

# Sustainable and Energy-Efficient Industrial Systems: Modelling the Environmental Impact of Logistics Facilities

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**Abstract:** In the last decade industrial systems have been affected by increased challenges, and among those the need for more sustainable production and logistics has been called into question by both practitioners and academia. Within industrial networks, logistics facilities traditionally represent key nodes as they have a direct impact on both companies' service levels and logistics costs. Recently, their complexity has dramatically increased due to their ever-demanding requirements and pressures from stakeholders and society. In this context, companies have started to search for solutions for greener warehousing processes and energy efficiency improvements. Still, on the academic side, a limited number of studies have been found addressing the quantification of logistics facilities' environmental performance, the impact of the green warehousing practices in place, and the related effects on warehouse consumption and emission reduction. This paper aims to address this research gap by proposing a simulation-based approach where multiple scenarios of a real logistics facility are discussed, grounded on a conceptual framework that offers a roadmap towards sustainable and energy-efficient warehousing. Different scenarios are outlined, and the related performances are examined in terms of energy consumption and CO<sub>2eq</sub> emissions. Implications of the results are discussed and streams for future investigation are identified.

**Keywords:** Environmental sustainability, Sustainable warehousing, Energy efficiency, GHG emissions, Simulation.

## 1 Introduction

Warehouses play a critical role in maintaining service levels, managing costs, and serving as central nodes within industrial systems for storing, sorting, and distributing goods [1]. In the last decade, industrial systems have been affected by increased chal-

allenges, and among those the need for more sustainable production and logistics has received increasing attention. Regarding the logistics operations, traditionally, efforts to reduce emissions have primarily been focused on transport activities due to their significant contribution to the companies' overall environmental impact [2]. However, a growing awareness has started to emerge on the role of logistics facilities due to their energy-intensive nature ([3];[4]). This has induced companies to look at the implementation of energy efficiency measures and green warehousing solutions [5]. In this context, Bartolini et al. [6] defined green warehousing (GW) as "a managerial concept integrating environmentally conscious solutions to minimize energy consumption, reduce energy costs, and mitigate emissions within warehouse environments". This concept is applied to any logistics building regardless of the corresponding market, operating conditions, and structural of structure. Nevertheless, conditioned logistics warehouses have emerged as crucial components of industrial networks in terms of their environmental impact, due to the large amount of energy that is required to uphold multiple temperature zones within a single warehouse environment [7]. Thus, conditioned warehouses are exceptionally complex to operate in terms of energy efficiency and environmental impact, due to their demanding logistics requirements and limitations [8].

Consequently, the implementation of GW practices in conditioned warehouses are critical to achieve Net Zero Emission goals. Moreover, literature still lacks empirical studies to assess the impact of GW practices on environmental impact and energy consumption in logistics facilities, especially in conditioned warehouses [4].

To fill this gap, this study proposes a simulation-based approach, supported by empirical data, to examine the consequences of GW practice implementation in a conditioned logistics facility. More specifically, it explores how these practices impact energy consumption by conducting multiple simulation scenarios using a real conditioned logistics facility located in Northern Italy. The simulation-based approach is underpinned by a conceptual framework that highlight the GW practices selection process. Starting from an initial analysis of the base case, each alternative scenario is systematically explored through an iterative process to identify and assess the most suitable GW measures in terms of energy efficiency and environmental performance.

Accordingly, the paper is structured as follows: The next section provides a review of the existing literature related to GW practices investigated in the simulated scenarios. Subsequently, the proposed conceptual framework and employed methodology are the described, followed by an analysis on the results of each investigated scenario. Finally, conclusions are addressed, limitations of the study are highlighted, and recommendations for future research are provided.

## **2 Research Background**

### **2.1 Lighting Systems in Logistics Facilities**

Lighting has traditionally been identified as a significant contributor to energy consumption in warehouses. However, the literature lacks a consistent estimate of its exact share [9]. Some scholars posit that lighting alone may account for as much as

65% of the total energy consumption in ambient-temperature (non-conditioned) warehouses [10], while this share drops to a value of 5 - 10% in the case of conditioned warehouses. LED lighting holds remarkable promise for energy savings and has already gained popularity as the preferred lighting solution within the warehousing sector [11]. LED lighting adoption not only offers substantial energy savings but also aligns with the contemporary trend toward more adaptable and environmentally conscious lighting solutions.

## **2.2 Warehouse Heating and Cooling Through Heat Pumps**

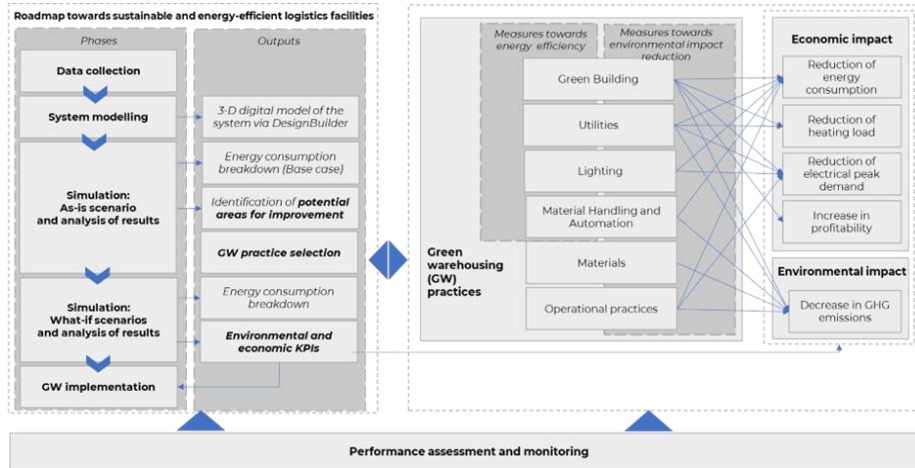
Heat pumps can operate for both heating and cooling. During the winter season, they can extract heat from the outdoor air, ground, or water sources and transfer it into the building. On the other hand, they can extract heat from the indoor air and transfer it outside during summer season, effectively cooling the building. Heat pumps are considered a promising technology for conditioned logistics facilities due to their high efficiencies compared to fossil fuel combustion, resulting in energy savings and reduced greenhouse gas emissions ([12]; [13]). Moreover, an additional benefit of the heat pump lies in the electrification of the heating technology, for which gas-fed systems are conventionally used.

## **2.3 Building Envelope's Thermal Insulation**

Thermal insulation is a crucial aspect of building design, particularly in conditioned logistics facilities maintaining a stable internal temperature (i.e., by reducing heat exchange with the external environment) is essential [14]. According to Paraschiv et al. [15], thermal insulation on building walls can lead to a reduction in energy consumption of approximately 13 - 16% depending on variations in outside air temperature, thus contributing to decrease the resulting GHG emissions of the HVAC (heating, ventilation and air conditioning) system.

# **3 Methodology**

Several companies have committed to achieving net-zero emissions goals. To support practitioners throughout their decarbonisation path and address an identified lack in the extant literature, a framework has been outlined as per Figure 1. The framework is intended to provide guidance in the selection of the most suitable GW practices given the specific requirements and existing constraints of the industrial system and logistics facility under examination, and to assess their impact from an energy, environmental and cost-effectiveness perspective. The framework was developed based on both academic literature and secondary sources, and further refined by means of empirical analysis. The research approach combines deductive and inductive methods, in line with Siems et al. [16], allowing flexibility for application across logistics facilities varying industries, sizes, and operating conditions, without reliance on specific simulation software.



**Fig. 1.** Sustainable and energy-efficient industrial systems: framework for GW practice selection and implementation at logistics facilities. Adapted from: Perotti and Colicchia (2023).

The identification process of GW practices requires a closed-loop simulation process with a priority-based approach. Each practice is selected based on its impact on end-use types, related environmental (i.e.,  $\text{CO}_2_{\text{eq}}$ ) and economic KPIs in order to implement the most convenient measures in terms of energy efficiency improvement and environmental impact, without neglecting the related economic benefits. Design Builder has been selected as the modelling and simulation software, coherently with previous studies in the literature that were dedicated to building energy simulation in other sectors [17]. Design Builder (based on Energy Plus engine) is a comprehensive software for energy simulations and energy analysis. It encompasses detailed 3D digital model allowing the assessment of energy consumption and  $\text{CO}_2_{\text{eq}}$  emissions through simulating alternative scenarios.

For the application of the proposed framework, a conditioned logistics facility of a cosmetics distributor located in Northern Italy was selected. In accordance with the proposed methodological framework, the 3D model of the logistics facility was developed leveraging data concerning the corresponding employed units, operational factors, and structural features of the building, gathered directly from semi-structured interviews and ad hoc on-site visits.

A base case scenario was first simulated, including all the GW practices already implemented by the company (i.e., photovoltaic (PV) panels on rooftop, LED lighting system in some areas of the logistics facility). Starting from the base case, four alternative scenarios were then simulated:

1. Scenario A: Installation of LED bulbs throughout the entire logistics facility,
2. Scenario B: Heat pump system's implementation,
3. Scenario C: Thermal insulation of the logistics facility (i.e., building envelope),
4. Scenario D: Building envelope's thermal insulation and heat pump system implementation.

For each scenario the resulting yearly energy consumption, disaggregated the corresponding energy sources (i.e., electricity and natural gas), the average monthly self-consumption ratio, the corresponding CO<sub>2</sub><sub>eq</sub> emissions, and economic KPIs related to the implemented GW practices were then presented and discussed.

## 4 Simulation Model

The investigated conditioned warehouse has a total floorspace of 3,500 m<sup>2</sup> and a building clear height ranging from 8 to 10 m (i.e., sloping roof). Eight different zones can be identified, namely receiving, storage, picking, order preparation, e-commerce, packing, shipping and offices, each with a temperature ranging between 15 °C and 28 °C, set both for employees' well-being and goods' requirements.

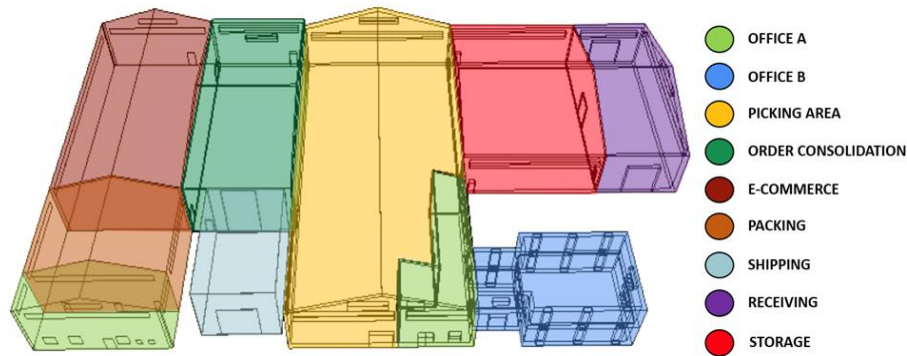


Fig. 2. Warehouse representation by zone

### 4.1 Base Case Scenario

Artificial lighting is provided by LED and fluorescent bulbs in line with the illuminance levels (lux) identified by the UNI EN 12464-1 standard. According to Füchtenhans et al. [10], LED bulbs luminous efficiency is estimated to be approximately equal to 100 lm/W in warehouse areas for residential use (e.g., offices) and 200 lm/W in industrial ones (i.e., all the others). On the other hand, the luminous efficiency of fluorescent bulbs is estimated to be approximately equal to 50 lm/W and 100 lm/W for offices and industrial zones respectively.

Table 1. Lighting requirements for each warehouse zone

Zone	Floorspace [m <sup>2</sup> ]	Illuminance [lux]	Lighting power [kW]
Office A	345.0	500	1.73
Office B	305.7	500	3.06
Picking	917.2	200	0.92
Order consolidation	414.6	200	0.41
E-Commerce	509.2	200	0.51

Packing	197.8	300	0.30
Shipping	138.4	200	0.14
Receiving	259.1	200	0.52
Storage	458.9	150	0.69

Material handling is executed manually by using forklift trucks powered by lead-acid batteries. Table 2 provides a detailed overview on size and features of the material handling equipment (MHE) fleet, as well as energy consumption required by charging operations.

**Table 2.** Size and features of MHE fleet

Type	Fleet size [No.]	Battery capacity [kWh]	Avg. charging time [h]	Avg. charging rate [kWh/h]	Charging Frequency [charges/day]	Total energy consumption [kWh/day]
Reach Trucks	2	20.8	8	2.6	1	41.6
Counterbalanced	2	29.1	8	3.6	1	58.2

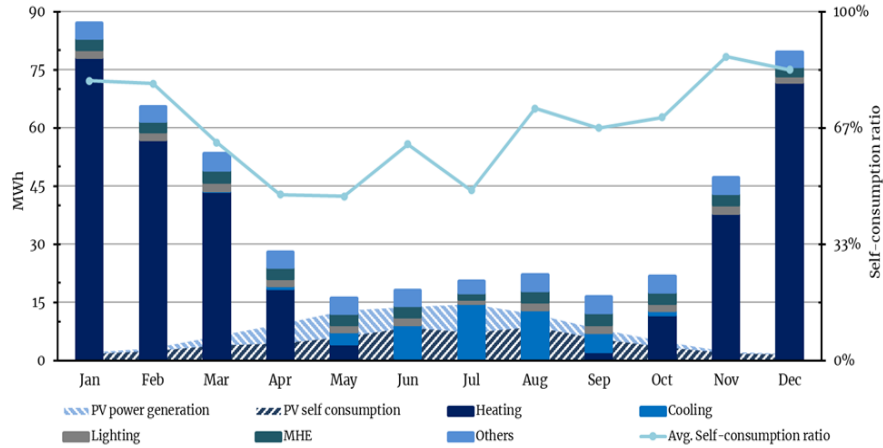
To perform the above-mentioned scenarios, the following assumptions has been made:

- Forklifts charging operations were carried out overnight,
- Forklift charging losses were assumed to be 15% of the battery's capacity according to Rand et al. [18]
- The grid-related energy losses referred to on-site power renewable generation units (i.e., PV panels) are assumed as negligible,
- The air circulation rate for mechanical ventilation is assumed to be 0.9 Vol/h.
- Packing system requires an average electrical power of 5 kW,
- One Standard Cubic Meter ( $\text{Sm}^3$ ) of natural gas used for energy, environmental and economic assessment is assumed equal to 10,69 kWh,
- In the assessment of  $\text{CO}_2_{\text{eq}}$  emissions, a conversion factor of 0.259  $\text{gCO}_2_{\text{eq}}/\text{kWh}$  for electricity and 0.233  $\text{gCO}_2_{\text{eq}}/\text{kWh}$  for natural gas has been adopted according to the ISPRA report [19],
- The investment cost of GW practices has been estimated using DesignBuilder database,
- In the economic assessment, the average price electricity and natural gas was assumed 0.23 €/kWh and 0.80 €/Sm<sup>3</sup> respectively, according to ARERA [20].

In accordance with the previously highlighted framework, the base case scenario was simulated to compare results with real data collected by the company and identify any critical consumption areas. To achieve this purpose, heating-related natural gas consumption was converted to electricity in terms of kWh, so that consumption from different energy sources can be compared.

The monthly consumption breakdown by main end use type (i.e., heating, cooling, lighting, MHE, and mechanical ventilation or others) is reported in Figure 3. Con-

sumption results are in line with real data collected by the company, thus validating the model.



**Fig. 3.** Monthly electricity consumption breakdown

#### 4.2 Scenario A

The installation of LED bulbs throughout warehouse floorspace, replacing fluorescent light bulbs (Scenario A) was first simulated. This measure can be considered a mutually beneficial solution thanks to its ease of implementation and minimal capital expenditure, as documented by GILA [21].

#### 4.3 Scenario B

As a second step (Scenario B) the implementation of a heat pump system was simulated. This system replaced the traditional boiler system for heating generation completely electrifying the building energy load. In this context, the Coefficient of Performance (COP) for the heat pump was set equal to 2.0 for heating and 2.5 for cooling as suggested by Nyers et al. [22]. Based on yearly heating and cooling loads of the logistics facility, the heat pump system must have a power capacity of 250 kW to meet them.

#### 4.4 Scenario C

Thermal insulation of the envelope was then implemented by setting parameters related to the building construction layers. Specifically, variations of the insulation thicknesses added to the external envelope and structural and thermal features of the openings were simulated. Each intervention was estimated in compliance with the current technical standards UNI EN ISO 9946 (i.e., related to the external envelope) and UNI EN ISO 10077-1 (i.e., related to openings). Thus, transmittance values achieved are 0.22 W/m<sup>2</sup>K for roofs and external walls, 0.57 W/m<sup>2</sup>K for external and internal walls and 1.22 W/m<sup>2</sup>K for openings.

#### 4.5 Scenario D

Lastly, the joint adoption of both thermal insulation of the envelope insulation and heat pump system was simulated. As modifying the envelope's thermal insulation results in a significant impact on the buildings' demand profile (and thus the resulting peak load) ([23]; [24]), thermal insulation was assumed to be first implemented, followed by the heat pump system's installation, so that it could be sized according to the already reduced demand profile. Accordingly, based on the new yearly heating and cooling loads of the logistics facility, the heat pump system required a power capacity of 90 kW.

### 5 Results and Discussion

The simulation results of Scenario A show that the logistics facility's annual electricity demand slightly decreased. Even though LED light bulbs have a notable impact on lighting consumption compared to the base case (-25%), the introduction of such GW practice has a negligible impact due to the small contribution of lighting to total energy consumption. Such measure is also extremely cost-effective, with a high Return on Investment (ROI) equal to 70%, and a quick Payback Period (PBP) of about 1 year.

Regarding Scenario B, results demonstrate that the total yearly energy demand further decreases (-53%), compared to the base case, mainly due to both energy savings in cooling (-68%) and heating (-60%). On the other hand, average monthly self-consumption ratio further increases (+5%) due to the large increase in electrical loads (i.e., electrification of heating system). Nevertheless, such a scenario is not particularly economically viable due to limited electricity savings. Although gas consumption was totally removed, electricity consumption doubled due to high building thermal loss. Looking at Scenario C, findings indicate that total yearly energy demand decreases (-34%) compared to the base case but at a lesser extent if compared to Scenario B (+41%). These results are mainly due to the inefficiency of the current HVAC system (i.e., conventional gas-fired boiler) leading to financial consequences (i.e., long payback period, limited cost savings). Finally, in Scenario D the joint implementation of thermal insulation envelope followed by heat pump system was simulated. Hence, results show a large yearly energy consumption decrease compared to the previous case (-62%) and base case (-75%) scenario. On the other hand, the average monthly self-consumption ratio was reduced compared to the base case scenario (-4%) due to the lowest value achieved in terms of annual energy consumption compared to all other scenarios investigated. To provide further insights on the impact of the investigated interventions, monthly energy consumption by energy source (electricity and natural gas), environmental KPIs – e.g., Energy Used Index (EUI), CO<sub>2</sub><sub>eq</sub> emission intensity – and some relevant economic KPIs (e.g., ROI, PBP) for the examined scenario are reported in Table 4.

**Table 3.** Monthly energy consumption [MWh] breakdown and KPIs for each scenario.

Months	BASE CASE		SCENARIO A		SCENARIO B		SCENARIO C		SCENARIO D	
	* Net Electricity	Gas	* Net Electricity	Gas	* Net Electricity	Gas	* Net Electricity	Gas	* Net Electricity	Gas
Jan	7,1	78.3	6,6	78.7	38,3	-	7,1	46,0	17,5	-
Feb	6,0	57.0	5,6	57.5	28,6	-	6,2	35,4	13,7	-
Mar	5,7	43.7	5,4	44.1	21,9	-	6,1	28,7	11,0	-
Apr	4,8	18.6	4,6	18.9	10,6	-	5,2	13,7	6,4	-
May	5,8	4.3	5,6	4.3	5,9	-	5,3	4,0	4,5	-
Jun	8,9	0.7	8,5	0.8	5,2	-	5,9	0,9	4,1	-
Jul	13,2	0.1	12,7	0.1	4,5	-	5,2	0,1	2,7	-
Aug	13,2	0.3	12,6	0.3	6,3	-	7,6	0,3	4,8	-
Sep	8,7	2.3	8,2	2.3	6,9	-	7,3	2,3	5,7	-
Oct	6,5	11.8	6,1	12.0	10,5	-	6,8	8,4	7,2	-
Nov	7,3	38.0	6,8	38.4	22,5	-	7,7	23,7	12,4	-
Dec	6,3	71.8	5,9	72.1	34,9	-	6,3	36,3	14,5	-
Total energy consumption [MWh]	93,4	326.8	88,6	329.5	196,2	-	76,8	199,7	104,5	-
EUI [kWh/m <sup>2</sup> ]	420,2		418,1		196,2		276,5		104,5	
Avg. monthly self consumption ratio	120,1		119,5		56,0		79,0		29,9	
CO <sub>2</sub> e emission intensity [kgCO <sub>2</sub> e/m <sup>2</sup> ]	67 %		65 %		70 %		62 %		63 %	
ROI	28.5		28.3		14.3		18.8		7.6	
PBP [years]	-		70%		6%		3%		5%	
	-		1.4		14		35		20	

\* Net Electricity refers to the electricity required minus energy produced and self-consumed on-site from renewable energy (i.e., PV panels).

Moreover, monthly CO<sub>2</sub>e emissions for each scenario were also computed, as reported in Figure 4.

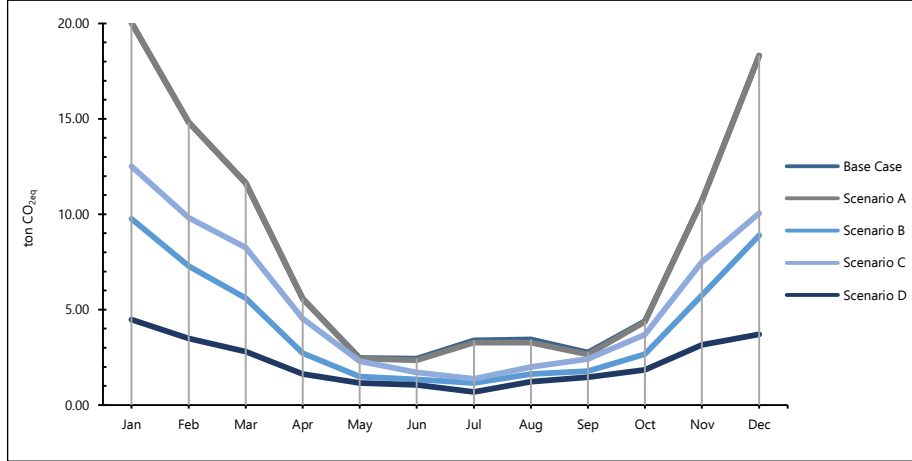


Fig. 4. Monthly CO2eq emissions for each scenario

## 6 Conclusions

In this study, a simulation-based approach was proposed with multiple scenarios of a real conditioned logistics facility, grounded on a conceptual framework that offers a roadmap towards sustainable warehousing. The simulation was conducted under five scenarios: existing condition, LED lighting systems implementation, heat pumps installation, thermal insulation of the envelope, and the simultaneous implementation of thermal insulation and heat pump system. Results were analyzed and discussed based on different KPIs such as monthly energy consumption by energy source, Energy Used Index (EUI), CO<sub>2eq</sub> emission intensity, ROI and PBP. It was demonstrated that LED light bulbs are the most cost-effective measure with a high return on investment and a short payback time in line with [10]. However, a critical correlation was noted between heat pump system's implementation and thermal insulation envelope. Even though these GW measures provide significant energy savings, they appear as not cost-effective if implemented individually. Conversely, by thermally insulating the logistics building first, heat pump size is determined based on a much lower energy demand compared to sizing on base case, avoiding potential energy inefficiencies and providing economic benefits. Although this study addresses a notable gap in the existing literature, it does come along certain limitations, since maintenance expenses of GW measures investigated were neglected. Moreover, it focused exclusively on electricity and gas consumption intentionally ignoring other sources (e.g., refrigerants, waste, water) that have typically a small impact (i.e., around 5% of the GHG emissions of ambient temperature sites in Italy can be allocated to this sources of consumption) as pointed out by Perotti & Colicchia [5]. However, this contribution can pave the way for promising developments for future investigation: (a) performing an economic analysis that considers all the benefits and costs direct and indirect of the GW measure under investigation; (b) the simulation model can be extended by con-

sidering other energy sources; (c) battery energy storage for self-consumption ratio increase can be further evaluated.

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