Flexibility in the low voltage PV-rich distribution network with demand response and BESS

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Abstract. *With the increase of electricity generation from variable renewable energy sources, such as photovoltaic (PV) systems and wind power plants, the flexibility of the power system is required. In this paper, the flexibility of the power system is demonstrated on the example of a PV-rich low-voltage (LV) distribution network. Sources of the flexibility implemented in this example include demand response (DR) and battery energy storage systems (BESS). Both sources of flexibility on their own significantly contribute to increasing the flexibility in the LV distribution network, while the best results were achieved with the simultaneous implementation of both sources.*

Keywords. Flexibility, Photovoltaic, PV-rich distribution network, Demand response, Battery energy storage system

1 Introduction

The energy sector is responsible for 75 % of greenhouse gas emissions in the European Union (EU) (European Commission, 2023), and to reduce greenhouse gas emissions, of which carbon dioxide is the most abundant, conventional fossil fuel-based energy sources are being replaced by low-carbon renewable energy sources (RES). The most represented RES used for electricity generation are wind power plants with 37.5 % and solar photovoltaic (PV) systems with 27.5 % (Eurostat, 2026). Despite the clean electricity, the mentioned RESs are characterized by the unpredictability and variability of electricity generation. Unlike conventional power systems, where electricity production follows and adapts to electricity demand, in power systems with a high share of electricity generation from unpredictable and variable RESs, it is the entire power system that adapts to fast and unpredictable changes in electricity generation. The ability of the power system to react quickly to rapid changes in electricity generation and demand, even when events are not predicted, is defined as the flexibility of the power system (Rahman et al., 2024).

According to (Babatunde et al., 2020), the flexibility of the power system refers to the level to which a power system is capable of adapting the generation and consumption of electricity. The definition of the International Energy Agency (IEA, 2019) emphasizes that the flexibility of the power system should be reliable and cost-effective. According to the International Renewable Energy Agency (IRENA, 2018), flexibility must be implemented in all parts of the power system, from flexible electricity generation, more flexible transmission and distribution systems, to more flexible demand and more installed storage capacity.

The implementation of flexibility at all levels of the power system is not enough on its own but requires interaction between all levels of the power system (Salman et al., 2022). In addition to the integration of variable RESs, the drivers of the flexibility of the power system are fluctuating fuel prices, especially the price of natural gas, and the uncertainty of electricity consumption, which is becoming even more pronounced with the increasing number of electric vehicles (EVs) (Kaushik et al., 2022). The main sources of flexibility are demand side management (DSM) and demand response (DR), energy storage systems, and flexible electricity generation (Babatunde et al., 2020). Some other sources of flexibility include the diversity of RESs, a dynamic capability assessment of power lines, new ancillary services, and restructuring the electricity market (Rahman et al., 2024). Active power curtailment and electricity price mechanisms can also be considered as sources of flexibility of the power system (Abrahamsen et al., 2026).

The number of PV systems installed in Croatia in February 2025 was 27,540, with a total installed power of 835 MW (TehnoEko, 2025). In October 2025, this number was increased to 38,947 PV systems, and the total installed power increased to 1106 MW (Lider, 2025). In the majority, PV systems are connected to low voltage (LV) distribution networks, and the significant increase in PV systems requires the need for flexibility in LV distribution networks. Distribution System Operators (DSOs) can use flexibility to avoid or post-

pone the high investments in network infrastructure, mainly in new transformers and power lines (Mehinovic et al., 2025).

The sources of flexibility that can be applied in LV distribution networks are DR and energy storage systems. The applications of sources of flexibility are demonstrated in this paper through power flow simulations of a PV-rich LV distribution network. In this work, the impact of DR and energy storage is analyzed based on results of power flow simulations for different scenarios. DR is achieved by shifting the real measured consumption profiles of household appliances. In addition to a separate analysis of the impact of DR and energy storage on the flexibility of the power system, the combined impact is also analyzed and compared with isolated impacts.

In the next chapter, the LV distribution network case study, input data, and the sources of flexibility are explained. In Chapter 3, results are presented and analyzed. The last chapter is the conclusion.

2 Flexibility in a PV-rich LV distribution network

The flexibility of the power system is demonstrated by simulation of the power flows in a PV-rich LV distribution network. Fig. 1 represents the schematic diagram of the LV distribution network used in the case study. There are 4 radial feeders with 10 grid users in each feeder, or 40 grid users in total. Of the 40 grid users, 20 are prosumers, and 20 are consumers.

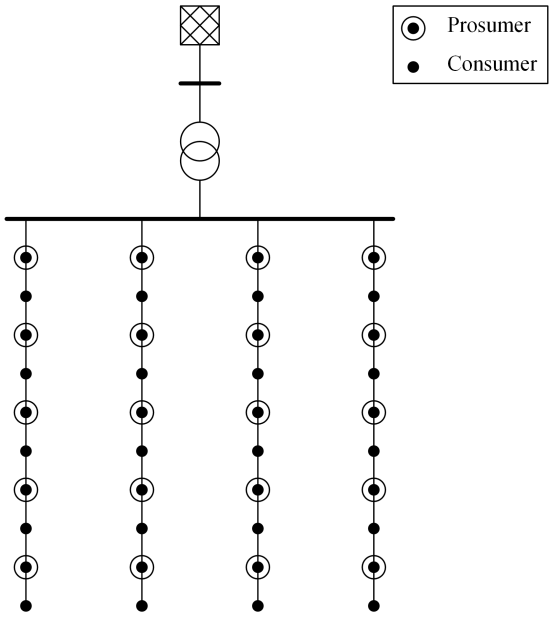

Figure 1. Low voltage distribution network

Consumers are grid users who buy electricity from the electricity supplier, while prosumers are grid users who produce electricity for their own needs from their own PV power plant. Each prosumer has a PV power plant connected behind the meter. In addition to a PV power plant, there is a battery energy storage system (BESS) that allows storing produced electricity and using it when electricity generation is not available.

Table 1 represents the parameters of the LV distribution network that include the rated power of each PV power plant. As the rated power of a PV power plant for each prosumer is 3 kW, the total installed PV power with 20 prosumers in the observed LV distribution network is 60 kW.

Table 1. Network parameters

Parameter	Value
Transformer ratio	20/0.4 kV
Transformer rated power	630 kVA
LV feeder length	120 m
LV cable type	NAVY 4x120 SE
PV rated power	3 kW
Total installed PV power	60 kW

2.1 Input data

The assumption that 10 households in one feeder have the same daily consumption profile is considered due to the simplification. As there are 4 feeders in the LV distribution grid, 4 different consumption profiles are represented. Different daily consumption profiles with a 15-minute time step are presented in Fig. 2. There is also a daily profile of electricity generation from a PV power plant on a clear, sunny day. The peak of electricity generation occurs in the middle of the day, while the peak of electricity consumption occurs in the evening. The electricity generation during a clear, sunny day is predictable and does not represent a challenge for distribution system operators in terms of the variability of the electricity generation as it is during cloudy days. A clear sunny day is selected as the worst scenario due to the highest difference between electricity generation and consumption.

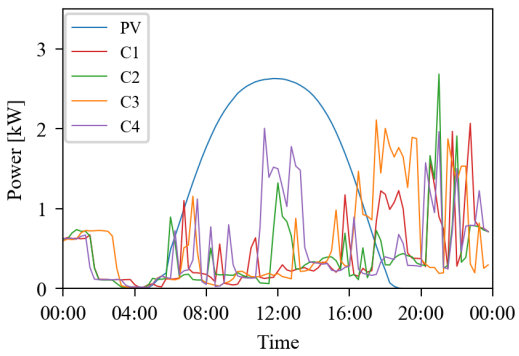

Figure 2. Daily consumption profiles and electricity generation from a PV power plant

2.2 Demand response

Time-shiftable devices are household appliances that can be used at any time of the day. The idea is to match the use of time-shiftable devices with the electricity generation. DR as a source of flexibility is shown in Fig. 3. A significant share of the electricity consumption in households is for domestic water heaters, which can also contribute to a demand-side flexibility (Seljom et al., 2024). Around 50 % of global energy consumption is for heating and cooling, and with smart control it can also contribute to demand-side flexibility (Parreño-Rodríguez et al., 2026).

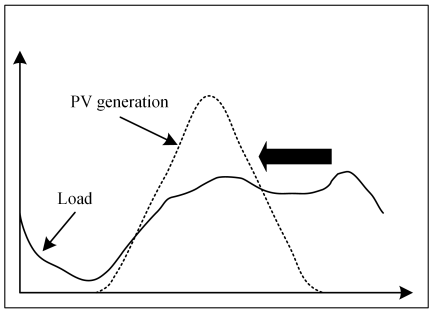

Figure 3. Demand response as the source of flexibility of the power system

DR in this study is achieved by shifting the time of use of the washing machine, tumble dryer, and dishwasher to a period with electricity generation. The daily electricity consumption for C1, C2, C3, and C4 are 10.3, 9.8, 13.4, and 12.1 kWh respectively. The electricity consumption of time-shiftable devices is 2.75 kWh, which represents 27, 28, 20, and 23 % of daily consumption, respectively. The daily electricity generation is 23 kWh, and the daily consumption of time-shiftable devices is equal to 12 % of the daily electricity generation. The daily consumption profiles of 4 different users, with a 15-minute time step, when the demand response is applied, are presented in Fig. 4. It can be seen that electricity consumption is better matched with electricity generation.

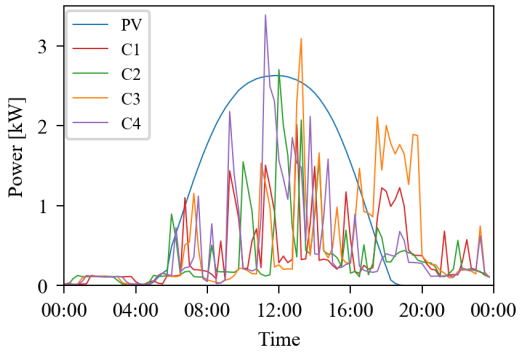

Figure 4. Daily consumption profiles with applied demand response

All prosumers and consumers participate in DR. Before DR, the start times for the washing machine and dishwasher were between 20:00 and 22:00, while the start time for the tumble dryer was after the end of the washing machine cycle. With DR, the washing machine start time is between 08:00 and 12:00, the dishwasher start time is between 12:00 and 14:00, while the tumble dryer start time is after the end of the washing machine cycle.

2.3 Energy storage

Energy storage is an important source of flexibility in the power system as it helps to balance variable electricity generation and consumption (Khalili et al., 2025). Different storage technologies are represented, such as pumped hydro, flywheels, compressed air, hydrogen, thermal storage, super capacitors, and batteries (Degefa et al., 2021). As a source of flexibility in the LV PV-rich distribution networks, BESSs are the most represented storage technology. Using BESS as a source of flexibility is presented in Fig. 5. The role of BESS is to store electricity generated from a PV power plant instead of exporting excess to the grid. The stored electricity can be used to supply electricity consumption instead of importing electricity from the grid.

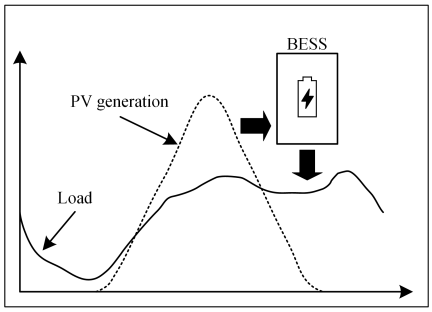

Figure 5. BESS as the source of flexibility of the power system

In this work, two different BESS capacities are used. A larger 10.24 kWh BESS is used when BESS is the only source of flexibility, and a smaller 5.12 kWh BESS is used when BESS and DR are sources of flexibility, Table 2 represents the parameters of BESS.

Table 2. BESS parameters

Parameter	Value
BESS capacity	100 Ah / 200 Ah
Rated voltage	51.2 V
Rated energy	5.12 kWh / 10.24 kWh
Maximum power	3 kW
Minimum SOC	0.2
Maximum SOC	1.0
Initial SOC	0.2
Final SOC	0.2

The rule-based algorithm of the BESS charging and discharging strategy is shown in the flow diagram in Fig. 6. The input data for the algorithm are the electricity generation and consumption data, while the output data are the BESS charging and discharging power.

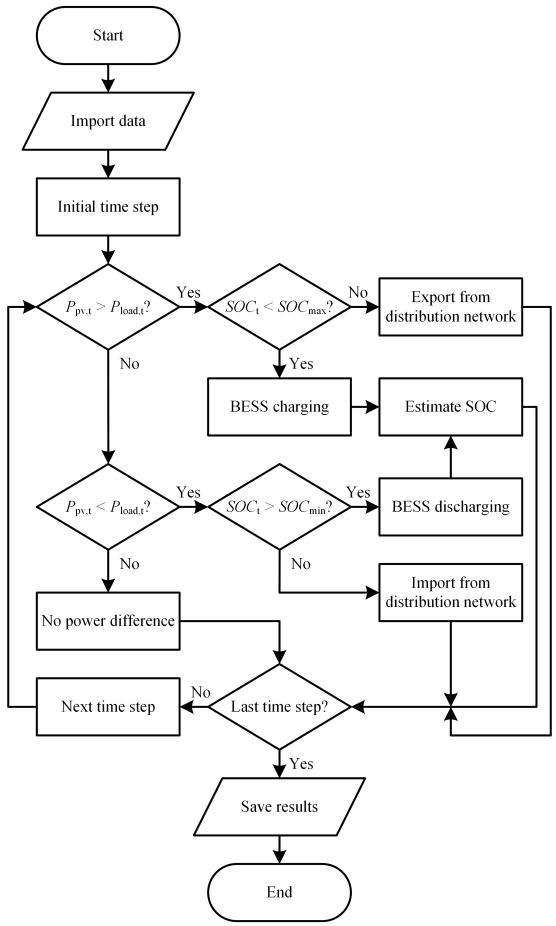

Figure 6. Flow diagram of the BESS charging and discharging strategy

2.4 Scenarios overview

Power flow simulations are performed for an initial scenario without PV power plants and for 4 different scenarios with integrated PV power plants, as presented in Table 3. In Scenario 1, there are no sources of flexibility. In Scenarios 2 and 4, the source of flexibility is the DR, while energy storage is the source of flexibility in Scenarios 3 and 4.

Table 3. Scenarios overview

Scenario	PV	DR	BESS
Initial	-	-	-
S1	+	-	-
S2	+	+	-
S3	+	-	+
S4	+	+	+

3 Results

In this section, the results are presented through five different scenarios described in the previous section. The scenarios are compared according to the electricity exchange with the main grid. Power flow simulations are conducted using Panda Power open-source software in a Python environment, with a 15-minute time step. In addition, the loading of the initial section of feeder 2 and the voltage at the end of feeder 2 are compared for different scenarios.

3.1 Scenario 1

The power of electricity generation and consumption in Scenario 1 is presented in Fig. 7. Between 06:30 and 17:00, more electricity is generated from PV power plants than is needed to cover the electricity demand.

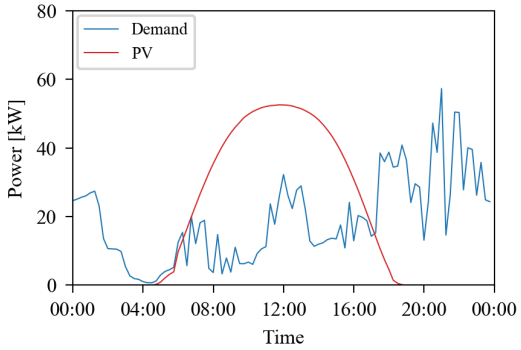

Figure 7. Electricity generation from PV power plants and electricity consumption in Scenario 1

Scenario 1 is compared to the initial scenario through a power exchange with the main grid, as shown in Fig. 8. In the initial scenario, the exchange power is positive for the entire day, which indicates that electricity is imported from the main grid for the entire day. In Scenario 1, negative power occurs between 06:30 and 17:00, which indicates that an excess of produced electricity is exported to the main grid.

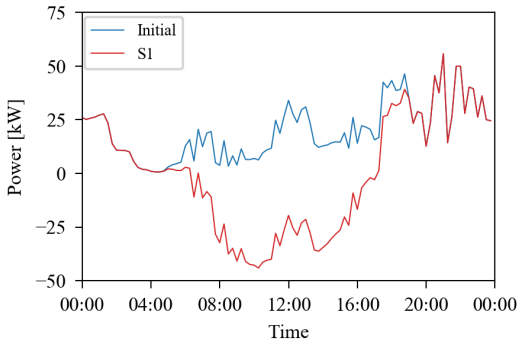

Figure 8. Exchange with the main grid in Scenario 1

3.2 Scenario 2

In Scenario 2, the DR is applied and part of the electricity consumption is shifted from evening to midday. The higher electricity consumption during the day and the lower electricity consumption in the evening are more in line with the daily electricity generation curve, as shown in Fig. 9.

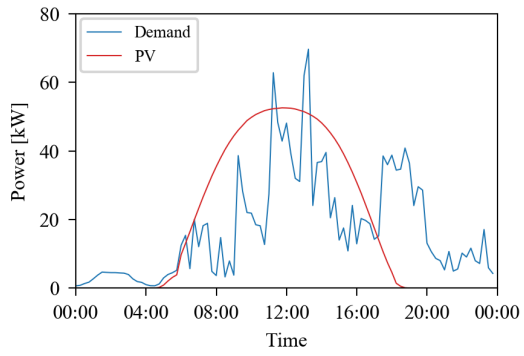

Figure 9. Electricity generation from PV power plants and electricity consumption in Scenario 2

With DR in Scenario 2, between 09:00 and 15:30, less electricity is exported than in Scenario 1, as presented in Fig. 10. In the evening, from 20:00 to 00:00, the amount of imported electricity is decreased compared to Scenario 1.

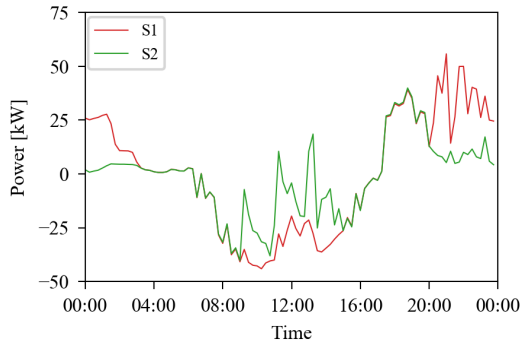

Figure 10. Exchange with the main grid in Scenario 2

3.3 Scenario 3

In Scenario 3, the source of flexibility is BESS. In Fig. 11, the positive power of BESS indicates charging, while the negative power of BESS indicates discharging. Charging during a period of high electricity generation and low electricity consumption helps reduce the amount of electricity exported to the main grid, which can be seen in Fig. 12 as a decrease in the power of exported electricity in Scenario 3. However, BESS discharge after 17:30 helps reduce the amount of imported electricity from the main grid when there is not enough electricity generation.

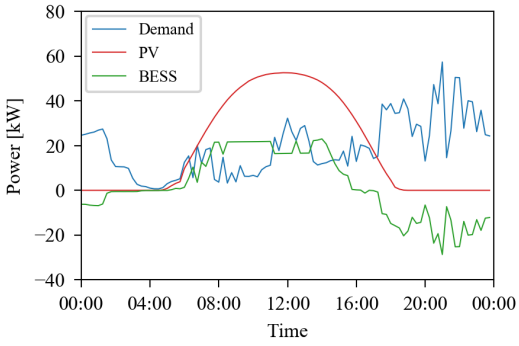

Figure 11. Electricity generation, consumption and BESS utilization in Scenario 3

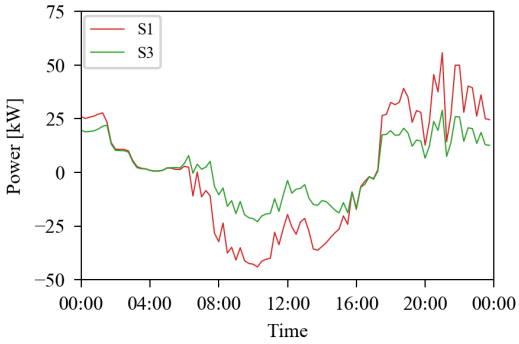

Figure 12. Exchange with the main grid in Scenario 3

3.4 Scenario 4

The sources of flexibility in Scenario 4 are DR and BESS. As electricity demand shifts to the period with high electricity generation, BESS is discharged between 17:30 and 20:00 when consumption is high, compared to Scenario 3, when BESS is discharged between 17:30 and 00:00, as can be seen in Fig. 13.

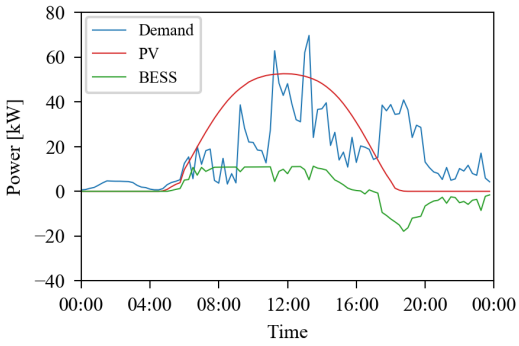

Figure 13. Electricity generation, consumption and BESS utilization in Scenario 4

From the comparison of the exchange power in Scenario 1 and Scenario 4, presented in Fig. 14, it can be seen that the amount of electricity exported to the main grid is significantly lower in Scenario 4 compared

to Scenario 1. However, the amount of electricity imported from the main grid in the period between 17:30 and 00:00 is significantly lower in Scenario 4 compared to Scenario 1.

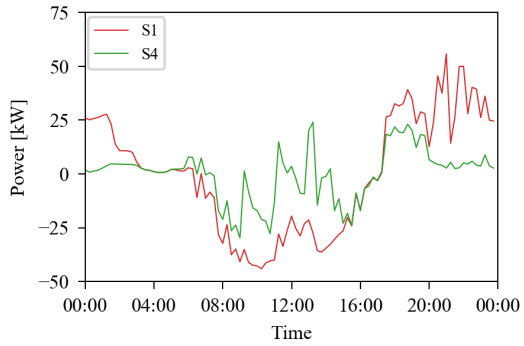

Figure 14. Exchange with the main grid in Scenario 4

The amount of electricity exchanged with the main grid for an entire day is presented in Table 4. In Scenario 2, the DR leads to a significant reduction in imported electricity. In Scenario 3, the use of BESS results in a greater reduction in exported electricity. However, the best results are achieved with DR and BESS as sources of flexibility. The total amount of imported electricity in Scenario 4 is 499 kWh, which is 58 % lower than in Scenario 1 and 74 % lower than in the initial scenario. The total amount of electricity exported in Scenario 4 is 398 kWh, which is a 63 % decrease compared to Scenario 1.

Table 4. Electricity exchange

Scenario	Import [kWh]	Export [kWh]
Initial	1954	0
S1	1193	1082
S2	637	687
S3	753	456
S4	499	398

Due to the large cross-sectional area of LV cables, the line loading is not high, as can be seen in Fig. 15. The highest line loading occurs in the evening when electricity consumption is high. The implementation of BESS in Scenario 3 slightly contributes to the reduction of the line loading, while the impact of DR on the line loading in Scenarios 2 and 4 is more significant. However, the line loading increase caused by PV integration can be significantly reduced with DR and also with BESS. Fig. 16 represents the voltage at the end of feeder 2, and due to the short length of the feeders, the voltage variations are not significant. The voltage drop in the evening improves slightly when BESS is applied in Scenario 3 and more significantly when DR is applied in Scenarios 2 and 4. The voltage increase caused by PV integration can be reduced with BESS and also with DR.

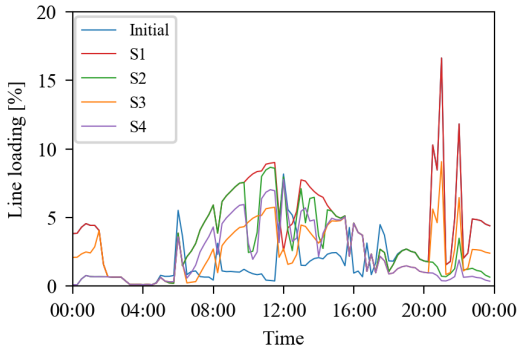

Figure 15. Loading of the first line section in feeder 2

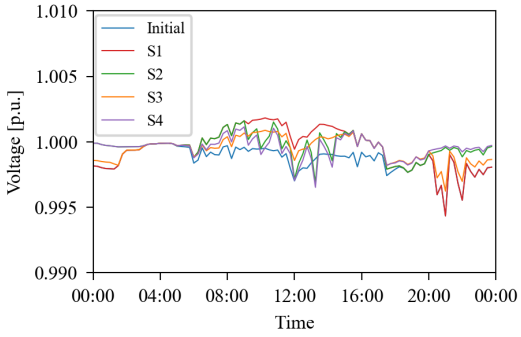

Figure 16. Voltage at the end of feeder 2

4 Conclusion

With the increase in variable and intermittent RESs, there is an increasing need for flexibility of the power system. The focus of this work is on the flexibility in the LV distribution network with a significant increase in the number of installed PV power plants. The sources of flexibility in the PV-rich LV distribution network in the case study are DR and BESS. The impact of flexible sources was evaluated according to the exchange of electricity with the main grid. Although the contribution of DR is more visible in the reduction of electricity imported from the main grid, the contribution of BESS is more significant in the reduction of electricity exported to the main grid. The contribution of DR and BESS together as sources of flexibility is significant in the reduction of imported and exported electricity.

In recent years, the number of EVs has increased, which has contributed to an increase in total electricity consumption. Future work may include EVs as sources of flexibility in LV distribution networks. As domestic water heaters and room heating and cooling have a significant share in electricity consumption, their contribution to flexibility in PV-rich LV distribution networks should be investigated in future work.

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