Energy management strategy with maximum grid consumption level and supplementary energy sources for grid-connected charging stations

Matej Tkac [1*], *Filip* Petrik[1], *Martin* Matejko[1], and *Peter* Bracinik[1]

[1]Department of Power Systems and Electric Drives, University of Zilina, FEIT, Zilina, Slovakia

Abstract. The expanding growth of electric vehicle (EV) adoption and the expansion of charging infrastructure introduce new operational challenges for low-voltage distribution networks. To mitigate potential grid overload and stability issues, this paper proposes an advanced energy management strategy (EMS) for grid-connected charging stations equipped with optimally sized local energy resources. The developed control algorithm operates with a 15-minute resolution, enabling real-time optimization of power exchange between the grid and complementary energy sources. By enforcing predefined maximum grid consumption limits, the proposed strategy effectively reduces the dependency on external power supply and alleviates stress on the electrical network. The EMS was simulated and evaluated on two types of charging stations (residential and public), demonstrating its ability to maintain stable operation while supporting efficient and sustainable EV charging.

1 Introduction

With year-to-year electric vehicle (EV) sales increasing by more than 25% globally in 2024 and continuing to rise in the first quarter of 2025 [1], [2], a further growth in sales is expected in the coming years. This rapid increase in EV adoption and utilization, combined with decarbonization goals, may lead to potential challenges for the electrical network. Some of the main problems are the increase in total energy demand [3], [4], altered load patterns [5] and the increased power losses or problems with the power quality of the electrical network [6], [7], [8]. To mitigate these issues, innovative models and strategies are required. One significant strategy for minimizing the impact of EV charging on the electrical network involves implementing coordinated and optimized charging algorithms as presented in [9], [10] and [11]. A methodology for optimally allocating renewable energy to maximize social welfare using incentive mechanisms is proposed in the study [9]. This methodology is for a centralized EV charging control system. The investigation in [10] presents a dynamic intelligent EV recharging enhancement strategy based on a consensus-driven Proof of Need process, employing real-time information to harmonize grid load and reduce maximum demand. The study [11] employs a data-driven forecasting methodology based on machine learning models trained using high-resolution, hourly EV charging and grid data.

This paper proposes the use of an energy management strategy (EMS) in combination with a predefined maximum consumption limit (MCL) and optional supplementary energy sources as a tool to mitigate potential problems associated with EV charging. The presented system is based on [12] where the EMS and MCL were defined and tested on a simulation model with an hour time step. This paper tested the proposed EMS on a simulation model with 15-miute time step. Additionally, this paper presents an optimization algorithm for optimal sizing of a photovoltaic system (PVS) and a battery energy storage system (BESS).

The rest of the paper is organized as follows. Section 2 describes the simulation model of the electric vehicle charging station system. Section 3 defines the energy management strategy for the electric vehicle charging station system. Section 4 defines the optimization strategy for sizing supplementary energy sources. Section 5 presents results from simulated operational scenarios of the electric vehicle charging station system, and finally, section VI concludes the paper.

2 Model of electric vehicle charging station

To evaluate the EMS and the support mechanisms presented in this paper, a simulation model of an electric vehicle charging station (EVCS) system was constructed. The modeled EVCS system represents an energy system consisting of several interconnected components, including energy sources and loads. The EVCS system used for testing comprises a charging station connected to the electrical network with a

* Corresponding author: matej.tkac@uniza.sk

predefined MCL, a PVS, and a BESS. The connected PVS and BESS serve as supplementary local energy sources for EV charging, while the electrical network remains the main energy source. The MCL is defined through an agreement with the distribution system operator (DSO), limiting the maximum power drawn from the electrical network and EMS is ensuring that the agreed limit is not exceeded. This agreement helps manage fluctuations in power consumption measured or expected in the EVCS system. To ensure realistic operation of the modeled system, historical weather data were used to calculate the PVS output [13]. Additionally, two sets of historical charging data were applied to simulate utilization of residential [14] and public [15] charging stations for EMS testing. For both charging station types, the model includes 10 Level 2 charging points, each with a maximum charging power of 11 kW.

A visual representation of the simulation model for the EVCS system used in this paper is shown in Figure 1.

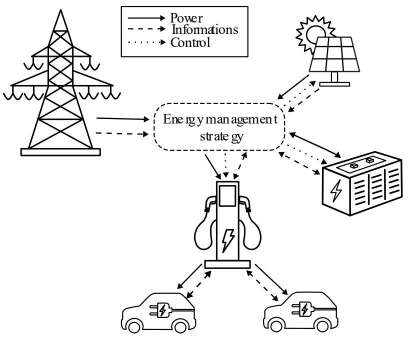

Fig. 1. Illustration of the EVCS system operational layout

3 Energy management strategy for grid-connected charging stations

The energy management strategy developed for grid-connected charging stations is designed to manage energy flows during EV charging and to distribute available energy among the connected sources within the charging station system. The EMS operates as a quasi-real-time control algorithm, updating all relevant system information at each 15-minute time step. To achieve the desired EMS performance, three main objectives are defined and must be considered during the management process:

- minimizing the difference between the charging demand and the energy from available local energy sources,
- maximizing the utilization of the local energy sources,
- maximizing the power delivered for EV charging.

Based on these objectives, the EMS computes the optimal distribution of charging power among all EVs connected to the charging station, ensuring maximal charging performance while ensuring the maximal utilization of local energy sources and maintaining power balance. The optimization problem is solved using the predefined optimization function "fmincon" in MATLAB software [16].

Depending on the state of the charging station at each time step, the EMS selects one of two objective functions. The selection is based on whether at least one EV is connected. The decision logic is visualized in Figure 2, and can be expressed as:

$$if\ n_{EV}(t) = 0 \begin{cases} true \rightarrow F_1(t) \\ false \rightarrow F_2(t) \end{cases} \quad (1)$$

where $n_{EV}(t)$ [-] is the number of EVs connected to the charging station at time step t, F_1(t) is the first objective function and F_2(t) is the second objective function.

When no EVs are connected, the EMS applies the first objective function F_1(t), which manages only the utilization and operation of local energy sources. In this case, the power output from the PVS is used to charge the BESS, maximizing PVS utilization. The objective function is defined as:

$$F_1(t) = \min_{P_{PV}(t), P_{BESS}(t)} \left(\left(P_{PV}(t) - P_{BESS}(t) \right)^2 - \gamma_1 \cdot P_{PV}(t) \right) \quad (2)$$

where $P_{PV}(t)$ [kW] is the utilized power from the PV system at time step t, $P_{BESS}(t)$ [kW] is charging/discharging power of the BESS at time step t (in simulation results, discharging is indicated by negative values) and $\gamma 1$ [-] is the weighted parameter used for the optimization.

The constraints considered for the first objective function are defined as:

$$P_{BESS}^{-} \leq P_{BESS}(t) \leq P_{BESS}^{+}, \quad (3)$$

$$0 \leq P_{PV}(t) \leq P_{PVout}(t), \quad (4)$$

$$P_{BESS}(t) \leq P_{PV}(t), \quad (5)$$

$$if\ SoC_{BESS}(t) \cdot C_{BESS} = C_{BESS} \begin{cases} true & P_{PV}(t) \leq 0 \\ false & 0 \end{cases} \quad (6)$$

$$SoC_{BESS}^{-} \leq SoC_{BESS}(t) + \frac{P_{BESS}(t) \cdot \eta_{BESSc}}{C_{BESS}} \leq SoC_{BESS}^{+}, \quad (7)$$

where P_{BESS}^{-} [kW] and P_{BESS}^{+} [kW] are the maximal discharging and charging power limits of the BESS respectively, P_{PVout} [kW] is the PV system output power, $SoC_{BESS}(t)$ [pu] is the state-of-charge (SoC) of the BESS at time step t, C_{BESS} [kWh] is the capacity of the BESS, SoC_{BESS}^{-} [pu] and SoC_{BESS}^{+} [pu] are the minimal and maximal SoC values of the BESS, respectively, and η_{BESSc} [%] is the charging efficiency of the BESS.

The second objective function F_2(t) is applied when one or more EVs are connected to the charging station. In this case, the EMS coordinates EV charging, manages the utilization of the PVS and the BESS, and regulates power consumption from the electrical network. The objective function is defined as follows:

$$F_2(t) = \min_{P_{Grid}(t), P_{PV}(t), P_{BESS}(t), \boldsymbol{P}_{EV}(t)} \begin{pmatrix} \begin{pmatrix} P_{Grid}(t) + P_{PV}(t) \\ -P_{BESS}(t) - \sum \boldsymbol{P}_{EV}(t) \end{pmatrix}^2 \\ -\gamma_1 \cdot P_{PV}(t) \\ -\gamma_2 \cdot \sum \boldsymbol{P}_{EV}(t) \end{pmatrix} \quad (8)$$

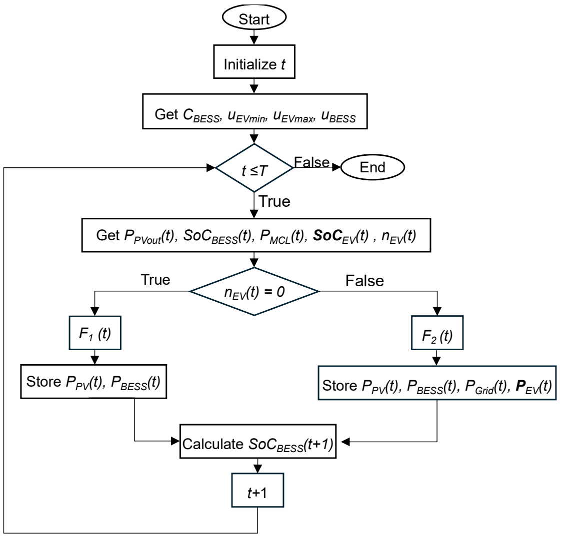

Fig. 1. Flow chart of EMS operation

where $P_{Grid}(t)$ [kW] is the utilized power from the electrical network at time step t and $\sum \boldsymbol{P}_{EV}(t)$ [kW] is the sum of power supplied for charging of all EVs connected to the charging station at time step t.

The constraints considered for the second objective function are defined as:

(3) – (6)

$$0 \leq P_{Grid}(t) \leq P_{MCL}(t) \quad (9)$$

$$P_{EVmin} \cdot z \leq P_{EV,i}(t) \leq P_{EVmax} \cdot z \quad (10)$$

$$if \left(\left(P_{MCL}(t) + P_{PVout}(t) + SoC_{BESS}(t) \cdot C_{BESS}\right) > P_{EVmin} \wedge SoC_{EV,i}(t) < 0.98 \right) \begin{cases} true & z = 1 \\ false & z = 0 \end{cases} \quad (11)$$

$$0 \leq SoC_{EV,i}(t) + \frac{P_{EV,i}(t)}{C_{EV,i}} \cdot \eta_{EV} \leq 1 \quad (12)$$

$$if \left(\left(SoC_{BESS}(t) \cdot C_{BESS}\right) + P_{PV}(t) > \sum_{i=1}^{n_{EV}(t)} P_{EV,i}(t) \right) \wedge \left(\sum_{i=1}^{n_{EV}(t)} P_{EV,i}(t) \leq P_{BESS} + P_{PVout}(t) \right) \begin{cases} true & P_{Grid}(t) \leq 0 \\ false & P_{Grid}(t) \leq \sum P_{EV}(t) - \left(P_{PV}(t) - P_{BESS}(t)\right) \end{cases} \quad (13)$$

$$-P_{BESS}(t) + P_{PV}(t) + P_{Grid}(t) + \sum_{i=1}^{n_{EV}(t)} P_{EV,i}(t) \leq 0 \leq -P_{BESS}(t) + P_{PV}(t) + P_{Grid}(t) - \sum_{i=1}^{n_{EV}(t)} P_{EV,i}(t) \quad (14)$$

$$if\ P_{Grid} > 0 \begin{cases} true & P_{Grid}(t) \leq \sum P_{EV}(t) \\ false & 0 \end{cases} \quad (15)$$

where $P_{MCL}(t)$ [kW] is the MCL value defined at time step t, P_{EVmin} [kW] and P_{EVmax} [kW] are minimal and maximal technical charging powers usable to charge EVs, respectively, z [-] is a parameter used to decide if the EV can be charged, $P_{EV,i}(t)$ [kW] is the charging power of i^{th} EV connected to the EVCS at time step t, $SoC_{EV,i}(t)$ [pu] is SoC of i^{th} EV connected to the EVCS at time step t, $C_{EV,i}$ [kWh] is the battery capacity of i^{th} EV connected to the charging station, and η_{EV} [%] is the charging efficiency of EVs.

4 Optimal sizing of photovoltaic and battery energy storage system for electric vehicle charging station

Another important aspect of minimizing the negative impact of EVCS operation on the electrical network, namely the mitigation of consumption volatility, is the integration of PVSs and BESSs into charging infrastructure. To ensure effective utilization of both the PVS and BESS, maintain customer satisfaction, and support economic feasibility, it is necessary to employ methods for their optimal sizing. Therefore, this paper presents an optimization framework for determining the optimal sizes of the PV system and BESS used in the simulated EVCS model. The proposed optimization is based on one-year simulation of EVCS operation in baseline operation (operation without the support mechanisms) and an evaluation of system performance according the defined criteria.

To determine the optimal PVS and BESS sizes for the EVCS simulation model, an optimization function incorporating four key parameters was defined. These parameters represent essential aspects of optimizing the supplementary energy sources. The first parameter is the total operational cost of the simulated system ($Cost_{systemtotal}$[€]). The next two parameters are the utilization of the PVS (U_{PV}[%]) and the BESS (U_{BESS}[%]), and the final parameter is the load satisfaction (L_{sat} [%]), representing the proportion of EV charging demand successfully met. The optimization function is defined as:

$$F(t) = \min_{Size_{PV}, Size_{BESS}} \begin{pmatrix} \omega_1 \cdot Cost_{systemtotal} - \omega_2 \cdot U_{PV} \\ -\omega_3 \cdot U_{BESS} - \omega_4 \cdot L_{sat} \end{pmatrix} \quad (16)$$

where $Size_{PVS}$ [kW] and $Size_{BESS}$ [kWh] are the optimal sizes of the PVS and BESS, respectively, and $\omega_1, \omega_2, \omega_3, \omega_4$ [-] are the weight parameters used for the optimization.

Since the optimization parameters differ in units and scales, normalization was applied. Through this process, all objectives were transformed into a unified minimization problem. The normalization of each objective is defined as follows:

$$f_1 = \frac{Cost_{systemtotal} - Cost_{systemtotal}^{min}}{Cost_{systemtotal}^{max} - Cost_{systemtotal}^{min}} \quad (17)$$

$$f_2 = \frac{U_{PV}^{max} - U_{PV}}{U_{PV}^{max} - U_{PV}^{min}} \quad (18)$$

$$f_3 = \frac{U_{BESS}^{max} - U_{BESS}}{U_{BESS}^{max} - U_{BESS}^{min}} \quad (19)$$

where $Cost_{systemtotal}^{min}$[€] and $Cost_{systemtotal}^{max}$ [€] are the maximal and minimal permissible total operational costs of the system, U_{PV}^{max} [%] and U_{PV}^{min} [%] are the minimal and maximal permissible PV system utilization values, U_{BESS}^{max} [%] and U_{BESS}^{min} [%] are minimal and maximal permissible BESS utilization values, and L_{sat}^{max} [%] and L_{sat}^{min} [%] are the maximal and minimal permissible load satisfaction values.

Based on the normalized values the equation (16) can be defined as:

$$F(t) = \min_{Size_{PV}, Size_{BESS}} (\omega_1 \cdot f_1 + \omega_2 \cdot f_2 + \omega_3 \cdot f_3 + f_4), \quad (20)$$

The optimization constraints used for the optimization process are such as:

$$Size_{PV}^{min} \leq Size_{PV} \leq Size_{PV}^{max} \quad (21)$$

$$Size_{BESS}^{min} \leq Size_{BESS} \leq Size_{BESS}^{max}, \quad (22)$$

$$Cost_{systemtotal} \leq Cost_{systemtotal}^{max}, \quad (23)$$

$$U_{PV}^{min} \leq U_{PV} \leq U_{PV}^{max}, \quad (24)$$

$$U_{BESS}^{min} \leq U_{BESS} \leq U_{BESS}^{max}, \quad (25)$$

where $Size_{PV}^{min}$ [kW] and $Size_{PV}^{max}$ [kW] are the minimal and maximal sizes of the PV system, $Size_{BESS}^{min}$[kWh] and $Size_{BESS}^{max}$ [kWh] are the minimal and maximal sizes of BESS.

5 Simulation results of charging station operation with proposed mechanisms

To validate the effectiveness of the presented EMS for the EVCS system and to assess the optimal sizing of supplementary energy sources, several operational scenarios were simulated. These scenarios include the baseline operation of the EVCS system, in which none of the mechanisms introduced in this paper were applied. Results from the baseline scenario also serve as reference values for evaluating the optimized supplementary energy sources. The second scenario represents the operation of the EVCS system with the proposed EMS but without supplementary energy sources. The final scenario evaluates the EVCS system equipped with both the EMS and optimally sized supplementary energy sources. The proposed mechanisms were tested on two different charging station types to further evaluate EMS performance. All scenarios were simulated over a one-year period with a 15-minute time step, enabling detailed observation of system behavior.

5.1 Baseline operational scenarios of the EVCS system

The baseline scenario represents EVCS system operation in a configuration where the EVCS system operator does not consider the impact of charging demand on the electrical network. It is assumed that the low-voltage network to which the EVCS system is connected has sufficient capacity and that no control strategy is applied. Consequently, EVs charge freely according to user needs. Under these conditions, customers satisfaction can be considered maximal, as no external imposed limitations influence the charging process.

Figure 3 illustrates the annual power consumption profile of the residential EVCS system. As shown, the EVCS system exhibits highly volatile and uncoordinated power demand, with several peak events randomly distributed throughout the year. A similar consumption profile is observed for the public EVCS system, presented in Figure 4. The total annual energy consumption in the baseline scenario reached 241.51 MWh for the residential system and 224.9 MWh for the public system. These differences arise from typical utilization patterns of the two station types.

Figures 5 and fig. 6 further demonstrate the distinct daily consumption profiles. Residential charging sessions primarily occur during late afternoon and evening hours and typically last longer. In contrast, public charging stations are mainly utilized during daytime hours for shorter sessions.

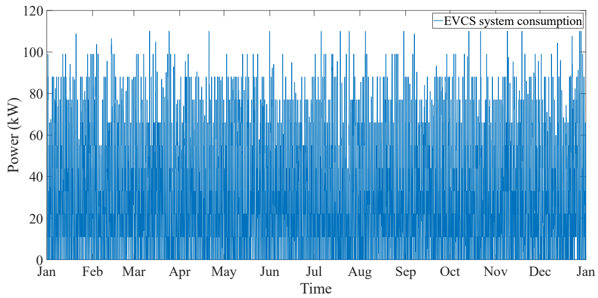

Fig. 3. Power consumption of the residential EVCS system over a one-year

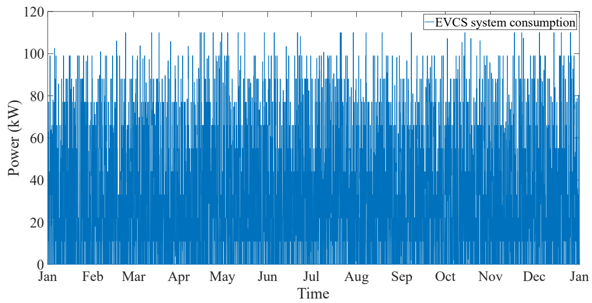

Fig. 4. Power consumption of the public EVCS system over a one-year

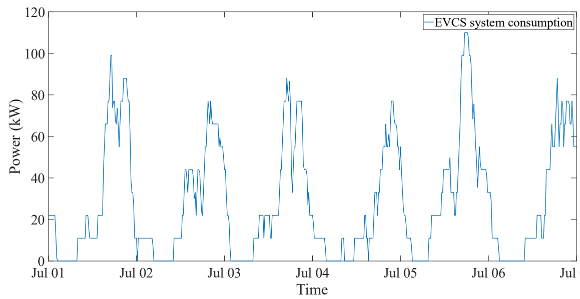

Fig. 5. Power consumption of the residential EVCS system over one week in July

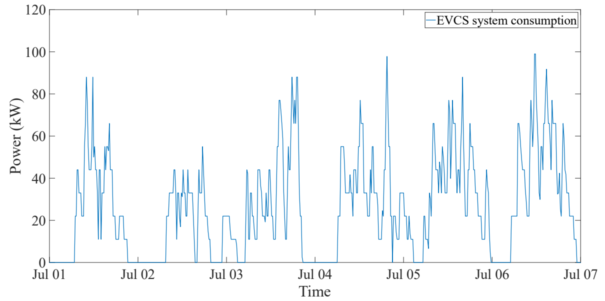

Fig. 6. Power consumption of the public EVCS system over one week in July

Based on the EVCS utilization data, 74.42% of charging sessions in the residential system concluded with a final EV battery SoC in the range 95-100%. For the public system, this proportion was 43.14%, as summarized in Table 1. As was mentioned, since no limitations were applied, it is assumed that customers were fully satisfied with their final SoC values.

Table 1. The SoC of EVs connected to the EVCS system in the baseline scenario

SoC range (pu)	Residential		Public	
	Initial SoC (No./%)	Final SoC (No./%)	Initial SoC (No./%)	Final SoC (No./%)
0.95-1	0	4574/74.42	0	5126/43.14
0.9-0.95	0	336/5.47	0	702/5.91
0.85-0.9	0	327/5.32	684/6.08	732/6.16
0.8-0.85	0	281/4.57	748/6.65	612/5.15
0.75-0.8	352/5.73	211/3.43	822/7.31	605/5.09
0.7-0.75	303/4.93	178/2.9	796/7.08	617/5.19
0.65-0.7	270/4.39	129/2.1	754/6.71	569/4.79
0.6-0.65	256/4.17	67/1.09	765/6.8	522/4.39
0.55-0.6	226/3.68	36/0.58	785/6.98	483/4.07
0.5-0.55	211/3.43	6/0.1	693/6.16	462/3.89
0.45-0.5	902/14.68	1/0.02	726/6.46	383/3.22
0.4-0.45	786/12.79	0	749/6.66	345/2.9
0.35-0.4	675/10.98	0	707/6.29	247/2.08
0.3-0.35	576/9.37	0	687/6.11	213/1.79
0.25-0.3	507/8.25	0	676/6.01	151/1.27
0.2-0.25	409/6.65	0	601/5.35	74/0.62
0.15-0.2	378/6.15	0	554/4.93	35/0.29
0.1-0.15	295/4.8	0	497/4.42	4/0.03

5.2 EVCS system operation with the proposed EMS and defined MCL

In this scenario, the distribution system operator (DSO) imposes a maximum consumption limit (MCL) on the EVCS system to ensure stable operation of the electrical network. The EMS is therefore responsible for controlling power flow and EV charging in order to ensure that the defined MCL is not exceeded. Exceeding the MCL would result in financial penalties for the EVCS operator.

Figure 7 presents the annual consumption profiles for both residential and public EVCS systems, highlighting the system's adherence to the MCL of 55 kW (red line). In both cases, the EMS successfully maintains consumption below the defined limit. Imposing an MCL inherently restricts the total charging power available, which can negatively affect customer satisfaction. However, the EMS partly mitigates this issue by optimally distributing the available power. This is reflected in total energy consumption, where the residential system consumed 233 MWh (a reduction of only 3.5% compared to the baseline), while the public system consumed 207.06 MWh (a reduction of 7.93%). The higher reduction in the public system is likely due to shorter connection times, which limit the EMS's ability to redistribute charging demand.

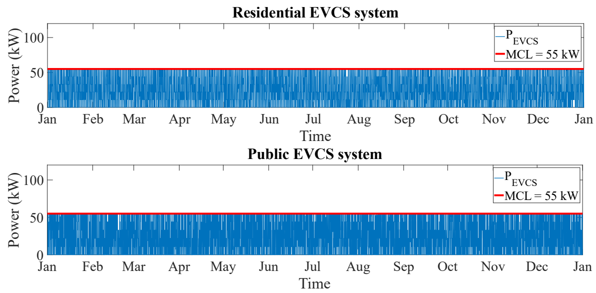

Fig. 7. Power consumption of the residential and public EVCS systems with proposed EMS and defined MCL over a one-year period

A more detailed view of customer satisfaction differences can be seen by examining the final SoC values. As shown in Table 2 and compared with Table 1, the number of charging sessions reaching high final SoC values decreased in both systems. This demonstrates the trade-off between adhering to network constraints and maintaining high charging satisfaction.

Table 2. The SoC of EVs connected to the EVCS system in the scenario with proposed EMS and defined MCL

SoC range (pu)	Residential		Public	
	Initial SoC (No./%)	Final SoC (No./%)	Initial SoC (No./%)	Final SoC (No./%)
0.95-1	0	4300/69.96	0	4605/38.76
0.9-0.95	0	292/4.75	0	726/6.11
0.85-0.9	0	331/5.39	684/6.08	693/5.83
0.8-0.85	0	347/5.65	748/6.65	687/5.78
0.75-0.8	352/5.73	250/407	822/7.31	617/5.19
0.7-0.75	303/4.93	238/3.87	796/7.08	684/5.76
0.65-0.7	270/4.39	185/3.01	754/6.71	588/4.95
0.6-0.65	256/4.17	105/1.71	765/6.8	564/4.75
0.55-0.6	226/3.68	55/0.89	785/6.98	493/4.15
0.5-0.55	211/3.43	29/0.47	693/6.16	509/4.28
0.45-0.5	902/14.68	5/0.08	726/6.46	470/3.96
0.4-0.45	786/12.79	6/0.1	749/6.66	406/3.42
0.35-0.4	675/10.98	2/0.03	707/6.29	285/2.4
0.3-0.35	576/9.37	1/0.02	687/6.11	231/1.94
0.25-0.3	507/8.25	0	676/6.01	174/1.46
0.2-0.25	409/6.65	0	601/5.35	97/0.81
0.15-0.2	378/6.15	0	554/4.93	43/0.36
0.1-0.15	295/4.8	0	497/4.42	10/0.08

5.3 Simulations of the EVCS system with the proposed EMS, optimally sized PVS and BESS, and a defined MCL

To increase the number of fully charged EVs without exceeding the MCL (55 kW) defined by the DSO, it is necessary to integrate supplementary energy sources capable of providing additional energy for EV charging. Therefore, optimization algorithms were designed which, based on the optimization function (20), determine the required size of the PVS and BESS for the

EVCS system operation. Based on the optimization results for the residential EVCS system, the PVS was sized to 80 kWp and the BESS to 200 kWh. For the public EVCS system, the PVS was sized to 113 kWp and the BESS to 22 kWh.

To manage power flow among the connected energy sources and to control charging of the BESS and EVs, the proposed EMS is applied. In Figures 8 and Fig. 9, the power flow among the integrated energy sources over one week in July is shown for both EVCS types. From the power curves, it is evident how the EMS coordinates the operation of all interconnected sources to supply energy for EV charging while addressing the optimization problem. The figures also show that the power drawn from the electrical network (magenta line) remains below the defined MCL, demonstrating that the EMS is capable of maintaining compliance with network constraints even under more complex system conditions and different charging behaviors.

Table 3 summarizes the total annual energy balance from individual energy sources and the total consumption of each EVCS system. As shown, both EVCS system types exhibit an increase in total energy consumption. The table also illustrates how the individual sources contributed to covering the EVCS demand. However, when comparing the total energy consumption to the scenario without supplementary energy sources, the residential EVCS system experiences only a minor increase. This is reflected in the relatively small improvement in customer satisfaction (table 4), despite the integration of a relatively large PVS and BESS. This discrepancy is primarily attributable to the temporal mismatch between PVS generation peaks and the utilization characteristic of the residential EVCS system, which peaks predominantly in the late afternoon and evening.

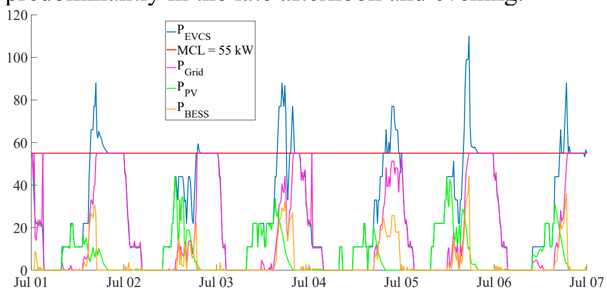

Fig. 2. Power flow in the residential EVCS system with supplementary energy sources and defined MCL over one week in July

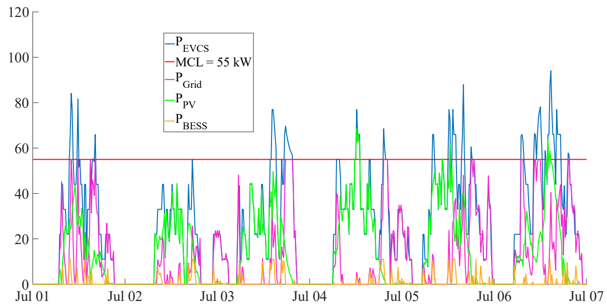

Fig. 3. Power flow in the public EVCS system with supplementary energy sources and defined MCL over one week in July

Conversely, the public EVCS system benefits more substantially from the additional energy sources. The alignment of PVS generation with daytime charging demand enables a more efficient utilization of the supplementary sources, leading to a marked increase in total delivered energy and a significant improvement in the final SoC values of connected EVs. Compared to the baseline scenario, the system achieves a reduction of only 2.22% in total annual consumption, indicating that the addition of PV and BESS nearly compensates for the imposed MCL constraint.

Table 3. Summary of total energy balance from individual sources and consumption for both EVCS systems

CS type	Total EVCS consumption (MWh)	Total energy from grid (MWh)	Total energy from PVS (MWh)	Total energy from BESS (MWh)
Residential	237.57	188.87	30.25	18.47
Public	219.91	137.34	75.22	7.58

Table 4. The SoC of EVs connected to the EVCS system in the scenario with proposed EMS, optimally sized PV system and BESS, and defined MCL

SoC range (pu)	Residential		Public	
	Initial SoC (No./%)	Final SoC (No./%)	Initial SoC (No./%)	Final SoC (No./%)
0.95-1	0	4388/71.4	0	4939/41.57
0.9-0.95	0	308/5.01	0	713/6
0.85-0.9	0	343/5.58	684/6.08	719/6.05
0.8-0.85	0	298/4.85	748/6.65	643/5.41
0.75-0.8	352/5.73	252/4.1	822/7.31	613/5.16
0.7-0.75	303/4.93	226/3.68	796/7.08	647/5.45
0.65-0.7	270/4.39	160/2.6	754/6.71	566/4.76
0.6-0.65	256/4.17	96/1.56	765/6.8	527/4.44
0.55-0.6	226/3.68	48/0.78	785/6.98	480/4.04
0.5-0.55	211/3.43	18/0.29	693/6.16	485/4.08
0.45-0.5	902/14.68	5/0.08	726/6.46	414/3.48
0.4-0.45	786/12.79	1/0.02	749/6.66	367/3.09
0.35-0.4	675/10.98	0	707/6.29	266/2.24
0.3-0.35	576/9.37	0	687/6.11	221/1.86
0.25-0.3	507/8.25	0	676/6.01	156/1.31
0.2-0.25	409/6.65	0	601/5.35	85/0.72
0.15-0.2	378/6.15	0	554/4.93	33/0.28
0.1-0.15	295/4.8	0	497/4.42	8/0.06

6 Conclusion

This paper presented an energy management strategy (EMS) for the electric vehicle charging station (EVCS) system operation under a defined maximum consumption limit (MCL), with optional integration of supplementary energy sources. The proposed EMS was able to ensure that the EVCS system did not exceed the MCL defined by the distribution system operator (DSO) and successfully coordinated the power flow among the components integrated within the EVCS system.

Simulation results demonstrated that, although the application of the MCL reduces total consumption and decreases the final SoC of EVs, the use of the EMS minimizes this impact by distributing the available power more efficiently. The integration of optimally sized supplementary energy sources further improved the system operation by increasing total delivered energy and enhancing customer satisfaction.

While the residential EVCS system experienced only a small improvement due to the temporal mismatch between charging periods and PV generation, the public EVCS system showed a significant increase in energy delivery and SoC values, indicating a more effective utilization of supplementary sources. The results confirm that the proposed EMS and optimal sizing approach can enhance EVCS system performance under DSO constraints, contributing to more stable and efficient operation of low-voltage electrical networks.

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