Evaluating the Self Balancing Potential of Rooftop Photovoltaic Systems and its Impact on the Net Demand Profile

Nida Riaz
Tampere University
Tampere, Finland
nida.riaz@tuni.fi

Sami Repo
Tampere University
Tampere, Finland
sami.repo@tuni.fi

Anders Lindfors
Finnish Meteorological Institute
Helsinki, Finland
anders.lindfors@fmi.fi

***Abstract*—This paper investigates the self-balancing potential of rooftop PV systems in Finland, focusing on the features of net demand in Finland for the electricity network scenario of the year 2045. Net demand is calculated as the difference between total consumption and renewable generation. Four comparative cases were analyzed related to PV panel orientations which includes south-facing panels, southeast and southwest facing panels, east and west facing panels, and PV panels oriented according to the actual rooftop orientations. The study demonstrates that alternative orientations, such as east-west and rooftop orientation, offer improved balancing of the net demand profile compared to conventional south-facing PV systems. PV systems facing east west orientation or actual rooftop orientations reduce the average mid-day overgeneration by 38 % and 44 % respectively as compared to south facing PV systems thus minimizing the need for balancing. Moreover, the evening ramp rates were reduced by 53 % and 61 % for rooftop PV systems and east west facing PV systems respectively, when compared with south facing PV systems. The paper also analyses the interactions between PV and other non-dispatchable generation resources, such as wind power, as they impact the net demand profile and require holistic assessment for balancing measures. The paper finally concludes that rooftop PV orientations and east west PV panel orientations aid in shifting the generation towards the demand interval.**

Keywords*—*Net demand, photovoltaic generation, balancing, ramps, overgeneration.

I. Introduction

The large-scale integration of renewables has been motivated by the need to reduce carbon emissions and dependence on fossil fuels. Finland, for instance, estimates that its generation capacity of photovoltaics (PV) and wind power plants will increase to 16 GW and 14 GW, respectively, by the year 2045 [1]. This future scenario estimates that combined heat and power plants (CHP) and outdated nuclear power plants will be phased out, which would reduce system inertia. As a result of declining PV system costs, increasing flexibility requirements, market opportunities for prosumers, and self-sufficiency, rooftop PV plants are expected to be integrated on a large scale in the future [2]. Consequently, the growing prevalence of behind-the-meter rooftop PV is lowering the net electricity demand (ND) or net load, which is the difference between the total consumption/load and the renewable generation [1]. However, this reduction in the net demand for high PV penetration has caused concerns in some countries. For instance, some countries have experienced extremely low mid-day demand during peak solar irradiance in low loading situations, high ramp rates, overgeneration, negative electricity prices, flexibility service requirements, and system instability [2], [3]. The surplus solar power generated by PV systems can create imbalances in the power system, resulting in renewable energy curtailment or requiring other energy sources to adjust their output to maintain grid stability. Additionally, sudden changes in PV power output due to cloud movements can lead to voltage and frequency fluctuations, posing challenges to power grid stability [2].

The California Independent System Operator (CAISO) has raised concerns regarding the overgeneration of PV output by introducing the term "duck curve", which is a graph that displays the disparity between the electricity demand and supply under high PV penetration, over the course of a day. During periods of high solar energy production, such as midday, the demand for electricity is relatively low, leading to a steep decline in the net demand on the grid. However, as the sun sets and solar energy production decreases, the demand for electricity increases rapidly, resulting in a steep increase in the net demand on the grid which necessitates the activation of ramping reserves within a short period of time, thereby increasing the need for fast-acting synchronous reserves [2], [3]. Similar trends of overproduction have also been observed in other countries with high shares of PV and wind in the generation mix, such as Australia, Germany, and Denmark [4], [5]. Higher mid-day production of electricity not only create a steep downward ramp of net load but it may also result in negative net load, which calls for curtailment of PV power and impacts the electricity market mechanism with extremely low prices as reported in [4].

The academia and researchers are proposing different solutions to enhance grid flexibility and reducing renewable generation curtailment such as the authors in [3] find distributed PV systems with storage as a solution to accommodate increased levels of PV. Whereas, the authors in [5] propose a methodology for the optimal placement and sizing of battery energy storage systems (BESS) in a distribution system, with the aim of mitigating the duck curve effects of PV integration. Moreover, a study in [2] mentions that PV generators coupled with BESS of 5000 MW, 19411 MWh can help in modifying the daily load profile such that the ramp rate is reduced to almost 50% and the peak load is reduced from 22580 MW to 18747 MW. However, the integration of storage systems and batteries can add significant upfront costs to the installation of residential rooftop PV systems and most of the rooftop PV owners optimize the batteries for increasing self-consumption, energy management and cost minimization. Another study in [6] has suggested an approach of substituting thermal power stations with fast regulating units of Concentrated Solar Power (CSP) coupled with thermal storage systems such that the CSP station can store the solar thermal energy during the midday and can generate electricity during the sunset hours to supply the power shortage of duck curve using its faster ramp rate. Such an idea seems viable for utility scale projects due to cost and space constraints. A study made in three different regions of the United States including Ontario, British Columbia, and

Texas in [7] presents improvements in morning and evening ramps of the net load in one of the simulation models by using east west PV panels' orientation with maximum possible tilts. The idea of modifying PV panel's orientation may mitigate the issue from its origin, but residential roof top PV systems have a limitation of fixed roof pitch and orientation. Moreover, some residential or industrial PV owners have motivation to orient PV panels in order to maximize their self-consumption as presented in [8], [9].

Since the orientation of roof top PV panels have a limitation of available roof pitch and roof azimuth, therefore the novelty of this paper exists in bridging the gap between the recommended east west orientation of PV panels vs available roof top orientations. The analysis builds a realistic scenario of rooftop PV by deriving roof orientations from two municipal areas of the city of Tampere using ArcGIS software. The study focuses on the self-balancing potential of actual orientations of rooftop photovoltaic (PV) systems by calculating the net power curtailment, ramp rates, morning and evening ramps of the net load profile of Finland in the year 2045. The projected penetration of PV and wind generation in the Finnish energy landscape is expected to reach 12.4% and 49.5% respectively by the year 2045 [1]. Moreover, a comparative analysis of the conventionally oriented PV systems towards south, optimally oriented PV systems towards east west directions and realistically oriented PV systems according to the rooftop orientations is made to analyze the net load profile under high penetration of PV generation. Since, both PV and wind generations are stochastic and may result in a different net load profile when correlated and when uncorrelated. Thus, in order to holistically assess the need of balancing and ramping measures, two scenarios of daily net load profiles are discussed when both PV and wind generation are correlated and when both are uncorrelated. Further, the discussion part of the paper addresses the possibility of exporting the excess generation to reduce curtailment which is dependent of available interconnection capacity with the neighboring countries power systems.

II. RESEARCH METHODS

A. Research Data

Historic market data for the year 2018, obtained from the Open Data platform of the Finnish transmission system operator, Fingrid, was used in this research study. The data includes hourly resolution and encompasses total hourly production data from different types of production units in Finland, as well as import, export, and total electricity consumption [10]. The choice of the 2018 dataset is based on the availability of estimates provided by Fingrid in their report [1], which compares the values for each type of generation and consumption of the year 2018 to those projected for the year 2045. According to the high PV penetration case outlined in [1], solar power and wind power are estimated to generate 13 TWh and 52 TWh of electricity annually, respectively, while nuclear power is expected to decrease to 1.9 TWh. There are no anticipated changes in hydro power capacity, but CHP plants are estimated to be decommissioned. Due to increased electrification and industrialization, total electricity consumption is expected to reach 125 TWh. To simulate the year 2045 scenario, the market data from the year 2018 has been scaled accordingly.

Since the share of electricity generation from PV was approximately zero in the year 2018, therefore, the estimated generation from PV systems for the year 2045 for different orientations has been derived using solar irradiance data. Numerical weather prediction (NWP) data, including global and direct surface solar radiation, wind speed and direction, pressure, and temperature at hourly resolution, was collected from the Finnish Meteorological Institute (FMI) from nine locations in Finland. This data is commonly employed by PV producers to forecast day ahead PV production and participate in the day ahead market Additional information regarding the data can be found in [11], [12]. The calculation of PV generation for various case studies using the NWP data is described in Section B. To estimate the percentage share of rooftop PV in each region of Finland, it is assumed to be proportional to the percentage of the total population residing in that area, as obtained from [13].

B. Extracting Rooftop Orientations and Generating PV Cases for Different Orientations

The idea of reducing the overgeneration of electricity during the mid-day and alleviating steep morning and evening ramps, resides in shifting the PV generation towards the intervals of high electricity demand. Therefore, to assess the generation shifting impact of spatially and geographically distributed PV systems, four cases based on PV panels' orientations are studied which are as follows,

- Case S: All panels are orienting towards south azimuth with tilt angle = 45˚. This is the base case.
- Case SESW: PV panels are equally oriented towards southeast (SE) and southwest (SW) azimuths with tilt angle = 45˚.
- Case EW: PV panels are equally oriented towards east (E) and west (W) azimuths with tilt angle = 45˚.
- Case Rooftop: PV panels are oriented towards the actual rooftop orientations.

In order to construct a realistic case of available rooftop orientations in Finland, this paper has selected two areas of the city of Tampere for extracting actual distribution of rooftop orientations, utilizing ArcGIS geospatial software. The detailed method of extracting rooftop orientations with the assistance of ArcGIS software is available at [14]. The maps of the areas under study were extracted from OpenStreetMap [15]. Fig. 1 presents the distribution of available generation capacity of rooftop PV panels oriented in different directions based on the roof pitch (= panel tilt) and roof azimuth (= panel azimuth). Moreover, the PV panels on the flat roof type were assumed to be oriented towards eastern and western azimuths instead of southern azimuth for this specific case. The size of each rooftop PV system has been estimated based on the size of the roof. The rated capacity, P_{rated} of each rooftop is given by (1).

$$P_{rated} = 60\% \times \frac{\text{Area of the rooftop}}{\text{Area of one PV panel}} \times P_{MPP} \quad (1)$$

where, P_{MPP} is the maximum power output of one PV panel i.e., 190 W under standard test conditions with an area of 2.16 m2 as given in [16]. Total generation capacity of selected areas is 95 MW respectively. In order to compute the power output of the PV systems at hourly resolution for the whole year, NWP data from nine locations has been utilized to

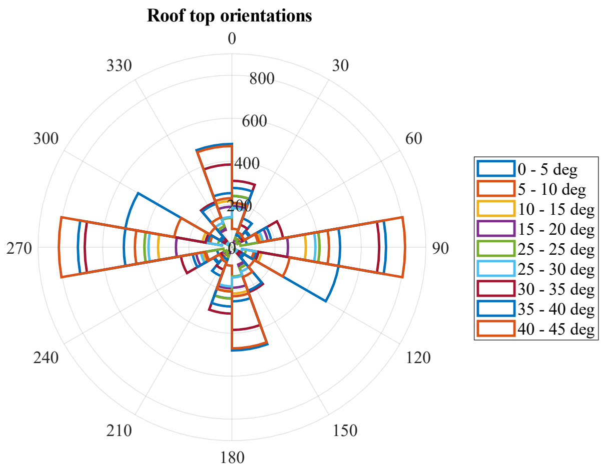

Fig. 1. Distribution of orientation of rooftop PV panels. The colour bar show the panel tilts and circular disc show the azimuth

compute global, direct, and diffused irradiance incident on inclined PV panels having different orientations (azimuth angles and tilt angles), by utilizing the trigonometric and algebraic equations given in [17]. Derived irradiance data along with temperature and PV module specifications are then fed to an experimentally verified MATLAB Simulink model of a PV module based on the one-diode model of a PV cell to obtain PV output power [18]. The aggregated power output of the ensemble of each case is normalized and scaled to the percentage share of each of the nine considered regions from 16 GW, which is the estimated installed capacity of PV in Finland for the year 2045. The total power $P_{\text{total}}(t)$ at an instant t for N number of aggregated PV systems at a location, *loc* can be calculated using (2).

$$P_{\text{total}}(t) = \sum_{loc=1}^{9} \frac{\sum_{n=1}^{N} P_{\text{PV}}^{n}(t)}{\sum_{n=1}^{N} P_{\text{rat}}^{n}} \times C_{loc} \tag{2}$$

where, P_{rat}^{n} is the rated power of the nth PV plant and $N \geq 1$ and C_{loc} is the percentage share of the installed generation capacity at each measurement location.

C. Analytical Indices

Four analytical attributes are considered to assess the impact of rooftop PV system orientations, spatial distribution, and geographical distribution. These attributes offer valuable insights into the dynamics of the demand profile: net electricity demand, electricity overgeneration, and morning and evening ramps of the net demand profile. The net demand $D_{net}(t)$ at any instant t can be calculated using (3).

$$D_{net}(t) = D_t(t) - G_{ren}(t) \tag{3}$$

where, $D_t(t)$ is the total demand and $G_{ren}(t)$ is the total renewable generation. Since the idea is to explore the impact of PV generation on the net demand but PV generation is not the only responsible source of overgeneration in the power systems. Therefore, the $G_{ren}(t)$ includes PV, wind, and nuclear power generation. Nuclear generation is considered along with renewable generation because nuclear power plants are the must run generating units with almost zero carbon emission and its generation would be dispatched anyway. However, nuclear power generation would not change the shape of the profile of net demand as it generates nearly constant output, but it may contribute to the morning and evening ramps with a constant offset. The hourly ramp, *Ramp*(t) at any interval t is given in (4), where $t = 1, 2, 3, \ldots, 24$.

$$Ramp(t) = D_{net}(t) - D_{net}(t-1) \tag{4}$$

Under high PV penetration, morning ramps around 5:00 – 9:00, mid-day ramps around 9:00 – 12:00 and evening ramps around 15:00 – 21:00 would be specifically analyzed for the impact of different PV orientations. Moreover, the overgeneration of electricity, $OG(t)$ in each of the PV case would be the remaining available generation after electricity export to the neighboring countries as given in (5).

$$OG(t) = \left|(D_{net}(t) - Exp_{cap}(t)) < 0\right| \tag{5}$$

where, $Exp_{cap}(t)$ is the export capacity of the interconnection between Finland and neighboring power systems. The current interconnection capacity is 3316 MW whereas, it is expected to reach 5466 MW by the year 2045 [1], [19].

III. Results

A. Analysing the netdeamnd profiles different PV orientation cases

In order to evaluate the self-balancing potential of rooftop PV systems with PV panel orientations according to the available roof pitch and direction, fig. 2 presents the box plots of net demand profiles of four comparative cases of PV orientations, as described in section II. The conventional south facing PV orientation shows higher net demand during the morning and evening hours as shown in fig. 2 whereas, all the other cases show lower net demand for the early 3 hours of morning (5:00 – 7:00) and last 3 hours of evening (18:00 – 21:00). Moreover, the mid-day generation of S and SESW cases are considerably higher with negative net demand of -7190 MWh and - 4542 MWh respectively. However, case EW and case rooftop lead to 56 % (-3175 MWh) and 65% (-2537 MWh) reduction in mid-day overgeneration respectively, confirming improved balancing of the demand profile. Overgeneration in east west and rooftop orientation cases is lower than the available interconnection capacity between Finland and the neighboring countries, which is 3316 MW in the year 2023. Thus, there is a possibility of exporting the overgeneration to the neighboring countries instead of curtailing by utilizing hydro storage reserves of the interconnected power systems. However, Finland's transmission capacity would increase to 5466 MW by the year 2045 to aid large scale integration of renewables [1]. But the magnitude of overgeneration from the PV systems facing south is considerably high to fully export even after the expansion of transmission capacity. Thus, extremely high generation of electricity from south facing PV systems would need additional control reserves, curtailment strategies, demand response or battery storages. Whereas, if the PV systems follow their rooftop orientations or east-west orientations, the self-balancing of PV output increases which also generate power in the hours of high market prices [4].

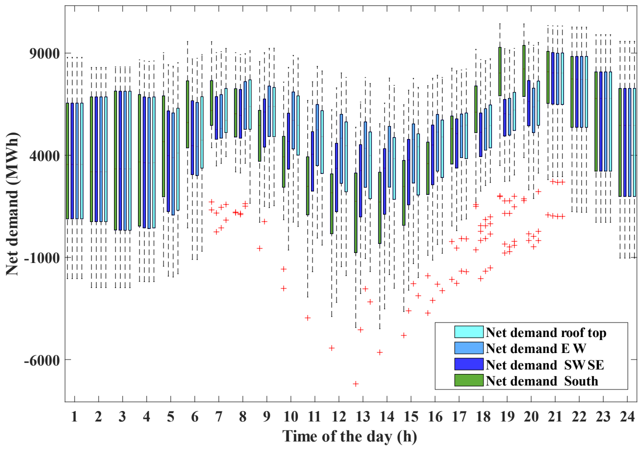

Fig. 2. Box plot of net demand of electricity for the month of July of the year 2045 for different scenarios of orientations for the aggregated PV ensemble in Finland.

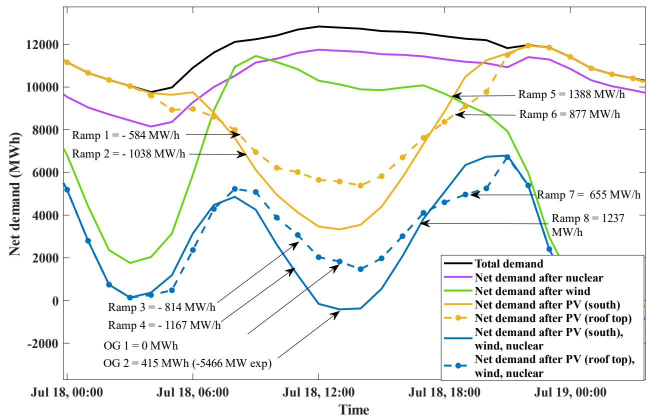

Fig. 3. Net demand profiles of electrcity for different types of non dispatchable generations in case when wind and PV generation are uncorrelated. Ramp rates are mentioned for morning and evenbing ramps with mid day overgeneration (OG)

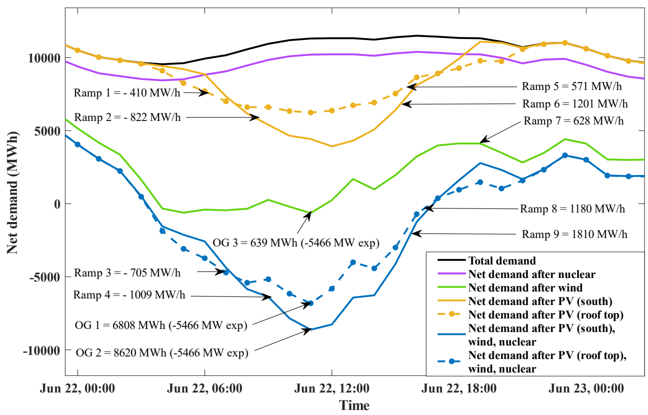

Fig. 4. Net demand profiles of electrcity for different types of non dispatchable generation in case when wind and PV generation are correlated. Ramp rates are mentioned for morning and evenbing ramps with mid day overgeneration (OG)

B. Interaction of wind and PV generation and its impact on net demand profile

The interactions of PV and other non-dispatchable generations should be investigated in order to fully gauge the balancing concerns related to diurnal pattern of PV generation. PV generation is not the only responsible source of overgeneration in the power systems, therefore fig. 3 and fig. 4 presents the net demand profiles after subtracting different combination of non-dispatchable generations including PV, wind, and nuclear generations. However, nuclear power plants generally run at a constant set point and only create an offset change in the net demand, whereas wind and solar being variable resources may interact towards increasing or decreasing the net balancing requirements. Thus, in order to explore the impact of wind and PV generation on net demand curve, two different daily scenarios are considered i.e.,

- When both PV and wind generations are uncorrelated i.e., wind generation is high when PV generation is unavailable and vice versa as shown in fig. 3.
- When both PV and wind generations are correlated i.e., wind generation is high when PV generation is high as shown in fig. 4.

Since the PV generation is zero at night and wind generation is high, thus fig. 3 shows that the downward ramp starting at 00:00 and 20:00 and upward ramp from 04:00 to 06:00 are mainly because of high wind generation and decreasing wind generation respectively. At 06:00, PV generation is ramping up and at the same time wind generation is ramping down and at 12:00, PV generation reaches its peak, responsible for the morning ramp down event as wind generation is low and rather uniform. Moreover, net demand after subtracting nuclear, wind and rooftop PV generation shows 30 % reduction in the rate of morning downward ramp and 47 % reduction in evening upward ramp with no excess generation during the mid-day as compared to the net demand calculated with generation from south facing PV systems.

When both PV and wind penetration are simultaneously high, balancing becomes more difficult in contrast to the uncorrelated generation scenario. High share of wind generation is ramping up during 0:00 – 04:00 as shown in the net demand curve after adding wind generation only in fig. 4. After 04:00 wind generation stays uniformly high with PV generation ramping up from 06:00 until 12:00, resulting in a steep downward ramping event of 11 h whereas, from mid-day until evening net demand ramps up at an extreme rate of 1810 MW/h for 9 h. Moreover, excess generation of electricity during the mid-day in both south facing PV systems and roof top PV systems cases is respectively 3154 MW and 1342 MW more than the transmission capacity of 5466 MW. However, net demand scenario with nuclear, wind and rooftop PV generation shows 30 % reduction in the first downward ramp and 34 % reduction in second upward ramp with 21 % reduction in excess generation during the mid-day as compared to the net demand scenario with generation from south facing PV systems.

C. Ramp charactericties of net demand

In order to assess the impact of different PV orientations on the net demand ramping events, significant ramping events are identified as 5 % or greater of the total demand [20], [21]. Table I shows the number of ramping hours for total demand, net demand (without PV generation) and each of the four PV orientation cases as defined in section II. It can be observed that the number of ramping hours significantly increase for demand to net demand (without PV generation), with highest number of ramping events for the net demand where PV systems are facing south (Case S). Thus, it can be inferred that wind generation is also responsible for introducing ramping events in the net demand curve along with PV generation. Around 800 h are increased for ramping up event without PV

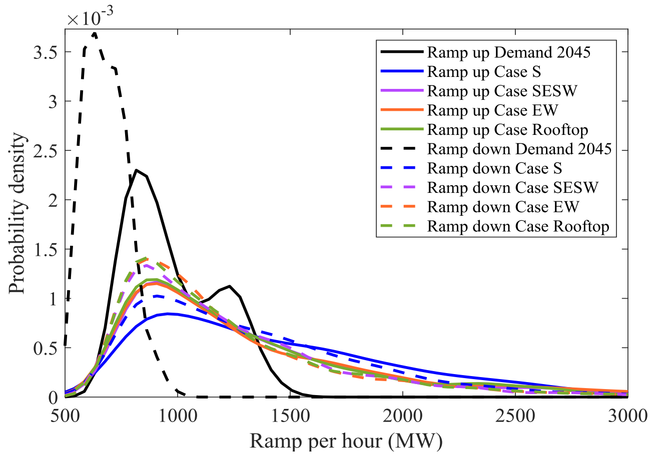

Fig. 5. Distribution of ramp up and ramp down events (x axis zoomed in or better view – range of axis is from 500 to 5000)

TABLE I. NUMBER OF RAMPING HOURS FOR DIFFERENT CASES

No. of hours	Demand	Net demand (w/o PV)	Case S	Case SESW	Case EW	Case rooftop
Ramp up	388	1188	1832	1509	1340	1408
Ramp down	424	1018	1839	1437	1247	1268

generation, whereas if PV generation from the systems with east west orientation or rooftop orientations is considered while calculating the net demand, there would be around 540 or 608 additional ramping hours respectively. Number of ramping hours reduces for both ramp up and ramp down events for east west and rooftop cases with 27% and 23% reduction for ramp up and 32% and 31% reduction for ramp down events respectively.

The probability distribution of significant ramping events in fig. 5 shows that the probability of smaller magnitudes i.e., 632 MW to 770 MW of ramp down events significantly decreases for all PV cases if compared with the ramping events of total demand curve. Moreover, the second peak in the probability curve of ramp up events of total demand disappears for the net demand with PV cases (for all four cases). PV cases including case EW, case rooftop and case SESW show higher probability of smaller magnitude ramps if compared with Case S, where the distribution of ramps is more dispersed towards high ramp rates with comparatively less probability of smaller magnitude ramps.

Since PV generation is limited to certain hours of the day therefore, table II presents the statistics of morning ramp rates (09:00 – 12:00), evening ramp rates (16:00 – 19:00) and overgeneration of electricity. Morning and evening ramp rates for the net demand without PV generation is the lowest among all cases but still significant which must be because of the overgeneration of wind. However, morning and evening ramp rates are the highest for case when PV systems are facing south. Ramp rates for the morning ramp of case EW and case rooftop reduce to 57% and 44 % respectively as compared to ramp rates of case S. Similarly, the reduction of 53 % and 61 % in the evening ramp rates can be observed for rooftop PV systems and east west orientations respectively.

TABLE II. STATISTICS OF NET DEMAND FOR DIFFERENT CASES

Statistics	Net demand w/o PV	Case S	Case SESW	Case EW	Case rooftop
Morning Ramp (MW/h)					
Maximum	-2277	-3802	-3415	-2980	-3199
Mean	-60	-899	-614	-383	-501
Std	653	854	793	770	771
Evening Ramp (MW/h)					
Maximum	2988	5011	4710	4288	3978
Mean	-2.654	1337	747	517	623
Std	554	914	954	902	816
Overgeneration (MW)					
No. of hours	9	171	111	81	89
Maximum	431	6843	5200	3837	4165
Mean	174	1873	1478	1046	1153
Std	151	1493	1187	831	946

The problem of overgeneration of electricity associated with renewables and PV generation has been improved from 171 h of overgeneration of case S to 81 h or 89 h of overgeneration in case EW and case rooftop. Moreover, net demand without PV (i.e., with wind generation only) results in merely 9 h of overgeneration. It should be worth noted that overgeneration is calculated by subtracting the transmission capacity of 5644 MW as excess energy would be exported to the interconnected power systems.

IV. CONCLUSION

The study evaluated the self-balancing potential of rooftop PV systems in Finland for the future network scenario of the year 2025, considering different PV panel orientations. The study examined four PV orientation cases including south-facing PV panels (Case S), PV panels equally oriented towards southeast and southwest (Case SESW), PV panels equally oriented towards east and west (Case EW), and PV panels oriented according to the actual rooftop orientations (Case Rooftop). The results demonstrated that conventional south-facing PV systems exhibit higher morning and evening ramp rates which reduces by 44 % and 57 % for the morning ramp and 53 % and 61 % for the evening ramp in case of rooftop orientations and east west orientations of PV systems respectively. Moreover, the hours of overgeneration and ramping events were reduced considerably for alternative orientations other than south orientation. The paper also discussed the interaction between PV and wind generation and found out that highly correlated generation from PV and wind results in steep ramping events lasting for as long as 9 h to 11 h in the considered scenario. The results and analysis of the paper concludes that rooftop orientations and east west orientations of distributed PV systems provide balancing support and may reduce the need of flexibility reserves, storages, or possible curtailment. However, some extreme generation scenarios may still need activation of balancing reserves.

V. REFERENCES

[1] FINGRID, "Fingrid Network vision." Accessed: May 23, 2023. [Online]. Available: https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/fingrid_network_vision.pdf

[2] R. Sharma and M. Karimi-Ghartemani, "Addressing Abrupt PV Disturbances, and Mitigating Net Load Profile's Ramp and Peak Demands, Using Distributed Storage Devices," Energies, vol. 13, no. 5, p. 1024, Feb. 2020.

[3] P. Denholm, M. O'Connell, G. Brinkman, and J. Jorgenson, "Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart," NREL/TP--6A20-65023, 1226167, Nov. 2015.

[4] . López Prol, K. W. Steininger, and D. Zilberman, "The cannibalization effect of wind and solar in the California wholesale electricity market," Energy Economics, vol. 85, p. 104552, Jan. 2020

[5] L. A. Wong, V. K. Ramachandaramurthy, S. L. Walker, and J. B. Ekanayake, "Optimal Placement and Sizing of Battery Energy Storage System Considering the Duck Curve Phenomenon," IEEE Access, vol. 8, pp. 197236–197248, 2020

[6] Wang, Chang, Bai, Liu, Dai, and Tang, "Mitigation Strategy for Duck Curve in High Photovoltaic Penetration Power System Using Concentrating Solar Power Station," Energies, vol. 12, no. 18, p. 3521, Sep. 2019

[7] M. Doroshenko, "Quantifying the Effects of Solar Panel Orientation on the Electrical Grid".

[8] G. B. M. A. Litjens, E. Worrell, and W. G. J. H. M. Van Sark, "Influence of demand patterns on the optimal orientation of photovoltaic systems," Solar Energy, vol. 155, pp. 1002–1014, Oct. 2017

[9] E. Sánchez, Á. Ordóñez, A. Sánchez, R. García Ovejero, and J. Parra-Domínguez, "Exploring the Benefits of Photovoltaic Non-Optimal Orientations in Buildings," Applied Sciences, vol. 11, no. 21, p. 9954, Oct. 2021

[10] Fingrid, "Open data on the electricity market and the power system," FINGRID Open data. https://data.fingrid.fi/en/ (accessed Mar. 22, 2023).

[11] V. Kallio-Myers, A. Riihelä, P. Lahtinen, and A. Lindfors, "Global horizontal irradiance forecast for Finland based on geostationary weather satellite data," Solar Energy, vol. 198, pp. 68–80, Mar. 2020

[12] A. Riihelä, T. Carlund, J. Trentmann, R. Müller, and A. Lindfors, "Validation of CM SAF Surface Solar Radiation Datasets over Finland and Sweden," Remote Sensing, vol. 7, no. 6, pp. 6663–6682, May 2015

[13] Statistics Finland, "Population of Finland in 2021, by region," Statista. https://www.statista.com/statistics/524679/total-population-of-finland-by-region/ (accessed Mar. 22, 2023).

[14] D. Khanna, "Estimate solar power potential," ESRI, May 25, 2022. https://learn.arcgis.com/en/projects/estimate-solar-power-potential/ (accessed Mar. 22, 2023).

[15] [15] "OpenStreetMap." https://www.openstreetmap.org/#map=8/62.727/28.938 (accessed Mar. 22, 2023).

[16] T. Lobera, "Operation of TUT Solar Photovoltaic Power Station Research Plant Equipped with Climatic and Electric Measuring Systems".

[17] S. Mousavi Maleki, H. Hizam, and C. Gomes, "Estimation of Hourly, Daily and Monthly Global Solar Radiation on Inclined Surfaces: Models Re-Visited," Energies, vol. 10, no. 1, p. 134, Jan. 2017

[18] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," IEEE Trans. Power Electron., vol. 24, no. 5, pp. 1198–1208, May 2009

[19] [19] Stattnet, ENERGINET.DK, SVENSKA KRAFTNÄT, FINGRID, "Challenges and Opportunities for the Nordic Power System." Accessed: Mar. 23, 2023. [Online]. Available: https://www.fingrid.fi/globalassets/dokumentit/fi/yhtio/tki-toiminta/report-challenges-and-opportunities-for-the-nordic-power-system.pdf

[20] M. Cui, J. Zhang, A. R. Florita, B.-M. Hodge, D. Ke, and Y. Sun, "An Optimized Swinging Door Algorithm for Identifying Wind Ramping Events," IEEE Trans. Sustain. Energy, vol. 7, no. 1, pp. 150–162, Jan. 2016, doi: 10.1109/TSTE.2015.2477244.

[21] B. Huang, V. Krishnan, and B.-M. Hodge, "Analyzing the Impacts of Variable Renewable Resources on California Net-Load Ramp Events," in 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR: IEEE, Aug. 2018, pp. 1–5.