Evaluating the Emissions Reduction Potential of Solar PV in the Finnish Energy Systems

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Abstract— **This study evaluates the emission reduction potential of photovoltaic (PV) systems in Finland's low-carbon electricity grid, where solar production peaks during periods of low emissions. Hourly PV production simulations were conducted for various tilt angles and orientations using the PVGIS-SARAH3 dataset, and results were integrated with hourly emissions data from 2018 to 2023 for consumed energy in the Finnish energy system. The findings indicate that a 5° east orientation provided the highest emissions reduction, though differences from a strictly south-facing system were minimal. The most effective tilt angle among those studied was 45°, even though steeper angles produced more power during high-emission winter months. Over the studied years, the emission reduction potential has significantly declined due to recent changes in the energy system. As demand for electricity grows, future research should explore the most effective combination of renewable energy sources to efficiently meet increasing energy needs.**

Index Terms-- **Emission reduction, Nordic energy systems, photovoltaic systems, solar energy, system optimization**

I. Introduction

The European Union (EU) has established an ambitious framework for the large-scale deployment of photovoltaic (PV) systems as part of the REPowerEU plan, in alignment with the EU Solar Energy Strategy [1]. This initiative promotes the integration of PV systems in public, commercial, and new residential buildings to accelerate solar adoption in the building energy sector. From a building perspective, relevant adoptions are implemented through the Energy Performance of Buildings Directive (EPBD), which also introduces lifecycle global warming potential (GWP) calculations for the new buildings—mandatory from 2028 or 2030, depending on building size [2]. However, in Finland, climate impact assessment for buildings will be incorporated into the country's building regulations as early as 2025 [3], [4].

As part of this transition, assessing the carbon reduction potential of solar PV systems within different national contexts becomes essential, as each country's energy system has distinct region-specific characteristics. In Finland, electricity generation is already largely decarbonized, with nuclear and renewable energy sources accounting for 94% of electricity production in 2023 [5]. As a result, emissions remain relatively low, even during winter months when electric heating demand peaks. While Finland's energy system is among the cleanest in Europe, the potential for PV systems to further reduce emissions is constrained by the temporal mismatch between solar generation and high-emission periods. PV production peaks in summer, when electricity demand and emissions are at their lowest, limiting its effectiveness in displacing high-carbon electricity.

At the same time, PV systems—like all power plants—are not entirely emissions-free over their lifecycle. However, studies indicate that advancements in manufacturing, installation, and recycling can significantly reduce their overall greenhouse gas (GHG) emissions [6]-[10]. Additionally, installation location plays a crucial role in emission reduction potential. Kawajiri (2012) found that optimally located PV systems can reduce CO_2 emissions nearly tenfold compared to those placed in countries with the largest current market share [11]. Meanwhile, the ongoing electrification of various sectors—including hydrogen production [12], transportation [13], data centers [14], steel manufacturing [15], [16], and district heating[17]—will require substantial increases in renewable energy production in Finland [18], [19].

Numerous studies have examined the carbon footprint of PV systems, typically comparing emissions to the amount of electricity produced (gCO_2/kWh). A review by Silva et al. covering 45 studies from 2002 to 2017 found PV emissions ranging from 12.5 to 126 gCO_2/kWh, with a mean of 50.9 gCO_2/kWh [20]. This value approaches that of onshore wind power, which has a mean of 14.4 gCO_2/kWh, and is significantly lower than coal (948.9 gCO_2/kWh) and natural gas (446.1 gCO_2/kWh) [20]. Similarly, Tawalbeh et al. (2021) reported a range of 14–73 gCO_2/kWh [6]. More recently, the IEA (2023) estimated that a 3 kWp roof-mounted PV system in Europe emits 35.8 gCO_2 eq/kWh with mono-silicon panels and 43.6 gCO_2 eq/kWh with multi-silicon panels, reflecting a 17% reduction in mono-silicon emissions over two years [21].

Since annual PV production varies by region, comparing total lifecycle emissions of installed PV systems using energy-based values can be challenging across different studies. When evaluating PV lifecycle emissions, it is more meaningful to compare emissions relative to system capacity in kW—provided that the study's assumed annual production is known. The IEA Fact Sheet reports annual emissions of 34.9 $kgCO_2/kW/year$ for total systems with mono-Silicon panels and 42.6 $kgCO_2/kW/year$ for those with multi-Silicon panels [21]. A 2015 study from the UK and Spain, using German-manufactured products, calculated emissions for installed systems at 42.8 $kgCO_2/kW/year$ for mono-Silicon and 37.4 $kgCO_2/kW/year$ for multi-Silicon panels [22]. A Swedish study identified the most optimal scale for minimizing CO_2 emissions as a 1 MW system, with median emissions of just 12 $kgCO_2/kW/year$ [23].

This study expands on previous research by examining the emission reduction potential of PV systems within Finland's current energy system. Additionally, it examines how panel orientation influences emission reductions, challenging the assumption that south-facing panels are always the most effective at minimizing carbon emissions.

By integrating hourly PV production data for various orientations with Finland's electricity emissions data from 2018 to 2023, this study aims to quantify the contribution of PV systems to reducing carbon emissions in the existing energy system. Specifically, it analyzes the impact of panel orientation and tilt angle on emission reductions, providing insights into how PV systems can maximize their environmental benefits in Finland.

II. METHODOLOGY

A. PV Simulations

To evaluate the emission reduction potential of PV systems across various orientations, hourly production simulations were conducted using the EU Science Hub's PVGIS platform, utilizing data from the latest PVGIS-SARAH3 database [24]. The study focused on the Pirkanmaa region in Finland, where a 1 kWp PV system was modeled as a reference. The simulations assumed an overall system efficiency loss of 14%, as preselected in PVGIS, with Crystalline Silicon panels being used for the analysis.

Given the objective of this study to examine the impact of panel orientation on emission reductions, production simulations were performed under different orientations and tilt angles. Orientations were selected at 5-degree intervals across the east-west axis, while the tilt angles were varied between 15° and 90° in 15-degree increments. This approach allowed for a comprehensive analysis of how different panel configurations affect the emission reduction potential of PV systems in Finland's unique energy system context.

B. Emission data

This study adopts the perspective that the emission reduction potential of PV systems is evaluated by considering the electricity consumption displaced by the self-generated solar power. The emission reduction effect is then determined by the total emissions associated with the electricity consumed from the grid at that moment.

The transmission system operator (TSO) in Finland, Fingrid, maintains an open data database that provides emissions data for electricity consumed in Finland, with emissions reported in three-minute intervals [25]. This data accounts for the emissions from Finland's domestic electricity production, as well as the impacts of imported and exported electricity.

The emissions associated with consumed electricity in Finland are calculated as:

$$E_c = \frac{E_d + E_i - E_e}{C_d + C_i - C_e} \qquad (1)$$

where E_c represents the emissions of consumed electricity, C_d is the domestic electricity capacity, C_i is the imported electricity capacity, and C_e is the exported electricity capacity. The emissions from domestic production, imported electricity, and exported electricity are represented by E_d, E_i, and E_e, respectively.

This calculation is based on predefined emission factors for each production source. However, it is important to note that this methodology only accounts for emissions from electricity production and does not consider the lifecycle greenhouse gas emissions of power plants and infrastructure or other environmental impacts. Furthermore, the calculation does not include the effects of the EU Emissions Trading System (ETS) or guarantees of origin. The emission factors for combined heat and power (CHP) production are estimated based on Statistics Finland's energy production statistics [26]. In CHP plants, the emissions from separate production are included in the combined emission factors based on the energy share of the different production methods.

The emission factors for electricity imports are defined on a country-specific basis, based on historical production data. These factors are updated annually following International Energy Agency (IEA) guidelines for countries such as Sweden, Norway, and Estonia. Finland's current electricity production mix primarily includes nuclear (39%), wind (25%), hydro (18%), and biomass (12%), supplemented by minor fossil-based production [27]. Table 1 presents the updated emission factors for various production methods as of March 29, 2023.

TABLE I. EMISSION FACTORS FOR FINLAND'S ELECTRICITY PRODUCTION AS OF MARCH 29, 2023 (gCO_2/kWh) [25], [26].

Hydro/Nuclear/Wind/ Solar Power	*District heating CHP*	*Industrial CHP*	*Other production, small[1]*	*Other production, large[2]*
0	279	144	75	902

[1]*Emission factor for separate generation under 150 MW*
[2]*Emission factor for separate generation over 150 MW*

C. Calculations

In the initial analysis, we investigated the characteristics of emissions and photovoltaic (PV) production in Finland throughout different times of the year and day, utilizing 3-minute emissions data for consumed electricity in Finland from 2018 to 2024, which was then averaged to obtain 1-hour emission values. This emissions data was integrated with hourly PV production data from various system configurations spanning 2018 to 2023, as data for 2024 was not yet available. The first step involved summing the monthly emissions data to observe how emissions varied across different months over the past seven years. Subsequently, we performed a similar monthly analysis of the production of a 1 kW south-facing PV system with tilt angles of 15°, 45°, and 75° for the same time period. This allowed us to compare how PV production and emissions from existing electricity generation align at the monthly level.

In the next step, we categorized the data into summer months (May to September) and winter months (November to February) to evaluate the seasonal variations in both production and emissions. For this analysis, we calculated average hourly emissions and PV production for each hour of the day. PV production was simulated using a fixed tilt angle of 45°, which was chosen as the most optimal slope for production in the studied region, with orientations at 45° east, south, and 45° west. This comparison enabled an analysis of how emissions and production vary throughout the day and across seasons.

Finally, we expanded the analysis to include hourly PV production data from 2018 to 2023, considering orientations in 5° increments from east to west and tilt angles in 15° steps from 15° to 90°. This hourly production data was combined with averaged hourly emissions data, matched to the corresponding hours over the same period. For each combination of orientation, tilt angle, and year, the hourly emission reduction was calculated as:

$$E_R(\mathrm{t}) = P_{PV}(t) \times E_C(t) \ (2)$$

where E_R represents the reduced emissions at time t, P_{PV} is the energy produced by the 1 kWp PV system with the selected orientation and tilt angle, and E_c is the emissions of consumed electricity, as presented in (1). Finally, the total reduced emissions were summed for each year, and different setups were compared to evaluate the potential for emission reduction based on various orientations and tilt angles.

III. RESULTS

Fig. 1 presents the monthly and yearly average emissions per kWh of consumed energy in Finland from 2018 to 2024, based on the 3-minute resolution data used in this study. The bars on the far left of each month represent data from 2018, while those on the far right correspond to 2024. The lower section of the figure shows the average monthly production of a simulated 1 kW south-facing PV system with three different slopes, using data averaged from 2018 to 2023.

The yearly average emissions decreased significantly from 118.8 gCO_2/kWh in 2018 to 30.6 gCO_2/kWh in 2024, mainly due to Finland's disconnection from the Russian grid in 2022, the full integration of Finland's fifth nuclear power plant in 2023, and increased renewable production, particularly from wind power. Additionally, monthly emissions during winter can be more than double those observed in summer.

When comparing these emission bars with the production bars at the bottom of the Fig. 1, it becomes clear that production

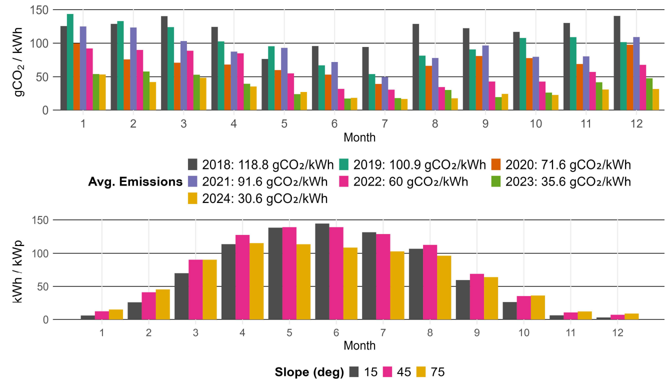

Figure 1. Monthly and yearly average emission values of consumed energy in Finland, alongside the monthly average production of a 1 kWp south-oriented PV system.

is minimal during the coldest winter months compared to the summer months. However, when comparing monthly production for different slopes, it is evident that the 75-degree slope generates more power during the winter months, from October to February. Although the total yearly production with this 75-degree slope is only 88.3% of that of the 45-degree slope, the 75-degree configuration performs better during the periods of high emissions. This observation provides a valuable basis for identifying the slope with the highest emission reduction potential in this study.

In Fig. 2, we compare the daily profiles of emissions and PV production over the summer and winter seasons. The emission graphs are shown at the top, presenting the average emissions per kWh for each hour from 2018 to 2024. The higher blue line represents emissions during the winter months, while the lower yellow line shows emissions during the summer months.

At the bottom of the figure, the hourly average production of a 1 kW PV system with a fixed 45° tilt is compared across three different orientations. The red line, which shows peak production during the morning hours, corresponds to a 45° east orientation, while the blue line, with peak production in the evening, corresponds to a 45° west orientation. The middle green line represents a south-facing orientation. Solid lines indicate average production during the summer months, while the dashed line represents production during the winter months.

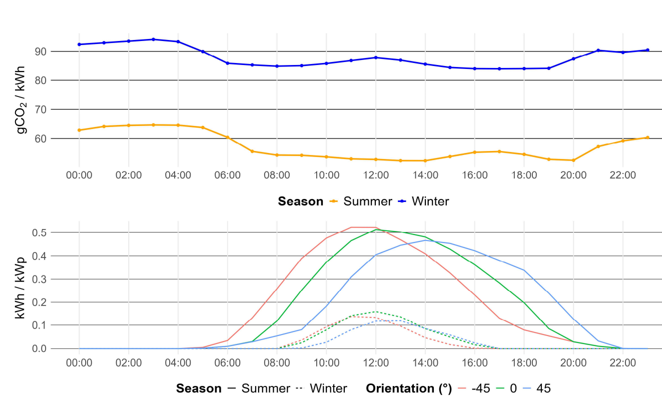

Figure 2. Average hourly emissions of consumed energy (gCO_2/kWh) and PV production per kWp, categorized by season.

From this figure, we observe that emissions are slightly higher during nighttime hours compared to daytime hours. While this represents an average across multiple years, a more detailed yearly analysis reveals that since 2022, peak emissions intensity (gCO_2/kWh) has slightly shifted from nighttime towards daytime hours. In 2023, average emissions during daytime hours ranged from 20.7–23.0 gCO_2/kWh on summer days and 48.3–51.9 gCO_2/kWh on winter days. When comparing the production graphs with the emissions data, it is evident that the peak production times are opposite to the periods of highest emissions, since PV production in Finland highly peaks during summertime. Once again, slightly east- or west-oriented PV systems may better align their production with higher emissions. Therefore, it is important to examine which orientation results in the greatest emission reduction potential.

The primary objective of this study was to identify the optimal orientation for emission reduction and quantify the total reduction potential of a 1 kW PV system. To achieve this, we first analyzed the total emission reduction over the study period for each slope and orientation setup, using 15-degree increments, to determine the most effective tilt angle. The results indicated that a 45° slope provided the highest emission reductions for orientations between 60° east and 60° west. However, the differences compared to the 30° and 60° slopes were minimal, with reductions being only 1.8% to 3.4% lower for south-oriented systems. Based on these findings, the 45° slope was selected for further analysis in the next phase of the study.

Fig. 3 presents the yearly reduced emissions for a 45° slope with orientations in 5-degree increments. The results highlight the most optimal orientations, ranging from 15° east to 15° west, and illustrate how the reduction potential varies throughout the year. This analysis assumes no demand response or energy storage systems to shift the utilization of PV production. The figure shows that in 2023, the 5° east orientation achieved the highest total reduction potential at 28.4 $kgCO_2/kWp$, consistently ranking as the most effective across all studied years. These results provide a clear numerical estimate of the emission reduction capacity of the PV system, based on 2023 emission data for consumed energy. In particular, they highlight variations over the studied period and across different orientations.

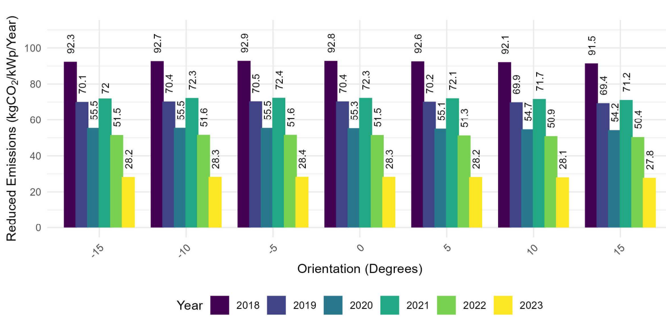

Figure 3. Total reduced emissions by PV system orientation with a 45-degree slope.

Fig. 4 illustrates how emissions reduction potential varies across different orientations compared to a south-oriented PV system with a 45° slope. The results are presented in 5-degree orientation increments, covering directions from 90° east to 90° west, and include a comparison across all studied years. Additionally, it includes a black line representing the average value for each orientation, providing insight into the most optimal orientation over multiple years and highlighting the relative differences between orientations.

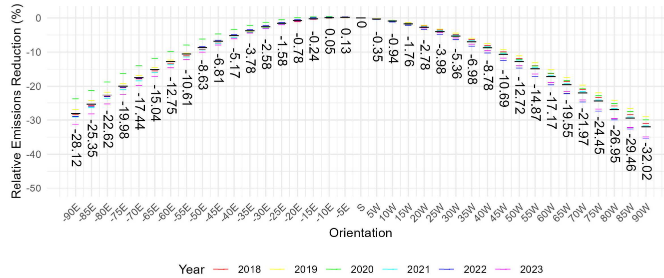

Figure 4. Relative reduced emissions by orientation as a percentage of the south-facing configuration, with a 45-degree slope.

The results in Fig. 4 indicate that the 5° and 10° east orientations provided a slightly higher emission reduction potential compared to the south-facing configuration, with the 5° orientation being the most optimal. However, these differences—0.13% for the 5° east and 0.05% for the 10° east orientations—are minor. Similar trends were observed across different tilt angles: the 5° east orientation yielded the highest emission reductions for slopes ranging from 15° to 60°, whereas for 75° and 90° slopes, the 10° east orientation performed slightly better.

IV. Discussion

This study examined the impact of tilt angle and orientation on the emission reduction potential of PV systems in Finland's already largely decarbonized energy system. The findings indicate that east-facing panels provide a slight advantage over west-facing ones, but precise tilt and orientation adjustments have only a minor effect on emissions reductions.

With 94% of Finland's electricity being fossil-free in 2023, PV's role in offsetting emissions differs from regions with higher-carbon energy systems. The effectiveness of PV in reducing emissions depends on whether its generation aligns with high-emission periods and displaces fossil-based electricity. In Finland, PV production peaks during summer, when grid emissions are lowest, limiting its impact compared to regions with higher fossil-based electricity year-round. A similar effect was observed by Kawajiri et al. when comparing emissions reduction potential across countries with low-carbon electricity production [11].

In 2023, the emission reduction potential of new PV installations, when replacing existing operational emissions, was 28.4 $kgCO_2/kWp$ per year. However, this analysis compares PV lifecycle emissions with operational emissions of existing plants, thus omitting their lifecycle emissions. Given Finland's current electricity system—dominated by nuclear, wind, hydro, and biomass-based CHP—these comparisons must be interpreted cautiously. Furthermore, the use of hourly average emission factors may underestimate actual marginal emissions reductions when PV production replaces fossil-based electricity. Future research should incorporate marginal emission factors and comprehensive lifecycle assessments to more accurately quantify PV's true emissions reduction potential.

These findings raise critical questions for policymakers regarding the prioritization of PV in low-emission power systems, particularly when solar generation does not align with periods of high demand and high emissions. While PV remains essential for expanding renewable capacity, its emissions reduction benefits in Finland may be more limited compared to regions with a more carbon-intensive electricity mix.

Several limitations should be acknowledged. First, this study did not model dynamic grid interactions and instead assumed that PV offsets grid electricity based on hourly average emissions data. Additionally, using marginal emissions factors, which assess the actual displaced generation at any given time, could provide a more accurate estimate of PV's emissions reduction potential.

Second, this study focused solely on replacing existing production and did not evaluate PV's potential role in future energy expansion. As Finland's electricity demand is expected to rise significantly, driven by electrification, hydrogen production, and data centers, further research is needed to identify cost-effective, low-carbon, and grid-stabilizing energy production solutions.

As recent regulations encourage residential PV adoption and mandate climate impact assessments for buildings, it is essential to consider other emission impacts in the overall evaluation. For example, terrain modifications such as tree removal to maximize PV production could reduce carbon sinks and increase building cooling demands due to decreased shading, potentially offsetting some of the emissions reductions from PV systems.

Furthermore, energy storage was not considered, despite its potential to shift PV generation to higher-emission periods and enhance emissions reductions. However, given the relatively stable daily emissions profile in recent years, particularly in summer, the need for such a shift at the daily level remains minimal. Future studies could explore the role of seasonal storage in optimizing emissions reductions.

V. CONCLUSION

This study examined the optimal PV tilt angle and orientation for maximizing emissions reduction within Finland's existing energy system. Given Finland's high share of carbon-free electricity and the seasonal mismatch between solar production and high-emission periods, the findings provide insights into the role of PV in the Finnish energy system by integrating hourly PV production data with hourly average emissions data from electricity consumption in Finland.

Across the studied period (2018–2023), the most effective tilt angle in 15-degree increments was 45°, despite higher-tilt panels generating more power during high-emission winter months. However, differences between the 30°, 45°, and 60° slopes were minimal, with annual emissions reductions for south-facing systems only 1.8% to 3.4% lower than the most optimal setup.

When analyzing all tilt and orientation configurations, the 5° east orientation provided the highest emissions reduction potential for slopes ranging from 15° to 60°, while for 75° and 90° slopes, the optimal orientation shifted to 10° east. However, these differences remained marginal, with no more than a 0.43% improvement over a strictly south-facing system. East-oriented systems consistently outperformed west-oriented setups, but precise orientation adjustments yielded only minor benefits in Finland's energy context.

With the most optimized setup, the emissions reduction potential in 2023 for the existing energy system in Finland was only 28.4 $kgCO_2/kWp$ per year. This potential value decreased significantly from 92.9 $kgCO_2/kWp$ in 2018, presenting a great change in emissions in Finland's energy system.

This study provides valuable insights for policymakers, energy planners, and PV stakeholders, guiding decision-making toward the most environmentally beneficial PV installations. The findings also support previous studies indicating that photovoltaics achieve greater emissions reduction in regions with more carbon-intensive electricity generation, higher solar production rates, and better alignment with peak energy demand.

Since this study focused only on PV replacing existing production, future research should explore the most effective long-term strategies for expanding Finland's renewable electricity portfolio to meet increasing electricity demand. Such studies should integrate lifecycle GWP assessments of various energy sources to determine the most cost-effective and emission-efficient energy mix, alongside demand response and storage solutions to balance seasonal variations.

Looking ahead, PV system optimization research should extend beyond technical orientation and tilt angle adjustments by incorporating building-specific consumption profiles, energy market price fluctuations, and emission intensity dynamics. Additionally, this study highlights the potential of leveraging open emissions data to analyze seasonal and daily emission trends, as well as conducting similar assessments for other residential energy investments to maximize emissions reductions.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Promotion Centre for Electrical Engineering and Energy Efficiency (STEK ry). Their support was essential to the successful completion of this study.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used ChatGPT-4o to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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