Sustainable Energy Technologies and Assessments 84 (2025) 104717

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Optimized energy and task management in sustainable warehouses with Automated Forklifts and V2G-enabled Electric Vehicles ☆

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ARTICLE INFO

Keywords:
Electric Vehicles
Energy management system
Sustainable warehouse logistics
Automated Forklifts
Smart charging

ABSTRACT

The improvement of energy efficiency in the logistics sector is central to the European Union's sustainability goals. To this purpose, the electrification of delivery fleets and the adoption of smart warehouses equipped with Renewable Energy Sources (RESs) and Battery Energy Storage Systems (BESSs) represent the main solutions. Current research often treats the logistics and warehouse task scheduling aspects and the energy management of warehouses and charging infrastructres for Electric Vehicles (EVs) as separate challenges, leaving a gap in solutions that capture the interdependence of logistics and energy flows. To fill this gap, the present paper proposes a comprehensive Energy Management System (EMS) that couples logistic task planning with energy optimization through a Mixed Integer Linear Programming (MILP) model. The proposed EMS coordinates a warehouse equipped with a Photovoltaic (PV) power plant, a BESS, Vehicle-to-Grid (V2G)-enabled EVs and a fleet of Automated Forklifts (AFs) minimizing, on the energy side, the electricity costs of the warehouse and, on the logistics side, the penalties related to unexecuted tasks. Dedicated task scheduling constraints are included in the EMS. Three operational scenarios are analyzed: (I) both the BESS and V2G-enabled EVs are in operation, (II) BESS is out of service but EVs still provide V2G support, and (III) BESS is unavailable and EVs cannot operate in V2G mode. The results demonstrate a 75% reduction in operating costs in Scenario I compared to Scenario III, while a 42% reduction in operating costs is observed when compared to Scenario II. Also, self-consumption increases by 15% in Scenario I with respect to Scenario III, while it increases by 6% in Scenario I with respect to Scenario II. The impact of EV arrival time and transportation demand is assessed too, showing how costs are negatively affected when considering longer traveled distances or shifted arrivals.

Introduction

Background

The European Union is committed to minimize Greenhouse Gas (GHG) emissions across sectors [1] such as transportation and energy production [2]. Member states have to reach a share of 42.5% of Renewable Energy Sources (RESs) in the final energy consumption mix [3]. The integration of Battery Energy Storage Systems (BESSs) is crucial to address the fluctuations in energy production from RESs [4].

Freight transport remains the largest contributor to GHG emissions related to transport in the EU [5]. Incentives on Electric Vehicles (EVs) have boosted the share of new electric light commercial vehicles, reducing emissions from new registrations. However, medium and heavy-duty vehicle electrification remains slow due to range concerns, underscoring the need for further advances in sustainable transport policies [6]. The deployment of fast charging stations coupled with RESs for mid-route and destination charging is essential for the adoption of heavy-duty EV fleets in freight transportation, opening possibilities for Vehicle-to-Grid (V2G) applications to alleviate network congestion [7].

On the supply chain side, logistic facilities are shifting from conventional material handling equipment to Electric Material Handling Equipment (EMHE), Automated Guided Vehicles (AGVs), other Automated Material Handling Equipment (AMHE), or a combination of all [8]. This transition is driven by companies' increasing focus on reducing emissions across the supply chain, including internal logistics

☆ This article is part of a Special issue entitled: 'Sustainable Mobility MOST' published in Sustainable Energy Technologies and Assessments.

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https://doi.org/10.1016/j.seta.2025.104717
Received 31 March 2025; Received in revised form 23 September 2025; Accepted 21 November 2025
Available online 29 November 2025

and freight transport [9]. Additionally, the use of AGVs helps reduce internal logistics operating costs in warehouses, with studies supporting this transition [10]. Simulation studies in [11] and [12] primarily explore green warehousing strategies, focusing on the use of EMHE to reduce emissions, while the study in [13] explores charging strategies for AGVs in manufacturing industries. The use of both EMHEs and AGVs presents scheduling challenges, as they must synchronize with RES energy availability and warehouse operational shifts to reduce operating costs, which constitute nearly 20% of logistics expenses [14].

For efficient task assignment and scheduling in smart warehouses, an advanced management system is essential to seamlessly integrate RESs, BESSs, EV charging, and AMHE while aligning with operational shifts. This ensures optimized energy use, reduced operating costs and emissions, and enhanced coordination within the broader sustainable transport framework.

Relevant literature

Currently, the research literature is diverse, employing various approaches to achieve global optimality, with a significant focus on optimal RES management in smart grids, AMHE scheduling, and fast charging strategies for EVs. The Mixed Integer Linear Programming (MILP) model reported in [15] adopts a linear battery degradation model to schedule BESS operations in a microgrid to minimize operational costs taking into account the uncertainties in RES energy production. In [16], the MILP based Energy Management System (EMS) seeks to reduce operational costs by efficiently scheduling RES and BESS to meet active and reactive power demands while minimizing the dependency on the diesel generator in a campus microgrid. A multiobjective optimization problem utilizing a MILP-based approach to size and schedule RESs to minimize energy expenditures and greenhouse gas emissions is presented in [17]. The benefits of Vehicle-to-Building (V2B) technology are highlighted in [18], where an EMS developed as a MILP model is used to minimize operating and carbon emission costs in a ski resort, utilizing visitors' vehicles in V2B mode to alleviate network congestion. The MILP optimization model in [19] minimizes total losses in a microgrid serving industrial, commercial, and residential users by accounting for uncertainties in RES production. This is achieved through demand response on shiftable loads and the utilization of EV bidirectional charging capabilities. In [20], an energy management strategy is proposed for the grid integration of EVs, incorporating the Black–Scholes model to account for future carbon emission price fluctuations over a given time horizon. To address inaccuracies in load forecasting, [21] introduces a novel pseudo-local reserve market mechanism that enables distribution system operators to utilize EV flexibility to compensate for load deviations in competitive electricity markets. The MILP-based EMS in [22] optimally schedules shiftable loads and storage systems to coordinate with RESs in a hydrogen-based energy community, offering operational flexibility to the microgrid. The profitability of business models for bidirectional charging, applied to aggregate residential EVs and industrial heavy-duty fleets, is analyzed in [23], where a MILP model minimizes total costs, including energy and battery degradation expenses. Refs. [24] and [25] exploit Deep Reinforcement Learning and learning-based Model Predictive Control, respectively, in developing energy management strategies to improve the operational efficiency in fuel cell vehicles. In [26], the EMS aims to maximize the profits of mobile charging stations combined with integrated energy systems based on a MILP approach, analyzing daily operating costs under multiple scenarios. Integration of Energy Storage Systems (ESSs) in the energy mix is crucial in providing power stability and improving the flexibility of the utility grid. In [27], the authors explore the effectiveness of Hybrid Energy Storage Systems (HESS) in tackling power fluctuations in RESs by adopting two power smoothing techniques, Moving Average and Ramp Rate, and integrating them with a real-world HESS setup. The Model Predictive Control approach in [28] coordinates BESS cycles with Photovoltaic (PV) generation and EV charging in residential complexes, reducing energy costs while ensuring the BESS inverter supports both active energy and reactive power management. In [29], an EMS for an industrial microgrid, member of a renewable energy community is proposed, considering an EV fleet made of two cars and two trucks, nevertheless without considering any logistic constraints related to operations within the industrial plant.

Optimizing AGV operating schedules while considering their charging patterns based on energy consumption is crucial for ensuring a smooth logistics flow. Various studies investigate the scheduling of AGVs in logistics facilities such as ports, terminals, etc. For AGVs used in warehouses, their optimal scheduling is best categorized as the AGV Scheduling Problem and closely related to the Parallel Machine Scheduling Problem (PMSP). MILP models are employed in [30–34] and [35] for the optimal scheduling of AGVs. In particular, [30, 31] introduce an improved MILP formulation of the PMSP applied to battery-powered AGVs employed in warehouses for joint minimization of makespan and energy consumption of AGVs. The MILP optimization models in [32] and [33] examine AGV scheduling in a campus microgrid with a PV system, optimizing job assignments based on RES energy availability and personnel schedules. In [34], a MILP formulation is introduced for scheduling AGVs, considering partial and full charging. The MILP formulation in [35] considers conflicts in AGV scheduling to optimize the unloading time of AGVs working in tandem with quay cranes in container terminals. In [36], an arc-based Mixed Integer Programming model is employed to optimize task assignment for automated guided vehicles, aiming to minimize battery energy consumption and optimize job scheduling of AGVs in container terminals. In [37], the MILP approach is utilized to formulate a multi-objective function to optimize energy consumption and makespan of AGV operations in warehouses.

Contributions

The research literature separately explores the challenges of scheduling automated vehicles for logistics and the optimal management of RESs and ESSs in microgrids. In order to fill this existing gap, this study focuses on the combined optimal management of RESs, BESSs, EVs and AMHEs operating in a warehouse. Although the optimal management of RESs and ESSs falls under energy management, while the optimal scheduling of automated means is classified as a job scheduling problem, both are recognized as day-to-day operational challenges. The scheduling problem is computationally intensive, as highlighted by the authors in their previous studies [32,33]. As such, the combined optimal management of RESs, ESSs, and charging infrastructure, alongside the simultaneous scheduling of automated handling systems in warehouse environments, is inherently complex and computationally demanding. To the best of the authors' knowledge, the research theme is scarcely explored, despite its growing significance. In fact, this study is believed to be the first of its kind to address this specific integration. Building upon the foundational work in [32] and [33], this paper proposes a MILP-based EMS for the simultaneous management of RESs, ESSs, and the optimal task assignment of Automated Forklifts (AFs) in warehouses, while considering various trade-offs. The primary contributions of this study are:

- Integrated energy and task planning: this paper proposes a novel coupled approach to integrate the energy management of RESs, BESS, and EV fleets serving a warehouse with the scheduling of the task to be executed by AFs in the warehouse. Unlike existing approaches that address energy management and logistics separately, the proposed MILP-based model integrates both aspects into a unified optimization framework.

- Impact of energy management on AFs scheduling: the present study optimizes AF task scheduling by providing a linear task execution model, that fully aligns with the MILP formulation of

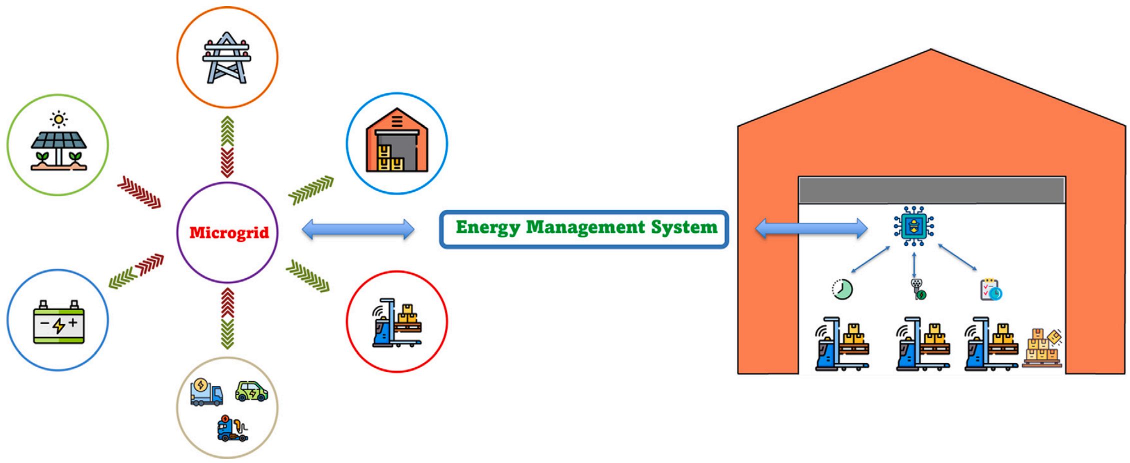


Fig. 1. Graphical representation of the considered system.

the EMS. This ensures that warehouse internal operations adapt dynamically to RES availability and electricity prices, allowing the shifting of AFs, thus opening the doors to sustainability and operational efficiency.

- Assessment of V2G benefits on warehouse operations: this study explores the benefits of the V2G techniques in minimizing energy costs and minimizing energy curtailments from RESs. Moreover, the present study evaluates the role of V2G technology in compensating for the unavailability of the BESS.

The remainder of this paper is organized as follows: Section "Mathematical model" formulates the MILP model with emphasis on both the energy and logistics aspects, Section "Results" introduces the case study and presents the results of the optimization. Finally, Section "Conclusion" concludes this study, highlighting the main contributions and introducing the scope for future developments of the proposed model.

Mathematical model

Problem description

The developed EMS provides the optimal scheduling for the daily operations of a warehouse. In particular, an ambient-temperature warehouse is considered, connected to the electricity distribution network and equipped with a PV power plant and a BESS to address the active energy demands. AFs are utilized for the handling operations in the warehouse. Additionally, the facility supports bidirectional charging for the incoming EV fleet, owned by the company running the warehouse. The EV fleet is composed of cars, used by warehouse workers to move between home and workplace, and vans and trucks, used for delivering goods. The EVs are differentiated depending on the time availability at the warehouse and on the travel distance (i.e., transportation demand). A graphical representation of the considered system is illustrated in Fig. 1.

The optimization problem has been modeled as a MILP model with an optimization horizon subdivided into T time intervals of duration Δ. The choice of Δ is critical when simultaneously addressing energy management and AF scheduling. Longer intervals may be suitable to describe energy-related dynamics and may lead to shorter computational times; nevertheless, they are not suitable for detailed AF scheduling. On the other hand, shorter intervals significantly increase the computational effort. The proposed mathematical model of the EMS combines an energy model to efficiently manage the energy technologies of the warehouse with a task assignment model for optimally planning the operations of the AFs of the warehouse.

Energy model

This subsection outlines the functioning of the technologies within the facility to address the active power demand, P_t^{El}, and the reactive power demand, Q_t^{El}, of the warehouse, with index t denoting the time interval ($t = 1, \ldots, T$).

PV system

The warehouse is equipped with a rooftop PV system to meet the active energy demands. The PV powerplant performance closely follows the relations described in [38,39] and [40]. These relations, along with the solar irradiance data from the Photovoltaic Geographical Information System (PVGIS) software [41], provide the available active power production, $P_t^{PV,av}$, from the PV plant. As per the Italian electrical network specifications, the operating range of the PV inverter is determined by the CEI 0-16 standard (see "Appendix A") of the Comitato Elettrotecnico Italiano [42]. The decision variables regarding active power are the actual active power production, P_t^{PV}, and the curtailed active power, $P_t^{PV,curt}$, as reported in [32]. The inductive reactive power supplied or absorbed by the PV inverter, $Q_t^{PV,inj}$ and $Q_t^{PV,abs}$, are related to P_t^{PV} as determined by the CEI 0-16 standard.

Network connection

The warehouse is connected to the external public distribution network through a medium-voltage connection. It serves multiple purposes: active and reactive power demand satisfaction and revenue generation through sale of surplus production from the PV system. Relevant decision variables are the active power injected into the grid or withdrawn from the grid, $P_t^{G,sell}$ and $P_t^{G,buy}$, and the reactive power injected into the grid or absorbed from the grid, $Q_t^{G,inj}$ and $Q_t^{G,abs}$: relevant constraints are reported in [43], defining a circular operating range related to the rating of the connection transformer (see "Appendix B").

BESS model

The BESS offers operational flexibility for the warehouse during periods of fluctuating energy production from the PV system. The relevant decision variables are the charging and discharging power, $P_t^{B,ch}$ and $P_t^{B,dch}$, and consequently, the energy content of the BESS, E_t^B. These variables are correlated through the energy balance of the BESS. Relevant constraints are discussed in [43] and [44], along with constraints ensuring smooth operation of the BESS. The CEI-016 standard allows the BESS inverter to operate within a circular capability curve, correlating $P_t^{B,ch}$ and $P_t^{B,dch}$ to the reactive power absorbed or injected by the BESS inverter, $Q_t^{B,abs}$ and $Q_t^{B,inj}$, that are decision variables too.

EV model

The EVs at the warehouse serve both personnel and freight transport needs, including electric vans for short-distance freight transport, and electric trucks for long-distance transport. It is assumed that the EVs at the facility exchange only active power.

EVs for personnel transport and long-distance freight transport spend a considerable duration of time at the facility: thus, they can act as mobile storage units, exploiting V2B/V2G mode to satisfy the active energy demands of the facility. The decision variables are the charging and discharging power of each EV, $P_{v,t}^{EV,ch}$ and $P_{v,t}^{EV,dch}$, and consequently, the energy content of each EV, $E_{v,t}^{EV}$, with index v denoting a generic EV ($v = 1, \dots, V$), where V is the total number of EVs. For relevant constraints involving the energy content of each EV at the arrival and departure time (t_v^{arr} and t_v^{dep}), see "Appendix D".

AFs model

AFs are assumed to handle the internal logistics within the facility. Each AF can be in one of three states: working, idling, or charging. The energy content of each AF, $E_{f,t}^F$, depends on the energy consumption rates while working or idling and on its charging power $P_{f,t}^F$, with index f denoting a generic AF ($f = 1, \dots, N^F$), where N^F represents the number of AFs. The energy balance that depends on the state of operation of each AF is reported below.

$$E_{f,t+1}^F = E_{f,t}^F + \Delta \cdot \left(P_{f,t}^F \cdot \eta^{F,ch} - \lambda^{F,W} \cdot y_{f,t}^{F,W} - \lambda^{F,I} \cdot y_{f,t}^{F,I}\right) \quad \forall f = 1, \dots, N^F, \quad \forall t = 1, \dots, T-1 \tag{1}$$

where $\lambda^{F,W}$ and $\lambda^{F,I}$ are energy consumption of AFs while working and idling respectively, while $y_{f,t}^{F,W}$ and $y_{f,t}^{F,I}$ are binary decision variables indicating the working or idling status of each AF f in each time interval. The constraints that govern the energy balance of the AFs are analogous to the relations outlined in [33].

The total number of jobs to be performed at the facility, N^J, is assumed to be allocated across the work shift and distributed among the total number of AFs. Three distinct binary decision variables are utilized to schedule the operations of the AFs: $w_{j,f,t}^F$, which indicates whether a job j ($j = 1, \dots, N^J$) is initiated by AF f at time interval t; $z_{j,f,t}^F$, which indicates whether a job j is performed by AF f at time interval t; u_j^F, which denotes the non-completion of job j. $w_{j,f,t}^F$ is set to 1 when an AF f initiates a job j at time t while it is 0 otherwise. $z_{j,f,t}^F$ is set to 1 when an AF f is performing a job j at time interval t and is set to 0 otherwise. u_j^F is equal to 0 if the job j is completed within the optimization horizon and equal to 1 otherwise. The constraints for the optimal scheduling of AFs are reported in "Appendix C".

Electric power balances

The facility is modeled as a single-busbar microgrid, comprising the PV system, BESS, EVs, and AFs, with a dedicated connection to the external distribution grid. The EMS must ensure that the active power demand of the warehouse, the active power demand related to the charging of EVs at the facility along with the active power demand related to the charging of the AFs and the reactive power demand of the warehouse must be satisfied at all time intervals. The electric power balances of the warehouse are reported below.

$$P_t^{El} + P_t^{G,sell} + P_t^{B,ch} + \sum_{v=1}^{V} P_{v,t}^{EV,ch} + \sum_{f=1}^{N^F} P_{f,t}^F = P_t^{PV} + P_t^{G,buy} + P_t^{B,dch} + \sum_{v=1}^{V} P_{v,t}^{EV,dch} \quad \forall t = 1, \dots, T \tag{2}$$

$$Q_t^{El} + Q_t^{G,abs} + Q_t^{B,abs} + Q_t^{PV,abs} = Q_t^{PV,inj} + Q_t^{G,inj} + Q_t^{B,inj} \quad \forall t = 1, \dots, T \tag{3}$$

Objective function

The goal of the proposed EMS is to reduce the operational costs of the facility, incorporating expenses associated with energy demand fulfillment and penalties for non-completion of logistic tasks. The objective function to be minimized is formulated as follows.

$$Obj = \sum_{t=1}^{T} \left(c_t^{PV,curt} + c_t^{Grid}\right) + c^F \tag{4}$$

where $c_t^{PV,curt}$ is the cost related to the curtailment of active power production by the PV inverter and c_t^{Grid} is the cost related to the exchange (absorption and injection) of active and reactive energy with the external network. c^F denotes the penalties incurred on the facility due to unassigned tasks over the considered time horizon.

Results

The results of the study are presented in this section after a brief description of the input data used in the optimization model.

Input data description

The input data used in the optimization model referred to the proposed technologies are reported in this subsection.

The optimization horizon is 1 day ($T = 96$) with a time interval duration Δ of 15 min. The size of the PV inverter, $A^{inv,PV}$, is 340 [kW] while the unit cost of PV curtailment, $p^{PV,curt}$, is 0.128 [€/kWh] [45]. The rated size of the BESS inverter, $A^{inv,B}$, is 250 [kVA]. The BESS has a rated capacity of 900 [kWh], with charging and discharging efficiencies both assumed to be 97 [%].

The size of the transformer, $A^{trf,G}$, connecting the warehouse to the MV distribution network is 750 [kVA]. The electricity selling price matches the zonal market clearing price, while the purchase price is increased using a multiplier coefficient to take into account fixed tariff components and taxes. Penalties for inductive reactive power absorption apply during peak hours, while penalties for inductive reactive power injection are applied in off-peak hours, with rates determined by the Italian regulatory authority, ARERA.

Nine EV chargers are present at the facility: four of them have a rated power of 250 [kW], while the other ones have a rated power of 50 [kW]. The warehouse owns two electric trucks with a rated battery capacity of 450 [kWh] and an energy consumption rate of 1.1 [kWh/km], two electric vans with a 79 [kWh] battery capacity and a consumption rate of 0.352 [kWh/km], and five electric cars with a 40 [kWh] battery capacity. While the electric trucks and vans are dedicated to transport goods to customers, the electric cars are assigned to warehouse personnel. The distances traveled by the trucks and vans are predefined and serve as inputs to the optimization model. Their energy content at departure must be at least equal to the energy required for a roundtrip to their destinations and back. For electric cars, it is assumed that they arrive at the warehouse with a minimum acceptable energy content and must depart with an energy content higher than at arrival.

The warehouse is assumed to be equipped with three AFs, each with a rated battery capacity of 21.12 [kWh] for logistics operations. The AFs have a rated charging power of 7.4 [kW] and a charging efficiency of 90 [%]. The warehouse operates on weekdays and remains closed on weekends. Each functional day consists of a work shift from 8 AM to 6 PM. During each operational shift, the AFs are assigned 30 tasks, with each task having a duration of 15 to 45 minutes. A penalty coefficient is applied to prioritize critical operations.

Optimization results

The model was implemented in Matlab R2022b environment using the Yalmip toolbox [46] and solved using the Gurobi solver [47] on a Intel(R) Core(TM) i7-10750H CPU @ 2.60 GHz PC with 16 GB RAM and with a computational time close to 420 min to achieve a solver gap of 0.02 [%]. The gap is used by Gurobi as stopping criterion. To explore the effectiveness of the proposed optimization model, three scenarios are analyzed: in the first one (Scenario I), V2G is considered along with the BESS, while the second one (Scenario II) considers the provision of V2G services with the BESS being out of service; in Scenario III V2G functionality is deactivated, in addition to the BESS being out of service, in order to analyze how the facility would operate without any storage technology. For brevity, graphical results for this latter scenario will not be disclosed, while energy scenarios will be discussed in Section "Comparison among scenarios". A single day of operation in summer is chosen for the study, in which the active and reactive energy demand of the warehouse is equal for the three scenarios, as well as the energy availability from the PV system.

Scenario I

Fig. 2(a) presents the active power balance of the warehouse over the considered day. It can be seen that the active power production from the PV system is sufficient to cover the active energy demand of the warehouse, including that of the AFs during the central hours of the day. Moreover, the surplus production is stored in the BESS for charging the EVs at the end of the shift when the active energy production from PV is negligible.

The reactive energy demand is met by the PV inverter, as presented in Fig. 2(b), thereby preventing any penalties related to reactive power exchanges with the public grid.

In Fig. 2(a), it can be seen that at certain time intervals the EVs are discharged to meet the active energy demand of the warehouse. This trend is also visible in Fig. 3, where most of the charging processes that require significant amount of active power occur at intervals when the electricity purchase prices are comparatively lower.

The tasks to be completed within the work shift are allocated among AFs in an optimized manner to minimize task non-completion as illustrated in Fig. 4(a): it can be noted that most of the charging of the AFs is scheduled during the central hours of the day, utilizing the surplus PV active energy production, thereby minimizing electricity purchase costs.

Scenario II

In Scenario II, PV energy availability and EVs availability and transportation demand remain unchanged with respect to Scenario I. The active power balance in this case is presented in Fig. 5.

Since the BESS is out of service, the EMS either injects the surplus production into the network or satisfies the active energy demand of the EVs after meeting the energy requirements of the warehouse including the AFs. The V2G functionality allows the EVs to discharge at intervals when the PV production diminishes. The trend of the charging and discharging cycles of EVs on a weekday and a weekend are reported in Figs. 6(a) and 6(b).

From Figs. 5 and 6(a), it can be also noted that EVs at higher energy content discharge to meet the immediate needs of other EVs.

Since the PV inverter satisfies the whole reactive energy demand by its own, similarly to Scenario I, the relevant figure is omitted for brevity. Similarly to Scenario I, the operations of the AFs are scheduled in an effective manner avoiding penalties incurred due to unexecuted tasks. A heatmap representing the State of Charge (SoC) of the three AFs in Scenario II is represented in Fig. 4(b). From Fig. 4(b), it is evident that the charging states of the AFs are centered around the time intervals involving high PV production, thus reducing the operating costs of the facility.

Table 1
Energy and economic quantities of the optimization results.

	Scenario		
	I	II	III
E^{El} [MWh]	9.41	9.41	9.41
E^{AF} [MWh]	0.44	0.44	0.44
$E^{truck,ch}$ [MWh]	3.33	3.96	2.93
$E^{truck,dch}$ [MWh]	0.44	0.83	–
$E^{van,ch}$ [MWh]	0.59	0.97	0.31
$E^{van,dch}$ [MWh]	0.48	0.78	–
$E^{car,ch}$ [MWh]	0.20	0.62	0.20
$E^{car,dch}$ [MWh]	–	0.34	–
$E^{B,ch}$ [MWh]	3.21	–	–
$E^{B,dch}$ [MWh]	3.01	–	–
$E^{G,b}$ [MWh]	1.55	2.46	3.70
$E^{G,s}$ [MWh]	2.24	3.07	4.47
E^{PV} [MWh]	14.06	14.06	14.06
$E^{PV,curt}$ [MWh]	0	0	0
Self Consumption [%]	84.11	78.15	67.2
Total costs [€]	113.50	262.64	450.27

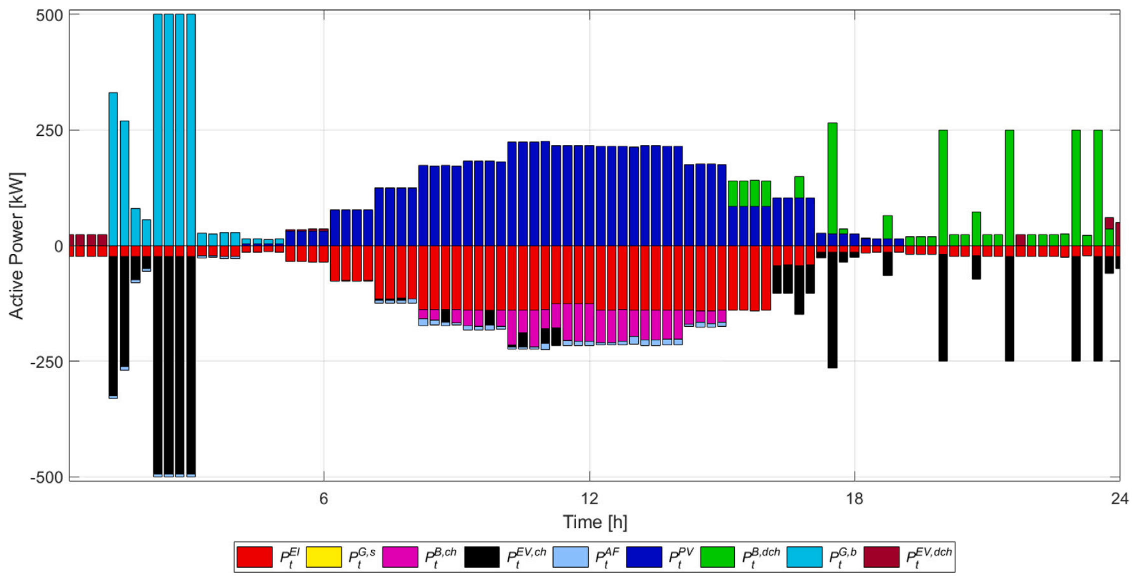
Comparison among scenarios

Although the optimization considered an optimization horizon of one day, for a better understanding of the effectiveness of the developed model the weekly active energy and economic quantities from the optimization results for the three scenarios are presented in Table 1

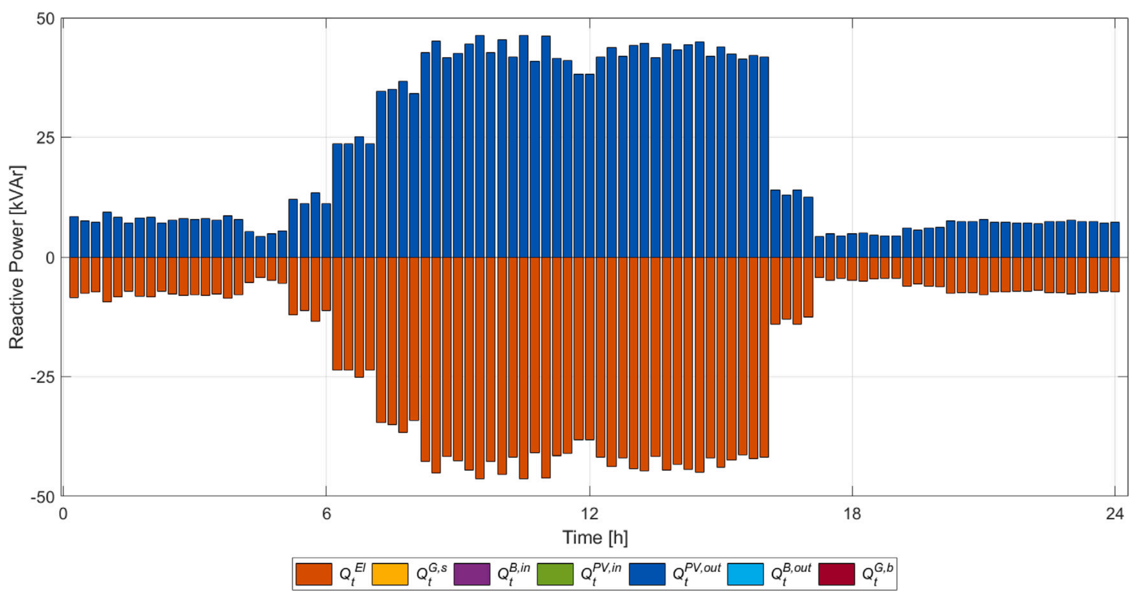
From Table 1, it is evident that in Scenario II, where only the BESS is out of service, EVs function as a mobile storage, helping to minimize the absorption of energy from the network. Due to limitations on the depth of EV battery discharge and due to the unavailability of some EVs during periods of excess PV energy production, the warehouse still relies on the public distribution network to meet active energy demand, leading to a larger energy exchange with external network if compared to Scenario I, where the self-consumption is maximized thanks to the presence of the BESS. In Scenario II, net costs are larger than in Scenario I. However, these costs remain lower than in Scenario III, where the V2G functionality is unavailable. Scenario III shows a higher amount of active energy exchanged with the public distribution network since no storage forms are available: thus, the non-differable EV charging demands during periods of minimal PV energy generation are still met by the public distribution grid, leading to increased operating costs. This increases energy absorption from the public distribution grid and is reflected in a reduction of the facility self-consumption rate, calculated as described in [48], which decreases notably in the absence of storage. The PV inverter operates within the capability curve, eliminating any curtailments in production. Compared to Scenario III, a reduction in operating costs equal to 74.8% and 41.7% are reported for Scenarios I & II respectively. However, the task assignment to AFs remains unaffected, as all tasks are completed in all scenarios and as the active energy demand of the AFs is always met, leading to avoidance of penalties related to unfinished tasks.

Sensitivity analysis

To evaluate the impact of V2G functionality on the operation of the facility, a sensitivity analysis was performed by varying two key parameters: the distance traveled by freight vehicles prior to arrival and their arrival times at the warehouse. Variations in travel distance affect the battery's SoC upon arrival, while changes in arrival time influence the duration of the vehicles' stay at the facility: both factors directly influence the dynamics and effectiveness of V2G operations. The travel distance is incrementally increased by 5%, 10%, 15%, and 20% relatively to the distances traveled by the vehicles in Scenario II, while the arrival times are shifted forward by 15 to 60 min, in 15-minute intervals. The corresponding results are presented in Table 2.



(a) Active power balance in Scenario I.



(b) Reactive power balance in Scenario I.

Fig. 2. Electric power balances in Scenario I.

Table 2
Sensitivity analysis varying the distance traveled and the arrival time.

	Distance				Arrival Time			
	+5%	+10%	+15%	+20%	+15 min	+30 min	+45 min	+60 min
$E^{truck,ch}$	+3.4%	+7.21%	+11%	+14.38%	+0.04%	+0.35%	+1.05%	+1.62%
$E^{truck,dch}$	−0.7%	−0.56%	−0.22%	−1.5%	+0.36%	+1.54%	+4.28%	+6.47%
$E^{van,ch}$	+2.13%	+3.19%	+3.93%	+7.15%	−1.64%	−7.85%	−14.74%	−20.77%
$E^{van,dch}$	+0.08%	−1.28%	−2.95%	−2.14%	−1.3%	−7.55%	−14.49%	−20.57%
$E^{G,b}$	+5.87%	+12.07%	+18.26%	+24.51%	−0.02%	+1.68%	+3.46%	+5.26%
$E^{G,s}$	−0.55%	−1.05%	−1.55%	−2.05%	+0.27%	+1.87%	+3.46%	+5%
Total Costs	+14.2%	+28.68%	+43.21%	+59.8%	+0.14%	+2.28%	+4.57%	+6.92%

From Table 2, it is evident that variations in travel distance have a significantly greater impact on operational costs compared to variations in arrival time. A clear, steady increase in costs is observed as travel distance increases. This is primarily due to the lower SoC of the freight vehicles upon arrival, which results in higher energy requirements to meet departure needs. Consequently, the amount of energy charged to the trucks and vans increases accordingly. Since the vehicles arrive with reduced energy content, outside the central hours of RES availability, and given that the BESS is out of service in Scenario II, the EMS is forced to rely heavily on the external network. This leads to a consistent

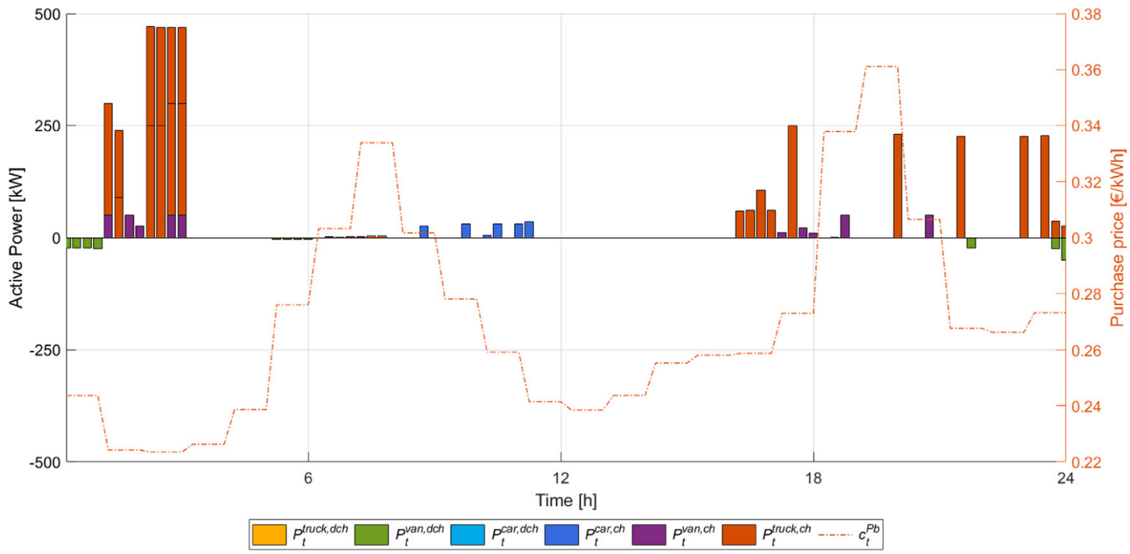


Fig. 3. Trend of the charging and discharging cycles of EVs at the warehouse.

rise in the amount of active energy absorbed from the utility network, further contributing to the increase in operating costs. Variations in arrival times lead to an increase in the energy discharged from the trucks. However, this change resulted in a noticeable decrease in the energy discharged from the vans, primarily because their availability at the warehouse is limited to a much shorter duration compared to the trucks. To align with overall energy requirements, the EMS reduces energy discharge from the vans and, owing to shorter availability, they are not charged to their maximum capacity. This shift increases the reliance on trucks for active energy discharge, which in turn raises the amount of energy charged to them. Nonetheless, both the energy purchased from the grid and the total operating costs remain lower compared to the scenario where travel distances were varied.

Conclusion

The integration of EVs and RESs is crucial for reducing GHG emissions. Efficient management of AFs powered by local RESs in a warehouse enhances sustainability in logistics. However, coordinating RESs, BESSs and EVs to minimize operating costs while optimizing AF task scheduling remains a complex task, not comprehensively addressed in the current scientific literature.

To provide an holistic approach, this present study proposes an EMS for the optimal combined energy and task planning management of a green sustainable warehouse. The warehouse is equipped with a PV plant, coupled with a BESS, and hosts charging stations for EVs, used both for goods and personnel transportation. It also employs AFs for internal material handling activities. The EMS aims to minimize the net operating costs of the warehouse, related to the exchange of electricity with the distribution network, along with the minimization of the number of unexecuted tasks. Three scenarios have been analyzed, demonstrating that the application of V2G to EV fleets is beneficial, significantly reducing net electricity costs, especially when the BESS is out of service. In fact, the simultaneous availability of BESS and V2G services reduces the facility's operating costs by more than 75%, compared to a configuration without them.

Since a coupled approach for the optimal dispatch of energy resources and task planning is computationally intensive, the simultaneous optimization involves various trade-offs and future developments of the study will focus on a detailed bi-level model of the EMS. In this structure, the first level will optimize energy flows using a time resolution aligned with energy profile dynamics, while the second level will optimize logistics with a time resolution suitable for AF scheduling. This approach is expected to reduce overall computational complexity. Furthermore, the bi-level formulation will act as a heuristic method, and its solution may not be globally optimal. To evaluate the performance of the bi-level approach, it will be compared against the results obtained from the single-level EMS model proposed in this study. Additionally, the bi-level EMS will initially focus on a single warehouse. However, by introducing additional constraints, it will be possible to extend the approach to optimize an entire supply chain through a distributed optimization framework, where each warehouse is optimized independently. Moreover, different electricity sale strategies and the participation of BESS and EVs in flexibility markets could be investigated.

CRediT authorship contribution statement

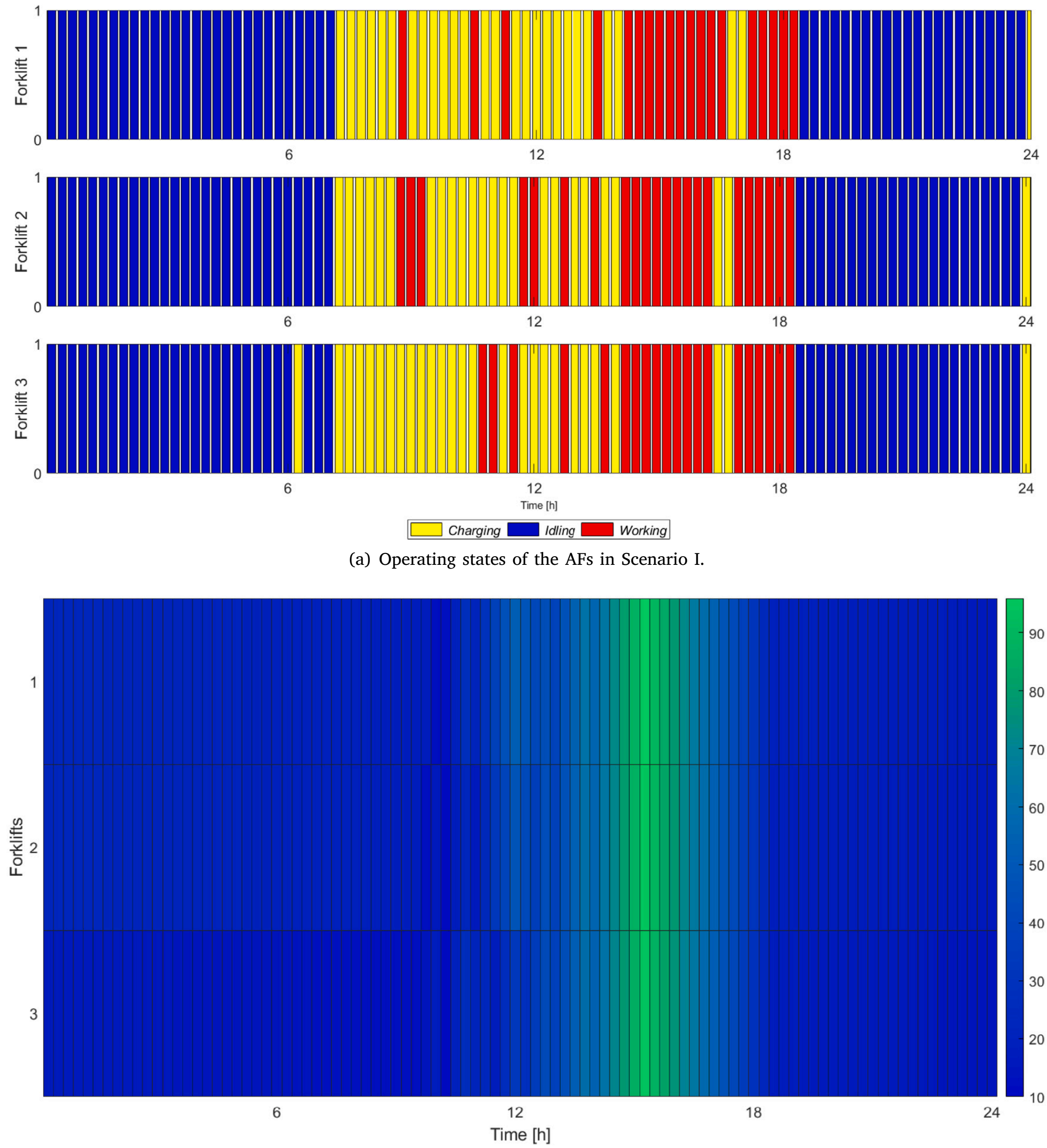
Alphonse Francis: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Matteo Fresia:** Writing – review & editing, Visualization, Software, Methodology, Conceptualization. **Bahareh Ghavidel:** Software, Data curation. **Sebastián García:** Writing – review & editing, Methodology, Conceptualization. **Silvia Siri:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Stefano Bracco:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the National Recovery and Resilience Plan, Mission 4, Component 2, Investment 1.4 "Strengthening research facilities and creating national R&D facilities on some Key Enabling Technologies" funded by the European Union–NextGeneration EU. Code CN000023–Title "Sustainable Mobility Center (National Center for Sustainable Mobility CNMS)".



(a) Operating states of the AFs in Scenario I.

(b) SoC heatmap of AFs in Scenario II.

Fig. 4. Operating states and SoC heatmap of AFs in Scenarios I and II respectively.

Appendix A. PV system

The operating ranges defined by the CEI-016 standard and the relevant relations are reported below.

$$0 \le Q_t^{PV,abs} \le 0.436 \cdot A^{PV,in} \cdot y_t^{PV,abs} \quad \forall t = 1,\dots,T \tag{A.1}$$

$$0 \le Q_t^{PV,inj} \le 0.436 \cdot A^{PV,in} \cdot y_t^{PV,inj} \quad \forall t = 1,\dots,T \tag{A.2}$$

$$y_t^{PV,abs} + y_t^{PV,inj} \le 1 \quad \forall t = 1,\dots,T \tag{A.3}$$

$$(P_t^{PV})^2 + (Q_t^{PV,abs})^2 \le (A^{in,PV})^2 \quad \forall t = 1,\dots,T \tag{A.4}$$

$$(P_t^{PV})^2 + (Q_t^{PV,inj})^2 \le (A^{in,PV})^2 \quad \forall t = 1,\dots,T \tag{A.5}$$

Constraints (A.1) and (A.2) define the operating limits of the PV inverter and restrict the reactive power output to 0.436 p.u. in compliance with the CEI standards as detailed in [49]. Constraints (A.4) and (A.5) define a semicircular portion of the operating range. The arc describing the circular segment is divided into smaller arcs, each one approximated with the chord drawn between the initial and final points of the arc and the relevant constraints are reported in [49].

The costs related to the curtailment of PV active power production, $c_t^{PV,curt}$, are calculated as reported below.

$$c_t^{PV,curt} = \Delta \cdot p^{PV,curt} \cdot P_t^{PV,curt} \quad \forall t = 1,\dots,T \tag{A.6}$$

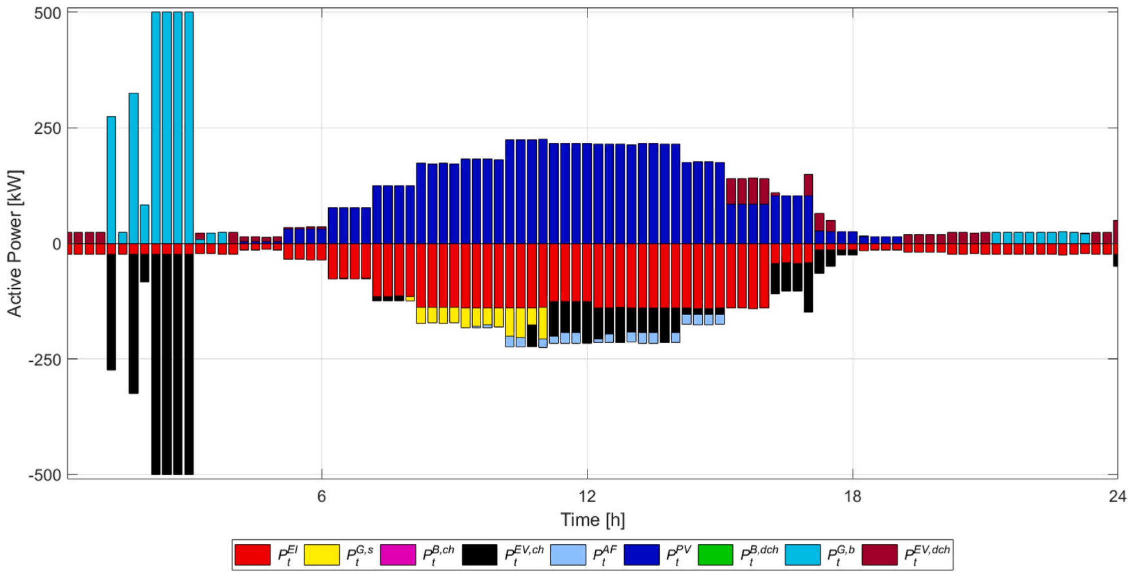


Fig. 5. Active power balance in Scenario II.

Appendix B. Grid connection and BESS inverter

Grid connection transformer and the BESS inverter are characterized by a circular operating range, linking active and reactive power exchanges. However, these limits introduce nonlinearity in the MILP model and must be linearized, similarly to that of the PV inverter. The relevant constraints related to the exchange of inductive reactive power from the public network are reported in [49].

The net costs related to the exchange of active and reactive energy with the network at each time interval, c_t^{Grid}, is expressed as reported below:

$$c_t^{Grid} = \Delta \cdot \left(c_t^{Pb} \cdot P_t^{G,b} + c_t^{Q,abs} \cdot Q_t^{G,abs} + c_t^{Q,inj} \cdot Q_t^{G,inj} - r_t^{Ps} \cdot P_t^{G,s} \right) \quad \forall t = 1, \dots, T \tag{B.1}$$

In Eq. (B.1), c_t^{Pb} and r_t^{Ps} are respectively the unitary cost related to the purchase of active energy from the distribution network in [€/kWh] and the unitary revenue generated from the sale of active energy to the distribution network in [€/kWh], while $c_t^{Q,abs}$ and $c_t^{Q,inj}$ are the unitary penalties related to the absorption and injection of reactive power from the distribution network in [€/kVArh].

Appendix C. Autonomous Forklift

The operations of the AFs at the facility need to be synchronized with two key factors: the presence of warehouse personnel according to scheduled work shifts and the availability of sufficient energy in its batteries to ensure task execution. The binary decision variables $w_{j,f,t}^F$, $z_{j,f,t}^F$, and u_j^F govern the constraints that ensure optimal scheduling of AFs. The associated constraints are presented below.

$$\sum_{j=1}^{N^j} z_{j,f,t} = y_{f,t}^W \qquad \forall f = 1, \dots, N^F, \quad \forall t = 1, \dots, T \tag{C.1}$$

$$\sum_{j=1}^{N^j} z_{j,f,t} \leq 1 \qquad \forall f = 1, \dots, N^F, \quad \forall t = 1, \dots, T \tag{C.2}$$

$$\sum_{f=1}^{N^F} z_{j,f,t} \leq 1 \qquad \forall j = 1, \dots, N^j, \quad \forall t = 1, \dots, T \tag{C.3}$$

Constraints (C.1) ensure that AFs cannot perform a job while charging or idling, while constraints (C.2) and (C.3) limit each job to a single AF per shift and prevent multiple AFs from performing the same job simultaneously.

$$\sum_{j=1}^{N^j} w_{j,f,t} \leq 1 \qquad \forall f = 1, \dots, N^F, \quad \forall t = 1, \dots, T \tag{C.4}$$

$$\sum_{l=1}^{N^j} \sum_{h=t+1}^{t+D_j-1} w_{l,f,h} \leq M \cdot (1 - w_{j,f,t}) \qquad \forall f = 1, \dots, N^F, \quad \forall j = 1, \dots, N^j, \quad \forall t = 1, \dots, T \tag{C.5}$$

$$w_{j,f,t} \leq z_{j,f,h} \qquad \forall f = 1, \dots, N^F, \quad \forall j = 1, \dots, N^j, \quad \forall t = 1, \dots, T - D_j + 1, \quad \forall h = t, \dots, t + D_j - 1 \tag{C.6}$$

$$\sum_{f=1}^{N^F} \sum_{t=1}^{T} z_{j,f,t} + D_j \cdot u_j = D_j \qquad \forall j = 1, \dots, N^j \tag{C.7}$$

$$\sum_{f=1}^{N^F} \sum_{t=1}^{T} w_{j,f,t} + u_j = 1 \qquad \forall j = 1, \dots, N^j \tag{C.8}$$

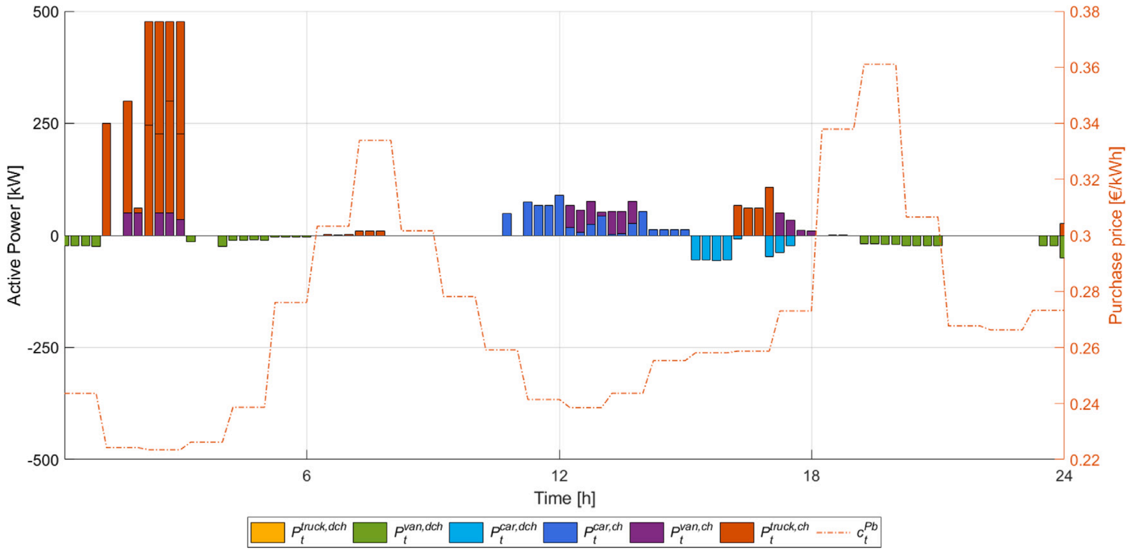
$$c^F = \sum_{j=1}^{N^j} p_j \cdot u_j \tag{C.9}$$

Constraints (C.4) ensure that an AF can perform only one job at a time. Constraints (C.5) ensure that, once an AF f initiates a job j with a duration of D_j, it does not start any new job during the subsequent D_j time intervals. Constraints (C.6) enforce that, if a job j is initiated at time t by the AF f, the AF needs to perform that job for the D_j time intervals. Constraints (C.7) ensure that, once an AF initiates a job, it must be completed within its specified duration, while constraints (C.8) allow the AF the flexibility to choose whether to perform a job, as tasks are not mandatory. In Eq. (C.9), c^F represents the total penalty incurred on the facility due to the non-completion of the jobs, where p_j denotes the penalty associated with each job j in [€].

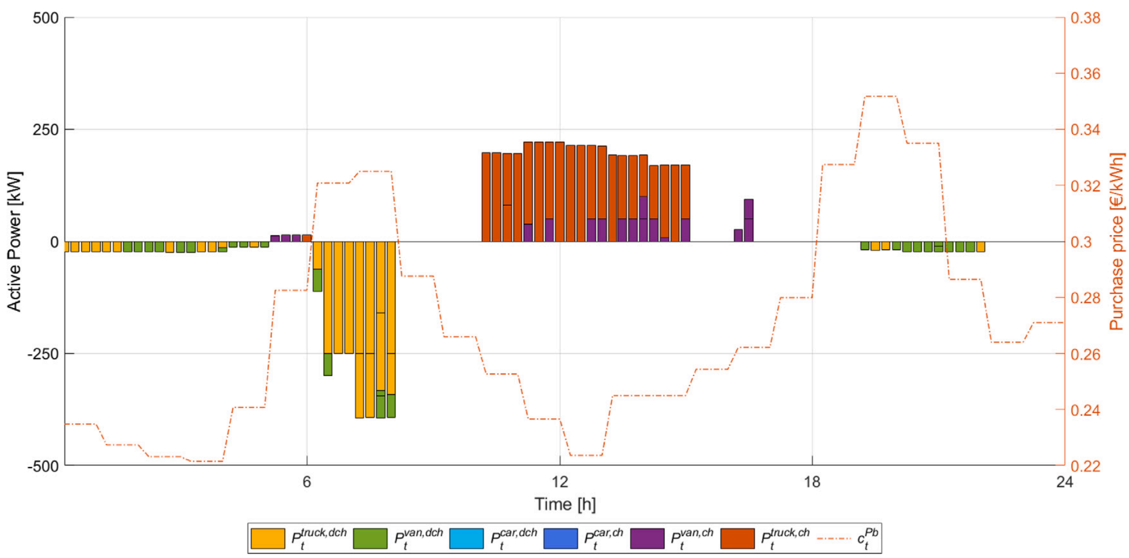
Appendix D. EV model

For the three classes of EVs present at the facility, the energy content of each EV at the time of departure is defined to be above an acceptable, minimum energy content, depending on the class of the vehicle as reported in the constraint below.

$$E_{v,t_v^{dep}}^{EV} \geq E_{v,t_v^{dep}}^{EV,min} \qquad \forall v = 1, \dots, V \tag{D.1}$$



(a) Weekday charging and discharging trend



(b) Weekend charging and discharging trend

Fig. 6. Trend of EV charging and discharging cycles in Scenario II.

For the EVs committed for freight transport, the distances that need to be covered by each EV also play an important role in the energy content of each EV as defined below.

$$E^{EV}_{v,t_v^{arr}} \leq E^{EV}_{v,t_v^{dep}} - F_v \cdot D_v \qquad \forall v = 1, \ldots, V \tag{D.2}$$

In (D.2), F_v represents the energy consumption of each vehicle in [kWh/km] while D_v represents the distance covered by an EV in each shift. Given the short optimization horizon, the effects of V2G functionality on EV battery life and the impact of battery degradation dynamics have been excluded from the model, as these factors become significant only over longer time horizons.

Data availability

The data that has been used is confidential.

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