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Original article

Green warehousing practices: Assessing the impact of PV self-consumption enhancement strategies in a logistics warehouse

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ABSTRACT

Logistics facilities, while critical to industrial systems, significantly contribute to greenhouse gas emissions, necessitating improved operations, energy use, and renewable energy integration. The use of distributed renewable energy sources, with their intermittent and unpredictable generation, disrupts energy balance and leads to curtailment issues. This places a significant load on the electrical grid, increasing emissions and environmental problems, hindering the effective use of renewable energy. To address these challenges, modifications can be made to existing warehouses to increase their self-consumption. Empirical studies assessing the impact of such modifications, particularly in the logistics field, are lacking. This work contributes to the ongoing research by proposing a simulation-based approach that evaluates multiple scenarios for a real-world logistics facility to enhance the self-consumption ratio. This analysis is based on a conceptual framework providing a roadmap towards sustainable warehousing practices. The study simulates and presents multiple scenarios, including the base case, electrification of the heating system, and an opportunity charging strategy for MHE, aiming to enhance self-consumption, while examining environmental and economic performances, followed by a sensitivity analysis. Findings demonstrate a 25% increase in self-consumption and significant energy consumption reduction (-110 MWh/year) and CO2e emissions (-67.8 tons CO2e/year) for the final proposed scenario.

Introduction

Over the past few years, there has been a persistent escalation in global carbon dioxide emissions, recognized as a pivotal catalyst for global warming, correlating with significant environmental harm [1]. Logistics facilities are crucial in industrial systems, profoundly influencing both service quality and the logistic costs of businesses. Logistics operations such as transportation and storage of materials and finished goods, while indispensable for sustaining economic prosperity and guaranteeing customers' order fulfillment, emerge as significant contributors to emissions, representing major sources of environmental pollution within global supply chains [2]. While research has largely focused on the transportation sector, it is increasingly recognized that the most effective strategy for companies to reduce the carbon footprint of their products and services is by addressing emissions across their entire supply chain [3]. Notably, a considerable portion of logistics-related carbon dioxide emissions originates from logistics facilities, such as warehouses [4]. Warehousing activities constitute a substantial portion, around 11%, of the total greenhouse gas emissions generated within the global logistics sector, underscoring their significant environmental impact [5].

Warehouses are vital components of supply chains, as they buffer material flow to handle variability, consolidate products for streamlined delivery, and provide value-added services such as kitting and customization [6]. The surge in e-commerce and the rising desire for personalized mass production have heightened the demand for warehouse infrastructure and facilities [7]. This trend has led to the rise of urban distribution centers strategically positioned for efficient last-mile logistics distribution, which are proving to have a non-negligible environmental impact [8]. Thus, the interplay of these factors has highlighted the key role of warehouses in the environmental sustainability of the entire supply chain [9,10]. This has led practitioners concerned with sustainable goals to focus more on the sustainability of warehouses [11], prompting companies to adopt energy efficiency measures and Green Warehousing (GW) practices [12] towards a new managerial concept called "sustainable warehousing", which has been defined by some scholars as "a set of technological and organizational solutions aimed at efficient warehouse processes while minimizing environmental impact and maintaining the highest social standards in terms of financial efficiency" [13,14]. This managerial concept can be

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Nomenclature

ACR	Air change rate [Vol/h]
BC	Battery Cost $[\frac{€}{\mathrm{kWh}}]$
BEV	Battery Electric Vehicles [−]
CAV	Constant air volume [−]
COP	Coefficient of Performance [−]
ECF	Emission Conversion Factor $[\frac{\mathrm{gCO_2e}}{\mathrm{kWh}}]$
EUI	Energy Use Index $[\frac{\mathrm{kWh}}{\mathrm{m}^2}]$
$GSCM$	Green Supply Chain Management [−]
GW	Green Warehousing [−]
$HVAC$	Heating, Ventilation, and Air Conditioning [−]
KPI	Key Performance Indicators [−]
LLE	Lamp Luminous Efficiency $[\frac{\mathrm{lm}}{\mathrm{W}}]$
LSP	Logistics Service Provider [−]
MH	Material Handling [−]
MHE	Material Handling Equipment [−]
NGP	Natural Gas Price $[\frac{€}{\mathrm{kWh}}]$
Ppv	Photovoltaic power capacity [kWp]
PV	Photovoltaic [−]
RBT	Resource based theory [−]
ROI	Return on Investment [%]
Scm	Standard Cubic Meter [Sm^3]
YCO_2e	Yearly CO2e emissions $[\frac{\mathrm{kgCO_2e}}{\mathrm{year}}]$

categorized within a broader concept that is referred to in the literature as green supply chain management (GSCM), i.e. “the integration of environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as the end-of-life management of the product after its useful life” [15]. The literature on the various topics of GSCM is very extensive and addresses various and interconnected aspects, including sustainable warehousing [16,17]. In this broad perspective, practitioners are motivated by the potential benefits associated with GSCM practices, such as enhanced reputation, increased efficiency, and revenue growth. However, the cost-benefit trade-offs associated with GSCM practices remain controversial and practitioners may be uncertain about which practices are the most valuable to adopt [18,19]. This uncertainty is reflected in all GSCM topics, including sustainable warehousing [16]. Therefore, the effectiveness of GW practices has yet to be validated and the literature lacks a broader perspective that would enable the achievement of Net-Zero targets. In this context, the resource-based theory (RBT) provides the foundation for the development of GW practices as strategic capabilities to create a sustainable competitive advantage [20]. According to RBT, companies compete based on a bundle of resources and capabilities. By combining and coordinating resources, technical and organizational capabilities, strategic capabilities are established, creating opportunities for a sustainable competitive advantage over the years [21]. Moreover, RBT is used to recognize the value of possessing strategic resources and capabilities and to understand how they can be configured and leveraged [22]. Therefore, from a RBT perspective, PV energy self-generation could be considered as a valuable resource for logistics facilities. When combined with technical and organizational capabilities, it has the potential to lead to the creation of a sustainable competitive advantage. These combinations can be realized by increasing PV self-consumption through the implementation of specific GW measures and strategies.

On the other hand, as warehouses are significant contributors to greenhouse gas emissions, several studies have been dedicated to leveraging management strategies, technologies, and equipments to reduce the total emissions of GHG directly caused by activities taking place in these facilities. Some recent studies have included “green warehousing” as a key element of environmentally sustainable supply chain practices [23,24]. Dubey et al. [25], however, provided a more specific definition, describing green warehousing as an organizational framework designed to incorporate and implements environmentally friendly operations to minimize energy consumption, energy costs, and GHG emissions in a warehouse. According to Ulucak et al. [26], achieving a sustainable warehouse involves implementing various strategies and approaches focused on minimizing waste generation and reducing energy consumption.

According to Burinskiene et al. [27], the main source of logistics-related CO2 emissions is storage and material handling in warehouses, while, as noted by Sundarakani et al. [28], the earlier research had mostly focused on transportation aspects, often overlooking the importance of green practices, technologies, and regulatory measures within warehouse operations. Bartolini et al. [16] identified three macro-themes in GW literature including: “green warehouse management”, “environmental impact of warehouse building”, and “the energy saving in warehousing”. The environmental impact of warehouse facilities (i.e. buildings) was then categorized into two key sub-themes: warehouse building, and its lighting and HVAC systems. In this context, optimizing the lighting and heating systems in warehouses is one of the fundamental strategies for improving energy efficiency and reducing their environmental footprint [29]. Studies have shown that warehouses often struggle with inefficient energy use due to the high demand for lighting, cooling, equipment, heating, and ventilation systems [14]. Stolaroff et al. [30] revealed that in temperature-controlled warehouses, heating and cooling systems are the major energy consumers. In contrast, Mashud et al. [31] highlighted that in non-temperature-controlled warehouses, lighting and equipment draw the most energy. As noted in their literature review, Oloruntobi [14] emphasized that heating systems in warehouses should utilize electrical energy or renewable sources. Additionally, Ali et al. [32] found that integrating green energy, which is defined by Seroka-Stolka and Ociepa-Kubicka [33] as the generation of energy from nearby low-carbon renewable sources such as solar panels, in warehouses is a key strategy that provides a lasting foundation for reducing the energy consumption and emissions in these facilities. Mashud et al. [31] further asserted that adopting green energy solutions can significantly reduce a warehouse’s carbon footprint and contribute to achieving zero carbon emissions. Photovoltaic (PV) systems, as a prominent source of green energy, offer a viable means to achieve these goals by generating clean electricity on-site.

However, in case the generated electricity from the PV panels in specific intervals (e.g. midday and early afternoon) is substantially higher than the facility’s consumption, the generated electricity should be sold to the grid (thus consumed in another location), leading to grid losses and the resulting carbon emissions. Furthermore, in regions with a high penetration of solar generation (which will become increasingly common as a result of policies that encourage green energy integration), may lead to curtailing the grid injection of the generation from other renewable sources [34], thus reducing the overall expected carbon emission saving. On the other hand, having intervals (e.g. evening and night) with high electricity consumption and low or no PV generation (e.g. in the case of all material handling devices being charged at night), results in purchasing electricity from the grid, which in turn has a specific carbon intensity (due to the higher reliance of the grid on fossil fuel-based generation and grid losses [35]). For instance, generating 1 kW of electricity in the Italian grid produces 259.8 g of CO2e (on average), as highlighted in the ISPRA report [36]. Thus, enhancing the self-consumption rate from on-site PV generation in warehouses can notably reduce the carbon footprint of these facilities and help achieve the expected influence of green energy generation, which can thus be considered a green warehousing practice.

From an economic perspective instead, green practices have been shown to result in benefits for businesses by reducing energy consumption costs over time [14]. Selling excess energy to the grid is often less profitable since in these intervals (e.g.midday and afternoon) supply is high and demand is low, thus the received compensation for injecting electricity into the grid is substantially lower than the purchasing price of the electricity from the grid (e.g. during evening/night). Therefore, improving PV self-consumption is considered a green warehouse practice, as it allows businesses to directly use the solar energy generated on-site, reduce the need to buy electricity during peak hours (when prices are also typically higher), reducing the overall energy costs. This was confirmed by a study conducted by Camilo et al. [37], which compared various scenarios for on-site PV consumption. These scenarios included: (i) injecting all generated PV energy into the grid while consuming all electricity from the grid, (ii) self-consuming PV-generated energy with the option to inject surplus into the grid, (iii) using battery storage to store surplus energy for later use, with the option to inject any remaining surplus into the grid, and (iv) a net-metering model. The study showed that configurations without self-consumption are not economically attractive. Furthermore, due to the high cost of batteries, storing surplus energy in dedicated battery systems alone is not the most viable option.

In this context, increasing self-consumption by avoiding additional investments in new batteries such as utilizing the existing charging demand of material handling units (e.g. forklifts) can significantly improve the cost-effectiveness of the solution. By leveraging existing battery systems, the warehouse can reduce reliance on costly dedicated storage solutions, improving both energy efficiency and overall cost savings. Moreover, self-consumption helps warehouse owners stabilize their energy costs (apart from helping the grid through preventing imbalances [38]), shielding them from fluctuating electricity prices. Lastly, transitioning from gas-fed boilers to electric heat pumps, permits eliminating natural gas consumption and significantly reducing CO2e emissions, offering an opportunity to provide a substantial portion of the energy required in the building from the onsite generated PV.

Thus, self-consumption enhancement strategies empower the integration of green energy (in line with the findings of Oloruntobi [14] and Ali et al. [32]) and allow reducing in energy consumption (and its associated costs) along with decreasing the GHG emission and the carbon footprint of the warehousing activities, which is in line with the concept of "green warehousing" as defined by Dubey et al. [25] and Bartolini et al. [16].

Unlocking self-consumption: A crucial priority

As one of the key measures to reduce the consumption of fossil fuels, global efforts have been specifically dedicated to expanding the scale of distributed renewable generation [39,40]. The global installation of photovoltaic (PV) panels experienced a substantial increase, due to improvements in cost and efficiency. This surge led to a total installed PV capacity worldwide reaching 591 GW in 2019 [41]. Warehouses, with their expansive rooftops offering significant surface area, present a strong potential for the installation of PV systems without major altercations in their design. Yet, the integration of decentralized renewable energy sources, particularly at the level of individual buildings, due to the variability and unpredictability inherent in their generation, presents the challenge of balancing fluctuating generation with real-time energy demand [42,43]. A discrepancy occurs due to excessive PV generation during low-demand periods and insufficient PV output during relatively high-demand periods, resulting in both diurnal mismatch and PV curtailment challenges [41]. The disproportionate PV generation during daylight hours and the restricted flexibility of existing power plants, result in PV generation curtailment, diminishing its value. Consequently, the cost of self-generated PV electricity becomes lower than retail prices, rendering self-consumption economically viable even without subsidies [44]. For these reasons, from a RBT perspective this could be considered a valuable resource to be exploited for practitioners to increase their economic and environmental performances [21,22].

Moreover, during periods of low demand and elevated distributed generation, there is a risk of the voltage exceeding the acceptable range within the low-voltage feeder, potentially leading to the disconnection of the generator [45], which can potentially be addressed through self-consumption. Self-consumption would be the share of the total PV production directly consumed by the PV system owner, and there is a growing interest in the self-consumption of PV electricity within grid-connected systems, both among PV system owners and within the scientific community [46]. Installing PV panels while having a low rate of self-consumption (lack of synchronization between the consumption and PV generation with the subsequent exchange with the local grid, which results in grid losses and a significant increase in the resulting CO2e emissions) is rarely elaborated in the public discussions focused on increasing the share of renewable energy generation. The latter point can be considered as a form of greenwashing. The adoption of renewable self-consumption not only leads to savings on consumers' electricity bills but also yields a variety of additional benefits. This includes the prevention of electrical power losses in the transmission network, reduction in CO2 emissions, lowering of electricity prices (EP) in the wholesale market, and a decrease in the rate of energy dependence [47], providing a potential opportunity for companies to create a sustainable competitive advantage in line with an RBT perspective.

Self-consumption strategies

Electrification strategies

The global transition towards electrification is widely recognized as a crucial strategy in mitigating climate change, given that the adoption of low-carbon electricity has the potential to substitute current fossil fuel consumption in building infrastructure [48]. Electrification strategies could be pivotal in increasing the self-consumption of energy across various domains [49]. The adoption of electric technologies has been shown to have a significant impact on energy consumption leading to a decline in electricity usage. For instance, the integration of PV panels with smart charging of electric equipment has demonstrated improved PV self-consumption and peak load reduction in residential buildings and industrial systems, highlighting the potential for electrification to enhance self-consumption of renewable energy [50]. Similarly, the adoption of electric vehicles (EVs) has led to an increase in self-consumption rate, as more local energy is utilized for EV charging, thereby reducing reliance on external energy sources (e.g., national power grid). In [51], the potential for electrifying a logistics center in a case study in Sweden was explored, emphasizing the optimization of electricity supply to minimize reliance on grid power upon acquiring a new battery-powered truck. Additionally, NG has been extensively employed for heating purposes, particularly in Italy as most Italian buildings are supplied by traditional NG boilers [52]. The literature and policymakers widely acknowledge that rapid decarbonization of buildings can be achieved through electrifying heat production with heat pumps [53]. Moreover, the integration of an electrified HVAC system in warehouses would allow for offering flexibility to the electrical grid [54] or better incorporating the charging load of electric trucks [55] through modulating the consumption. Heat pumps stand out as the pivotal technology for the electrification of heating systems [48]. The coupling of heat pumps with PV systems presents a highly promising pathway to heat buildings with lower greenhouse emissions. In a study conducted by Kemmler and Thomas [56], the feasibility of increasing self-consumption in family houses using heat pumps has been investigated and demonstrated that a significant saving in consumption can be obtained when heat pumps are coupled with PV panels. Nevertheless, the impact of load electrification strategies within warehouses has been neglected so far, outlining a notable literature gap. More specifically, the efficacy of electrification of the heating system as a prominent solution for self-consumption enhancement in warehouses needs to be further investigated.

Opportunity charging strategy for warehousing processes

Warehouses have increased their energy consumption due to real-time demands and growing energy needs associated with the extended use of information technology and automated solutions for Material Handling (MH), storage, and picking. The longer operating times require more intense use of Material Handling Equipment (MHE), which has been appointed as one of the most crucial areas of energy consumption in warehouses and a major contributor to the increase in CO2e emissions [11]. Focusing on resource capabilities, potential energy savings could be realized through the use of Lithium-ion batteries, due to their high energy density, low self-discharge rate, and fast charging capabilities [57,58]. In particular, the fast charging capability helps to improve the efficiency and flexibility of warehousing processes by optimizing the forklift battery charging strategy [59]. When these batteries are incorporated into an opportunity charging strategy (which involves quickly charging them partially during warehousing activities), they have the potential to be a promising option for meeting the needs of warehouse operations while also minimizing the environmental effect [60]. Hence, this solution is crucial for reducing the environmental impact of MHE in warehouses, as they represent a useful lever to improve energy efficiency, sustainability, and to reach a sustainable competitive advantage [61]. This is done by matching partial charges to peak power generation by PV panels. However, the potential of such a solution to increase the self-consumption ratio is still overlooked and there is a lack of empirical data in the logistics sector [16,60].

Case for simulation methods: the essential role of simulation in supply chain and logistics management

A growing number of companies have committed to achieving net-zero emissions goals. Becoming a net-zero energy logistics hub requires a long and challenging strategic pathway, which requires specific strategies and targeted resource allocation [62]. Nevertheless, GW practices are constantly evolving, thereby there is still uncertainty about their features and application areas, as well as related constraints. This highlights the challenges faced by potential investors to identify the best suitable measures that can provide high environmental performance and a good return on investment since they lack a guideline on how to proceed and what steps to embrace [63]. Nevertheless, the high implementation cost of GW practices and their cross-cutting implications could make it extremely challenging to conduct comprehensive experimental analyses in real-world settings. In this context, simulation plays a crucial role since it is arguably the only research method that provides a controlled environment in which experiments can be repeated purposefully over (simulation) time [64]. Thus, simulation is widely used and generally accepted in supply chain and logistics management because it facilitates the study of complex systems less expensively compared to real-life experiments [65–67].

Research gap and the contributions of the current study

As previously indicated, the diurnal mismatch and the working hours of the warehouses lead to an imbalance in the energy load and PV generation. Nevertheless, it is crucial to evaluate the effectiveness of innovative charging methods that utilize on-site generated PV energy, rather than relying solely on traditional overnight charging methods (draw power from the grid). Moreover, the impact of utilizing electrified HVAC systems rather than conventional systems (common in Italy) and their impact on the self-consumption of warehouses needs to be investigated [68]. Moreover, the high implementation costs and complex implications of these measures limit the conducting of comprehensive real-world experimental analyses, necessitating the use of simulation-based methods to support practitioners throughout their Net-Zero path and address the existing gap in the extant literature. Finally, acquiring simulation input data from real case studies is essential for attaining practical results. Most studies in the literature use a qualitative approach to assess the environmental sustainability issues of warehouses without providing a methodology to quantify the real impact of GW practices [14,16,32]. No previous work has dedicated a systematic approach to finding, implementing, and assessing the best practices in GW to increase the self-consumption of warehouses [14].

To fill this gap, this study proposes a simulation-based approach, supported by empirical data, to examine the impact of GW practices on a warehouse's energy demand by performing multiple simulation scenarios on a real ambient-temperature logistics facility located in Northern Italy. The simulation-based approach is grounded on a conceptual framework involving the GW practices selection process. Its goal is to enhance the self-consumption ratio of logistics facilities, thereby mitigating the diurnal mismatch issue of PV panels, decreasing reliance on grid electricity (by boosting the utilization of renewable energy sources), and fostering the development of a sustainable warehousing concept. In particular, this study focuses on crucial GW strategies to mitigate the environmental impact of logistics facilities by increasing PV self-consumption while taking into account its energy load and operational needs. A sensitivity analysis is then carried out to increase the robustness and reliability of the findings, as well as to assess how the variations of logistics performances and climates could affect the effectiveness of GW strategies involved. Hence, the main contributions of this work can be summarized as:

- Utilizing a 3D digital model of an actual warehouse case study, incorporating cross-docking, to simulate the consumption in the base case scenario, thereby establishing a baseline for comparison and highlighting potential consumption areas improved by facilitating GW practice selection (Simulation-based approach has been adopted in line with [69])
- Selecting the best GW practices systematically and implementing them to enhance self-consumption of the warehouse in line with the RBT;
- Proposing two scenarios alongside the baseline, aimed at optimizing different aspects of energy consumption within the warehouse environment to facilitate the enhancement of self-consumption
- Offering insights on the impact of the analyzed GW practices through the examination of monthly energy consumption by sources of consumption (electricity and natural gas), PV self-consumption, and other relevant simulation outputs for each scenario
- Providing various key performance indicators (KPI) to assess the environmental and economic viability of the investigated GW practices along with a sensitivity analysis to enhance the robustness of the study.

Following this introduction, the paper proceeds as follows: The subsequent section outlines the proposed framework and methodology, detailing the adopted simulation model, underlying assumptions, and inputs, along with a comprehensive description of each scenario considered. Next, the results obtained for each investigated scenario are provided. This is followed by the presentation of results for each investigated scenario. Finally, conclusions are drawn, study limitations are acknowledged, and recommendations for future research are provided.

Methodology and simulation process

The following section offers an in-depth explanation of the adopted methodology, including the case study, simulation model, assumptions, inputs, and considered scenarios. In line with the Resource Based Theory supported by Strategic Choice Theory, and previous literature [19], the methodology applied aims to investigate how exploiting the potential of PV panels and related energy generation can create a sustainable competitive advantage. This advantage may be achieved by increasing PV self-consumption which leads companies to better cope with the uncertainty of external factors that a company faces in its competitive business (i.e., energy supply disruption, energy price fluctuations due to political tensions, natural disasters, and accidents). Particularly, this methodology is based on a deductive-inductive approach to select and incorporate GW practices according to features, operational performances, and technological level of the logistics facility under investigation, and to assess their impact from an energy, environmental, and cost-effectiveness perspective. Firstly, based on data gathered from semi-structured interviews and on-site visits the 3D digital model of the distribution warehouse was first developed, then performing the related base case scenario. Subsequently, the model's accuracy was verified by comparing real consumption data with the base case scenario output. Real consumption data were gathered from interviews with company managers (i.e., Facility manager, Energy manager, and Logistics manager). Multiple sources and different roles are recommended to ensure the incorporation of both logistics requirements and energy performance information. This validation process ensures that the model faithfully represents the features of the case study investigated. Furthermore, base case scenario simulation aims to identify the critical consumption areas (e.g., heating, cooling, MH, lighting, etc.) for improvement to increase the self-consumption ratio and support the GW practice selection process. Hence, a set of initial GW practices – systematically gathered from literature – were established to possibly be implemented based on logistics facility needs and on energy-intensive consumption areas (deductive approach). These were then modified and extended through a closed-loop simulation process with a priority-based approach (inductive approach), to identify the most promising technology for the research objective. Finally, results were then reported highlighting the most significant contribution in terms of self-consumption ratio. However, the analysis was extended to encompass the computation of additional KPIs for each scenario, which specifically are:

- Yearly/monthly energy consumption by energy sources (i.e., electricity, natural gas) [MWh]
- Energy Use Index (EUI) [kWh/m^2]
- Yearly CO2e emissions [kgCO2e/year]
- Return on Investment (ROI) [%]
- Payback Period (PBP) [years]

These KPIs were chosen to evaluate the environmental and economic suitability of each investigated GW practice. This comprehensive approach facilitated the internal assessment of each practice and enabled cross-logistics facility benchmarking, thus fostering broader insights and comparisons. The following subsection outlines the simulation model, the case study utilized in the work, and the investigated scenarios.

Simulation model

DesignBuilder, which employs the EnergyPlus energy simulation program, has been selected as the modeling and simulation software, in accordance with prior studies in the literature that were dedicated to building energy simulation in other sectors [70,71]. The implemented formulations of EnergyPlus (developed by US Department of Energy), which is a widely utilized building simulation software, have been validated using experimental data in several studies. A brief list of the previous studies dedicated to validation of formulations implemented in this software, which has been provided by Lawrence Berkeley National Laboratory, can be found in EnergyPlus validation reports [72]. DesignBuilder serves as an advanced 3D modeling tool to perform multiple simulations specifically designed for a comprehensive energy consumption analysis by implementing a set of differential equations (i.e., mostly representing thermodynamics problems) that are solved over simulation time into a discrete event environment. Practically, based on a set of different inputs required for a comprehensive representation of the building's energy profile, the software can estimate the related energy and environmental performance of the logistics facility investigated by incorporating the main principles of thermodynamics and industrial system engineering.

Business case

To test and apply the proposed simulation process, the warehouse of an international logistics company that has recognized logistics environmental sustainability as a key prospect for the immediate future was examined. For this reason, an ambient-temperature warehouse managed by FERCAM S.p.A., a Logistics Service Provider (LSP) located in Bologna (Italy), has been selected. The warehouse was used as a national distribution center with storage and cross-docking areas. All MH operations took place at ambient temperature and were carried out manually with electric forklift trucks powered by lead–acid batteries. This warehouse setting is particularly widespread in Italy, so the selected business case is adequately representative of the Italian context of logistics buildings. Furthermore, this type of facility is extensively used in the logistics sector as they have different functions and impacts on inventory management, delivery times to customers, and energy costs [73]. Following the framework previously mentioned and presented in [74], the 3D digital model of the logistics facility was developed. It is noteworthy that The assumptions and input parameters, such as operational schedules and other details, are obtained through semi-structured interviews with facility managers, ensuring that no assumptions are made without real-world data. Specifically, to provide a comprehensive representation of the building's energy profile, secondary sources data and related relevant literature were also considered as needed. To achieve a micro-level assessment of the environmental impact of the logistics facility and provide an accurate representation of its energy consumption patterns, this study considered all main end-use types through the selection of relevant model parameters and inputs. These main end-use types aligned with the established framework for warehouse environmental impact assessment developed by Perotti et al. [11]. A summary of the main data collected is reported in Table 1. To further clarify the calculations, to provide empirical support for the utilized simulation approach, and to ensure the reproducibility of the results, the key utilized parameters, such as wall types and layers with their corresponding U-factors, lighting specifications for various zones, details of the zones' windows, occupancy, plug loads, processes, as well as design day conditions used for sizing the HVAC system, are provided in Appendix "Example parameters utilized in modeling and simulation procedure".

The following assumptions have been made to perform the above-mentioned simulation process.

- Material Handling Equipment:
  - Forklift charging losses were estimated to be 20% and 5% of the battery capacity for lead–acid and lithium-ion batteries, respectively [78]
  - Forklift self-discharge was assumed to be 5% of the battery capacity per month
  - Each forklift is fully recharged every working day. Thus, to preserve the operational capability of the warehousing activities, the daily forklift energy consumption was assumed equal to full battery capacity (i.e., considering forklift charging losses and self-discharge).
- Utilities (PV panels, heat pump, boiler, etc.)
  - The grid-related energy losses referred to on-site power renewable generation units were assumed as negligible

Table 1
Inputs required for model application.

Inputs		Short description	Value(s)	Source(s)
Building features	Warehouse layout	Design and configuration of physical elements within a warehouse facility (i.e., storage areas, aisles, workspaces, and equipment)	Warehouse floor plan	Interviews and on-site visits
	Warehouse functional zones	Purposes functionality of warehouse areas which contribute to perform warehousing operations.	- Storage - Cross-docking - Office	
	Surface features	Properties of the materials of the building surfaces (transmittance, reflection/absorption ratio, etc.)	- N.A.	
	Warehouse floorspace	Total occupiable space of the logistics building	- Total floorspace: 39,226 m^2	
Warehouse operation	Warehouse working hours	Operational time frame during warehouse building is actively engaged in the warehousing operations.	- From 6:00 a.m. until 10:00 p.m (250 days/year)	Interviews and on-site visits
	Operators' shifts and breaks	Scheduled working time frame and breaks for operators responsible to perform warehousing activities.	- 2 shifts per day (1.5 h each)	
Lighting system	Illuminance required	Measure of the level of light that reaches a surface, expressed in lux, for each warehouse functional zone. Illuminance levels identified are in line with UNI EN 12464-1 standard	- Storage: 200 lux - Cross-docking: 300 lux - Office: 500 lux	UNI EN 12464-1 standard
	Lamp luminous efficiency (LLE)	Measure for assessing the effectiveness of a lamp in producing visible light, measured in lm/W.	- LED (residential): 100 lm/W - LED (industrial): 200 lm/W	Füchtenhans et al. 2023 [75]
Utilities	Heating system	System that supplies heat to the building In the base case the heating systems use a single gas-fired boiler to generate heat (i.e., only for office area).	- Gas-fired boiler - Heating set point: 22 °C	- Interviews and on-site visits - IEA, 2021 [76] - ISPRA, 2023 [77]
	Cooling system	System designed to remove excess heat and maintain optimal temperature in the building In the base case the cooling systems use a single air-cooled chiller (i.e., only for office area).	- Air-cooled chiller - Cooling set point: 25 °C	
	Mechanical ventilation	System able to circulate and exchange air within a building ensuring proper air quality, temperature control, and removal of pollutants.	- Constant air volume (CAV) - Air change rate (ACR): 1 Vol/h	
	Power generation unit(s)	Sources and technologies used to generate electrical power. In the base case PV panels are installed to generate electrical power.	- Rooftop PV system - Installed power capacity: 575 kWp	
Material handling	Fleet size and features	MHE inventory, including its quantity, types, and battery units adopted. In the base case MH is executed manually by using forklift trucks powered by lead–acid batteries.	- Transpallet: 60 units - Reach trucks: 10 units - Counterbalanced: 8 units	Interviews and on-site visits
	Battery charging strategy	Selecting how to perform the battery charging operations for MHE (i.e., overnights, opportunity charges, battery swapping, etc.)	- Overnights - Full charges	

  - The average solar-cell efficiency for PV panels was assumed equal to 16.5% in line with [51];
  - Each PV panel (sized 1.7 × 1.0 m^2) generates 0.3 kWp
  - Heating, Ventilation, and Air Conditioning (HVAC) is fully powered by a heat pump system
  - The air circulation rate for mechanical ventilation was assumed 1.0 Vol/h,
  - Chiller and boiler are solely powered by the national electricity grid, not allowing them to benefit from on-site produced renewable energy

- Environmental assessment
  - The environmental impact assessment of GW practices has been performed without considering their entire life cycle
  - One Standard Cubic Meter (Sm^3) of natural gas was assumed equal to 10,69 kWh
  - An emission conversion factor (ECF) of 0.259 gCO2e/kWh for electricity and 0.233 gCO2e/kWh for natural gas has been adopted according to the ISPRA report (2022) [36]
  - The impact of other sources of consumption (e.g., refrigerants, waste, water) was assumed negligible [11,79,80]

- Economic assessment
  - The economic impact assessment of GW practices has been performed considering only the initial investment cost (i.e., expenditures associated with the purchase and installation of the measure)
  - Electricity and natural gas prices (NGP) were assumed 0.23 €/kWh and 0.80 €/Sm^3 respectively, in line with ARERA (2022)
  - Li-Ion batteries cost (BC) was assumed 140 €/kWh per unit according to IEA (2023)
  - Fast-charging devices cost for Li-Ion batteries was assumed 1500 €/unit in line with the Italian market [58]

Considered scenarios

Base-case scenario

Based on these assumptions, the base-case scenario was simulated to determine the average monthly electricity consumption over a year (i.e., illustrative) for the main consumption area (i.e., MHEs, lighting, heating, cooling, others) of the logistics facility under investigation. The insights gained from analyzing the base case made it possible to highlight the main critical aspects in terms of energy consumption

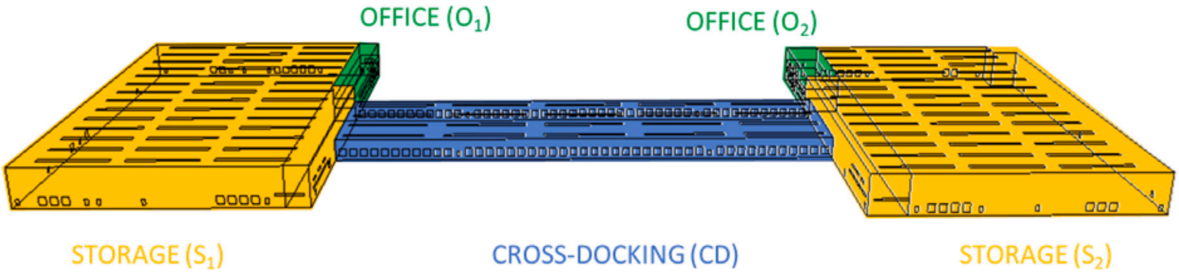

Fig. 1. 3D digital model of the base-case scenario: layout breakdown by warehouse functional zones [74].

and losses and helped to identify the most suitable GW practices to be considered for alternative simulation scenarios. As a first step, the 3D digital model was designed based on the inputs in Table 1. The 3D digital model was then represented by warehouse functional zones in Fig. 1 and the simulation results were then reported (see Section "Results and discussions") in terms of energy consumption. Based on these results, some critical points were identified to increase PV self-consumption: (I) The mismatch between the natural gas-fueled heating system and the electricity generated by the PV panels ensures that heating-related loads cannot be self-consumed; (II) Battery charging operations for MHEs are performed overnights, which prevents self-consumption of such loads from the PV generated energy. The following scenarios were therefore analyzed to close these gaps.

Scenario A: Heat pump installation

As a second step, the implementation of a heat pump system was selected as a suitable GW measure and then implemented and simulated. The current heating system is not connected to the photovoltaic generation system, since it is gas-fired, it cannot utilize the electricity produced by the photovoltaic panels. Hence, the implementation of a heat pump system replaced the single gas-fired boiler system for heating generation completely electrifying the building energy load. Thus, heating-related loads can be powered by PV panels during the power generation period. In this context, the Coefficient of Performance (COP) for the heat pump was fixed equal to 2.0 for heating and 2.5 for cooling as suggested by Nyers et al. [81]. Based on the yearly heating and cooling loads of the logistics facility (i.e., heating and cooling power capacity required equal to 160 kW and 120 kW, respectively) the heat pump system must have a power capacity of 160 kW to meet them. Regarding the economic assessment, the initial investment costs (i.e., purchasing and installation costs) were determined based on the average market prices of the leading manufacturers in Italy, to incorporate country-based values for the case study investigated.

Scenario B: Implementing opportunity charging for forklift truck with lithium-ion battery

The opportunity charging strategy through forklift trucks with Lithium-Ion batteries was selected as a suitable GW strategy and then implemented and simulated. The current MH charging strategy is to charge the forklift batteries overnight (i.e. outside warehouse working hours). This MH charging strategy has the advantage of not affecting the operational performance of the warehouse, but excludes the chance to self-consume MH energy loads and therefore does not allow the utilization of the PV energy generated. Meanwhile, the opportunity charging strategy gives the chance to perform fast partial charges (i.e., which allows to reach more than 50% of the total battery capacity in just half an hour of charging), adopting high-frequency charger (i.e., fast charger), during the time frame most convenient from an environmental and economic perspective. For this reason, in this scenario opportunity charging strategy was performed during operators' shifts and breaks (i.e., 2 shifts per working day and 1.5 h breaks per each), which have been merged in a single time window (recharging time window) to meet time working shifts and peak of PV electricity generation (from 00.30 p.m. to 03.30 p.m.). Based on fleet size and features of the current MHE, the Lithium-Ion battery pack has been intentionally selected based on the same energy capacity of the Lead-Acid battery of the base case scenario, in order to minimize the impact on operational warehousing performances.

Sensitivity analysis

To ensure the robustness and reliability of the simulation analysis, a sensitivity analysis is required. This procedure helps identify how changes in input parameters can affect the obtained results, guaranteeing that the results are reliable under a range of different conditions. Warehouse energy consumption is highly dependent on the operational activities and its demand can be variable over time. For instance, the throughput capacity of the warehouse may increase or decrease due to market demand and seasonality, resulting in higher/lower utilization of MH fleet size. This inevitably has an impact on EC, which can affect the effectiveness and efficiency of GW practices used. For this reason, in order to comprehensively analyze the implementation of GW practices, it is necessary to understand how the variation in warehouse operations could impact the effectiveness of GW strategies involved. To achieve this goal, a variation of MH fleet size (±20%) was considered for scenario B, and relevant economic and environmental KPIs were presented and then investigated. Scenario A remains unaffected by variations in operational conditions as the warehouse operates at ambient temperature. Additionally, the warehouse location can significantly affect the results due to climatic variations, which impact both heating consumption and PV energy generation. To ensure the applicability of this study to similar warehouses across different regions of Italy, a sensitivity analysis was conducted, taking into account the three various climatic zones throughout the country.

Results and discussions

The results on simulated monthly energy consumption breakdown by main consumption area for the base case scenario is reported in Fig. 2.

Findings indicate that the average self-consumption rate is below 40% for most of the year. In the summer months in particular, the self-consumption rate drops significantly, as the energy generated by the PV panels, boosted by optimal weather conditions, considerably exceeds the electricity demand of the logistics building. These results highlight the critical points already mentioned in Section "Base-case scenario".

Thus, Net total energy (NTE) (i.e., total energy consumption minus energy produced and self-consumed on-site from renewable energy sources) and the average self-consumption rate over the year for each scenario investigated are then reported in Fig. 3

As it can be observed, by fully electrifying the building energy load through the implementation of a heat pump system, in line with previous studies [51,82], notable energy savings can be achieved (−19% compared to the base case scenario) by increasing the self-consumption share during the winter period. These results are primarily due to the higher energy efficiency of the heat pump system [83], which leads to lower demand for heating and cooling loads, as well as the application

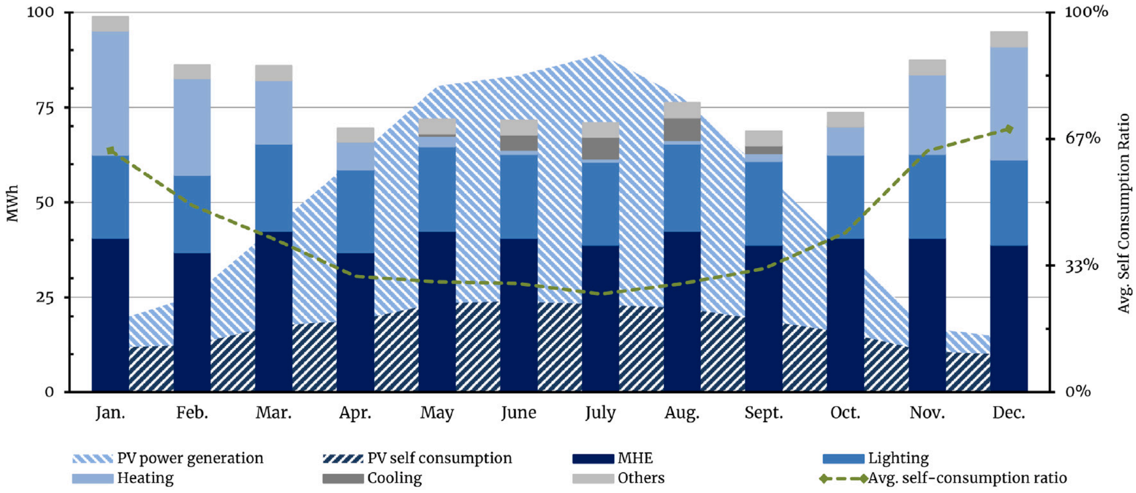

Fig. 2. Base case: Monthly energy consumption breakdown by main consumption area.
Source: Authors' own work.

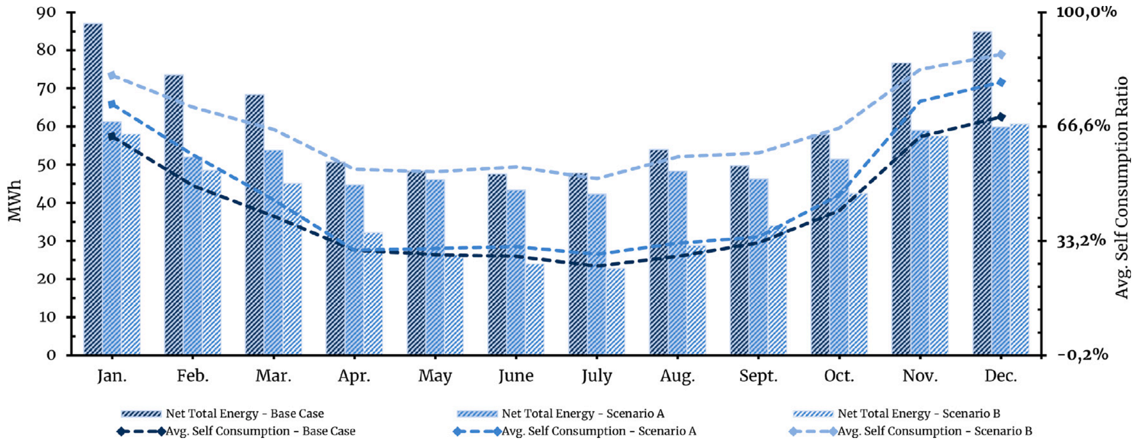

Fig. 3. Monthly net total energy consumption and average self-consumption rate for each scenario.
Source: Authors' own work.

of a load electrification strategy which ensures that the heating-related loads can be supplied by the onsite generated electricity during the periods with PV generation. Therefore, Scenario A enhances the self-consumption rate, resulting in reduced energy consumption from the grid and, consequently, a lower carbon footprint for warehousing activities. However, the building's energy demand still struggles to match PV generation during the summer, when solar energy production is at its highest and heating demand is low; therefore, additional storage capacity will be necessary to further enhance self-consumption during this time. However, as mentioned by Camilo et al. [37], storing the surplus in a dedicated battery system might not be an economical option. Therefore, Scenario B has been introduced to partially address this gap by taking advantage of the charging demand of the lithium-ion batteries existing in the building for MHE. Indeed, when operational demand meets the availability of renewable energy (Scenario B), it is evident that significant energy savings can be achieved (−21% compared to the results of Scenario A), primarily due to a remarkable increase in the self-consumption rate (+20% compared to the results of Scenario A). These results emphasize the substantial potential of this measure, and provide an even greater incentive to investigate possible future developments [59,60]. Finally, to provide further insights on the impact of the investigated practices, monthly energy consumption by sources of consumption (electricity and natural gas), PV self-consumption, and other relevant simulation outputs (see Section "Methodology and simulation process") for each scenario are reported in Table 2.

In Scenario A, the elimination of natural gas consumption combined with an increase in PV self-consumption significantly enhances the sustainability profile of the logistics operation. This shift is particularly impactful during colder months, as the use of on-site PV for heating reduces the reliance on external energy sources, notably natural gas. Instead of exporting excess electricity back to the grid, the self-consumption strategy ensures that the available renewable energy is optimally utilized. As shown in Fig. 3, this approach leads to a substantial reduction in carbon emissions during the winter months, contributing to both environmental sustainability and a decrease in overall energy costs. The broader implications of this strategy indicate that, by integrating renewable energy sources more deeply into heating systems (through self-consumption), logistics facilities can realize long-term economic benefits while reducing their carbon print. These benefits include lower energy bills, driven by reduced dependency on fluctuating natural gas prices, self-consuming the generated PV to avoid losses from the difference between selling to the grid at lower prices and buying back at higher rates, and long-term carbon tax savings as regulations tighten on greenhouse gas emissions. In scenario B, a consistent increase in self-consumption across all months, indicating the potential of warehouses equipped with MHE powered by Lithium-Ion batteries to increase their self-consumption share with the proposed opportunity charging strategy. Utilizing the batteries in the building for increasing the self-consumption not only maximizes the use of clean energy but also reduces the reliance on grid electricity during peak

Table 2
Monthly energy consumption [MWh] by sources of consumption and PV self-consumption for each scenario.

Month	Base case			Scenario A		Scenario B	
	Natural gas	[a]Overall electricity	PV self-consumption	[a]Overall electricity	PV self-consumption	[a]Overall electricity	PV self-consumption
Jan.	32.6	66.2	11.7 (63.7%)	74.7	13.5 (73.2%)	73.0	15.0 (81.5%)
Feb.	25.4	60.7	12.5 (49.3%)	66.7	14.8 (58.4%)	66.8	18.3 (72.3%)
Mar.	16.7	69.3	17.5 (40.4%)	73.4	19.6 (45.2%)	73.6	28.5 (65.8%)
Apr.	7.3	62.2	18.8 (30.5%)	63.5	18.8 (30.5%)	65.5	33.3 (54.1%)
May	2.7	69.2	23.5 (29.1%)	71.1	25.0 (31.0%)	69.4	43.0 (53.4%)
June	1.1	70.4	23.9 (28.6%)	69.6	26.3 (31.5%)	69.8	45.7 (54.8%)
July	0.8	70.1	23.0 (25.9%)	68.4	26.0 (29.3%)	68.5	45.7 (51.4%)
Aug.	1.0	75.2	22.3 (28.7%)	73.5	25.2 (32.6%)	73.6	44.8 (57.7%)
Sep.	2.1	66.6	18.9 (32.6%)	66.3	20.0 (34.4%)	68.2	34.2 (58.8%)
Oct.	7.5	66.2	15.6 (41.9%)	68.9	17.4 (46.6%)	67.1	24.7 (66.2%)
Nov.	21.0	66.4	10.7 (63.6%)	71.5	12.5 (74.0%)	71.6	14.1 (83.3%)
Dec.	29.8	65.1	10.0 (69.4%)	71.4	11.5 (79.6%)	73.4	12.6 (87.7%)
Overall yearly value [MWh/year]	148.0	807.4	208.5 (34.4%)	839.1	230.5 (38.0%)	840.6	359.9 (59.4%)

[a] Overall electricity refers to the total electricity amount required by the building.

Table 3
Comparison among different scenarios based on energetic, environmental, and economic KPIs.

KPIs	Base case	Scenario A	Scenario B
[a]Net total energy [MWh/year]	746.7	608.5	480.6
Net EUI [kWh/m^2]	19.0	15.5	12.2
Total CO2e emissions [tons CO2e/year]	189.5	157.67	124.5
CO2e emissions intensity [kgCO2e/m^2]	4.8	4.0	3.1
Return of Investment (ROI)	–	8.8%	10.9%
PBP [years]	–	11.3	9.1

[a] Net total energy refers to the total energy consumption of the building minus the energy produced and self-consumed on-site from renewable energy (i.e., PV self-consumption).

demand periods, further improving energy efficiency. From an economic standpoint, this shift yields long-term cost savings by reducing the need to purchase electricity at higher rates from the grid. Moreover, by increasing the self-consumption of renewable energy, facilities can mitigate the impact of future energy price fluctuations and rising grid tariffs, making their operations more resilient and cost-effective over time.

Table 3 demonstrates a comparison of different KPIs, highlighting substantial improvements in all metrics for the scenarios analyzed, confirming the positive impact of the proposed interventions from an environmental and economic perspective, in line with previous studies in the literature [49,58,60]. The reduction in Net total energy would signify less reliance on the electrical grid, which has been demonstrated to have a considerable carbon footprint and instead utilizing the clean PV generated in the buildings.

Lastly, monthly CO2e emissions for each scenario were also computed based on the assumptions previously defined in Section "Business case", and the results are reported in Fig. 4. As evident, in scenario A, the reduction in CO2e occurs primarily during colder months when heating is necessary, whereas scenario B facilitates a consistent reduction throughout the entire year. The reduction in the emission values is consistent with the proposed GW practices facilitated by increased self-consumption and reduced dependence on the electricity grid, thereby mitigating the environmental impact in accordance with [84]. In terms of ROI, results highlight that self-consumption enhancement practices can deliver tangible financial returns while supporting broader environmental goals. As the cost of renewable technologies continues to fall and energy efficiency measures become more widespread, these ROIs are likely to improve further, strengthening the business case for adopting such strategies in logistics and warehousing sectors.

Results and discussion on sensitivity analysis

The sensitivity analysis was carried out to ensure the findings obtained by the evaluated scenarios are reliable, generalizable, and applicable to similar cases. More specifically, the analysis was initially aimed to assess the extent to which the variations in the climatic conditions (through considering different locations) would influence the PV generation profile, the heating consumption, and the resulting impact of electrification of the heating system on the PV self-consumption rate (Scenario A). It was also aimed at determining the influence of the modifications in warehouse operations on the outcomes of the opportunity charging strategy. In this context, by varying these parameters, the robustness of the simulation model was demonstrated and the key drivers influencing the environmental and economic performance of GW practices were identified.

Table 4 provides the results of the sensitivity analysis by varying locations and thus the corresponding climate zones. Two different options have been considered for comparison with the current locations of the business case(i.e., Bologna): colder (i.e., Trento) and warmer (i.e., Catania) climate zones to cover three climatic zones of the Italian context.

The results show slight variations depending on the location chosen, indicating a degree of sensitivity. In colder climates, an increase in self-consumption occurs as anticipated, driven by higher heating demands. However, due to the warehouse storage areas being at ambient temperature and lower photovoltaic (PV) generation in colder climates, the observed changes are somewhat constrained. Moreover, in warmer locations characterized by higher PV generation, heating demand is lower, and due to the restricted opportunity charging duration, self-consumption remains limited. Furthermore, it is evident that across all locations, there is a noticeable improvement from the base-case to Scenario A and further to Scenario B, highlighting the effectiveness of the GW practices proposed in the current work for similar ambient temperature warehouses equipped with Lithium-Ion batteries.

Additionally, simulations were conducted changing the throughput capacity by ±20% to consider the variations in warehouse operations. Due to changes in fleet size, there were consequent changes in the MHE and their corresponding charging load. However, no variations in the building's self-consumption were observed. This is because the limited amount of PV energy available during the fixed and constrained charging period was insufficient to meet the charging load demand.

Discussions on the impact of various scenarios of logistics operations on the effectiveness of the proposed strategies

It is worth mentioning that in the discussions provided in the context of the current work the real operation of a warehouse building (located in Bologna, Italy) was assumed. Additionally, the conducted sensitivity analysis investigated how various climatic conditions in the Italian context can impact the self-consumption enhancement potential of electrification of the heating system (implemented in both scenarios

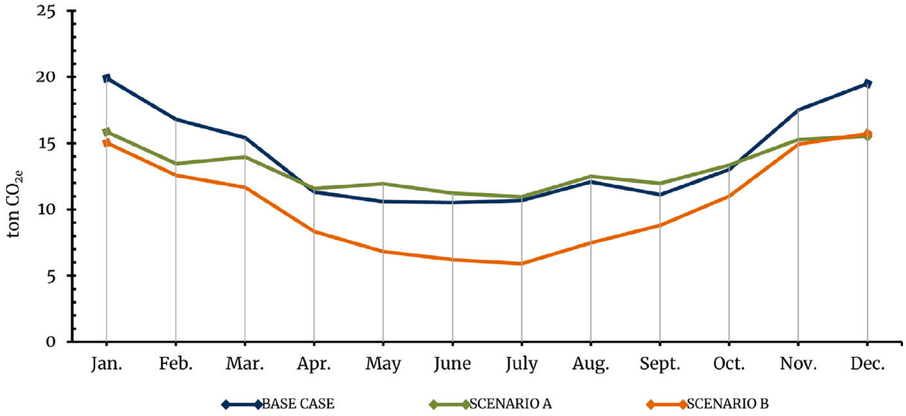

Fig. 4. Monthly CO2e emissions distribution for each scenario.

Table 4
The results of sensitivity analysis: location variation.

Warehouse location(s)	Base case			Scenario A			Scenario B		
	Trento (Colder)	Bologna (Current)	Catania (Warmer)	Trento (Colder)	Bologna (Current)	Catania (Warmer)	Trento (Colder)	Bologna (Current)	Catania (Warmer)
PV self- consumption [MWh/year]	209.7 (36.28%)	208.5 (34.4%)	223.8 (30.6%)	231.4 (40.6%)	230.5 (38.0%)	248.1 (33.9%)	346.1 (60.8%)	359.9 (59.4%)	403.8 (55.3%)
Net total energy [MWh/year]	740.5	746.7	675.7	605.4.8	608.5	590.4	505.2	480.6	425.8
Net EUI [kWh/m^2]	18.9	19.0	17.2	15.4	15.5	14.8	12.9	12.2	10.8
Total CO2e emissions [tons CO2e/year]	187.8	189.5	172.7	156.8	157.6	150.2	130.9	124.5	110.3
CO2e emissions intensity [kgCO2e/m^2]	4.8	4.8	4.4	3.9	4.0	3.8	3.3	3.1	2.8
ROI [%]	–	–	–	7.6%	8.8%	8.6%	8.8%	10.9%	12.6%
PBP [years]	–	–	–	13.1	11.3	11.6	11.4	9.1	7.9

I and II), considering the influence of climatic conditions on the generated PV and the heating consumption of the building. However, the impact of various scenarios of logistics operations (e.g. variations in material flow) on the effectiveness of the proposed strategies should also be analyzed. The results obtained for the electrification of the heating system are not impacted by such variations, as the heating demand is mainly governed by the outdoor weather conditions [85] and the imposed intervals of the heating system are commonly fixed. The self-consumption enhancement margin that is achieved by opportunity charging can instead be potentially impacted by the variations in the level of material flow. Nevertheless, since the opportunity charging strategy, which is simulated in the present work, only leverages the lunch break time within the building's schedule (representing a near worst-case scenario), it remains resilient even during higher demand periods, ensuring consistent performance without being adversely affected by increased operational activity. Thus, during periods with lower material flow (lower demand), lift trucks have extended idle times, which allows for more effective opportunity charging, which can further increase the achieved improvement in the PV self-consumption. It should be mentioned that these outcomes are prone to be impacted by other limiting factors that are discussed in the Section "Generalizability limitations of the present work" on generalizability limitations of the present work.

Discussions on the possible impact of the electricity market regulations/characteristics on the effectiveness of the proposed strategies

It is noteworthy that the potential changes in feed-in tariffs and incentives leading to higher financial benefit of selling the excess PV energy to the grid may affect the preference for self-consumption. However, as noted by Prahastono et al. [86], feed-in tariffs frequently change due to the agreements within the European union or the regulations of individual nations. Generally, these tariffs tend to decline each year as the technological advancements have made the investment costs of photovoltaic (PV) systems more affordable. Thus, the expected reduction [86] can further improve the influence (in terms of resulting economic benefit) of the proposed strategies.

Regarding the cost of the PV plants and the corresponding Levelized Cost of Energy (LCOE), in an analysis performed by Vartiainen et al. [87], it was revealed that in 2019, utility-scale PV LCOE in Europe ranged from 24 €/MWh in Malaga to 42 €/MWh in Helsinki, which was lower than the average electricity prices in those regions (47 €/MWh in Finland and 57 €/MWh in Spain). By 2030, PV LCOE is expected to drop to between 14 €/MWh in Malaga and 24 €/MWh in Helsinki, and by 2050, it will likely fall to 9–15 €/MWh. This trend makes PV the most cost-effective electricity source. The sensitivity analysis highlights that WACC, in addition to location, is a key factor influencing PV LCOE. Moreover, in a work performed by D'Adamo et al. [88] an economic analysis based on Net Present Value (NPV) also supported by the assessment of alternative scenarios (sensitivity, scenario and risk analysis) was proposed concerning a photovoltaic (PV) plant located in a mature market (Italy) under a collective self-consumption (CSC) scheme. The analysis was limited to a share of self-consumption between 30 and 60%. The aim was to assess the profitability of a PV plant by considering different political (tax deduction, subsidies) and market (purchase price, selling price) contexts. Two alternative policy scenarios were outlined, both aimed at minimizing public expenditure while still maintaining the cost-effectiveness of plant installations. One scenario focused on gradually decreasing subsidies over time, while the other proposed scaling back tax deductions. Even under these policy changes, the financial risk associated with PV installations were shown to remain low. The findings demonstrated that the PV plant remains profitable across all scenarios explored in the sensitivity analysis, consistently showing a positive financial outcome. The current work aims to provide general practices to improve the self-consumption of warehouse buildings. However, more detailed analysis in this context would be essential. Future works could focus more extensively on forecasting and developing strategies to cope with these changes, especially as policy and market conditions evolve. These works can focus on scenario modeling of potential policy changes. On the other hand, innovations in the energy storage technology can lead to a reduction in the cost of batteries, making the investment in new storage systems solely for storing excess photovoltaic (PV) energy a practical option. Lastly, external environmental factors, such as unpredictable extreme weather conditions like prolonged cloudy periods or rare instances of extreme cold conditions in the region in which the analysis was performed can disrupt photovoltaic (PV) generation and reduce the heat pump's efficiency, negatively impacting the obtained results.

Generalizability limitations of the present work

Practical implementation challenges are crucial part of deployment of such proposed interventions and the focus on theoretical strategies may not capture all real-world complexities. The unforeseen downtime or equipment maintenance, are among the factors that can impact the rate of self-consumption in the opportunity charging scenario. Staff compliance and proficiency is another factor that can impact the success of opportunity charging. Resistance or lack of understanding from operators can reduce effectiveness of the proposed strategy and impact the obtained results. The self-consumption rates from the heating-related scenarios are unlikely to be affected by such factors and the potential impact is primarily limited to the opportunity charging scenario. However, given the low frequency of such incidents during the specific times proposed for opportunity charging (lunch break), the overall impact on the obtained results is expected to be limited. Additionally, introducing additional shifts or modifying existing ones could affect the synchronization between energy demand and PV generation, influencing self-consumption rates. Lastly, the proposed scenarios would have limited effectiveness and impact in regions with low photovoltaic (PV) generation or a high reliance on renewable energy sources. For instance, in countries like Norway, where hydroelectric power dominates and the grid already has a very low carbon intensity, the benefits of these strategies would be minimal. The proposed scenarios are expected to have significant impacts in regions with higher levels of PV generation in the grid. Another limitation of the current work is the exclusion of battery maintenance costs, which some studies suggest should be accounted for [89]. However, in this model, such costs are considered negligible due to the small size of the batteries analyzed. Similarly, some sources of consumption were intentionally excluded (e.g., refrigerants, waste, water) as they normally account for a limited extent (i.e., these sources of consumption contribute to approximately 5% of the total CO2e emissions from ambient temperature logistics facilities in Italy [12]) and HVAC systems, lighting, and MHE are influential energy consumers and contributors to these warehouses' elevated carbon dioxide emissions [3,4].

Policy discussion

To incentivize the integration of PV electricity into the power grid, many countries have enacted supportive policies aimed at bridging the gap between the production costs of PV systems and the revenue generated from their electricity sale or utilization [90]. In many countries, including Italy where the case study is located, the price of selling electricity to the grid is much lower than the retail price, making self-consumption of the onsite generated PV profitable. Based on the findings of this study, incorporating heat pumps (scenario A) and integrating opportunity charging (scenario B) can notably enhance self-consumption within the proposed framework. Additionally, a significant reduction in CO2 emissions was observed, underscoring the potential of self-consumption enhancement in mitigating diverse environmental impacts. Moreover, the introduction of PV panels without self-consumption results in an increased reliance on electricity purchased from the grid. Given the substantial carbon emissions associated with current electrical grids, this situation is expected to lead to higher CO2 emissions. Nevertheless, applying these interventions requires a significant investment from the owners' side, resulting in a significant PBP. Enhancing self-consumption provides substantial economic advantages alongside environmental benefits, notably reducing the PBP of implemented measures as shown in this study.

Policymakers can design incentives focused on encouraging greater self-consumption and fostering grid independence among users. These measures can effectively shorten payback periods, making such investments appealing and economically viable. Energy communities currently provide some support for self-consumption, yet there is a need for additional incentives at the individual building level. Furthermore, policymakers can establish official guidelines for users, leveraging the findings of the current study and other similar related studies specifically for unconditioned warehouses equipped with Lithium-Ion battery-powered MHE.

Table A.1
Properties of various example wall types utilized in the simulation.

Wall	U-factor [W/m^2 K]	Layers
External walls	0.35	-EPC expanded polystyrene (Standard) -2010 NCM plasterboard (wallboard)
Ground foor	0.314	-Urea formaldehyde foam -Cast concrete -Floor/Roof screed -Timber flooring
Internal walls	1.054	-Plaster (Lightweight) -Concrete block (Lightweight -Plaster (Lightweight)
Rooftop	0.346	-Asphalt 1 -MW glass wool (rolls) -Airgap -Plasterboard

Conclusions

Warehouses significantly contribute to the environmental impact of supply chains, prompting a growing interest in green warehouse (GW) practices and the concept of sustainable warehousing. These initiatives aim to mitigate the environmental impacts associated with warehouse operations. Nevertheless, the literature still lacks empirical studies assessing the impact of such practices. Most studies rely on qualitative methods, which further emphasizes the need for empirical and quantitative approaches. This paper seeks to offer empirical evidence on the impact of GW practices on increasing PV self-consumption based on a systematic approach. The energy load and operational needs of the warehouse were considered and the related economic and environmental impacts were carefully investigated. A simulation-based approach was proposed with multiple scenarios of a real logistics facility, grounded on a conceptual framework that offers a roadmap towards a sustainable warehousing concept by enhancing the self-consumption ratio. The simulation process was conducted under three scenarios. Firstly, simulating the existing condition (i.e., base case scenario) to provide a baseline for comparison and assessing the efficacy of the proposed scenarios. The targeted building utilize NG for heating purposes and selling the excess generated PV to the grid, both of which are common practices in the Italian context. In the second scenario, the incorporation of a heat pump system (i.e., Scenario A) was proposed to eliminate the NG consumption and allow the building to meet a part of its heating demands by self-consuming on-site generated PV energy. Next, to provide a comprehensive solution for enhancing year-round self-consumption, Scenario B was introduced, incorporating both the use of heat pumps from Scenario A and a practical strategy for opportunity charging of MHE powered by Lithium-Ion batteries. Results

Table A.2
Lighting.

Zone name	Lighting power density [W/m^2]	Total power [W]	Scheduled hours/week [h]	Hours/Week > 1% [h]	Full load hours/Week [h]
Office 1	5.0000	2762.50	59.84	59.84	59.84
Office 2	5.0000	2762.50	59.84	59.84	59.84
CROSS-DOCKING	1.5000	12 487.50	112.00	112.00	112.00
Storage 1	1.0000	13 307.50	86.90	86.90	86.90
Storage 2	1.0000	1485.00	86.90	86.90	86.90
Storage 3	5.0000	2762.50	70.00	70.00	70.00
Storage 4	1.0000	765.00	86.90	86.90	86.90
Storage 5	1.0000	14 182.50	86.90	86.90	86.90
Office 3	5.0000	3037.50	59.84	59.84	59.84
Office 4	5.0000	3037.50	59.84	59.84	59.84
Storage 6	5.0000	3037.50	70.00	70.00	70.00

Table A.3
Zones summary.

Zone name	Area [m^2]	Conditioned	Above ground gross wall area [m^2]	Window glass area [m^2]	Lighting [W/m^2]	People [m^2 per person]	Plug and process [W/m^2]
Office 1	552.50	Yes	220.50	27.86	5.0000	36.83	2.0000
Office 2	552.50	Yes	220.50	29.79	5.0000	36.83	17.2036
CROSS-DOCKING	8325.00	No	3885.00	0.00	1.5000		9.9792
Storage 1	13 307.50	No	4788.80	0.00	1.0000	332.69	5.2414
Storage 2	1485.00	No	1330.60	0.00	1.0000	37.12	0.0000
Storage 3	552.50	No	558.60	36.95	5.0000		0.0000
Storage 4	765.00	No	867.10	0.00	1.0000	19.12	0.0000
Storage 5	14 182.50	No	4596.80	0.00	1.0000	354.56	6.5574
Office 3	607.50	Yes	175.50	18.00	5.0000		2.0000
Office 4	607.50	Yes	175.50	29.81	5.0000		2.0000
Storage 6	607.50	No	503.10	42.86	5.0000		0.0000

Table A.4
Design day conditions for HVAC sizing.

	Maximum dry bulb temperature [C]	Daily temperature range [deltaC]	Humidity value	Humidity type	Wind speed [m/s]	Wind direction
Winter design day	−4.2	0	−4.2	Wetbulb [C]	1.6	210

were analyzed and discussed based on different KPIs to evaluate the environmental and economic suitability of GW practice investigated, as well as enabling benchmarking between different logistics facilities. It was demonstrated that by installing a centralized heat pump system the yearly net energy consumption of the building is significantly reduced by 19% compared to the base case scenario, showing how electrification strategies could lead to significant benefits in terms of both energy efficiency and increased self-consumption in accordance with previous literature [51,82]. In addition, it is important to highlight that self-consumption enhancement not only mitigates the environmental impact but also yields substantial economic advantages, notably by significantly shortening the PBP of the implemented measure compared to a scenario without self-consumption (e.g., the PBP would be stretched by 8 years if the self-consumed energy increased is not considered), as also highlighted by [84]. Considering the implementation of an opportunity charging strategy for MHE with Lithium-Ion batteries, significant savings in both energy consumption and CO2e emissions were achieved, due to an additional increase in the self-consumption rate (i.e. +20% compared to the previous scenario), paving the way for further research, as also proposed by [59,60].

Nevertheless, the perceptions of GW measures and their impact on warehouse sustainability among practitioners remain unclear [11,16]. As shown by the findings, GW measures can bring numerous economic and environmental benefits if implemented based on a RBT perspective. It can be mentioned that the benefits of renewable energy sources are only realized through efficient integration of GW measures, organizational capabilities and logistics processes, which are closely tied to the type of warehouse involved (e.g., the operating temperature of the warehouse, warehouse working hours, warehouse envelope, products stored, etc.). Nonetheless, this contribution can provide a starting point for future developments: (a) performing an economic analysis that considers direct and indirect costs of the implemented GW practices, (b) battery energy storage system (BESS) for self-consumption ratio enhancement can be evaluated as a possible alternative to opportunity charging strategy, (c) the effect of trends and seasonality on energy consumption and emissions can be further investigated, carrying out an analysis that is flexible and versatile for different market scenarios.

CRediT authorship contribution statement

Luca Cannava: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation. **Farzad Dadras Javan:** Writing – original draft, Validation, Formal analysis, Data curation. **Behzad Najafi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sara Perotti:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara Perotti reports financial support was provided by European Union. Sara Perotti reports a relationship with European Union that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Example parameters utilized in modeling and simulation procedure

See Tables A.1–A.4.

Data availability

The data that has been used is confidential.

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