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Methodology for Sizing Regional Energy Storage for Large-Scale PV Deployment

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Abstract. When national plans for the deployment of photovoltaic (PV) systems significantly exceed the installed capacity of existing generation sources, the integration of energy storage systems becomes necessary. This paper presents a methodology for determining the required power rating and energy capacity of energy storage systems at the national level. The methodology is based on hourly electricity consumption and PV generation profiles from previous years, combined with data on the total installed PV capacity by month and projections of electricity demand growth and PV deployment over the next decade and beyond. Power system stability–related issues are not addressed in this study.
The proposed approach enables the identification of the required storage timescale—seasonal, monthly, weekly, daily, or hourly—as well as the corresponding power rating and energy capacity. The methodology is applied to a case study based on the national PV deployment plan in Slovenia. The resulting outputs may subsequently support the selection of appropriate energy storage technologies, which lies beyond the scope of this paper.

Key words. Electrical power systems, Photovoltaic (PV) systems, National deployment planning, Energy storage sizing

1. Introduction

The global transition towards decarbonised energy systems has accelerated the deployment of variable renewable energy sources, with solar photovoltaics (PV) playing a central role. At the national level, many countries are revising their National Energy and Climate Plans (NECPs) to reflect more ambitious climate targets. A notable example is the planned expansion of PV generation capacity by more than a factor of five within twelve years, while the generation capacity of other sources remains largely unchanged.
Although such an increase is essential for reducing carbon intensity, it introduces significant structural challenges to the power system, resulting in hourly, daily, monthly, and even seasonal mismatches between electricity production and demand. Even without considering power system stability issues, it is evident that energy storage systems represent one of the principal options for mitigating these imbalances. The key challenges lie in determining the required power rating, energy capacity, and storage duration, which are prerequisites for selecting the most appropriate energy storage technology for a given application.
The existing literature highlights various pathways for energy storage deployment. Dahash et al. [1] provide a critical review of advances in large-scale hot-water tank and pit thermal energy storage, demonstrating their technological maturity for solar district heating applications. Building on this technical foundation, Yang et al. [2] present a comprehensive techno-economic review assessing the cost-competitiveness of seasonal thermal energy storage technologies and identifying pit storage as one of the most economically viable solutions for the heating sector.
The integration of such systems into broader energy networks is further examined by Lyden et al. [3], who analyse seasonal energy storage within the framework of smart energy systems and emphasise the need for detailed modelling to align district-level applications with fluctuating electricity prices and multi-sector energy demands. For industrial applications, Baeuerle et al. [4] review pathways towards net-zero industrial heat, introducing Power-to-X concepts and renewable metal energy carriers as potential solutions for addressing seasonal imbalances. Dahash et al. [5] further demonstrate the importance of simulation-based planning to ensure that large-scale storage systems are both cost-effective and energy-efficient, particularly under complex hydrogeological conditions. Finally, Bizjak et al. [6] illustrate the utilisation of excess PV generation for aluminium smelting, highlighting the potential for coupling renewable electricity with energy-intensive industrial processes.

The aim of this work is to present a methodology for determining the required power rating, energy capacity, and storage duration of an energy storage system capable of mitigating the mismatch between PV-driven electricity production and demand. The approach is based on historical hourly data on electricity generation and consumption, combined with development plans that account for projected demand growth and the planned deployment of PV systems, with the possible inclusion of other generation sources.
Although the proposed methodology is general in nature, its implementation requires appropriate input data. Therefore, it is demonstrated through a case study of the Slovenian power system.
According to the National Energy and Climate Plan for Slovenia [7], the installed capacity of PV systems is expected to increase from less than 1.1 GW in 2023 to 5.8 GW by 2035, while the installed capacity of other generation sources will remain almost constant at approximately 3.3 GW. The development plans for the electricity distribution [8] and transmission [9] systems are aligned with [7]. All data used in this study are publicly available via the platform [10], provided by ELES d.o.o., the combined transmission and distribution system operator of the Republic of Slovenia.
A general description of the proposed methodology is presented in Section 2. The input data for the case study are described in Section 3, followed by the results in Section 4. The main conclusions are summarised in Section 5.

2. Methodology

The proposed methodology is based on the evaluation of energy consumption and generation at the monthly level. The generation term may include only PV production, a selected portfolio of renewable energy sources, or a combination of renewable and conventional generation.

A. Energy capacity for seasonal and monthly storage

For each month $\boldsymbol{m}$, the difference between the produced energy $\boldsymbol{W_{Gen\_m}}$ and the consumed energy $\boldsymbol{W_{Load\_m}}$ is calculated by (1).

$$\boldsymbol{\Delta W_m = W_{Gen\_m} - W_{Load\_m}} \tag{1}$$

If $\boldsymbol{\Delta W_m}$ is positive, it represents the monthly surplus of produced energy. If energy production exceeds consumption over several consecutive months, represented by the set $\boldsymbol{M}$, the cumulative surplus energy can be used for the initial sizing of the seasonal storage energy capacity $\boldsymbol{W_{seas}}$ (2).

$$\boldsymbol{W_{seas} = \textstyle\sum_{m \in M} \Delta W_m} \tag{2}$$

If energy production exceeds consumption in individual, non-consecutive months, the maximum monthly surplus is used for the initial sizing of the monthly storage energy capacity $\boldsymbol{W_m}$ (3).

$$\boldsymbol{W_m = \max(\Delta W_m)} \tag{3}$$

B. Energy capacity and power of daily storage

If no energy surplus is identified at the seasonal or monthly level, the required energy capacity and power for daily storage are determined.
The required power rating for daily, monthly, and seasonal storage is defined uniformly as the maximum positive hourly difference $\boldsymbol{\Delta P_h}$ between generation power $\boldsymbol{P_{Gen\_h}}$ and load power $\boldsymbol{P_{Load\_h}}$ over the entire observation period (4).

$$\boldsymbol{\Delta P_h = \max\,(P_{Gen\_h} - P_{Load_h})} \tag{4}$$

The required daily storage energy capacity is determined by identifying, across all days within the observation period, the day with the maximum cumulative surplus of generated energy over consumed energy during consecutive hours. The hourly energy surplus is defined by (5),

$$\boldsymbol{\Delta W_h = W_{Gen\_h} - W_{Load\_h}} \tag{5}$$

where $\boldsymbol{\Delta W_h}$ denotes the surplus of generated energy $\boldsymbol{W_{Gen\_h}}$ over the consumed energy $\boldsymbol{W_{Load\_h}}$ in the hour $\boldsymbol{h}$.
Let $\boldsymbol{D}$ denote a consecutive sequence of hours within a given day for which generation exceeds consumption. The cumulative daily surplus $\boldsymbol{\Delta W_d}$ is then defined by (6).

$$\boldsymbol{\Delta W_d = \textstyle\sum_{h \in D} \Delta W_h} \tag{6}$$

Finally, the required daily storage energy capacity $\boldsymbol{W_d}$ is defined as the maximum value of $\boldsymbol{\Delta W_d}$ (7), considering all days within the given interval of observation.

$$\boldsymbol{W_d = \max(\Delta W_d)} \tag{7}$$

Thus, $\boldsymbol{W_d}$ represents the minimum storage energy capacity required to absorb the highest daily surplus of generated energy over consumption within the analysed time interval.

3. Case study

The proposed methodology is applied in a case study of the Slovenian power system. Table I summarises the installed capacity of individual generation sources for the period 2023–2025. The corresponding monthly PV generation and installed PV capacity are presented in Table II. Table III provides the average monthly ratio between PV-generated energy and installed PV capacity for the period 2023–2025. Figures 1 and 2 show the hourly power profiles of electricity consumption and PV generation, respectively.

Table I. – Type and installed power of individual power sources

Type	Installed power (MW)		
	2023	2024	2025
Solar	1071	1383	1571
Small hydro	118	116	116
Wind	3	3	4
Hydro	971	971	971
Pump hydro	180	180	180
Nuclear	696	696	696
Coal/Lignite	847	847	847
Natural gas	486	486	486

Table II. – Monthly installed PV power, generated energy and their ratio for 2023-2025

Month	Installed power P_{inst} (MW)	Produced energy W_{PV} (GWh)	Full load hour W_{PV} / P_{inst} (h)
Year 2023			
1	699	15.38	22.00
2	723	37.57	51.97
3	746	61.10	81.90
4	778	82.85	106.49
5	808	89.90	111.26
6	840	116.28	138.43
7	898	121.45	135.24
8	937	112.24	119.79
9	970	100.22	103.32
10	1008	65.68	65.16
11	1044	42.96	41.15
12	1071	29.03	27.10
	Sum:	874.65	1003.80
Year 2024			
Month	Installed power P_{inst} (MW)	Produced energy W_{PV} (GWh)	Full load hour W_{PV} / P_{inst} (h)
1	1106	35.32	31.94
2	1122	54.00	48.14
3	1150	88.23	76.75
4	1175	133.77	113.85
5	1211	141.13	116.54
6	1244	153.97	123.77
7	1266	169.65	134.00
8	1295	168.55	130.16
9	1318	104.19	79.05
10	1345	70.24	52.22
11	1364	46.79	34.31
12	1383	39.59	28.63
	Sum:	1205.43	969.36
Year 2025			
Month	Installed power P_{inst} (MW)	Produced energy W_{PV} (GWh)	Full load hour W_{PV} / P_{inst} (h)
1	1405	39.00	27.76
2	1432	56.95	39.77
3	1449	118.23	81.60
4	1479	156.69	105.95
5	1499	179.79	119.94
6	1510	231.54	153.30
7	1524	197.67	129.70
8	1534	191.89	125.12
9	1539	136.08	88.41
10	1545	100.80	65.23
11	1559	59.79	38.36
12	1571	39.03	24.84
	Sum:	1507.44	999.96

Table III. – Average value W_{PV} / P_{inst} for 2023-2025

Month	Full load hour – W_{PV} / P_{inst} (h)			
	2023	2024	2025	Average
1	22.00	31.94	27.76	27.23
2	51.97	48.14	39.77	46.63
3	81.90	76.75	81.60	80.08
4	106.49	113.85	105.95	108.76
5	111.26	116.54	119.94	115.91
6	138.43	123.77	153.30	138.50
7	135.24	134.00	129.70	132.98
8	119.79	130.16	125.12	125.02
9	103.32	79.05	88.41	90.26
10	65.16	52.22	65.23	60.87
11	41.15	34.31	38.36	37.94
12	27.10	28.63	24.84	26.86
Sum:	1003.80	969.36	999.96	991.04

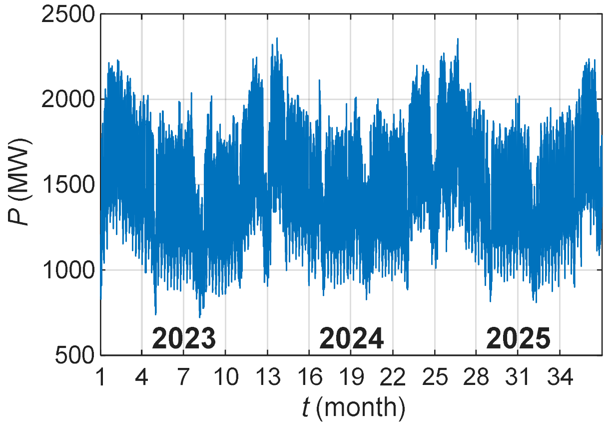

Fig. 1. Hourly diagram of consumption power for 2023-2025

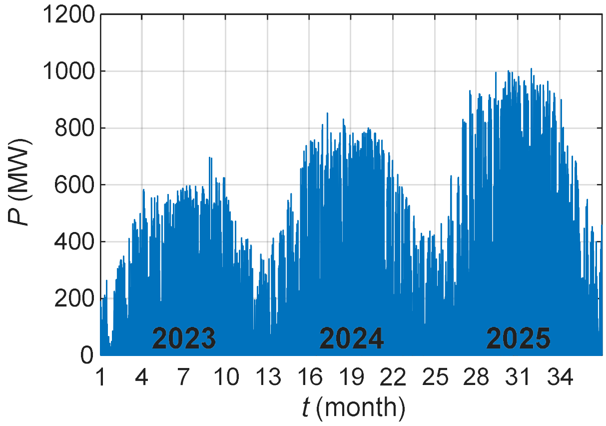

Fig. 2. Hourly diagram of PV generation power for 2023-2025

The installed PV capacity at the end of 2023 and 2025 was 1.07 GW and 1.57 GW, respectively. According to [7], this capacity is expected to increase to 5.8 GW by 2035, while the installed capacity of other generation sources is projected to remain largely unchanged. The estimated PV generation profiles, obtained by upgrading 2023 to 2025 profiles with the consideration of installed PV power of 5.8 GW, are shown in Fig. 3.

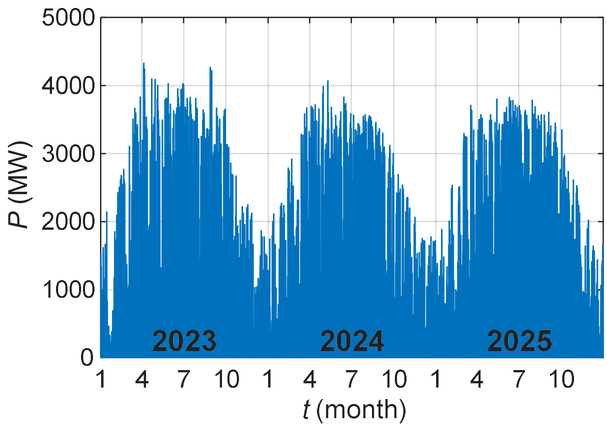

Fig. 3. Hourly diagram of PV generation power for 2035 considering installed PV power of 5.8 GW for upgrading 2023-2025 PV generation profiles.

4. Results

The methodology presented in Section II is applied using the hourly consumption and PV generation power profiles (Figs. 1 and 2), together with the average monthly ratio between generated energy and installed PV capacity (Table III), to estimate the need for energy storage systems at the monthly and daily levels. The analysis considers a projected installed PV capacity of 5.8 GW in 2035, resulting in estimated PV generation profiles shown in Fig. 3. They are based on measured 2023-2025 PV generation profiles considering the increase in installed PV power. Electricity demand is assumed to increase linearly at approximately 2% per year.

The results shown in Figs. 4, 5, and 6 present the monthly electricity consumption and the corresponding PV-generated energy, assuming unchanged consumption levels from the period 2023–2025 and a projected installed PV capacity of 5.8 GW in 2035. The results clearly indicate that PV-generated energy remains below total electricity consumption in all months. Consequently, no requirement for seasonal or monthly energy storage is identified under these assumptions, even without accounting for potential increases in demand.

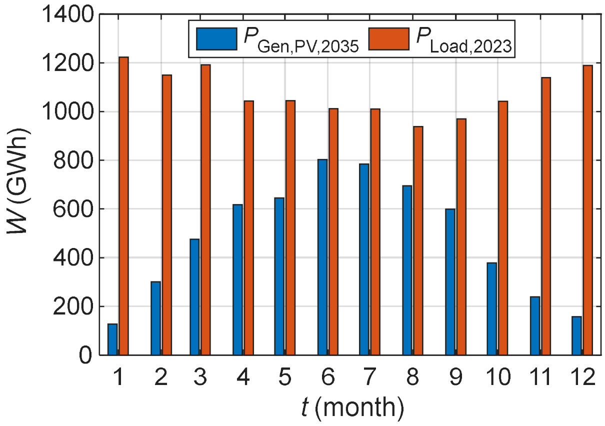

Fig. 4. Monthly energy profiles considering PV generation with installed PV power in 2035 and consumption in 2023

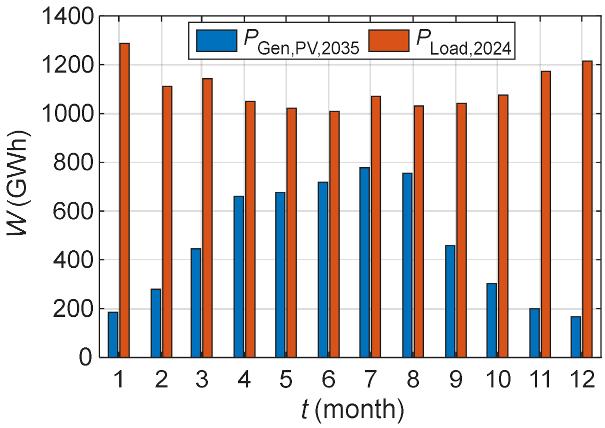

Fig. 5. Monthly energy profiles considering PV generation with installed PV power in 2035 and consumption in 2024

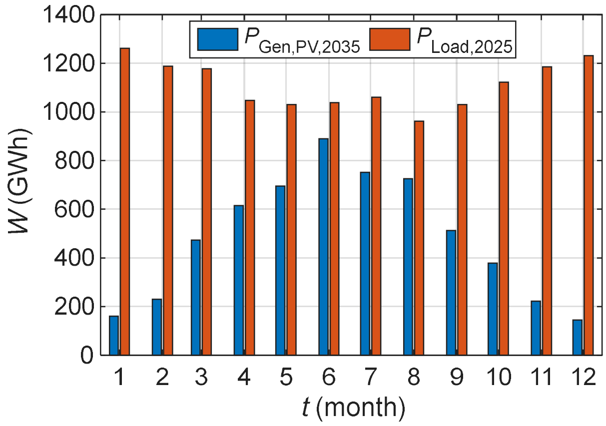

Fig. 6. Monthly energy profiles considering PV generation with installed PV power in 2035 and consumption in 2025

In the next step, the requirement for daily energy storage is assessed. All days within the period 2023–2025 are analysed using hourly PV generation and consumption power profiles in order to identify: (i) the day with the highest positive hourly difference between PV generation and consumption power, and (ii) the day with the highest daily surplus of PV-generated energy relative to consumption. Both days were identified in 2023. For these two representative days, the original PV generation profiles are scaled to reflect the projected installed PV capacity of 5.8 GW in 2035, while electricity consumption is increased by 24% (2% per year) compared with 2023 levels.

The resulting profiles are presented in Figs. 7 and 8, corresponding to the day with the highest hourly surplus of PV generation power and the day with the highest daily surplus of PV-generated energy, respectively. The numerical results are summarised in Tables IV and V.

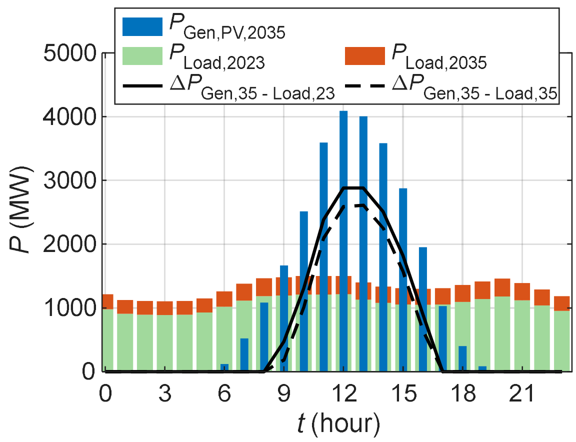

Fig. 7. The day with the highest positive hourly difference between PV generation and consumption power (29.4.2023)

Table IIIV. – Tabulated data for 29th April 2023 – the day with the highest hourly difference between the PV generation and consumption power (P_{exPV})

Hour	PV gen P_{PV} (MW)	Load P_{Load} (MW)		Excess PV P_{exPV} (MW)	
		2023	2035	2023	2035
0	0.3	978.8	1213.7	0.0	0
1	0.3	907.5	1125.4	0.0	0
2	0.3	891.8	1105.9	0.0	0
3	0.3	888.7	1102.0	0.0	0
4	0.3	893.4	1107.8	0.0	0
5	2.6	925.1	1147.1	0.0	0
6	119.9	1016.3	1260.2	0.0	0
7	521.3	1112.4	1379.4	0.0	0
8	1082.2	1181.8	1465.5	0.0	0
9	1664.0	1195.0	1481.9	469.0	182.1
10	2512.5	1210.3	1500.8	1302.2	1011.7
11	3596.4	1210.9	1501.5	2385.5	2094.9
12	4091.8	1211.5	1502.2	2880.3	2589.6
13	4008.3	1126.6	1397.0	2881.7	2611.3
14	3583.8	1076.7	1335.1	2507.1	2248.7
15	2876.0	1054.3	1307.3	1821.7	1568.7
16	1949.6	1049.3	1301.1	900.3	648.5
17	1025.6	1054.4	1307.5	0.0	0
18	398.1	1094.9	1357.6	0.0	0
19	85.4	1140.1	1413.7	0.0	0
20	0.6	1177.5	1460.1	0.0	0
21	0.3	1118.8	1387.3	0.0	0
22	0.3	1040.0	1289.6	0.0	0
23	0.3	954.5	1183.6	0.0	0
Energy sum (GWh):				15.15	12.96

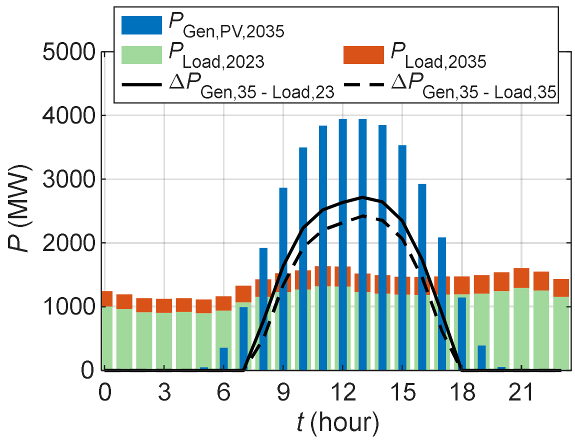

Fig. 8. The day with the highest daily surplus of PV-generated energy relative to consumption (25.6.2023)

The results presented in Fig. 7 and Table IV clearly indicate that the required power rating of the energy storage system is of the order of 3 GW, i.e. slightly below 2.9 GW for the 2023 consumption level and above 2.6 GW when considering the projected 2035 consumption.

In contrast, according to the results shown in Fig. 8 and Table V, the required usable energy capacity of the storage system exceeds 20 GWh for the 2023 load profile and 17 GWh for the projected 2035 consumption.

Table IV. – Tabulated data for 25th June 2023 - the day with the highest daily surplus of PV-generated energy relative to consumption

Hour	PV gen P_{PV} (MW)	Load P_{Load} (MW)		Excess PV P_{exPV} (MW)	
		2023	2035	2023	2035
0	0.3	1003.8	1244.7	0.0	0
1	0.3	964.0	1195.3	0.0	0
2	0.3	912.4	1131.4	0.0	0
3	0.3	904.5	1121.6	0.0	0
4	0.5	915.4	1135.1	0.0	0
5	49.0	899.1	1114.9	0.0	0
6	356.8	938.5	1163.7	0.0	0
7	990.8	1070.0	1326.8	0.0	0
8	1922.2	1152.7	1429.3	769.5	492.9
9	2866.6	1230.0	1525.3	1636.6	1341.3
10	3498.9	1267.3	1571.5	2231.6	1927.4
11	3838.4	1318.0	1634.4	2520.4	2204
12	3946.2	1313.3	1628.5	2632.9	2317.7
13	3943.6	1226.5	1520.8	2717.1	2422.8
14	3848.5	1205.3	1494.5	2643.2	2354
15	3536.3	1186.4	1471.1	2349.9	2065.2
16	2924.0	1182.3	1466.1	1741.7	1457.9
17	2086.1	1187.6	1472.7	898.5	613.4
18	1142.3	1191.3	1477.2	0.0	0
19	391.6	1206.1	1495.6	0.0	0
20	54.8	1243.4	1541.9	0.0	0
21	0.6	1294.5	1605.2	0.0	0
22	0.3	1252.2	1552.7	0.0	0
23	0.3	1155.2	1432.5	0.0	0
Energy sum (GWh):				20.14	17.20

The difference in the estimated storage power rating is slightly above 10%, which is lower than initially expected. By comparison, the difference in the required energy capacity is approximately 17%.

5. Conclusion

This paper presents a methodology for determining the required power rating and usable energy capacity of energy storage systems at seasonal, monthly, and daily timescales, necessary to support the large-scale deployment of PV systems. The methodology is based on available historical data of electricity generation and consumption, measured at hourly or 15-minute intervals, as well as projections of future consumption growth and deployment of various generation units.

The methodology comprises several steps. In the first step, the need for energy storage capacity at the monthly and seasonal levels is evaluated. If energy consumption exceeds the observed production, there is no requirement for installing seasonal or monthly storage. In the second step, the day with the maximum surplus of generated power over consumption is identified. This surplus can be used for the initial sizing of the storage system's power capacity. The next step involves identifying the day with the highest cumulative daily surplus of generated energy over consumption, which can subsequently be used to size the required daily energy storage capacity.

An extension of the basic methodology allows for consideration of projected generation and consumption profiles in the future. In this work, the methodology is applied in a case study of the Slovenian power system, focusing exclusively on consumption profiles, while generation is limited to PV output. This focus is motivated by the ambitious national PV deployment plan, which aims to increase installed PV capacity nearly fivefold over twelve years. Even without considering power system stability issues, it is important to estimate the required range of storage power and energy capacity prior to performing a detailed techno-economic analysis to identify the most suitable storage technologies.

Further development of the methodology should incorporate environmental and geospatial impacts, uncertainties and variations in input data, as well as sensitivity analysis. These improvements would enable more reliable sizing of energy storage systems.
The results presented in this work provide a preliminary estimation of the required power rating and energy capacity of storage systems, supporting an initial techno-economic evaluation of different energy storage technologies.

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