Quantifying the impact of day-ahead renewable forecasts on DER hosting capacity estimation

Author(s): Khajeh, Hosna; Seyyedeh-Barhagh, Sahar; Laaksonen, Hannu

Title: Quantifying the impact of day-ahead renewable forecasts on DER hosting capacity estimation

Year: 2024

Version: Accepted manuscript

Please cite the original version:

Khajeh, H., Seyyedeh-Barhagh, S., & Laaksonen, H. (2024). Quantifying the impact of day-ahead renewable forecasts on DER hosting capacity estimation. *IET Conference Proceedings,* 2024:5, 150-154. https://digital-library.theiet.org/doi/10.1049/icp.2024.1909

Quantifying the Impact of Day-ahead Renewable Forecasts on DER Hosting Capacity Estimation

Hosna Khajeh*, Sahar Seyyedeh-Barhagh, Hannu Laaksonen
Flexible Energy Resources, School of Technology and Innovations, University of Vaasa, Vaasa, Finland
**hosna.khajeh@uwasa.fi*

Keywords: DSO, OPTIMIZATION-BASED HOSTING CAPACITY ESTIMATION, DISTRIBUTION NETWORKS, DER FORECASTS

Abstract

This research paper presents a novel optimization approach to estimate short-term hosting capacity of distributed energy resources (DER) within a local distribution network. It emphasizes how DER day-ahead forecasts at various nodes can significantly impact both total and nodal hosting capacities. By analysing these forecasts, the distribution system operator (DSO) can proactively adjust the hosting capacity estimation to ensure network short-term operational security under different scenarios. Our study case with Finnish urban network model confirms that nodes at the beginning of the feeder have higher nodal hosting capacity. Crucially, even 40 % variations in DER forecasts for these high-capacity nodes can substantially affect the entire network's hosting capacity. This highlights the paramount importance of accurate DER forecasts, particularly for these critical points within the DSO network.

1. Introduction

Estimating the day-ahead hosting capacity (HC) of DER is vital for operational planning of distribution networks and making informed decisions about future actions. DER HC refers to the maximum amount of DERs that can be integrated into a distribution network without surpassing network operation limits, such as voltage or current limits, before needing control adjustments or system upgrades [1], [2]. Accurate DER hosting capacity estimation ensures that DSOs can integrate DERs into the network safely and reliably. However, day-ahead DER HC estimation is greatly affected by day-ahead DER forecasts.

Various research efforts have focused on estimating the HC of distribution networks, as detailed in [3], [4]. Notably, deterministic approaches, such as that analysed by [5], have delved into flexibility from storage, PV power curtailment scenarios, substation overloading possibilities, and different load penetration levels in HC estimation. Reference [6] explored HC by varying DER penetration levels and assessing impacts on voltage fluctuations across various loading conditions. Similarly, [7] aimed for faster convergence in estimating HC, considering composite load models and complex power. Reference [8] investigated relationships between maximum PV generation, feeder impedance, load, and network HC.

In general, HC estimation is affected by factors like load and DER scenarios, alongside network features and limitations such as voltage levels, the current carrying capacity of cables as well as overload limits of transformers, unbalances, harmonics, and flickers [9]. However, previous literature largely overlooked the effects of DER forecasts on HC estimation. This paper, therefore, tries to address this gap by examining the impacts of DER forecasts on nodal and total HCs of networks. The paper's main contributions can be summarised as follows:

- Proposing a new optimization-based method using a piecewise linearized power flow model to estimate HC of distribution networks.
- Suggesting that the DSO revises estimated short-term (day-ahead) HC based on day-ahead DER forecasts. This enables the DSO to ensure network operational security and reliability effectively.
- Utilizing a real-world Finnish urban distribution network model to estimate HCs based on the proposed approach, alongside conducting thorough sensitivity analyses to demonstrate how individual node's DER forecast can affect nodal and total HCs.

The rest of the paper is organised as follows. Section 2 introduces the new optimization-based HC estimation, while Section 3 discusses revised HC estimation and DER forecast effects. Section 4 presents the case study, and Section 5 implements the proposed methodology on the case study and conducts sensitivity analysis. Finally, Section 6 discusses results and concludes the paper.

2. Optimization-based Hosting Capacity Estimation

The objective of HC estimation is to determine the maximum amount of power that DERs at all nodes can inject into the network under scenario s:

$$\max_{HC_{n,s}} \sum_n HC_{n,s} \qquad (1)$$

Where, $HC_{n,s}$ represents the hosting capacity of node n (i.e. nodal hosting capacity) estimated for scenario s. The objective function (1) is limited by distribution network power flow constraints. This paper uses the piecewise linearized power flow equations as described by [10], [11]. These constraints are formulated as follows:

$$P^{2net}_{n=PoC,s} + HC_{n,s} - P^{D}_{n,s} - \sum_{n'}(P^{+}_{n,n',s} - P^{-}_{n,n',s} + R_{n,n'}SI_{n,n',s}) + \sum_{n'}(P^{+}_{n',n,s} - P^{-}_{n',n,s}) = 0 \quad (2)$$

$$Q^{2net}_{n=PoC,s} + Q^{DER}_{n,s}{}_{n,s} - Q^{D}_{n,s} - \sum_{n'}(Q^{+}_{n,n',s} - Q^{-}_{n,n',s} + X_{n,n'}SI_{n,n',s}) + \sum_{n'}(Q^{+}_{n',n,s} - Q^{-}_{n',n,s}) = 0 \quad (3)$$

$$SV_{n,s} - SV_{n',s} - Z^{2}_{n,n'}SI_{n,n',s} - 2R_{n,n'}\left(P^{+}_{n,n',s} - P^{-}_{n,n',s}\right) - 2X_{n,n',s}\left(Q^{+}_{n,n',s} - Q^{-}_{n,n',s}\right) = 0 \quad (4)$$

$$\underline{V}^2 \le SV_{n,s} \le \overline{V}^2 \quad (5)$$

$$\underline{I}_{n,n'}{}^2 \le SI_{n,n',s} \le \overline{I}_{n,n'}{}^2 \quad (6)$$

$$\underline{P} \le P^{2net}_{n,s} \le \overline{P} \quad (7)$$

$$\underline{Q} \le Q^{2net}_{n,s} \le \overline{Q} \quad (8)$$

$$P^{+}_{n,n',s} + P^{-}_{n,n',s} \le V^{rated}\overline{I}_{n,n'} \quad (9)$$

$$Q^{+}_{n,n',s} + Q^{-}_{n,n',s} \le V^{rated}\overline{I}_{n,n'} \quad (10)$$

$$V^{rated^2}SI_{n,n',s} = \sum_i (2i-1)\,\Delta S_{n,n'}\,\Delta P_{n,n',s,i} + \sum_i (2i-1)\,\Delta S_{n,n'}\,\Delta Q_{n,n',s,i} \quad (11)$$

$$P^{+}_{n,n',s} + P^{-}_{n,n',s} \le \sum_i \Delta P_{n,n',s,i} \quad (12)$$

$$Q^{+}_{n,n',s} + Q^{-}_{n,n',s} \le \sum_i \Delta Q_{n,n',s,i} \quad (13)$$

$$0 \le \Delta P_{n,n',s,i} \le \Delta S_{n,n'} \quad (14)$$

$$0 \le \Delta Q_{n,n',s,i} \le \Delta S_{n,n'} \quad (15)$$

$$\Delta S_{n,n'} = \frac{V^{rated}\,\overline{I}_{n,n'}}{N^i} \quad (16)$$

$$P^{+}_{n,n',s}, P^{-}_{n,n',s}, Q^{+}_{n',n,s}, Q^{-}_{n',n,s}, HC_{n,s}, \Delta P_{n,n',s}, \Delta Q_{n,n',s} \ge 0 \quad (17)$$

Where, constraint (2) is an active power balance equation, keeping balance between the active power entering/leaving the local distribution network, i.e. $P^{2net}_{n=PoC,s}$, the maximum power that can be injected into the network, $HC_{n,s}$, the power consumed by the local demand, $P^{D}_{n,s}$, and the active power flowing through lines, indicating by $\sum_{n'}(P^{+}_{n,n',s} - P^{-}_{n,n',s} + R_{n,n',s}SI_{n,n',s}) + \sum_{n'}(P^{+}_{n',n,s} - P^{-}_{n',n,s})$. In this term, $P^{+}_{n,n',s}$denotes the active power that flows in a downstream direction from n to n'. Correspondingly, $P^{-}_{n,n',s}$indicates the flowing active power from n to n' in an upstream direction.

Constraint (3) applies the same balance as (2), between the reactive power injections and consumptions. It includes the reactive power entering/leaving the local distribution network at point of coupling (PoC), i.e. $Q^{2net}_{n=PoC,s}$, the reactive power injected by the DER, $Q^{DER}_{n,s}$, the reactive power consumed by the local demand, $Q^{D}_{n,s}$, as well as the reactive power flowing through the lines. Similarly, $Q^{+}_{n,n',s}$represents the reactive power flowing in a downstream direction from n to n' and $Q^{-}_{n,n',s}$is the reactive power transmitting from n to n' in an upstream direction. Moreover, $R_{n,n'}, X_{n,n'}$ and $Z_{n,n'}$ refer to the resistance, reactance, and impedance of the line between n and n'.

It should be highlighted that (3) and (4) are applied at each node n for each scenario s.

Equation (4) describes the relationship between the lines' flowing power and the voltages of nodes. In this constraint, $SV_{n,s}$ serves as an alternative variable equal to the squared voltage at node n under scenario s. Also, $SI_{n,n',s}$is an alternative variable substituting the squared current flowing between n and n' under scenario s.

Constraints (5) and (6) restrict the squared voltages and squared currents to stay within their minimum values ($\underline{V}^2, \underline{I}_{n,n'}{}^2$) and their maximum values ($\overline{V}^2, \overline{I}_{n,n'}{}^2$). Similarly, constraints (7) and (8) limit the values of active and reactive power allowed to enter and exit the local distribution network, taking into account the capacity of the transformer. $\underline{P}$ and $\underline{Q}$ represent the minimum active and reactive power, while $\overline{P}$ and $\overline{Q}$ indicate the maximum active and reactive power ranges, respectively.

Constraints (9) and (10) ensure that there is no congestion within the lines, where V^{rated} denotes the rated voltage.

Constraints (11)-(16) pertain to the piecewise linearization technique applied to the power flow equations. In these constraints, i is the index showing the partition used in piecewise linearization and N^i indicates the total number of partitions. The parameter $\Delta S_{n,n'}$ refers to the maximum apparent power that can flow between n and n' in the piecewise-linearized power flow. The variables $\Delta P_{n,n',s,i}$ and $\Delta Q_{n,n',s,i}$ represent the discretised active and reactive power for partition i flowing between n and n' under scenario s.

After solving optimization problem (1)-(17) and identifying the maximum/optimum amount of nodal DER injection ($HC^{opt}_{n,s}$) for each scenario, the nodal HC of the network is determined by finding the minimum value of the nodal DER injection across all scenarios. This implies that the nodal HC is obtained as follows:

$$Nodal\ HC = {HC_n}^{opt} = \min_s HC_{n,s}^{opt} \quad (18)$$

The total HC of the network is obtained by summing up the nodal HCs of the distribution network:

$$HC = \sum_n {HC_n}^{opt} \quad (19)$$

3. The Impact of DER Forecasts on HC Estimation

Assume that a DSO executes equations (1)-(18) to determine the maximum values for the nodal HC of its distribution network on a day-ahead basis. Thus, the DSO should utilize forecasted values of nodal consumption for the parameter P_n^D. Additionally, it receives forecasts of nodal DER generation. Then, the following situations may arise:

Case I) The forecasted DER generations are all equal or below the nodal HCs of the network.

Case II) At some nodes, the forecasted DER generations exceed their estimated nodal HCs.

Case III) The DER generation forecasts for nodes indicate that all nodes are expected to generate power exceeding their nodal HCs.

The DSO does not need to take action in Case I. However, in Case II, the DSO can implement the following measures to ensure network security:

1) Set the value of the nodal HC with higher DER forecast to be equal to their forecasts:
   $HC_{n,s} = Forecast_n \ if \ Forecast_n \geq {HC_n}^{opt}$ (19)
   Where, $Forecast_n$ is the DER generation forecast for node n.
2) Execute (1)-(18) with the fixed parameters of HC for those nodes whose DER forecasts are higher. Subsequently, if the optimization problem is solved, it gives you a new set of values for nodal HCs. Thus, the DSO revises its nodal and total HCs according to the new results.
3) If the optimization problem is not feasible, indicating that the network is not secure. The DSO may employ flexible energy resources, as proposed by [10], [12], to ensure network security.

In Case III, the DSO can take the same measures and utilize flexible energy resources to make sure that its network will remain secure for the following day.

4. Case Study

This paper examines a Finnish urban LV network (Fig. 1) as a case study. The line parameters and line current capacities are detailed in [13]. The nominal voltage is set at 1 pu, with minimum and maximum voltage limits defined as 0.95 and 1.05 pu, respectively. Also, the power factor of loads and DERs were set to 0.8.

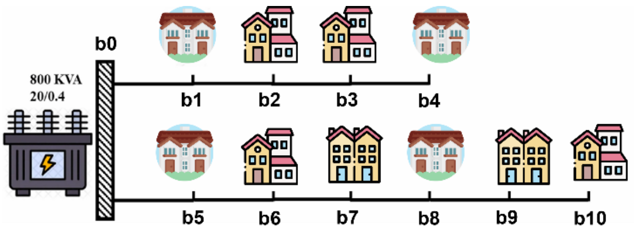

Fig. 1. The studied Finnish urban LV network

At each node of the Fig. 1 LV network, there are two or three detached houses. We extracted representative consumption data for one day from real data collected in 2019 in Finland. This data serves as representative scenarios for the optimization problem (1) to (17). The nodal consumption data is shown in Fig. 2.

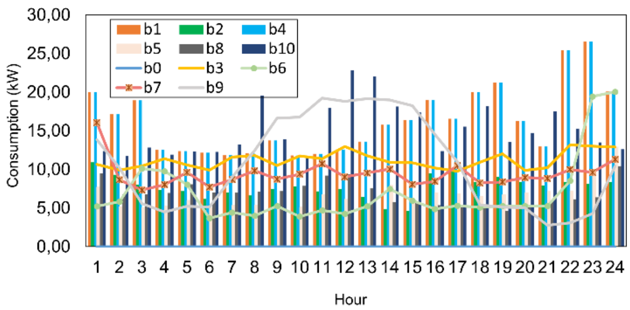

Fig. 2. Nodal consumption of the studied LV network (Fig. 1)

5. Simulation Results

5.1. HC Estimation

First, the optimization problem defined by equations (1)-(17) was modelled and solved. Then, equations (18) and (19) were used to calculate HC for each node (nodal HC) and the total HC for the entire network.

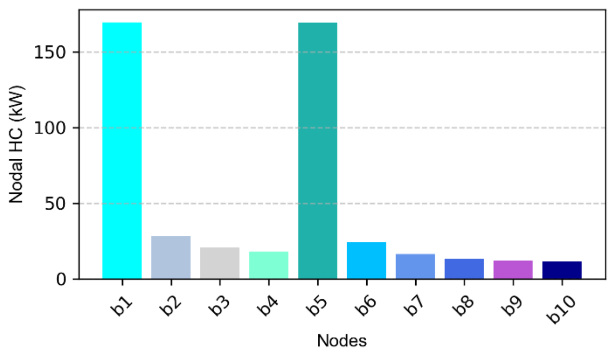

Fig. 3. Nodal HC estimated for the studied urban LV network in Fig. 1

To solve this optimization problem, we used a software package called CVXPY in Python [14]. The calculations were performed on a laptop equipped with 16 GB of RAM and a 13th Gen Intel Core i5-1335U processor.

Fig. 3 displays bar charts representing the HC at each node of the Fig. 1 LV network. The Fig. 3 illustrates that nodes closer to the beginning of the LV feeder exhibit higher HC. Nodes further away from the MV/LV transformer (Fig. 1) have less capacity to accommodate DERs. Therefore, nodes b5 and b7 have the highest HC, while nodes b9 and b10 are the least capable for integrating DERs. For example, the HC of b1 is 14 times higher than that of b10.

5.2. Impact of DER Forecasts on HCs

The HC value of each node was separately increased to observe how the DER forecast of each node affected both the nodal and total HCs. Generally, when the HC of one node increased, which can indicate the DER forecast of that node, the HC of other nodes either stayed the same or decreased. Fig. 4 illustrates how increasing the HC of node b1 affects the hosting capacities of other nodes in the studied LV network (Fig. 1).

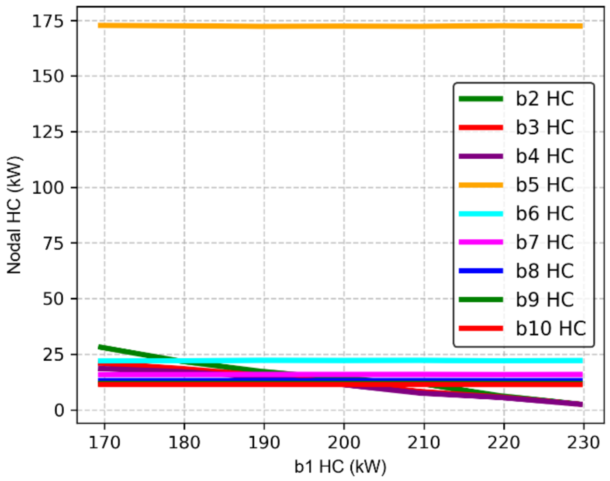

Fig. 4. Variation of nodal hosting capacities (HCs) in relation to the hosting capacity of node b1 in the studied LV network (Fig. 1).

On the other hand, a single HC increase up to a certain level did not affect the total HC of the network. This implies that if the DSO receives a higher DER forecast for a specific node, up to a certain threshold, it does not impact its original total HC estimation of the network.

Fig. 4 illustrates the impact of increasing the HC of each node (in %) on the total HC of the network. As depicted in the Fig. 4, nodes closer to the beginning of the LV feeder (b1 and b5 in Fig. 1) can have a greater effect on changing the total HC. This suggests that the total HC can be more sensitive to DER forecasts of these nodes.

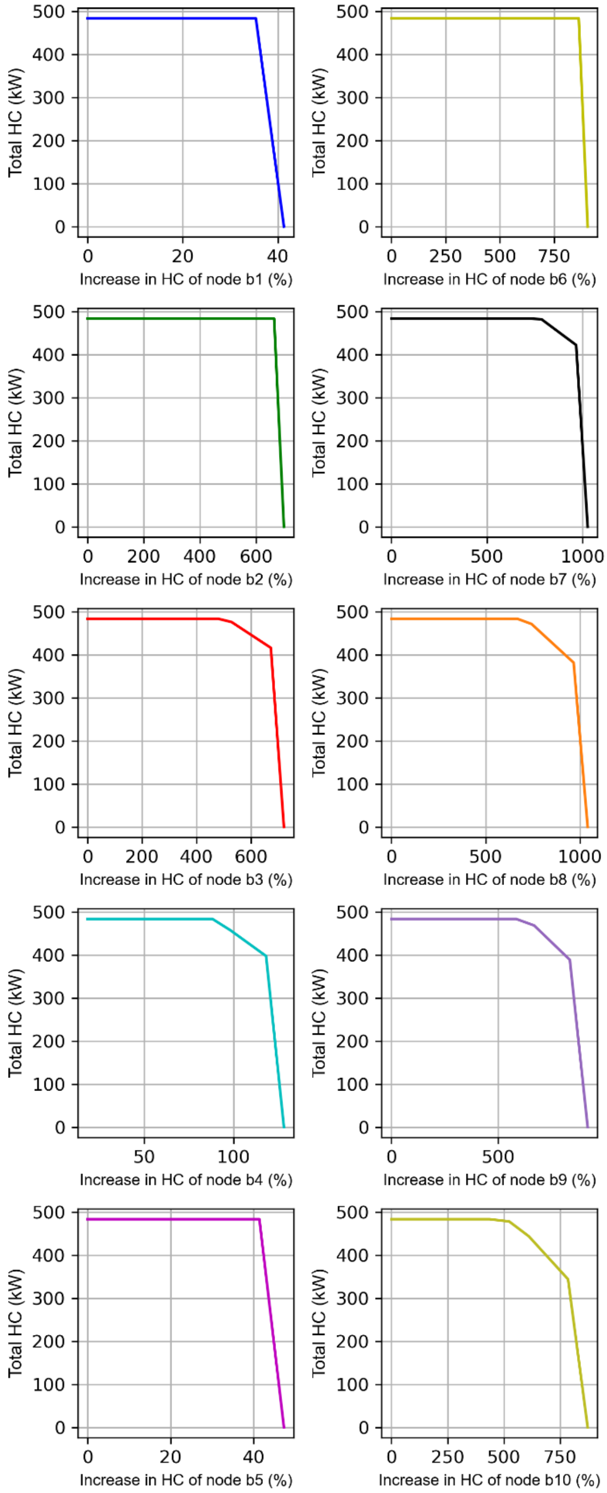

Fig. 5. Variation in total HC concerning changes in the HC of individual nodes in %

In Fig. 5, zero values for both total and nodal HCs indicate that the optimization problem (1)-(17) is infeasible. This infeasibility suggests that the distribution network cannot accommodate the planned amount of DER injection at the node. For example, if the forecasted DER at node b1 is 40

% higher than its primary estimated hosting capacity, the HC estimator optimization will not have a solution. This means that injecting such a high level of DER at b1 would violate one or more security limits of the network.

6. Discussion and conclusion

This paper proposed a new optimization-based approach to estimate the total and nodal DER hosting capacities in DSO network. The research emphasized that if the forecasted DER at a particular node exceeds the initial hosting capacity estimate, the DSO needs to revise its estimation of both the total network hosting capacity and the hosting capacity of nodes. This paper also studied different actions the DSO might take depending on the DER forecast scenario.

The proposed hosting capacity estimator was studied with a Finnish urban LV network model. As expected, the results showed that nodes closer to the beginning of the LV feeder and close to the MV/LV transformer have higher hosting capacities. More importantly, the findings revealed that for these nodes with higher hosting capacities, even 40 % variations in the forecasted DER can significantly impact the total network hosting capacity. This underlines the critical role of accurate DER forecasts, especially for these nodes with higher hosting capacity.

Based on the studies, it is recommended that DSOs first conduct a sensitivity analysis to assess how the network's hosting capacity reacts to different DER forecast levels. This analysis could help DSOs to identify which nodes have the greatest influence on the total network hosting capacity depending on the accuracy of the DER forecasts.

7. Acknowledgement

This work has been done as a part of “Smart Grid 2.0” project funded by Business Finland with grant No. 1386/31/2022. The work of Hosna Khajeh has been partly supported by “Finnish Foundation for Technology Promotion”.

8. References

[1] M. Alturki, A. Khodaei, A. Paaso, and S. Bahramirad, ‘Optimization-based distribution grid hosting capacity calculations’, *Appl. Energy*, vol. 219, pp. 350–360, Jun. 2018, doi: 10.1016/j.apenergy.2017.10.127.

[2] NREL, ‘Advanced Hosting Capacity Analysis’. Accessed: Mar. 08, 2024. [Online]. Available: https://www.nrel.gov/solar/market-research-analysis/advanced-hosting-capacity-analysis.html

[3] N. Qamar, A. Arshad, K. Mahmoud, and M. Lehtonen, ‘Hosting capacity in distribution grids: A review of definitions, performance indices, determination methodologies, and enhancement techniques’, *Energy Sci. Eng.*, vol. 11, no. 4, pp. 1536–1559, Apr. 2023, doi: 10.1002/ese3.1389.

[4] M. Zain Ul Abideen, O. Ellabban, and L. Al-Fagih, ‘A Review of the Tools and Methods for Distribution Networks’ Hosting Capacity Calculation’, *Energies*, vol. 13, no. 11, p. 2758, Jun. 2020, doi: 10.3390/en13112758.

[5] R. Luthander, D. Lingfors, and J. Widén, ‘Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage’, *Sol. Energy*, vol. 155, pp. 1319–1325, Oct. 2017, doi: 10.1016/j.solener.2017.07.083.

[6] D. O. Ampofo, I. K. Otchere, and E. A. Frimpong, ‘An investigative study on penetration limits of distributed generation on distribution networks’, in *2017 IEEE PES PowerAfrica*, Accra, Ghana: IEEE, Jun. 2017, pp. 573–576. doi: 10.1109/PowerAfrica.2017.7991289.

[7] S. S. Parihar and N. Malik, ‘Interval Arithmetic Power Flow Analysis of Radial Distribution System with Probabilistic Load Model and Distributed Generation’, *Process Integr. Optim. Sustain.*, vol. 6, no. 1, pp. 3–15, Mar. 2022, doi: 10.1007/s41660-021-00200-8.

[8] S. Heslop, I. MacGill, J. Fletcher, and S. Lewis, ‘Method for Determining a PV Generation Limit on Low Voltage Feeders for Evenly Distributed PV and Load’, *Energy Procedia*, vol. 57, pp. 207–216, 2014, doi: 10.1016/j.egypro.2014.10.025.

[9] S. Fatima, V. Püvi, and M. Lehtonen, ‘Review on the PV Hosting Capacity in Distribution Networks’, *Energies*, vol. 13, no. 18, p. 4756, Sep. 2020, doi: 10.3390/en13184756.

[10] H. Khajeh, H. Firoozi, M. R. Hesamzadeh, H. Laaksonen, and M. Shafie-Khah, ‘A Local Capacity Market Providing Local and System-Wide Flexibility Services’, *IEEE Access*, vol. 9, pp. 52336–52351, 2021, doi: 10.1109/ACCESS.2021.3069949.

[11] H. Khajeh, C. Parthasarathy, E. Doroudchi, and H. Laaksonen, ‘Optimized siting and sizing of distribution-network-connected battery energy storage system providing flexibility services for system operators’, *Energy*, vol. 285, p. 129490, Dec. 2023, doi: 10.1016/j.energy.2023.129490.

[12] H. Khajeh and H. Laaksonen, ‘Flexibility Utilization Enabling Business Models and Tariff Structures’, in *2023 19th International Conference on the European Energy Market (EEM)*, Lappeenranta, Finland: IEEE, Jun. 2023, pp. 1–6. doi: 10.1109/EEM58374.2023.10161810.

[13] H. Laaksonen, P. Saari, and R. Komulainen, ‘Control of voltage and frequency in inverter and synchronous generator based urban LV microgrid’, presented at the Proceedings The Sixth IASTED International Conference on European Power and Energy Systems, 2006, pp. 26–28.

[14] S. Diamond and S. Boyd, ‘CVXPY: A Python-embedded modeling language for convex optimization’, *J. Mach. Learn. Res.*, vol. 17, no. 83, pp. 1–5, 2016.