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Impact of Shared Electric Vehicles Availability to Provide Peak Reduction through Vehicle-to-Grid. A Case Study.

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***Abstract*—This paper presents a Mix Integer Linear Programming (MILP) optimization approach to reduce peak demand and maximize revenue in a grid-connected building with a PV-equipped charging station for Shared EVs. The study investigates the impact of EV availability on the effectiveness of the system by comparing the results for different connection times of a fleet of Shared EVs, a private EV used for commuting, and a stationary battery. Results from the case study conducted in The Netherlands demonstrate that not only the duration but also the timing of EV connection significantly influence system effectiveness, emphasizing the need for accurate availability estimation. The trade-off between peak reduction and Peak-to-Average Ratio (PAR) reduction is also highlighted, underscoring the importance of considering both factors for optimizing charging station usage. These findings provide valuable insights for optimizing energy management, reducing peak loads, and increasing the utilization of renewable energy sources in the context of Shared EVs and V2G technology.**

***Index Terms*—Electric Vehicle, Vehicle to Grid, Peak Reduction**

I. INTRODUCTION

Electrification of mobility is a growing trend, and a large increase in EV uptake is expected in the coming years. According to the European Union, the mobility sector needs to reduce GHG emissions by 37.5% in 2030, relative to 1990 levels, and this requires increasing the share of zero-emission passenger vehicles, mainly in the form of electric vehicles (EVs) [1]. However, the adoption of EVs is influenced by various factors, including consumer mobility concerns [2].

Electrification of mobility is not the only sector that is evolving into a more electrified operation, sectors such as transport, [3], heating, [4] and industry, [5] are also going electric. This change means that all sectors will end up using electricity as their primary energy carrier, enabling integrated and coordinated sector coupling [6].

The combination of the transport and power sector is possible thanks to bidirectional chargers and the use of Vehicle to Everything (V2X) technology, [7], where the energy stored on the Electric Vehicle (EV) battery can be discharged to power the grid, Vehicle to Grid (V2G), [8], a house or a building, (V2H and V2B), [9], or a standalone load, V2L. The use of this technology will not only integrate both sectors but can and must also be used to improve both of them. If EV charging is left uncontrolled, increased demand can negatively impact the power grid, [10]. On the other hand, V2G can be used to provide services to the grid such as frequency regulation, [11], decrease voltage deviations and power loss, [12], reduce grid congestion, [13], and overall increase grid safety and reliability, [14].

When EVs are coupled with buildings or houses the objective of discharging the battery is no longer only to help the grid, but to support the building energy needs like reducing the peak demand, and the electricity bill. Some studies considered EVs as active components inside a microgrid making use of an Energy Management System (EMS) to control the EV and other components' charging and discharging periods for buildings, [15]. In [16], another EMS in a smart building is integrated with V2G technology in a multiobjective optimization that maximizes the self-consumption of solar production and EV charging. A fleet of Plug-in Hybrid Electric Vehicles (PHEV) is used in [17] to optimize the energy consumption profile of the building, while in [18] a fleet is used to reduce peak demand, carbon intensity and energy cost in different scenarios. Battery degradation caused by the extra cycling of the battery and their economic implications is studied in [19].

As expected, EV availability is a key factor when optimizing the power flow, as it can only be done when the EV is connected. Some studies consider this issue and make a forecast of the expected availability of EVs, [20], and in [21], the effect of EV availability in a charging pool on the V2G capabilities is studied, without taking into consideration if the EVs were shared or private and how the availability changed between them.

Although there is research regarding the availability of an EV, a comparison between shared and private EV availability and its effects on the V2G capability is non-existent. In this paper, this difference is studied and applied to peak reduction and revenue maximization for shared and private EVs availability and also compared with a stationary battery. By comparing these different scenarios, the paper provides insights into the relative advantages and disadvantages of shared and private EVs for V2G applications. The findings contribute to the understanding of how different EV ownership models can impact the potential benefits of V2G systems, highlighting the importance of considering shared EVs as a viable option. The insights provided can inform decision-making processes regarding EV-sharing models, infrastructure planning, and revenue optimization strategies.

This paper is organized as follows: section II presents the MILP formulation; section III describes the case studies and results; finally section V presents the conclusions and proposes future work.

II. MILP FORMULATION

The following section describes the formulation used to solve the problem. A Mix Integer Linear Programming (MILP) optimization has been used to reduce the peak demand of the building as well as maximize revenue. The problem consists of a grid-connected building with PV generation and a bidirectional charging station where several EVs can charge but only one at each time, as can be seen in Figure 1. The problem involves high building peak loads, local PV generation outside peak hours, and underutilized shared EV batteries when the EV is connected for long periods of time. The combination of shared EVs, vehicle-to-grid (V2G) technology, peak load reduction strategies, and PV charging can be used to optimize energy management, reduce peak loads, and increase the utilization of renewable energy sources, ultimately enhancing efficiency and sustainability.

A total of 5 decision variables have been used, P_{ch_t} and P_{V2G_t} which set the charging and discharging power of EV respectively; P_{draw}^{Max} sets the maximum value of power that can be drawn from the grid (the peak grid demand); and two binary variables Bi_{ch_t} and Bi_{G_t} used for the constraints explained later. All of the variables used in the problem are positive.

The MILP formulation used in this study aims to reduce peak demand and maximize revenue in a grid-connected building with a PV-equipped charging station for Shared EVs. The objective function of the MILP formulation is formulated as follows:

$$\max_{\forall t} \sum_{t=1}^{T} P_{\text{feed}_t} \Delta t C_t S_c - P_{\text{draw}_t} \Delta t C_t - P_{\text{draw}}^{\text{Max}} N \tag{1}$$

Where P_{feedt} and P_{draw_t} are the power fed and drawn to/from the grid respectively, Δt is the timestep duration, in this case, 15 minutes. C_t and S_c are the electricity cost and a selling factor to indicate the selling cost is lower than the buying one. And N is a weight factor to make P_{draw}^{Max} binding so the objective function will try to reduce as much as possible the peak demand. As can be seen, in the objective function there is no term directly affecting PV consumption, this will be set following the energy price and the consideration of PV as a free energy, as the installation price was not considered for the PV system.

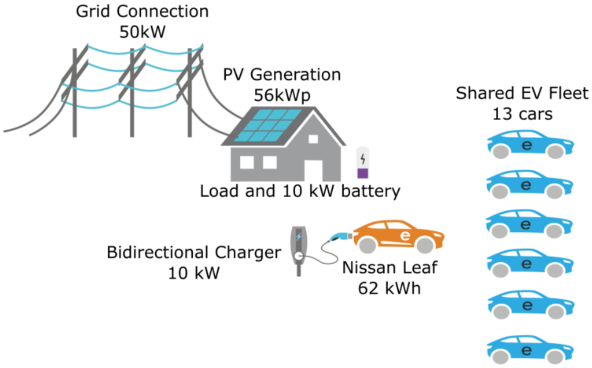


Fig. 1: Diagram of the system

The problem was formulated this way so the formulation was kept linear and had only one objective function. The project focused on two objectives, minimize peak reduction and maximize revenue from power exchange. The current formulation was used as it keeps the formulation simpler and linear so the computation times were reduced while maintaining satisfactory results.

The state function of the EV state of charge and its constraints are defined as:

$$\text{SoC}_{t+1} = \text{SoC}_t + \frac{P_{\text{ch}_t}\Delta t}{Q_{\text{bat}}}\eta_{\text{ch}} - \frac{P_{\text{V2G}_t}\Delta t}{Q_{\text{bat}}\eta_{\text{V2G}}} \quad \forall t \tag{2}$$

$$\text{SoC}_{\text{EV}}(\text{t}_{\text{dep}}) = \text{SoC}_{\text{dep}} \tag{3}$$

$$0.2 \leq \text{SoC}_\text{t} \leq 1 \qquad \forall t \tag{4}$$

Where SoC_t is the state of charge of the EV at timestep t, Q_{bat} the battery capacity and η_{ch} and η_{V2G} the charging and discharging efficiency respectively.

The constraints needed for the problem were formulated as follows:

$$P_{ch_t} + P_{load_t} + P_{feed_t} - P_{V2G_t} - P_{pv_t} - P_{draw_t} = 0 \tag{5}$$

In (5) the power balance equation is described, being P_{load_t} and P_{pv_t} the demanded and solar-generated power from the building respectively. As all the variables are positive, it is important to set the signs correctly in the balance equation. In this case, all power flowing to the building, P_{pv_t}, P_{V2G_t} and P_{draw_t} have a negative sign, while the power flowing from the building, P_{load_t}, P_{ch_t} and P_{feed_t} have a positive sign as can be seen in Figure 4.

$$P_{\mathrm{draw}_t} \leq P_{\mathrm{draw}}^{\mathrm{Max}} \tag{6}$$

$$P_{\mathrm{draw}}^{\mathrm{Max}} \leq P_{\mathrm{grid}}^{\max}(1 - Bi_{G_t}) \tag{7}$$

$$P_{\mathrm{feed}_t} \leq P_{\mathrm{grid}}^{\max} Bi_{G_t} \tag{8}$$

Equations (7) and (8) used the binary variable Bi_{G_t} to constrain that power cannot be fed and drawn from the grid at the same time and that power must be lower than the grid capacity, $P_{\mathrm{grid}}^{\max}$. The binary variable is used so the problem can be linear and a MILP optimization can be used.

$$Av_t = \begin{cases} 1 & t \in [t_{dep};\ t_{arr}] \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

$$P_{\mathrm{ch}_t} \leq P_{\mathrm{ch}}^{\max} Av_t (1 - Bi_{ch_t}) \tag{10}$$

$$P_{\mathrm{V2G}_t} \leq P_{\mathrm{V2G}}^{\max} Av_t Bi_{ch_t} \tag{11}$$

Equation (9) sets then the availability of a car connected to the charging station, having the possibility to provide V2G services. In the stationary battery case, the Availability is set to 1 at all timesteps. Equations (10) and (11) set that the vehicle can only charge or discharge if the EV is connected, $Av_t = 1$, only up to a certain charging and discharging maximum power, $P_{\mathrm{ch}}^{\max}$ and $P_{\mathrm{V2G}}^{\max}$ and it cannot charge and discharge at the same time, using the binary variable explained before. Although several EVs can use the charging station, it is not possible that several EVs to be connected at the same time. The data provided was from the charging station point of view, so which EV was charging was not known, only that one EV was connected and charging. For this reason, an index for the EV was not included in the formulation.

III. CASE STUDIES

The MILP formulation previously described was applied to three different scenarios, shared EVs, private EVs and a stationary battery, all of them compared to a base case scenario of uncontrolled charging, this is, the car starts charging until is fully charged as soon as it gets connected. Simulations were conducted using real data from the Santbergen building, located in Hilversum, The Netherlands. Santbergen is a multi-company building situated on the north side of Hilversum station. In 2019, Hilversumse Energie Transitie (HET) installed a 56kWp solar in collaboration with the building and since 2022 operates a shared EV fleet with 13 cars and 275 users.

The building and charger location is shown in Figure 3a and 3b respectively. The building's primary energy use is from a bakery, having a 10-15kW peak demand between 3-6 am when the bread is baked, making PV useless to reduce the peak demand. The rest of the day has a fairly flat consumption in comparison, as can be seen in Figure 2, where it also can be seen the EV uncontrolled charging is completely uncorrelated with the PV and Load profiles.

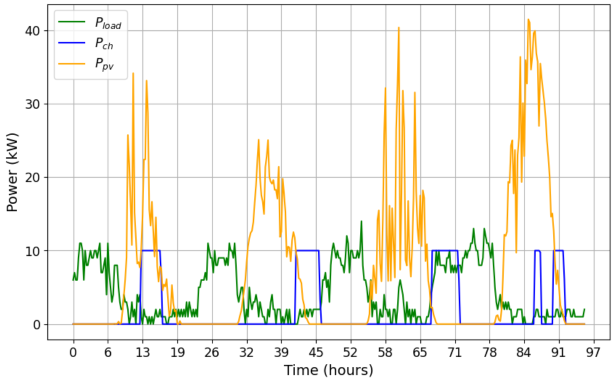


Fig. 2: Power curves for PV, Load and Uncontrolled Charging

The charging station has two connection points placed in the public space so that two vehicles can charge simultaneously the ChaDeMo, used for the cooperative cars exclusively and a CCS Combo that is open use. Private and shared EVs can use the charging station but only the shared ones, Nissan Leafs, can use the charging point that has V2G capabilities.

Data from March 2022 to December 2022 of the charging events made by the shared EVs in the ChaDeMo connector were used for the simulation. The data included the arrival and departure times and the energy charged on each charging session, as seen in Figure 2. The arrival SOC was calculated knowing the battery capacity of the Nissan leaf, 62 kWh and the energy charged in each session, as SOC data was not available. Energy price was obtained from the historic hourly data of the wholesale market in the Netherlands in 2022, so the energy price was known beforehand and entered the MILP as an input without uncertainty.

To assess the importance of EV availability in V2G three use cases where the availability is changed have been studied and compared to a base case. Only the availability of the EV is changed, PV generation and load demand data are the same in all of the scenarios. The constant use in the formulation is also the same in all the simulation scenarios, namely the charging and discharging efficiency, both 90%, $P_{\mathrm{grid}}^{\max}$ is 50 kW, as PV curtailment was not considered. The maximum charging and discharging power, P_{ch_t} and P_{V2G_t} respectively, was set by the charger to 10 kW.

- Base-case: The demand and PV generation of the building and the charging events conducted by the shared EVs. This base case is the uncontrolled charging that took place in the location.
- Shared EVs V2G: A V2G optimization using the formulation explained above and using data on the availability of the shared EVs during the charging events to control the charging and discharging processes.
- Private EVs V2G: the same optimization but a private vehicle use for commuting purposes has been assumed in this case. The vehicle is connected to the building during non-working hours, from 18-8 daily.
- Stationary battery: In this scenario, the EV is removed

and changed to a stationary battery with the same capacity and efficiency as the EV battery, so same efficiency and same capacity. The only change in the formulation will then be the availability, as in this scenario $Av_t = 1$ at all timesteps.

IV. RESULTS

All scenarios have been simulated for each month independently using the Pyomo package in Python and the linear solver GLPK. Results for peak demand and total revenue have been obtained for each month and scenario. The Peak to Average Ratio (PAR), was also calculated in (12), where D_{avg} is the average power demanded and P is the peak demand, this metric compares the highest value with the average value and it is used as a measure to indicate the variability of the power demand.

$$\frac{P}{D_{avg}} \tag{12}$$

A two days example of the power curves from the three scenarios has been plotted in Figure 4. It shows the EV (dis)charging power adapting to the Load Demand so the energy drawn from the grid is always lower than the P_{draw}^{Max} value set by the formulation over two different periods. In the shared EV scenario it can be seen how only the charging is regulated, with a higher power drawn from the grid. In the private EV scenario, the power drawn from the grid is lower and the EV is changing between charging and discharging to maintain this value. With the stationary battery, the power drawn from the grid is even lower so the battery is discharging during the peak load demand and charging with the PV generation. The maximum values for the charging and discharging can also be seen in the plot and the power generated by the PV installation, which are much larger than the power demand. It is for this reason that P_{draw}^{Max} has not been considered for feeding power back to the grid, as in the project PV curtailment has not been considered.

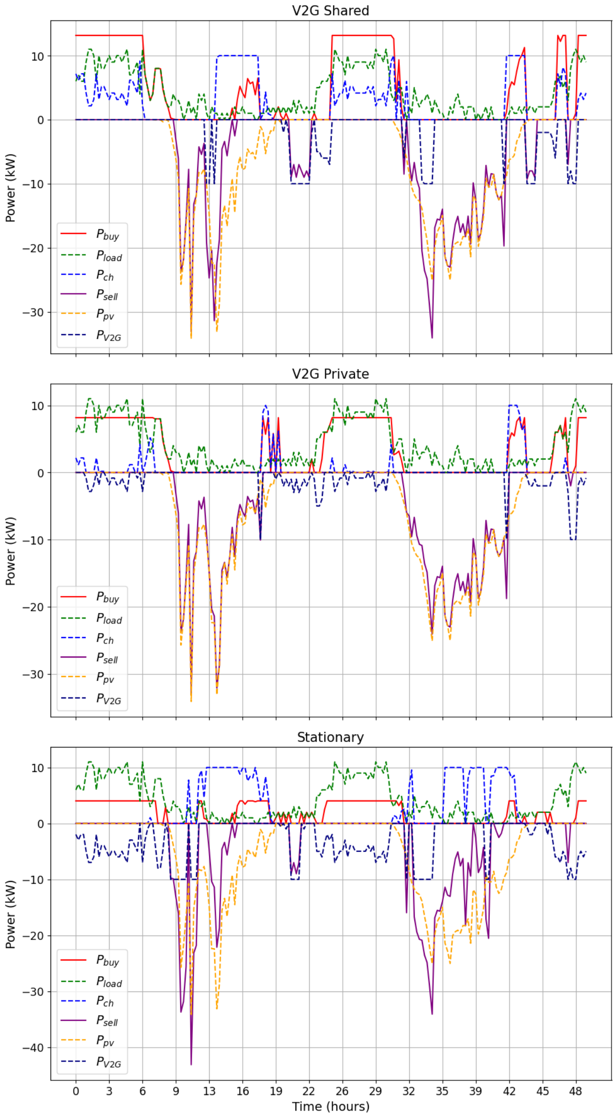
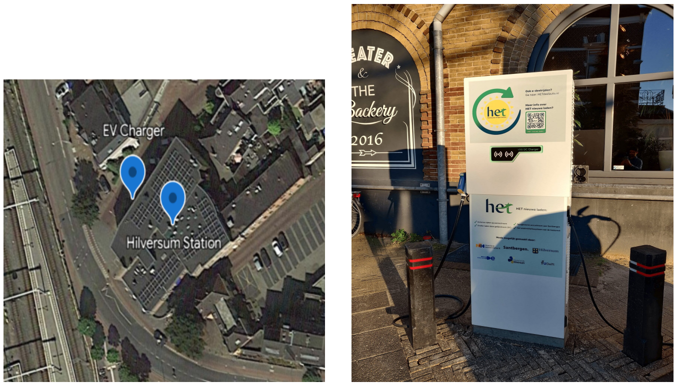


Fig. 4: Power curves for the three scenarios results



(a)

(b)

Fig. 3: a) Location of Building & b) EV Charger.

To better compare the improvements each scenario has over the uncontrolled base case three indicators have been calculated. The max peak demand reduction, α_i, was calculated as shown in (13), where P_U and P_{Bi} are the uncontrolled charging and bidirectional peak demand of the month respectively. The Peak to Average Ratio reduction, β_i, was calculated as shown in (14), where A_U and A_{Bi} are the uncontrolled charging and bidirectional Peak to Average Ratio of the month respectively. The increase in total revenue, γ_i, is also calculated in (15) from the difference in energy fed and drawn to/from the grid, where R_U and R_{Bi} are the uncontrolled and bidirectional total revenue respectively.

$$\alpha_i = \frac{P_U - P_{Bi}}{P_U} \times 100 \tag{13}$$

$$\beta_i = \frac{A_U - A_{Bi}}{A_U} \times 100 \tag{14}$$

$$\gamma_i = \frac{R_{Bi} - R_U}{R_U} \times 100 \tag{15}$$

Figure 5 presents the maximum peak, α_i and PAR reduction, β_i, solid and dashed lines respectively. The sub-indices Sta, Pri and Sha are for the Stationary, Private and Shared scenarios respectively. It is important to remember here that the objective was to reduce the maximum peak demand of the building during the whole month, as it was the time horizon used for the optimization, not to reduce the PAR value. However, as expected, if the maximum peak value is reduced the PAR value will also be reduced, as we see in the plot, having both of them a similar reduction in each of the three scenarios. It is important to mention nonetheless the difference between the stationary and V2G private scenarios. While the max peak reduction is always higher, or at least equal, in the stationary scenario, the PAR reduction is higher in the V2G private scenario on some months. This could seem like a better result at first sight, but the reason for the difference is the average demand. This result means that in the V2G scenarios, the average power drawn from the grid is closer to the peak demand so more energy is drawn from the grid overall. In the V2G private scenario, this happens because the EV is not connected during central hours of the day so it is almost impossible to charge the EV with the generated solar power, while in the V2G shared scenario is because the randomness of connection times, which can also be seen in the range of values presented in the plot, having some months close to 0% reduction and others more than 50% PAR reduction and close to 40% peak demand reduction. Private EVs are able to achieve a higher reduction than shared EVs in the peak demand as they are always connected at night when the peak demand is occurring, while shared EVs have random connection times so just one night a month is needed without the car connected to not have a reduction in peak demand.

As can be seen in Figure 5 and Figure 6 the stationary battery is the scenario where the peak demand is lowered more and where a greater revenue can be seen, with an average of 66% peak reduction and 72% increased revenue. This is an expected result, as a stationary battery is always connected having more time to charge and discharge in the needed moments. At the same time, the stationery battery calls for an additional capex investment besides the bidirectional inverter, while the indirect EV battery comes for free. The main differences are spotted in the private vs shared EV availability. The private one is always connected at night, so peak demand can be reduced up to a 42% average, while the shared EV has much more random connection times, being impossible to obtain a peak reduction in 4 out of 10 months and an average peak reduction of 15%.

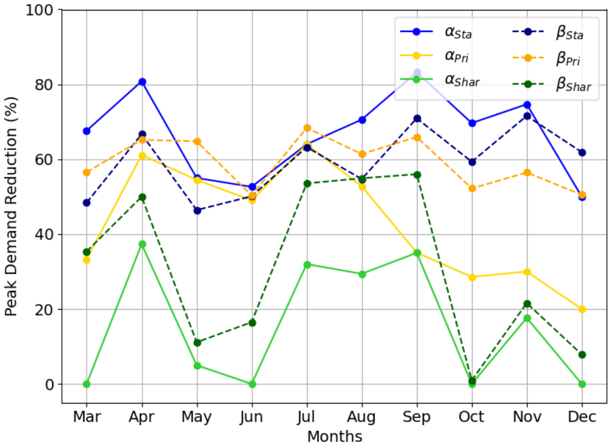


Fig. 5: Peak Reduction (%) by month and scenario.

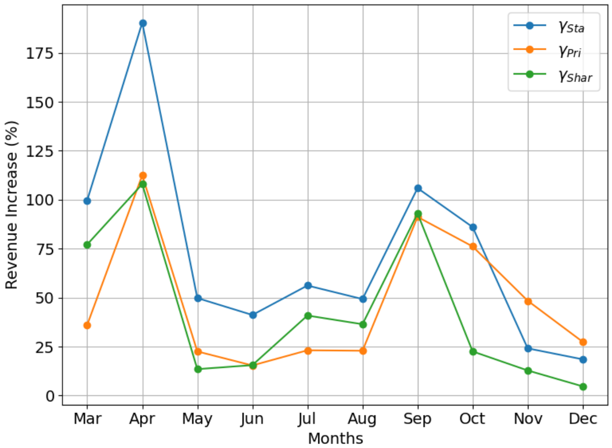


Fig. 6: Revenue Increase (%) by month and scenario.

Looking into the revenue increase, it shows that some months have a higher increase in the shared EV scenario, namely March, July and August, as the vehicle was connected to the charging station 70%, 82% and 83% of the time during the whole month respectively. While other months like October, November and December the vehicle was connected less than 20% of the time, making it very difficult to generate any increase in revenue. Another important thing to notice is the lower revenue increase in the summer months in the private EV scenario compared to the Stationary one. This is because the private EV is not connected during working hours, so almost no PV generation can be used to charge the EV and almost all the energy needed to charge the EV needs to be purchased from the grid.

V. CONCLUSIONS

In conclusion, this study addresses the challenges and opportunities posed by the adoption of Shared Electric Vehicles (EVs) and the implementation of Vehicle to Grid (V2G) technology. The problem of high building peak loads and underutilized shared EV batteries is tackled through an optimized approach using Mix Integer Linear Programming (MILP) to simultaneously reduce peak demand and maximize revenue. The impact of EV availability is examined by comparing the results of the MILP formulation for different connection times of shared EVs, private EVs used for commuting, and stationary batteries.

The findings emphasize the significance of both the duration and timing of EV connection to the charging station. Results from a case study conducted at a PV-equipped building in The Netherlands revealed that these factors play a critical role in system performance. The study highlights the need for careful consideration of EV availability and optimal connection times to maximize the utilization of charging stations. Furthermore, it demonstrates that the integration of shared EVs, V2G technology, and peak load reduction strategies presents a promising solution to optimize energy management and minimize peak demand.

These results were obtained with historic data from 2022 so the optimization has no uncertainties and energy prices were unusually high due to the peak pricing year of 2022. This limits the scalability of the study as in a real-case scenario forecasting and uncertainties will need to be implemented, making the problem more complex and taking longer to solve, especially if more CS and EVs are considered.

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