38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Optimizing Charging Infrastructure for Truck Depots: Cost-Minimal System for Truck Charging Combined with PV and Battery Storage Systems

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Executive Summary

With the increasing electrification of trucks, an intelligent charging infrastructure is becoming relevant for companies to reduce energy costs or to enable the operation of an electric truck fleet within the given grid connection capacity. We model a system that combines electric truck charging with photovoltaic generation and a battery storage system and determine the cost-optimal infrastructure configuration. A case study of a food logistics center reveals that load management generally reduces peak load and system cost. The stationary battery storage system is profitable in a regional distribution transport setting, whereas load management without additional battery storage is cost-efficient in an urban distribution transport setting. We identify electricity costs, network charges, and charging station costs as primary cost components of the system and identify the highest cost saving potential in the peak load-depending network charges.

Keywords: heavy-duty electric vehicles & buses, smart charging, energy storage systems, modelling & simulation, energy management

1 Introduction

1.1 Motivation

The transport sector in Germany is responsible for about 22% of national greenhouse gas emissions [1]. An important contribution in reducing these emissions is the adoption of electric vehicles. Long-term scenarios for the decarbonization of the German energy system indicate that battery electric vehicles will dominate passenger car but also light to heavy-duty truck stocks [2]. For trucks, most charging will most certainly occur at depots [3, 4]. Thus, fleet operators must invest in private charging infrastructure to ensure a reliable operation of their battery electric trucks (BETs). The transition to electric fleets requires careful infrastructure planning, considering each fleet owner's unique circumstances. Key factors include the specific usage profiles of the vehicles, the capacity of the existing grid connection, and the availability of on-site photovoltaic (PV) systems [5]. If uncontrolled, simultaneous charging in times when many BETs return to their depot might lead to load peaks, which result in a need for high-capacity grid connections and costly network charges. Load management systems (LMS) and the deployment of battery energy storage systems (BESS) might lower these costs by providing flexibility to reduce peak loads and to integrate on-site PV generation and may prevent grid connection capacity problems at the supplier side.

1.2 Existing literature and research gap

Existing literature shows that private depot charging is likely to emerge as the main charging option for trucks: Borlaug et al. (2021) [6] show that short-haul trucking under 200 miles, which represents 60% of total truck energy demand in the US, can be electrified, exclusively charging at their depots off-shift dwell periods. Speth and Plötz (2024) [4] show that most trucks in Germany can be recharged at private locations with moderate power, modeling a flat charging strategy. Depot charging is favorable for truck fleet operators as it is inexpensive and can be easily controlled [6].

Bong et al. (2025) [7] model the depot charging of battery electric trucks and analyze their influence on the high-voltage grid. They compare uncontrolled charging with a flat charging strategy, observing that the latter reduces grid utilization substantially, but do not consider flexible charging. Walz and Rudion (2024) [8] model five types of logistics centers, using synthetic driving profiles to characterize the mobility pattern of the electric truck fleets. They find that in two of their use cases – a general cargo depot and a parcel depot – half of the peak load in the afternoon can be shifted by more than 12 hours and that only a minor share of the load cannot be shifted at all, assuming the availability of 350 kW charging points. They do not analyze cost implications of this load shifting potential. Biedenbach and Strunz (2024) [9] present a cost minimization of bidirectional depot charging, combining PV self-consumption, expenses associated with the annual peak load, and profits from arbitrage trading. They used real-world driving data to analyze a single depot with 30 battery electric trucks in a case study. Annual savings from bidirectional charging in the depot under consideration varied from 2,000€ to 10,000€, depending on the year.

The existing literature does not consider the integration of passenger cars, which are likely to charge at the company location (e.g., fleet vehicles or employees' private cars) in their depot charging models. In addition, it does not consider the combination of depot charging with a stationary BESS. BESS have been extensively researched in their application to optimize the self-consumption of PV electricity [10,11,12], while their application within charging infrastructure systems is underexamined. Yan et al. (2019) [13] analyze charging stations combined with battery storage and PV generation but focus on public charging. Burges and Kippelt (2021) [14] analyze load management for high-power charging stations and do partially address PV generation and BESS but focus on grid challenges. Our work contributes to research by investigating the profitability of BESS combined with on-site PV generation from a private BET fleet operator perspective.

2 Data and Methods

We model the electrical energy flows of a truck depot, where the electricity demand of the company's truck fleet, the employees' passenger cars and the building can be covered by on-site PV generation or drawn from the power grid, depending on available grid connection capacity (see Fig. 1).

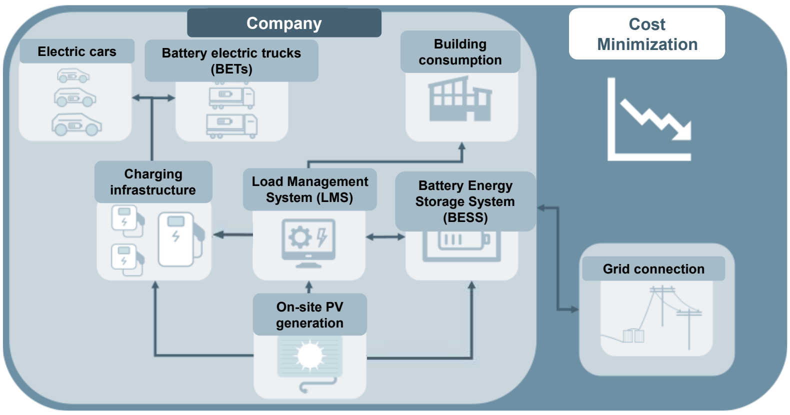

Figure 1: Overview of the modeled system

The modeled company site has DC charging stations for the BET fleet and AC charging stations for the electric cars of the employees. Two components, a LMS and a BESS, can be optionally added to the system: An LMS alone enables controlled charging of the vehicle fleet, allowing load shifting. If it is combined with a BESS, additional flexibility is added to the system through controlled charging and discharging of storage capacity. Energy demands and PV generation are exogenously given by hourly profiles. Grid connection capacity and BESS capacity are variable and optimized. Section 2.1 presents the formulation of the optimization model used. Section 2.2 outlines the case study and details the parameter assumptions.

2.1 Optimization model

We formulate a mixed-integer linear programming model to determine the cost-minimal system configuration. We model a working day D_{work} on which vehicles are driven and recharged in the depot in their idle times, and a non-working day D_{off} on which no vehicle operation (and no charging) takes place. The model minimizes the annual total cost of ownership, depending on the amount of investment, lifetime, and interest rate, as well as operating expenses of all system components. Eq. 1 shows the objective function.

$$\min \left(C_{\text{electricity}} + C_{\text{gridconnection}} + C_{\text{BESS}} + C_{\text{LMS}} + C_{\text{chargers}} + C_{\text{networkcharges}} - R_{\text{feed-in}}\right) \quad (1)$$

Central variable of the model is the total hourly load of the system, resulting from the electricity consumption of the building, the on-site PV generation, the charging or discharging of the BESS, and the charging of different vehicle types v:

$$L_{h,d}^{\text{total}} = l_{h,d}^{\text{building}} - g_{h,d}^{\text{PV}} + L_{h,d}^{\text{BESS}} + \sum_{v\in V} L_{h,d,v}^{\text{charge}} \quad (2)$$

Whereas building consumption and PV generation are given profiles, the load from vehicle charging and the BESS are variable in the model. The maximum vehicle charging load depends on the number of charging points n_v^{cp} for the vehicle type v and their charging power $P_v^{\max}$.

$$L_{h,d,v}^{\text{charge}} \leq n_v^{\text{cp}} \cdot P_v^{\max} \quad (3)$$

The 24 hours of the working day are divided into driving times and the idle times between trips, during which the vehicles are in the depot (charging windows). The model assumes that the energy that was consumed during the latest trip must be recharged before the subsequent trip begins. The total electricity demand during such a charging window w depends on the number of vehicles n_v, the distance $d_{v,w}$ driven in the trip prior to the charging window, and the vehicles' specific energy consumption e_v.

$$\sum_{h\in H_{v,w}^{\text{depot}}} L_{h,d,v}^{\text{charge}} = n_v \cdot d_{v,w} \cdot e_v \quad (4)$$

The maximum charging power is variable in the model and determines the required type of charging station. Total costs associated with charging infrastructure depend on the number of charging points n_v^{cp} and the type of charging station required (in terms of charging power). The annual costs per charging point, c_v^{cp}, comprise the equivalent annual cost (EAC) of the initial investment as well as annual maintenance.

$$C_{chargers} = \sum_{v\in V} n_v^{\text{cp}} \cdot c_v^{\text{cp}}(P_v^{\max}) \quad (5)$$

The EAC incurred by load management result from the initial investments in the LMS, in the connection components required for each charging point connected to the system, and in the necessary number of sub-distribution boards (depending on the number of connected charging points).

$$C_{\text{LMS}} = \left(I_{\text{LMS}} + \left\lceil \frac{\sum_{v\in V} n_v^{cp}}{n_{\text{cp,subdistr}}} \right\rceil \cdot I_{\text{subdistr}} + \sum_{v\in V} n_v^{cp} \cdot I_{\text{connection}}\right) \cdot \frac{i \cdot (1+i)^{t_{\text{LMS}}}}{(1+i)^{t_{\text{LMS}}} - 1} \quad (6)$$

Charging and discharging of the stationary BESS is variable but is constrained by the battery's feed-in capacity, which depends on C-rate r_C and capacity of the BESS $E_{\max}$.

$$|L_{h,d}^{\text{BESS}}| \leq r_C \cdot E_{\max} \quad (7)$$

Each working day begins and ends with a half-charged BESS. During the day, it can vary within the usable storage capacity. Losses occur with each charging or discharging process with efficiency $\eta < 1$.

$$E_{0,d}^{\text{BESS}} = E_{23,d}^{\text{BESS}} = \frac{1}{2} \cdot E_{\max} \quad (8)$$

$$E_{\min} \leq E_{h,d}^{\text{BESS}} \leq E_{\max} \quad (9)$$

$$E_{h,d}^{\text{BESS}} = E_{h-1,d}^{\text{BESS}} + \eta \cdot \max\left(0, L_{h,d}^{\text{BESS}}\right) - \frac{1}{\eta} \cdot \max\left(0, -L_{h,d}^{\text{BESS}}\right) \quad (10)$$

The costs for the BESS cover the EAC of the initial investment as well as annual maintenance. They are assumed to be proportional to the selected storage capacity:

$$C_{\text{BESS}} = c_{\text{BESS}} \cdot E_{\max} \quad (11)$$

The resulting total system load (if positive) needs to be covered by electricity purchased from the grid. The annual electricity purchase cost depends on the power price and the total amount of electricity drawn from the grid throughout the year:

$$C_{\text{electricity}} = \sum_{d \in D} \sum_{h \in H} \max\left(0, L_{h,d}^{\text{total}}\right) \cdot p^{\text{electricity}} \quad (12)$$

Correspondingly, the revenue generated from the feed-in of electricity into the grid depends on the feed-in tariff and the amount of unused on-site PV generation:

$$R_{\text{feed-in}} = \sum_{d \in D} \sum_{h \in H} -\min\left(0, L_{h,d}^{\text{total}}\right) \cdot p^{\text{feed-in}} \quad (13)$$

A key variable is the annual peak load $L_{\max}$, which influences both the required grid connection capacity and the annual network charges. Network charges are modeled after the regulation in Germany [15] and are hence made up of two components: one depending on the annual peak load and one depending on the total amount of electricity drawn from the grid.

$$L_{\max} = \max_{h \in H}\left(L_{h,d}^{\text{total}}\right) \quad (14)$$

$$C_{\text{networkcharges}} = p^{\text{capacity}} \cdot L_{\max} + p^{\text{unit}} \cdot \sum_{d \in D} \sum_{h \in H} \max\left(0, L_{h,d}^{\text{total}}\right) \quad (15)$$

The required grid connection is associated with the one-time costs c^{gc} incurred by the grid connection expansion (cables, panels, transformers; depending on the capacity required) as well as a one-time construction cost contribution that is to be paid to the grid operator. The latter is calculated based on the recommendation of *Bundesnetzagentur* [16].

$$C_{\text{gridconnection}} = c^{\text{gc}}(L_{\max}) + p^{\text{capacity}} \cdot L_{\max} \cdot \frac{i \cdot (1+i)^{t_{\text{gc}}}}{(1+i)^{t_{\text{gc}}} - 1} \quad (16)$$

2.2 Case study and scenario design

We use the model in a case study for a food logistics center, from which a truck fleet is operated. The case study includes employees' cars, which are recharged during their working hours; the electricity consumption of the buildings, including a refrigerated warehouse; rooftop PV generation; and optional load management and stationary battery storage systems. We analyze two years, 2025 and 2030, assuming 280 working days and 85 non-working days. We define two use cases, urban and regional distribution transport, which differ in the truck operation (see Table 1). For both scenarios, we compare three charging infrastructure system configurations:

- *Uncontrolled*: No load management. Uncontrolled vehicle charging (50 kW for trucks, 11 kW for cars) starts at arrival.
- *Controlled*: Addition of LMS enables delayed vehicle charging. Charging loads are shifted such that system costs are minimized.

- *Controlled + BESS*: Stationary battery storage is added in addition to LMS. The system cost-minimizing BESS capacity is determined. If BESS is generally not profitable for the considered case (i.e., system cost-minimizing BESS capacity is zero), the BESS capacity required to minimize the daily peak load is determined.

In the following, the parameterization of the cost minimization model for the case study is detailed. The interest rate for all EAC calculations is set to $i = 5\%$.

2.2.1 Vehicles

We assume a homogenous fleet of rigid trucks with a maximum authorized weight of 18 tons, consisting of 62 BETs in 2025 and 124 trucks in 2030. We assume the specific energy consumption of all BETs to be 1.10 kWh/km in 2025 [17] and 0.99 kWh/km in 2030 [4]. Their driving profiles differ between the two scenarios (see Table 1). In the *Urban* scenario, the trucks travel 70 km on a single tour between 5 a.m. and 2 p.m. In the *Regional* scenario, the trucks travel 280 km per day, 151 km between 5 a.m. and 12 p.m. and 129 km between 4 p.m. and 10 p.m. The truck driving patterns were derived based on real-world driving data collected from two truck fleets in food logistics.

Table 1: Scenario definition

	Urban scenario	Regional scenario
Daily mileage	70 km	280 km
Charging window #1	2 p.m. – 5 a.m.	12 p.m. – 4 p.m.
Charging window #2	-	10 p.m. – 5 a.m.

In addition to the company's trucks, we consider the employees' passenger cars that are parked at the company location during working hours and that are to be fully recharged during their users' shift. We assume a two-shift operation at the company site, from 6.am. to 2 p.m. and from 2 p.m. to 10 p.m. We assume 20 cars to be connected to charging points per shift in 2025 and 40 in 2030. Each car has a electricity demand that corresponds to 25.8 km of driving distance. This corresponds to one and a half times the average commuting distance of 17.2 km in Germany [18], considering the attractiveness of workplace charging. Specific energy consumption of the passenger cars is assumed to be 0.16 kWh/km in 2025 and 0.15 kWh/km in 2030 [5].

2.2.2 Charging infrastructure and storage

For truck charging, we assume that the number of dedicated charging points in the depot equals the number of trucks such that each BET can be connected to a charging point during the entire charging window. The optimization model can select between three different DC charging stations: 50 kW, 80 kW, and 150 kW. The investments associated with the different chargers are listed in Table 2. Their lifetime is assumed to be 10 years [19]. In addition, one-time costs for planning, installation, and commissioning of the charging stations are assumed to amount to 30% of the investment (based on [19]). For car charging, the model can choose between dumb chargers that only allow uncontrolled charging at 11 kW and charging points compatible with smart charging (see Table 2). Their lifetime is assumed to be 8 years [14,20]. One-time costs for planning, installation and commissioning are assumed to amount to 100% of the investment (based on [19]). For all charging infrastructure, annual maintenance costs of 1% of the investment [14,20] are assumed.

Costs associated with the load management were adapted from a provider that offers an integrated solution consisting of the LMS itself, sub-distribution (one sub-distribution board for every 14 connected charging points), and connection components (one for each charging point). Cost components are listed in Table 2. A lifetime of 10 years was assumed for all LMS components.

For the BESS, we assume a minimum state of charge of 10% [11] at all times. Charging and discharging efficiency is set to 95% [11]. We assume the storage's C rate to be 0.5 h^{-1} in 2025 and 1 h^{-1} in 2030. We assume a substantial decrease in BESS costs, from 413 €/kWh in 2025 to 175 €/kWh [14], a lifetime of 15 years [21], and annual maintenance costs of 2.5% of the investment [21].

Table 2: Investment in charging infrastructure and load management components and their lifetime

	Investment (€)	Reference
Car charging infrastructure		
Dumb charging point, 11 kW AC	160	[22]
Smart charging point, 11/22 kW AC	532	[23]
Truck charging infrastructure		
50 kW DC charging point	20,882	[24]
80 kW DC charging point	33,664	[25]
150 kW DC charging point	54,637	[26]
Load management		
Load management system	5,949	[27]
Sub-distribution board	4,272	[27]
Connection component	308	[27]

2.2.3 Grid connection capacity

Grid connection costs vary by location and depend on the length of cables that need to be installed. With higher grid connection capacity requirements, additional components (panels, transformers) might be needed We obtain our estimates for the different components (see Table 3) by averaging the low-cost and high-cost scenarios by Kippelt et al. (2022) [28].

Table 3: Investment in grid connection components (based on [28]) and their lifetime [14]

	Investment (€), depending on grid connection capacity			Lifetime (years)
	< 8 MW	8-20 MW	20-30 MW	
Underground cable	208,863	1,009,050	1,009,050	40
Panel	-	97,650	97,650	25
Transformer	-	-	2,115,750	25

2.2.4 Electricity prices and network charges

An electricity price of 0.139 €/kWh (including taxes, duties, and levies but excluding network charges) is assumed based on the BDEW statistics for commercial consumers in February 2024 [29]. The feed-in tariff is set to 0.06 €/kWh [30].

Network charges in Germany vary between the grid operators. We use the 2024 network charges from *Netze BW* [31], which are presented in Table 4. They differ depending on the utilization expressed in annual full-load hours, i.e., the ratio between the annual electricity consumption in kWh and the annual peak load in kW. For energy-intensive companies (>10 GWh p.a.), the network charge regulation prescribes that a reduction of network charges by 80% (85%; 90%) applies if they exceed 7,000 (7,500; 8,000) full load hours in one year.

Table 4: Assumed network charges (source: [31])

Annual full load hours	Capacity price (€/kW)	Unit price (€/kWh)
≤ 2500	22.79	0.09
>2500	208.38	0.01

2.2.5 On-site electricity consumption and generation

The electricity consumption of the building is based on actual figures from a food logistics center. The annual consumption amounts to 7 GWh and is dominated by a refrigerated warehouse. We use two average profiles, one for the working days, whose hourly loads vary between 0.7 and 0.9 MW, and one for the non-working days, whose hourly loads vary between 0.6 and 0.7 MW). For the on-site solar power generation, we assume a rated power of 0.2 kW/m^2 [33] and a roof area of 2,500 m^2, resulting in a 500 kW$_p$ PV system. The generation profile was taken from the *Global Solar Atlas* [34] using Karlsruhe as location and the default settings with an azimuth of 180° and a tilt of 36°.

3 Results

Section 3.1 analyzes the daily load curve that results from the different truck use cases and system configurations in 2025 and 2030. Section 3.2 compares the annual system costs and analyzes the profitability of load management and BESS in truck depots.

3.1 Load curves and grid connection capacity requirements

With uncontrolled charging, all 62 trucks in 2025 and all 124 trucks in 2030 begin to recharge their batteries immediately after their arrival at the depot. At 50 kW charging power, this results in a load of 3.1 MW (2025) respectively 6.2 MW, solely from BET charging. For comparison, the building (including the refrigerated warehouse), which might have determined the grid connection capacity requirement in the past, has an average daily peak load of 0.92 MW. Consequently, BET charging determines the peak loads of the modeled working days if uncontrolled. If investment in load management and BESS is possible in the model, the load curve of the working day changes substantially, depending on scenario. Table 5 contains an overview of the observed peak loads in the scenarios and years considered, depending on system configuration.

Table 5: Daily peak loads in MW at the truck depot, depending on scenario, year, and system configuration

Scenario	Year	Uncontrolled	Controlled	Controlled + BESS
Urban	2025	3.93	1.10	0.99
	2030	7.10	1.36	1.16
Regional	2025	3.93	3.29	1.67
	2030	7.04	5.35	2.38

Figure 2 shows the hourly load curve of the logistics center in the *Urban* scenario for the uncontrolled and controlled cases, with and without BESS. Uncontrolled vehicle charging causes a steep load peak at 2 p.m., reaching 3.93 MW in 2025 and 7.1 MW in 2030. Within less than two hours, the vehicle batteries are fully recharged and the total system load bounces back to less than 1 MW. If charging is controlled by an LMS, BET charging is delayed and distributed on the entire charging window from 2 p.m. until 5 a.m. the following day. This reduces the peak load to 1.1 MW in 2025 (-72%) and 1.36 MW in 2030 (-81%). A BESS with a storage capacity of 2.1 MWh allows a complete smoothing of the load curve in 2025 (2030: 3.75 MWh), resulting in a constant system load of 0.99 MW (2030: 1.16 MW). The difference enabled by BESS charging during truck absence and BESS discharging during truck charging is relatively small, -10% in 2025 and -15% in 2030, compared to the optimized load management without BESS. Most of the improvement already comes from the optimized load shifting. In the uncontrolled case, the grid connection capacity requirement increases from about 1 MW without electric vehicles to about 4 MW with 62 BETs and then almost doubles within 5 years, mirroring the assumed doubling of the electric vehicle fleet. In comparison, dynamic load management without BESS limits the peak load increase (and thus the necessary grid connection expansion) between 2025 and 2030 to 0.26 MW (with BESS: 0.17 MW) in the *Urban* scenario.

Figure 3 illustrates the hourly load curve of the logistics center in the *Regional* scenario. Uncontrolled charging results in two characteristic load peaks; between 12 p.m. and 2 p.m. and between 10 p.m. and 12 a.m., each starting when the BET fleet returns to the depot. The daily peak of 3.93 MW in 2025 (2030: 7.04 MW) is reached at 2 p.m. when the refrigerated warehouse has the highest electricity consumption. If charging is controlled, the daily peak reduces to 3.29 (-16%) in 2025 and 5.35 (-24%) in 2030. The reduction is small, compared to the urban distribution transport setting, where reductions of more than 70% were realized. This is due to the comparatively small charging window between 12 p.m. and 4 p.m., during which the BETs need a charging power of more than 40 kW on average to reach a fully charged battery at departure. With an additional system cost-minimizing BESS capacity of 8 MWh in 2025 (2030: 15 MWh), the picture changes: the BESS is charged during the trips of the BET fleet and supplies electricity in BET charging hours, especially in the short afternoon charging window, in which it provides up to 2.12 MW in 2025 (2030: 4.59 MW). This results in a substantially smoothed system load curve, which reaches a peak load 1.67 MW in 2025 and 2.38 MW in 2030, less than half of the peak load in the uncontrolled case. This limits the grid connection capacity expansion between 2025 and 2030 to 0.71 MW, compared to 2.06 MW without BESS and 3.11 MW without any load management.

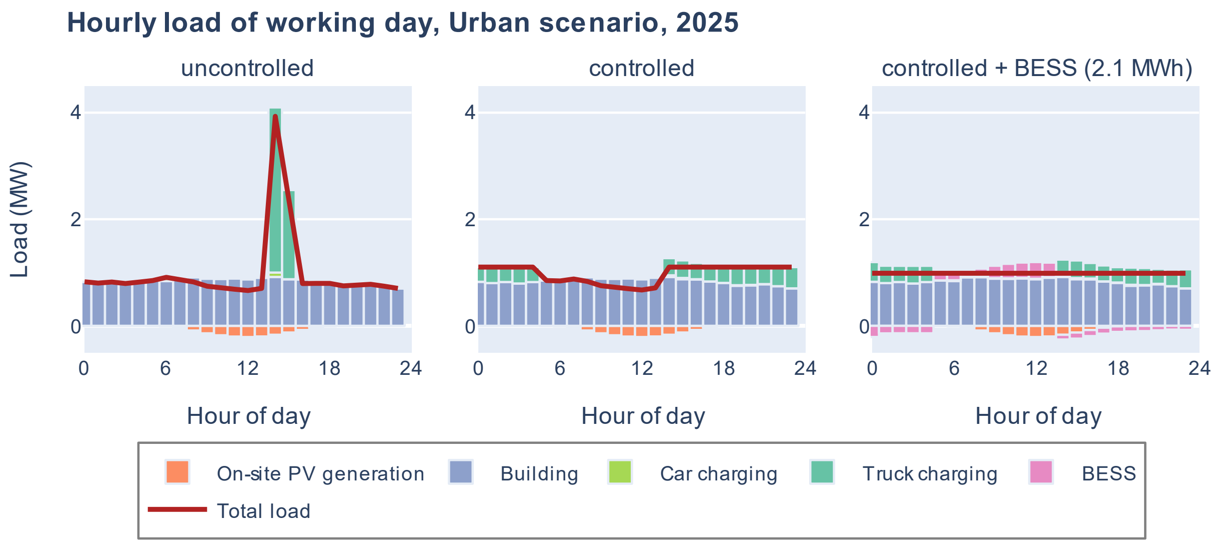

Figure 2: Hourly electricity demand (load > 0) and supply (load < 0) in the Urban scenario, working day 2025.

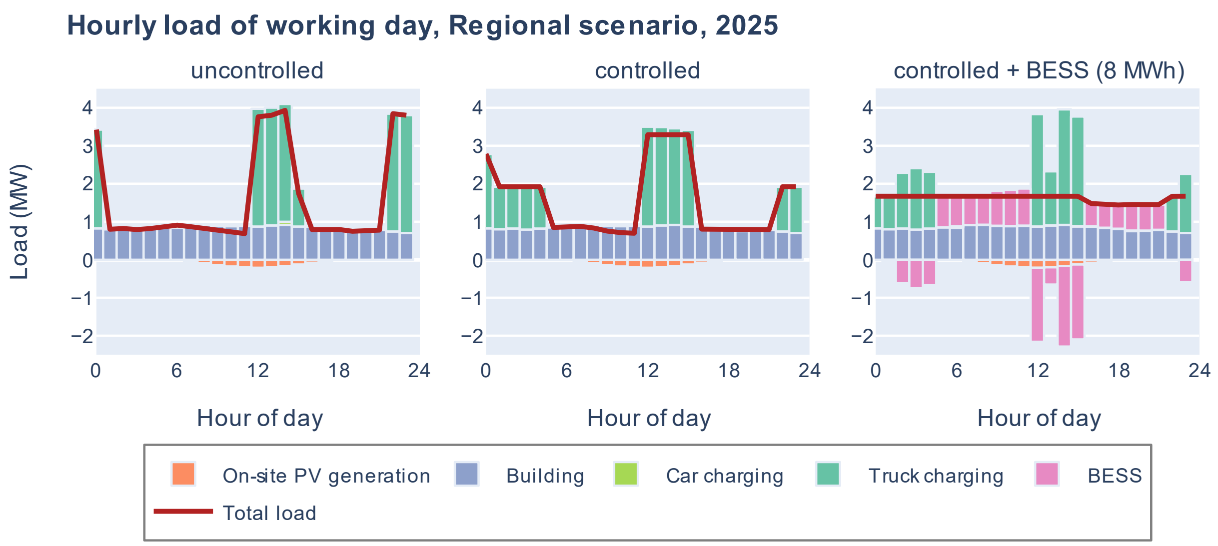

Figure 3: Hourly electricity demand (load > 0) and on-site supply (load < 0) in the Regional scenario, working day 2025.

3.2 Cost structure and profitability of smart charging

Figure 4 presents the annual costs of the *Urban* scenario in 2025 and 2030. Generally, they are dominated by the electricity that is purchased from the grid. Between 2025 and 2030, the electricity purchase costs increase by 150 k€ due to the doubling in the electric vehicle fleet. This, however, only corresponds to a 14% increase in electricity purchase costs as the electricity consumption at the logistics center is dominated by the refrigerated warehouse. The second most important cost component are network charges, which amount to 775 k€ in 2025 and 944 k€ in 2030 if charging is uncontrolled. With load management, they can be reduced by more than half to 334 k€ in 2025 and 403 k€ in 2030, providing the greatest saving potential of all cost components. Charging infrastructure is a notable cost component but does not differ between the scenarios, as the lowest considered power rating (11 kW for cars, 50 kW for trucks) was sufficient and cost-efficient in all scenarios. Grid connection expansion only has a small share in total annual costs, but can largely be avoided by using load management, whose cost is negligibly small. In both 2025 and 2030, optimized load shifting achieves a reduction of 22% in total annual costs. In total, it leads to a saving of 747 k€ in 2025, which translates to a saving of 7,650 € per truck or 0.39 € per kilometer driven. In 2030, total costs decrease by 610 k€ or 4,922 € per truck and 0.25 € per kilometer driven. The investment in a BESS, however, is not profitable, regardless of its capacity, since its additional costs exceed the additionally realized savings in network charges and grid connection costs.

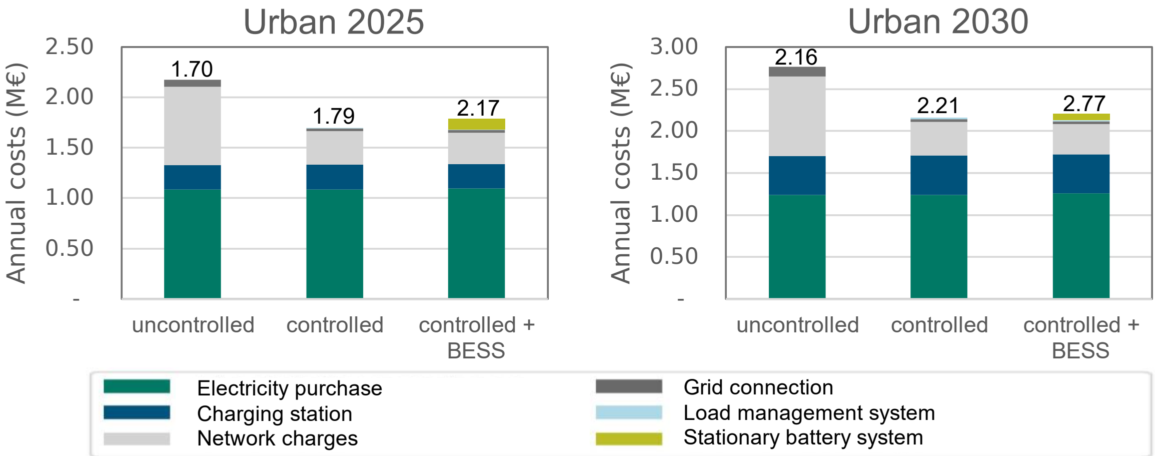

Figure 4: Total annual cost of the three system configurations in 2025 (left) and 2030 (right) in the *Urban* scenario. The addition of BESS capacity is not profitable; the displayed figures for the *controlled + BESS* configuration contain the load peak-minimizing BESS capacities of 2.1 MWh in 2025 and 3.75 MWh in 2030.

Figure 5 presents the annual costs of the *Regional* scenario in 2025 and 2030. Due to the higher truck driving performance compared to the Urban scenario, electricity costs are even more important and the impact of investments in charging infrastructure is lower. In both years, the addition of load management and BESS is cost efficient. The key cost component here are the network charges, which make up a third of total annual costs if the vehicle charging is uncontrolled. In 2025, they decrease to 102 k€ (-90%) if a BESS of 8 MWh is employed. The most of this reduction is accomplished due to the 80% reduction in network charges that applies if large consumers (>10 GWh p.a.) have such a evenly distributed load that they exceed 7,000 full load hours in year under consideration.

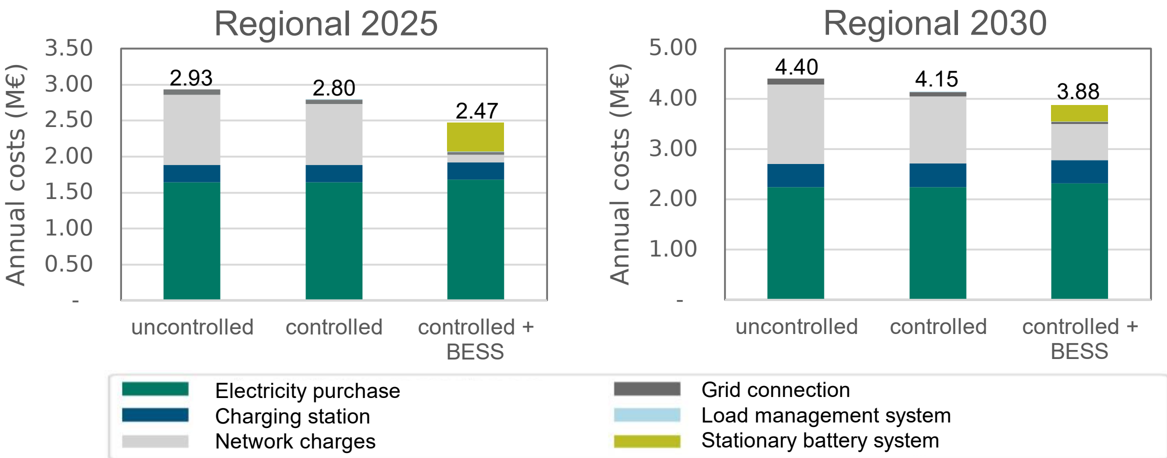

Figure 5: Total annual cost of the three system configurations in 2025 (left) and 2030 (right) in the Regional scenario.

Due to the announcement by the *Bundesnetzagentur* that it is planning to reform this regulation [35] we do not consider today's 7,000-hour rule in the 2030 scenario. Nevertheless, the investment in BESS is economically viable. The minimum system costs are reached with a BESS capacity of 15 MWh. The total cost reduction of 524 k€ (-12%) compared to the configuration without any load management translates to cost savings of 4,229 € per truck or 0.05 € per kilometer driven. Again, the highest cost saving potential lies in the network charges, which are almost halved compared to the controlled configuration without BESS: These savings of 613 k€ in network charges exceed the additional costs incurred by the BESS (319 k€ directly associated with the BESS as well as 69 k€ in additional electricity purchase due to storage losses). On top, 44 k€ are saved due to the lower grid connection requirement. The total cost reduction of 524 k€ compared to the configuration without any load management translates to cost savings of 4,229 € per truck or 0.05 € per kilometer driven.

4 Conclusion and outlook

We modeled the daily energy flows of a logistics center in a cost minimization model with hourly resolution, combining the charging of battery electric trucks with on-site PV generation, building consumption, the charging of passenger cars, and optional stationary battery storage. We apply it on a case study of a food logistics center, in which we analyze two truck operation scenarios, urban and regional distribution transport, and two years, 2025 and 2030.

In the urban distribution setting with one-shift truck operation, optimized load management reduces the peak load by more than 70%, limiting grid connection capacity expansion requirements to a minimum, and leads to annual system cost savings of about 20%. Here, the employment of a stationary battery only provides small additional improvements in terms of peak loads and is not economically viable. In the regional distribution setting with two-shift truck operation, optimized load management without the employment of stationary battery storage is profitable but can only slightly reduce the daily peak load due to a small recharging window. Here, stationary battery storage provides a substantial benefit, halving peak load and thus grid connection capacity requirement. In 2025, this can be leveraged to qualify for an 80% network charge reduction under current German regulation. For 2030, we show that even without this regulation currently under discussion [35], investing in stationary battery storage is cost efficient and leads to annual cost savings of 12%.

Generally, we find that electricity purchase is the major cost component of the system, followed by network charges and charging infrastructure. Network charges generally provide the major cost saving potential, as they reduce with a decreasing peak load. The employment of a load management system can be considered a no-regret option, as it results in savings in annual network charges and grid connection costs while its associated costs are negligibly small. The profitability of stationary battery storage depends on the use case, being particularly useful if charging windows between truck trips are small.

In the analyzed case study, on-site PV generation was considered but did not play a role in the optimization since it was fully integrated in each scenario, even without load management (i.e., no curtailment and no revenue from feed-in in the uncontrolled case). This was due to the comparatively high electricity consumption of the analyzed location, which contains a refrigerated warehouse. In future applications of the presented model, cases with lower building consumption may be interesting to analyze interaction with PV generation. Truck battery size was not analyzed in the presented model, which prescribed a full recharge of the energy consumed in the latest trip. In future applications of the model, battery size as well as the number of charging points could be made variable. Further development of the model may include bidirectional truck charging, facilitating a comparison of bidirectional charging to the presented combination of unidirectional charging and stationary storage.

Acknowledgments

The authors acknowledge funding from the German Federal Ministry of Education and Research (Ariadne project FKZ 03SFK5D0-2) as well as through the High Performance Center KAMO funded by the Fraunhofer-Gesellschaft.

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