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Year: 2026

Version: Accepted manuscript

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Please cite the original version:

Ylipaino, J., Kortetmäki, A., Kallioharju, K., Koskela, J., & Järventausta, P. (2026). Economic Optimization of PV System Orientation under Evolving Electricity Price Profiles in Nordic Detached Houses. In *2026 22nd International Conference on the European Energy Market (EEM)*, (pp. 1-6). IEEE.
<https://doi.org/10.1109/EEM68581.2026.11589695>

Economic Optimization of PV System Orientation under Evolving Electricity Price Profiles in Nordic Detached Houses

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Abstract— The rapid growth of photovoltaic (PV) systems has altered electricity market dynamics through increasing midday price depressions associated with the so-called “duck curve” phenomenon. Consequently, the economic performance of PV systems depends increasingly on the temporal alignment between production, consumption, and electricity prices. This study examines how evolving hourly electricity price profiles have influenced the economically optimal orientation of residential PV systems in Finnish detached houses. The analysis combines measured hourly electricity consumption data from 22 households with simulated PV production profiles derived from PVGIS data (2012–2023) and historical electricity prices from 2020 to 2025. PV production was simulated for system orientations ranging from 45° east to 45° west in 5° increments for four typical system sizes (3–12 kWp), and annual savings were calculated by combining hourly production, consumption, and spot price data. The results indicate a gradual eastward shift in the economically optimal orientation, particularly in 2025, reflecting increasing price differences between morning and midday hours, although the economic impact remains limited (below 0.3%).

Index Terms— photovoltaic systems, residential buildings, system orientation, self-consumption, techno-economic analysis, prosumers.

I. INTRODUCTION

The number of residential photovoltaic (PV) systems in Finland has grown rapidly in recent years due to declining investment costs and rising electricity costs. Although total installed solar PV capacity in Finland has continued to grow, the rate of new installations in detached houses has slowed in recent years [1]. However, as total installed PV capacity has increased, electricity market dynamics have begun to change. When a large share of electricity is generated by solar power, simultaneous midday production leads to oversupply and declining spot prices, resulting in the so-called “duck curve” phenomenon [2]. In addition to the rapid growth of solar power generation, electricity price formation in Finland is influenced by developments in interconnected European markets and cross-border renewable generation effects [3]–[5].

In addition to spot market price dynamics, a significant share of the economic value of building-applied PV systems arises from avoided distribution network charges and electricity taxes associated with self-consumed PV production [6], [7]. This development reduces the capture price of solar power generation relative to the average market price, thereby weakening the link between annual energy yield and economic profitability. The increasing share of solar power in the market causes the cannibalization phenomenon to intensify, as increasing production coincides with the same time [8]–[10].

In the Finnish price area (FI) of the Nord Pool market, this transition has become particularly visible during the past few years. Fig. 1 illustrates the evolution of average summer-day electricity price-profiles between 2020 and 2025. In 2020 and before, prices typically followed a relatively stable daily pattern, with lower prices during nighttime and early morning hours and higher prices in the afternoon and evening. In 2022, however, electricity prices increased sharply due to the European energy crisis, which is reflected in the significantly higher price level [11].

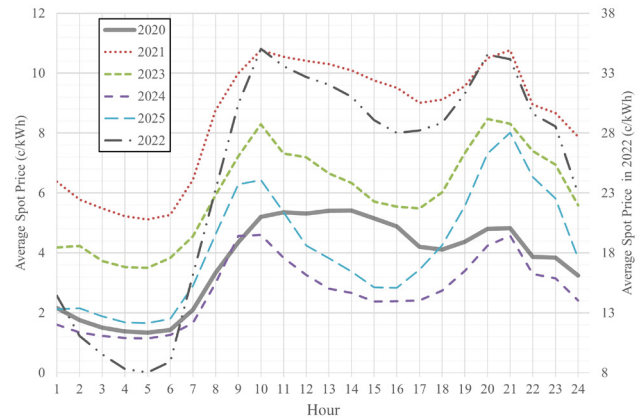


Figure 1. Average hourly electricity price profiles during summer months (June–August) in Finland for the period 2020–2025 [12]. The 2022 price profile is shown on the right-hand y-axis due to its significantly higher price level compared to other years.

In contrast, from 2021 onwards, price profiles have increasingly exhibited pronounced midday depressions, reflecting the growing influence of solar generation. This structural change alters the temporal value of solar power generation and creates new incentives for shifting generation away from midday hours or alternatively consumption to midday hours.

Recent Nordic studies have emphasized the importance of self-consumption and production profile shaping in maintaining the economic value of residential PV systems under changing market conditions. Jouttijärvi et al. demonstrated that, under Finnish conditions, PV system designs that modify the timing of production can influence economic performance, although profitability remains primarily driven by the amount of self-consumed electricity rather than total annual production [13]. Their subsequent analysis further demonstrated that increasing national PV capacity intensifies value cannibalization, while orientation-related mitigation measures provide only partial protection against declining market values [8]. Similarly, Sørensen et al. reported, based on monitored data from a Norwegian Plus-Energy school, that system orientation affects daily production patterns, but that cost savings are primarily driven by the alignment between PV production and building-specific demand profiles [14].

Beyond the Nordic context, Eeles et al. showed in the Iberian Electricity Market that increasing solar power generation can shift revenue-optimal orientations away from the energy optimum as midday prices depress (“duck curve”), highlighting the growing role of price-profile alignment in PV design [15]. While recent studies have examined PV orientation and self-consumption under various scenarios, relatively little empirical work has assessed how recent electricity price developments influence the economically optimal orientation of small-scale PV systems in Finnish detached houses.

This study addresses this gap by examining how evolving hourly electricity price profiles influence the economically optimal orientation of residential PV systems in Finland. The analysis combines measured hourly consumption data from detached houses with simulated PV production profiles and historical electricity prices from 2020 to 2025. Orientations ranging from -45° (east) to $+45^\circ$ (west) and four typical system sizes (3, 6, 9, and 12 kWp) are evaluated to quantify the economic significance of azimuth variation.

The main research questions of this study are:

- Has the evolution of electricity price profiles influenced the economically optimal orientation of residential PV systems in Finland?
- How large is the economic significance of orientation optimization in typical detached houses under recent market conditions?

II. METHODOLOGY

A. Study Households and Data

The study is based on hourly electricity consumption data from 22 detached houses located in the Pirkanmaa region in Finland. The buildings were constructed between 1952 and 2011. All properties were equipped with PV systems between 2022 and 2024, indicating that the homeowners had considered

the investment in solar electricity worthwhile. To avoid distortions caused by on-site electricity generation, only pre-installation electricity consumption data were used.

Electricity consumption data from the year 2021 were selected for all properties, as this year represents consumption behavior before PV systems were installed and allows the analysis to be carried out without interference from self-consumed solar electricity. After PV installation, smart meter measurements do not include internally used PV production, which would otherwise lead to underestimated electricity consumption and unrealistic consumption profiles.

Fig. 2 shows the average hourly electricity consumption profiles for the summer months (June–August) in 2021. For each property, hourly mean values were calculated over this period, resulting in representative 24-hour profiles. The figure includes both individual household profiles and their average.

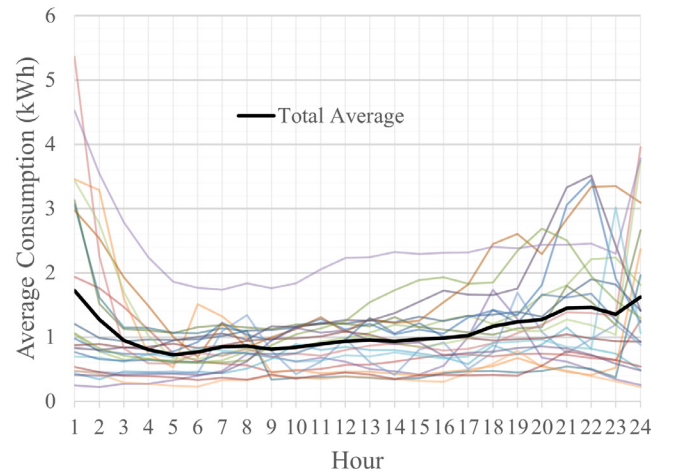


Figure 2. Average hourly electricity consumption profiles of the studied households during the summer months (June–August) in 2021.

Although electricity consumption differs between households, a broadly similar daily pattern can typically be observed. Demand is generally higher in the morning and evening hours, while lower consumption occurs around midday. In addition, some households exhibit night-time consumption peaks due to distribution system operator (DSO) time-of-use tariffs, which encourage the operation of controllable loads such as electric thermal storage heating or domestic hot water tanks during night-time periods with lower distribution charges.

B. PV Production Simulation

Photovoltaic electricity production was simulated using the PVGIS online tool provided by the European Commission [16]. Hourly production data were generated for a reference system with a nominal power of 1 kWp located in Tampere, Finland. The simulations were conducted using the PVGIS-SARAH3 solar radiation database and covered the years 2013 to 2023. Crystalline silicon modules with a fixed tilt angle of 18° and total system losses of 14% were assumed for the reference system.

To analyze the effect of system orientation, the azimuth angle was varied from -45° (east) to $+45^\circ$ (west) in 5° increments. For each orientation, an hourly production profile was obtained.

The resulting 1 kWp production data were then scaled linearly to represent system sizes of 3, 6, 9, and 12 kWp by multiplying the reference profile by the corresponding nominal capacity. These system sizes were selected to reflect typical residential PV installations.

To reduce the influence of interannual weather variability, hourly production values were averaged over the simulation period from 2013 to 2023. The average production profile was used in all subsequent calculations. This approach allows the analysis to focus on the impact of electricity price evolution and system orientation, while minimizing the effect of year-to-year fluctuations in solar irradiance.

C. Calculations

All calculations were performed at hourly resolution over the full year using the electricity consumption data from 2021 and the PV production profiles described earlier. For each household, system size, orientation, and electricity price year, the energy balance and economic performance were calculated on an hour-by-hour basis. The calculations are based on hourly spot prices and fixed electricity price components, including distribution tariffs, electricity tax, retail margin, and export margin, which are summarized in Table I.

TABLE I. ELECTRICITY PRICE COMPONENTS USED IN FINANCIAL CALCULATIONS

Price Description	Abbreviation	Value
Energy price ^a	p_{spot}	Day ahead
Volumetric price DSO (purchased) ^b	$p_{volumetric}$	2.93 c/kWh
Electricity tax ^b	T_e	2.253 c/kWh
Retail margin ^b	m_{retail}	0.363 c/kWh
Export volumetric margin ^b	m_{export}	0.363 c/kWh
Value added tax	VAT	25.5%

Note: All values are presented without VAT (0% VAT)
a. Time-dependent spot price from Nord Pool day-ahead market
b. Fixed price component (does not vary with time)

For each household, annual system values were calculated for all combinations of system size (3, 6, 9, and 12 kWp) and orientation (-45° to $+45^\circ$, in 5° increments). The optimization was performed only with respect to system orientation. For each household and electricity price year, the optimal configuration was determined separately for each system size.

The calculations are given by the following equations:

$$E_{sc}(t) = \min(E_{PV}(t), E_{load}(t)) \quad (1)$$

$$E_{surplus}(t) = \max(0, E_{PV}(t) - E_{load}(t)) \quad (2)$$

$$V_{sc} = \sum_{t=1}^a E_{sc}(t) \cdot (p_{spot}(t) + p_{volumetric} + T_e + m_{retail}) \cdot (1 + VAT) \quad (3)$$

$$V_{surplus} = \sum_{t=1}^a E_{surplus}(t) \cdot (p_{spot}(t) - m_{export}) \quad (4)$$

$$S_{annual} = V_{sc} + V_{surplus} \quad (5)$$

At each hour t , PV electricity was divided into self-consumed and surplus components based on simulated PV production and measured household electricity consumption. As shown in (1) and (2), self-consumed electricity (E_{sc}) corresponds to the minimum of production (E_{PV}) and load (E_{load}), while surplus electricity ($E_{surplus}$) represents production exceeding consumption. The monetary value of self-consumed

electricity was calculated as avoided electricity purchase costs, including the hourly spot price, distribution tariff, retail margin, electricity tax, and value added tax. Revenue from surplus electricity ($V_{surplus}$) was calculated using the hourly spot price reduced by the export margin, as shown in (4). After that the total annual system value was obtained by summing the values of self-consumed and exported electricity, as defined in (5).

III. RESULTS

A. Distribution of Optimal Orientations

As shown in Fig. 3, the optimal system orientations based on annual economic calculations for the period 2020–2025 are strongly concentrated in the range between -15° and 0° . Across all analyzed years and system sizes, the majority of optimal configurations are located within this interval, with a pronounced peak at -5° in most years.

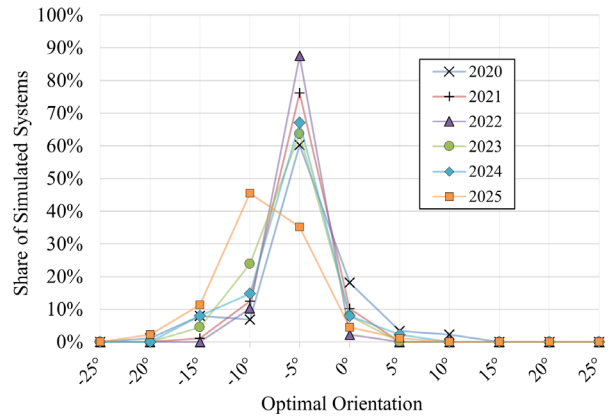


Figure 3. Share of optimal system orientations for all 22 households with four (4) simulated system sizes in 2020–2025. Negative orientation angles denote east-facing deviations from south, while positive angles denote west-facing deviations.

During the period 2020–2024, -5° represents the most frequent optimal orientation. In 2025, the distribution shifts further towards the east, with -10° becoming more frequent than -5° , indicating a continued eastward shift in optimal configurations. West-oriented systems occur only rarely as optimal solutions across the analyzed cases. Orientations above $+5^\circ$ account for only a small fraction of optimal cases across all years, as illustrated in Fig. 3. The observed distributions are consistent across different system sizes, indicating that the location of the optimal orientation is primarily influenced by temporal electricity price patterns rather than by installed capacity.

B. Annual Savings Relative to South-Oriented Systems

As shown in Fig. 4, the relationship between system orientation and annual savings remains stable across all analyzed years and system sizes, following a smooth, near-parabolic pattern with a clearly defined maximum. While the overall shape of the curves remains similar over time, the location of the maximum gradually shifts towards slightly east-oriented configurations in the later years of the study period.

Although the analysis considered orientations from -45° to $+45^\circ$, the extreme orientations are clearly not optimal based on the results. Therefore, a narrowed range from -15° to $+15^\circ$, differences in annual savings relative to the south-oriented (0°)

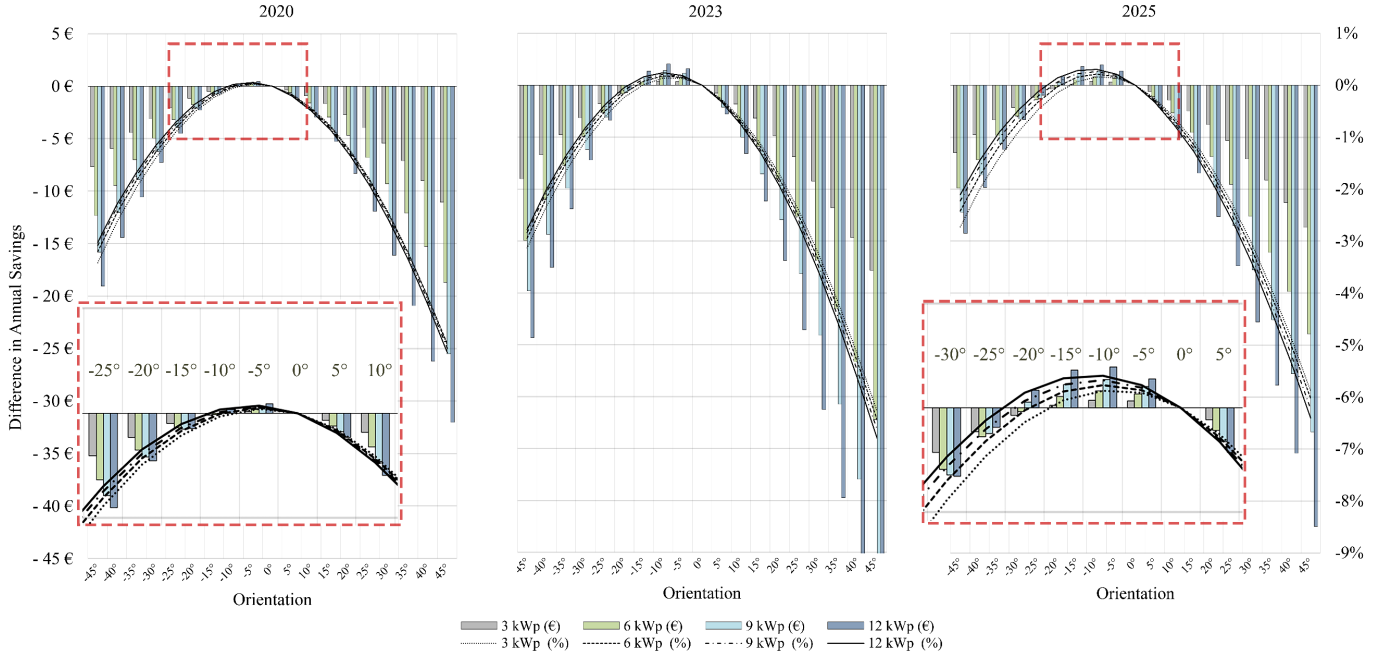


Figure 4. Average differences in annual savings relative to south-oriented (0°) systems for 2020–2025. Negative orientation angles denote east-facing deviations from south, while positive angles denote west-facing deviations.

systems are observed. Depending on the year and system size, the differences range from -22 € to $+2$ € per year, with corresponding relative changes of -1.3% to $+0.3\%$. When focusing on the optimal east-oriented range (-5° to -15°) in 2025, the annual savings advantage compared to a south-oriented system ranged from 0.12 € to 2 €, corresponding to relative differences of approximately 0.1% to 0.3% .

In 2022, characterized by elevated electricity prices, the absolute savings differences increase moderately compared to other years, while relative differences remain largely unchanged. Across all the years analyzed, deviations towards east-oriented configurations result in larger annual savings than comparable westward deviations. In addition, absolute savings differences scale approximately linearly with system size, while relative differences remain similar across capacities. When examining south-oriented and slightly east-oriented systems (-5° to -15°) across the four simulated system sizes, the relative differences in annual savings compared to the south-oriented configuration vary by at most 0.2 percentage points between system sizes.

IV. DISCUSSION

The results of this study indicate that the economically optimal orientation of small residential PV systems in Finland has gradually shifted towards slightly east-facing configurations during the period 2020–2025. This development reflects the increasing influence of midday price depressions associated with high solar generation. Although the resulting differences in annual savings remain modest in absolute terms, the systematic shift in the location of the economic optimum is a notable finding. Across all analyzed system sizes and study years, the optimal azimuth increasingly falls within the range from -5° to -15° (east), independent of system capacity. This indicates that changes in spot price structures alone—without modifications

in consumption or production profiles—can alter the economically preferred orientation.

The transformation towards east-facing configurations becomes particularly visible in 2025. Examination of the 2025 price profile in Fig. 1 shows that the slope of the midday price depression is steepest between 10:00 and 12:00. As the price difference between morning and midday hours increases, shifting PV production towards higher-priced morning periods becomes economically more attractive. Although duck-curve characteristics are observable in the price profiles of earlier years as well, the 2025 curve exhibits the most pronounced intraday gradient. In other words, electricity generated during late morning hours has gained relative value compared to production concentrated around midday.

An additional effect observed in 2025 is that eastward-oriented configurations yield relatively higher benefits for larger systems (Fig. 4). This can be explained by the increasing relative value of self-consumed electricity compared to exported surplus PV production. If other electricity price components—such as distribution fees and taxes—remain relatively stable while midday spot prices decline, the economic attractiveness of exported electricity decreases. Under such conditions, avoided purchase costs account for a larger share of total savings, increasing the importance of temporal alignment between generation and consumption. Among the four simulated system sizes, the 12 kWp system produces the highest surplus volumes and is therefore most exposed to low midday prices. Consequently, it both suffers more from depressed noon prices and benefits more from shifting production towards higher-priced morning hours. These findings are consistent with recent Nordic studies emphasizing the dominant role of self-consumption in determining the economic value of residential PV systems [8], [13], [14]. Compared with earlier research, the present work focuses specifically on detached houses operating under recent

Finnish electricity price conditions. While previous studies have demonstrated that alternative orientations and system configurations can enhance economic performance, the results presented here indicate that, in small-scale residential applications without significant load flexibility, the financial gains from orientation optimization remain modest in the short term. However, if current price dynamics persist or intensify over system lifetimes, the cumulative impact of orientation may become more relevant.

The analysis also shows that system size influences the absolute magnitude of orientation-related savings differences, while relative differences remain largely independent of installed capacity. Larger systems experience higher absolute gains and losses due to their increased production volumes, but the proportional effect of orientation remains comparable across capacities. This suggests that, under the studied market conditions and small-scale system-level, orientation-related optimization effects scale approximately linearly with system size.

From a practical perspective, traditional south-oriented installations have remained a reasonable default choice for residential PV systems in Finland during the studied period. While slight eastward deviations may improve economic performance under certain price conditions, these improvements are unlikely to be decisive for most investment decisions. Structural constraints such as roof geometry, shading, installation complexity, and construction costs are therefore typically more influential than minor differences in azimuth. Nevertheless, if the depth and steepness of the duck curve continue to increase in future electricity markets, the economic relevance of orientation may grow accordingly. For this reason, orientation should be considered already at the investment stage as part of a forward-looking and risk-aware system design strategy.

From a broader perspective, the results suggest a structural change in how value is created in the electricity market. As large-scale producers increasingly dominate midday generation, the economic value of peak solar production declines due to profit cannibalization in high renewable penetration markets [10]. Small residential PV systems without storage or significant load flexibility therefore derive a growing share of their economic value outside the hours of maximum production. In practice, this means accepting slightly lower peak output in exchange for better alignment with higher-priced morning or evening periods. Thus, economic optimization shifts from maximizing total energy yield toward improving the timing of production.

Several limitations should be considered when interpreting the results. PV production was simulated rather than measured, which may not fully capture site-specific characteristics such as shading, inverter clipping, or snow coverage. In addition, the analysis relies on electricity consumption data from 2021 and does not account for potential future changes in household demand patterns resulting from increased electrification, such as electric vehicles, heat pumps, energy storage systems, or active load shifting aligned with PV production (e.g., controlled hot water heating or EV charging). Consequently, the presented results primarily reflect current residential consumption behavior and market conditions. Because day-ahead electricity prices are

uniform nationwide in Finland, the economic signals affecting PV orientation are similar across regions. Nevertheless, the household sample is limited to the Pirkanmaa region, and regional differences in consumption patterns or building characteristics may influence the generalizability of the results.

Future research could extend this work by incorporating measured production data, dynamic load profiles, and alternative market scenarios. In particular, analyzing households with flexible loads and energy storage would provide further insight into how evolving residential energy systems may affect the economic relevance of PV system orientation and the relative role of orientation optimization compared with other approaches for shifting PV production in time. As electricity markets continue to evolve, such analyses will become increasingly important for supporting evidence-based system design.

V. CONCLUSION

This study examined how evolving hourly electricity price profiles have influenced the economically optimal orientation of residential PV systems in Finnish detached houses. Using hourly household consumption data from 22 households, simulated PV production profiles, and historical electricity prices from 2020–2025, the results show that recent electricity price developments have shifted the economically optimal orientation slightly eastward, while the overall economic significance of orientation optimization remains relatively modest under current Finnish market conditions. The main findings can be summarized as follows:

- The economically optimal orientation shifted gradually eastward during 2020–2025, reflecting the increasing influence of midday price depressions associated with rising solar penetration.
- During 2020–2024, the most frequent optimal orientation was approximately -5° (east), while in 2025 the optimum shifted further towards -10° (east).
- West-oriented configurations were rarely economically optimal under the market conditions studied.
- Although the annual financial differences between orientations remain relatively small in absolute terms, the shift in optimal azimuth demonstrates that recent electricity price developments systematically affect residential PV design choices.
- In 2025, the relative annual savings advantage from -5° to -15° east compared to a south-oriented system was approximately 0.1%–0.3%.
- The 2025 shift coincided with a stronger price drop from late morning to midday, increasing the relative value of electricity generated earlier in the day.

Overall, the results indicate that changes in hourly electricity price patterns are influencing the economically preferred PV orientation in the analyzed Finnish detached houses. While azimuth optimization alone does not fundamentally alter investment profitability under current conditions, it reflects broader structural changes in electricity markets that may become increasingly relevant if price differences between morning and midday hours continue to increase.

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