sensitivity analysis, the simulations were repeated with crisis prices (two-year fixed price contracts from 2022). For $MPV_{12}\_VBPV_L$ system, the annual values with fixed-price contract 250 and 218 €/kW for U- and D-scenarios, respectively, showing how energy crisis makes PV highly profitable.

The impact of energy sharing and electricity contract is shown in Fig. 4. The energy sharing within the building allows to convert a part of the surplus electricity into self-consumption via intra-building energy trading. As the value of a surplus kWh was less than 33% of the value of a self-consumed kWh in all cases, this conversion improved the profitability of PV systems. With MPV_{12} rooftop system, the self-consumption rate was improved by 12.8%-unit and 13.7%-unit with MPV_F and $VBPV_L$ façade systems, respectively. These numbers show how a large fraction of the annual production was converted from surplus into self-consumption when energy sharing within the building was enabled, being in line with 6–17%-unit improvement reported in [19] and 10–15%-unit improvement reported in [18]. These observations highlight that enabling energy sharing should be prioritized for policymakers aiming to promote BIPV, as suggested in [17]. With MPV_{45} rooftop system, the sharing potential as kWh remained almost identical to MPV_{12} system, but due to increased overall PV production the shared electricity formed only 6.6% and 7.0% of the total production with MPV_F and $VBPV_L$ façade systems, respectively. The value of the electricity was higher with the fixed-price purchase contract, since the mean spot price was low during the best PV production times (Fig. 3). Smaller PV systems had higher value per kW, since the self-consumption rate was higher with smaller production.

Since the exact calculation of NPV, LCOE, and payback time requires information on the investment cost, which is case-dependent, these values are always subject to the assumptions made. To provide benchmarks with reasonable assumptions, we calculated these values for $MPV_{12}\_MPV_F$ and $MPV_{12}\_VBPV_L$ systems with spot price electricity contract. Here, we assumed that the initial investment cost is 1.25 €/W for rooftop MPV, a reasonable value based on our previous works [1,39]. For the façade installations, we assumed higher (1.35 and 1.50 €/W for MPV and VBPV, respectively) investment costs. Annual operation and maintenance costs were set to 2% of the initial investment, lifetime to 30 years, and a discount rate of 5%. The LCOEs for these systems were 14.3 and 14.5c/kWh, respectively, whereas the payback times were 27 and 29 years with energy sharing. Decreasing the annual operation and maintenance costs to 1% of the initial investment decreased the payback time to 20 and 21 years. Although the payback times are long, we highlight that these calculations are strongly dependent on the initial investment costs, which are challenging to estimate for novel installation types. For example, reducing the initial investment costs by 20% dropped the payback times to 14 years for both systems.

3.2. Impact of shading on the electricity value

The impact of shading for the south-oriented building is shown in Fig. 5. The values are compared with the south-facing, unshaded building (‘ideal’), which is the case discussed in Section 3.1. To keep the amount of data shown reasonable, we present the results for the case

Table 4
The variables in each case study. Column ‘Results’ refers to a subsection of the Section 3. Results and Discussion.

Case study	Results	Rooftop PV	Façade PV	Shading scenarios	Building orientation	Electricity contracts	Monitoring level
Base	3.1	MPV_{12}, MPV_{45}	MPV_F, $VBPV_L$, $VBPV_S$, $VBPV_H$	Ideal	South-facing	Spot, fixed	Building
Shading	3.2	MPV_{12}	MPV_F, $VBPV_L$, $VBPV_S$, $VBPV_H$	Ideal, minor, medium, heavy	South-facing	Spot	Building
Rotation	3.3	MPV_{12}	MPV_F, $VBPV_L$	Ideal	Rotation, all orientations	Spot	Building
Apartment	3.4	MPV_{12}	MPV_F, $VBPV_L$	Ideal	South-facing	Mixed (spot, fixed, and ufn)	Apartment

Table 5
The key numeric results for the simulated PV systems with MPV$_{12}$ rooftop system and two façade systems.

Energy sharing	PV system	Production (kWh)	Contract	Self-consumption (%)	Self-sufficiency (%)	Annual value (EUR)	Value / power (EUR/kW)
U	MPV$_{12}$_MPV$_{F}$	12,500	Spot	84.6	19.5	1770	122
U	MPV$_{12}$_VBPV$_{F}$	13,200	Spot	87.9	21.3	1790	129
U	MPV$_{12}$_MPV$_{F}$	12,500	Fixed	84.6	19.5	1830	126
U	MPV$_{12}$_VBPV$_{F}$	13,200	Fixed	87.9	21.3	1970	136
D	MPV$_{12}$_MPV$_{F}$	12,500	Spot	71.8	16.5	1610	111
D	MPV$_{12}$_VBPV$_{F}$	13,200	Spot	74.2	18.0	1680	116
D	MPV$_{12}$_MPV$_{F}$	12,500	Fixed	71.8	16.5	1650	114
D	MPV$_{12}$_VBPV$_{F}$	13,200	Fixed	74.2	18.0	1760	121

Table 6
The key numeric results from the simulated PV systems with MPV$_{45}$ rooftop system and two façade systems.

Sharing	PV system	Production (kWh)	Contract	Self-consumption (%)	Self-sufficiency (%)	Annual value (EUR)	Value / power (EUR/kW)
U	MPV$_{45}$_MPV$_{F}$	27,600	Spot	55.5	28.1	3000	103
U	MPV$_{45}$_VBPV$_{F}$	28,200	Spot	57.0	29.6	3070	106
U	MPV$_{45}$_MPV$_{F}$	27,600	Fixed	55.5	28.1	3100	107
U	MPV$_{45}$_VBPV$_{F}$	28,200	Fixed	57.0	29.6	3200	110
D	MPV$_{45}$_MPV$_{F}$	27,600	Spot	49.0	24.8	2810	97
D	MPV$_{45}$_VBPV$_{F}$	28,200	Spot	50.0	25.9	2870	99
D	MPV$_{45}$_MPV$_{F}$	27,600	Fixed	49.0	24.8	2900	100
D	MPV$_{45}$_VBPV$_{F}$	28,200	Fixed	50.0	25.9	2970	102

studies with MPV$_{12}$ rooftop system and spot price contract, focusing on analyzing the impact of shading on different façade systems. The general conclusion based on Fig. 5 is that shading impacts more severely on VBPV façade systems than to MPV$_{F}$ façade system, since the production of facade PV peaks with low solar elevation. Especially, the large VBPV panels are vulnerable towards shading, while the small VBPV panels show more resilience. Moving from the ideal scenario to the ‘heavy shading’ decreased the value of PV systems from 12.9% (D_MPV$_{F}$) to 22.9% (U_VBPV$_{L}$). Even the ‘minor shading’ scenario cut the overall production by 5.6% for MPV$_{F}$ and 8.3% for VBPV$_{L}$ façade systems. However, all studied cases showed values of over 80 EUR/kW, indicating their potential for economic feasibility.

The average increase in PV value achieved with energy sharing varied from 9.7 to 11.3%, where the lower end of the scale stood for the VPBV$_{S}$ façade system. The value decreases were lower than the production decreases for all cases: the surplus production decreased relatively more than the self-consumed production. Thus, the relative self-consumption and the created value per produced kWh increases in more severe shading scenarios. This observation is in line with the analysis done in [1], where moving solar panels from south-facing, sloped roof to east- and west-slopes decreased production by almost a quarter, but the value decrease was slightly over 10%.

3.3. *Impact of building rotation*

The impact of the building rotation on the production and value of the generated PV electricity for the ideal (unshaded) scenario is addressed here. To avoid variability resulting from used profiles, only the spot price of electricity is considered when calculating the value of produced energy. Fig. 6 depicts three chosen systems facing directly south, daily energy production profiles and the spot price are shown for both clear sky and cloudy conditions. Similar figure for another season (spring) is shown in Supplementary Information, Section 4. Out of those profiles VBPV$_{L}$ matches the spot price the most closely as the peaks of both price and VBPV$_{L}$ energy production typically happen in the morning and evening with lower prices being typical at noon and during nighttime.

The annual productions of VBPV$_{L}$ and MPV$_{F}$ façade systems and MPV$_{12}$ rooftop systems are shown in Fig. 7a. The azimuth angle in this work is defined so that 0° corresponds to the south and the angle increases clockwise. VBPV$_{L}$ panels perform better than the MPV$_{F}$ panels regardless of the angle. MPV$_{12}$ produces the most energy at most orientations. Both VBPV$_{L}$ and MPV$_{F}$ panels have the highest output when they are placed on the south-facing wall, and their output decreases more noticeably after $\pm 45^\circ$. Realistically in most cases when the ‘front’ of the building faces more than 45° away from the south, another wall can be chosen for the PV installation to maximize sun exposure. Both MPV$_{F}$ and VBPV$_{L}$ have a higher output when rotated towards west than towards east, however the difference in both systems is minor. In the case of VBPV$_{L}$, the west-oriented VBPV$_{L}$ panel output only drops below 90% at 48°. Even on the worse performing east aligned side, the 90% threshold is only reached at -39° which demonstrates that the effects of building rotation are minor, provided the wall on which PV installation is situated is the southernmost wall. MPV$_{F}$ output stays above 90% at 69° to -61° and above 95% at 55° to -46°. Thus, it can be concluded that the building integrated PV system maintains high production well even if the orientation differs from an optimal angle. This allows for a more flexible architectural design and opens more opportunities to integrate PV systems on buildings with non-optimal orientation.

The average value of the produced energy taking into account only spot-prices is shown in Fig. 7b. Notably, MPV$_{F}$ results in a higher revenue per unit of produced energy when facing southeast than VBPV$_{L}$ while VBPV$_{L}$ results in the highest value at most other orientations because the VBPV$_{L}$ panels are installed perpendicularly to the wall. The value of MPV$_{12}$ is the lowest in nearly all cases. VBPV$_{L}$ outperforms MPV$_{F}$ both in electricity production and revenue in all orientations other than southeast, particularly when facing southwest. This is a result of a temporal match between production and demand, as afternoon electricity prices frequently spike causing energy produced at this time to frequently have a higher value. MPV$_{F}$ value drops quickly when the wall faces southwest dropping to 90% at just 25°, but it increases when directed southeast with the maximum value of 22.67 EUR/kWh at -26°. In contrast, VBPV$_{L}$ revenue per unit was highest when the front wall faced southwest, reaching the peak 22.67 EUR/kWh at 17° and dropping to 90% at -27° and 50° on the southeastern and southwestern side, respectively.

3.4. *Insight into energy sharing within the building*

We investigated the in-house electricity trading with a subset containing ten (south-facing) buildings and the ‘ideal’ scenario to keep the computational time feasible. The electricity contract for each individual

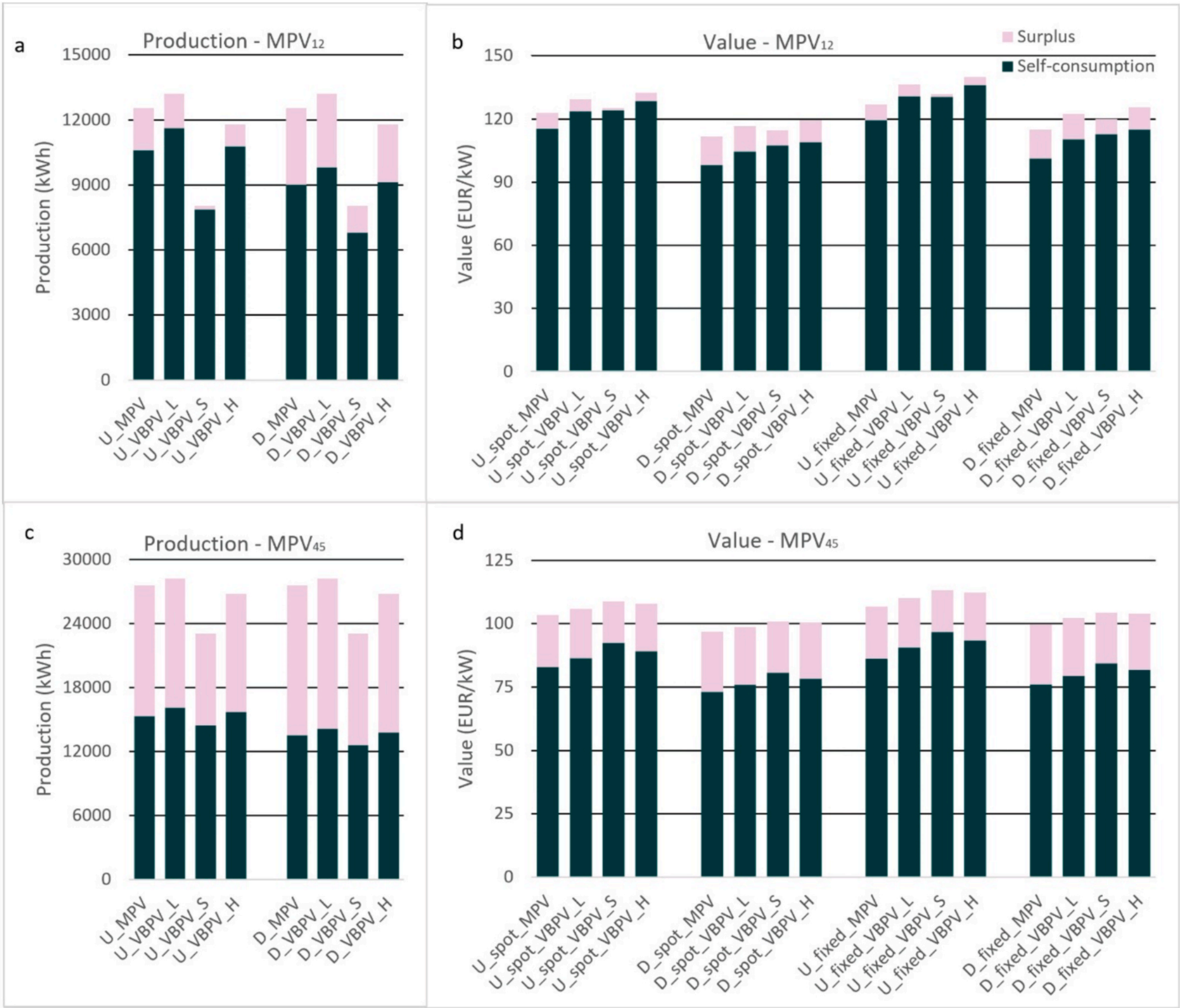

Fig. 4. The impact of the energy sharing, façade PV system, and electricity contract on the production (a&c) and the value (b&d) of the PV, when divided into self-consumed and surplus.

apartment was randomized as explained in Section 2.3. To ensure that using the subset supports the compatibility of the results, we compared all key indicators (PV electricity value, self-consumption, and self-sufficiency) for D-scenario for the averages of the ten buildings used here and the full hundred-building data set used in other Sections. The relative differences were less than 0.8% for all cases discussed in this section (in building level).

Scatter plots showing all apartments in the studied ten buildings, 180 apartments in total, with MPV_{12} rooftop system and either MPV_F or $VBPV_L$ façade system are shown in Fig. 8. The value of the generated PV electricity (as EUR/kW and as percentage of the annual electricity bill without PV) increases when the intra-building energy sharing is allowed. This increase is especially significant at the higher end of the apartment distribution: the apartments that have high consumption when PV production peaks, can utilize effectively the intra-building market to buy cheap PV electricity. For U-scenario, the mean PV value compared with the electricity bill varied based on the apartment type, from 20.8% (1-room) to 22.9% (studio), whereas with D-scenario, the corresponding range was 18.3% (1-room) to 20.9% (studio). However, the normalized value of PV was lower for studios and 2-room-L apartments, since they had high floor-area-to-electricity-consumption ratio and the investment cost was distributed based on the floor area.

The average trade volumes were 178 kWh / 9.3 EUR with MPV_F and 196 kWh / 9.7 EUR with $VBPV_L$ façade systems, respectively. The mean absolute values of the trade balance were 36 kWh / 2.1 EUR with MPV_F and 45 kWh / 2.2 EUR with $VBPV_L$ façade systems, respectively. Thus, an average apartment gained or paid 2.1 or 2.2 EUR in the intra-building market in annually. As a curiosity, one 3-room apartment with an atypical electricity consumption behavior bought an extensive amount of PV electricity. Even so, the value balance of the particular apartment was only −14.3 EUR and −10.5 EUR with MPV_F and $VBPV_L$ façade systems, respectively (Fig. 9b). Considering that the corresponding PV electricity trade balances were −220 kWh and −171 kWh, respectively (Fig. 9a), the average price that the particular apartment paid for the internally traded electricity was 6.5c/kWh with MPV_F and 6.1c/kWh with $VBPV_L$ façade system, far below the purchase cost of electricity (16.30c/kWh with fixed-price contract). Thus, this apartment benefits from the PV production, having the highest absolute PV value among all apartments and the highest relative electricity bill saving among the 3-room apartments.

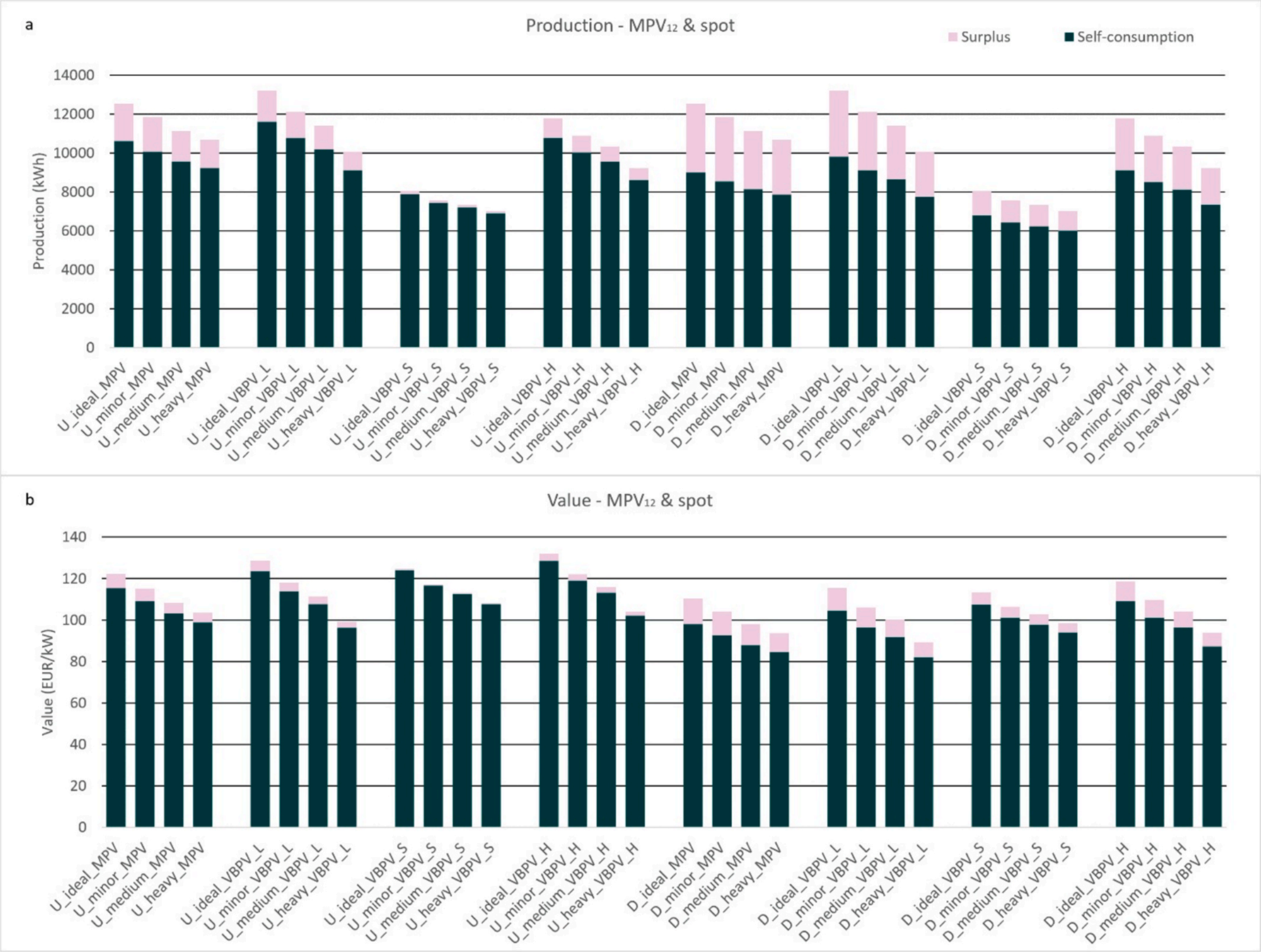

Fig. 5. The production (a) and value (b) of PV systems in different shading scenarios.

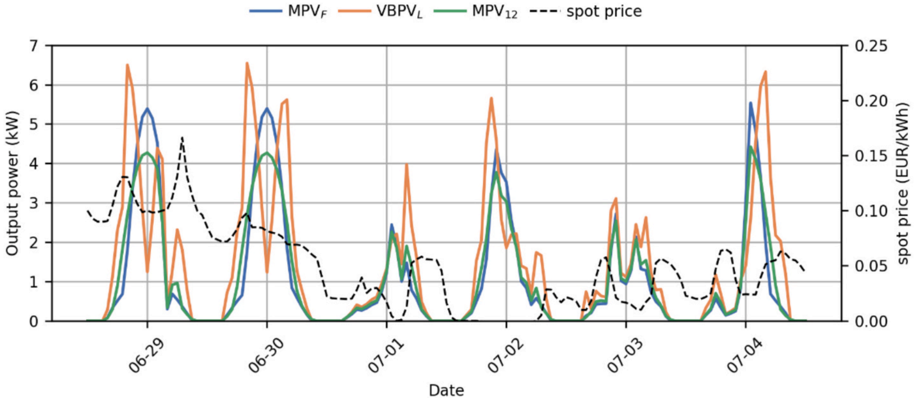

Fig. 6. Daily output of VBPV$_L$, MPV$_F$ and a MPV$_{12}$ installation, oriented south for select days including both clear sky (06–29 and 06–30) and cloudy conditions along with spot price. Note that the marker notes noon, e.g., 06–30 equals June 30th 12 pm.

The volume for both traded electricity and its value grow with the apartment size, which is expected due to larger electricity consumption and a larger share of the buildings PV production. Considering the balance, the studios and 2-room-L apartments are selling more electricity than buying. This phenomenon results from the high floor-area-to-electricity-consumption ratio (Table 2), which grants these apartments a high share of PV production compared with their consumption. Thus, these apartments are providing cheap solar energy to other apartments more than they are acquiring from them, which reduces the economic benefit they acquire from intra-building market compared with the net-buyers.

To sum up, the apartment-level analysis shows that PV electricity trade within the building. Thus, the major economic factor is the electricity bill savings due to PV production in the building-level, and this

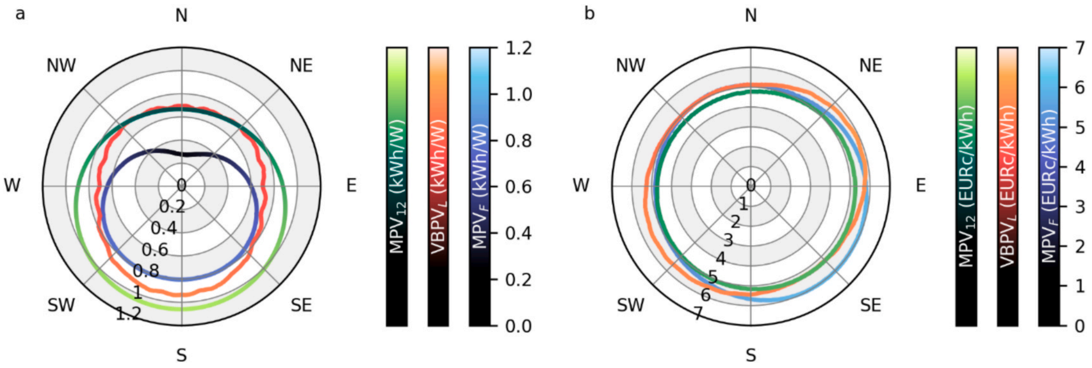

Fig. 7. Output (a) and revenue (b) of MPV_{12}, $VBPV_L$, and MPV_F installations at different mounting orientations.

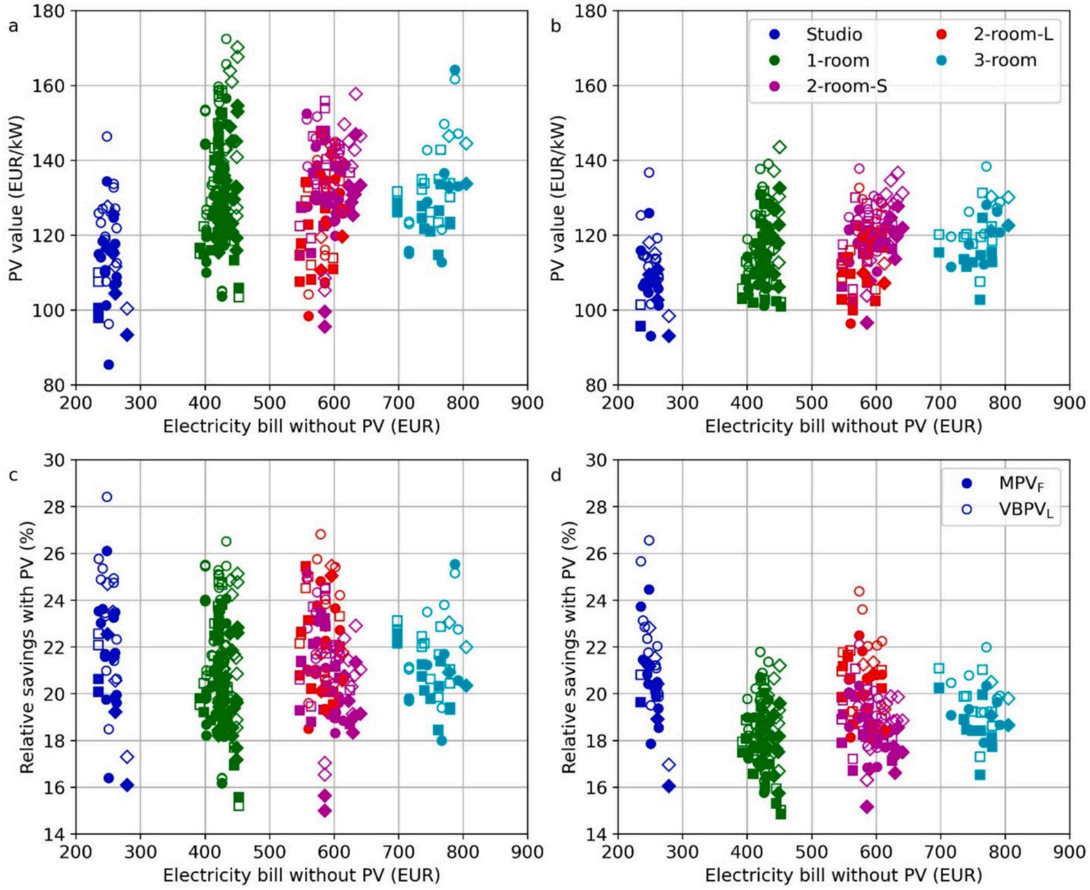

Fig. 8. The normalized value of PV electricity for the energy sharing scenarios U (a) and D (b). The relative savings compared with the annual electricity bill for the energy sharing scenarios U (c) and D (d). Colors indicate the apartment type, marker filling the façade system and marker the electricity contract of the particular apartment: circle = fixed, square = spot, and diamond = ufn.

benefit is distributed among the apartment owners fairly evenly: most of the apartments save 18–26% of their annual electricity bill due to PV. For instance, the average savings were equal between different apartment sizes (Fig. 8c). Therefore, the risk for significant conflicts among the apartment owners due to the distribution of the profits of the internal electricity trade is reduced. However, as the decisions about forming energy communities are made by individuals, here the share owners of a housing cooperative by vote, other factors than techno-economic facts may impact on the decision-making. For instance, personal experiences and values, political opinions, and argumentation skills of individuals may override the techno-economic perspective in decision-making.

4. Conclusions

This study found that the energy sharing potential within a five-story, 18-apartment building equipped with a PV system is significant and the benefits of energy sharing are distributed evenly. With a small (5.28 kW) rooftop PV system and a larger (9.24 kW) façade PV system, the additional self-consumption due to energy sharing was equivalent to 13–14% of the total annual PV generation. The economic value of the produced PV electricity was improved by 10–12% due to savings in the transfer fee and taxes. With a larger (19.8 kW) rooftop PV system, the energy sharing potential was reduced to 6.6–8.0% of the total annual generation and value improvement was 6.7–8.3%, since most of the

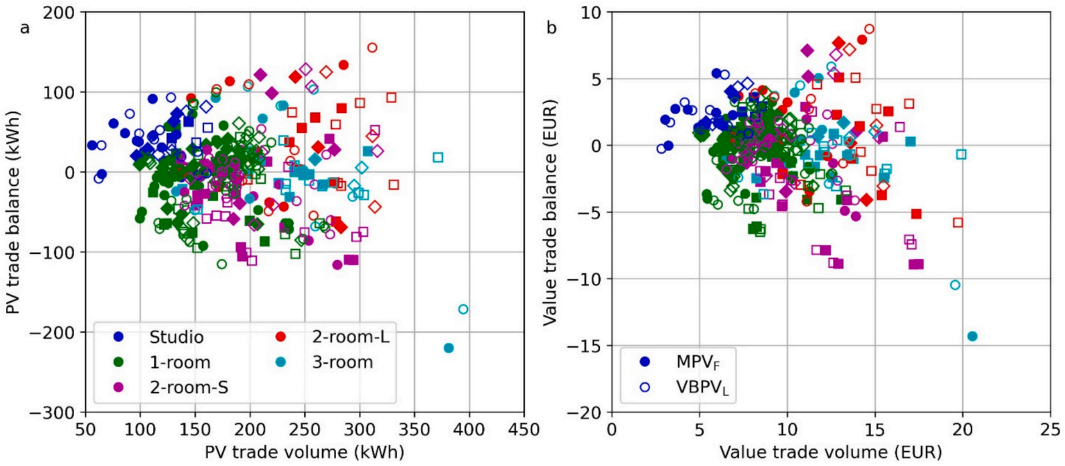

Fig. 9. The internal PV electricity trade when electricity sharing is enabled as kWh (a) and EUR (b). Colors indicate the apartment type, marker filling the façade system and marker the electricity contract of the particular apartment: circle = fixed, square = spot, and diamond = ufn.

added generation was sold to the grid. The economic benefits were higher when the building bought electricity with a fixed price contract than with a spot price contract, since the fixed price, and thus the overall electricity cost, was higher than the mean spot price. This effect will increase in the future as the impact of PV production on the electricity price in the Finnish market grows, lowering the spot price when PV production is high.

The shading from the surroundings affects more strongly the vertical bifacial façade systems than the monofacial, parallel-to-façade PV system. However, the economic impact is lower than the share of lost production since surplus production decreases relatively more than the self-consumed production when the shading scenario is worsened. Considering the building orientation, however, $VBPV_L$ façade system is more resilient when the building is rotated than MPV_F façade system. This resilience, combined with lower relative decrease in economic losses than in energy production, provides aesthetic design freedom for urban PV production in high-latitude conditions.

For most of the apartments, the electricity bill savings due to PV were 18–26% of their annual electricity bill without PV when electricity sharing was unconstrained. The economic revenue or cost for individual apartments in the intra-building electricity trade market is low. Increasing the building-level self-consumption benefits all, but even more those apartments that have high consumption peaks during PV peak production hours. Altogether, the benefits of electricity sharing within the building are distributed fairly among the apartment owners.

CRediT authorship contribution statement

Sami Jouttijärvi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Magda Szarek:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Bergpob Viriyaroj:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Kati Miettunen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2026.117382.

Data availability

Codes are available at: https://github.com/energy-systems-team/codes-j.enbuild.2026.117382. Data sources are properly referenced in the manuscript. As the data used in our calculations is generated with commercial software (PV production), acquired via collaboration (electricity consumption) or acquired under a commercial licence (electricity spot price), we are unable to provide raw data.

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Glossary

BAPV: building-applied photovoltaics
BIPV: building-integrated photovoltaics
D: disabled
MPV: monofacial photovoltaics
PV: photovoltaics
REC: renewable energy community
U: unconstrained
ufn: until further notice
VBPV: vertical bifacial photovoltaics
B: trade balance [EUR or kWh]
C: cost [€], price [c/kWh]
E: energy [kWh]
LCOE: levelized cost of electricity [c/kWh]
NPV: net present value [€]
V: trade volume [EUR or kWh]
VAL: value [EUR]