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Assessing the impact of smart lighting systems and on-site renewable generation in a distribution warehouse: a simulation-based approach

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Abstract

In the arena of logistics management, green warehousing has been achieving increasing attention from both practitioners and academia. On the one hand, practitioners – e.g., Logistics Service Providers (LSPs), manufacturers, and retailers – have been looking for solutions to decrease the environmental impact of their logistics facilities and incorporate measures towards greener warehousing processes. However, on the academic side, although a rising number of papers have been found addressing logistics sustainability, a need has emerged to focus on warehouses by analyzing the impact of the energy efficiency measures in place, and the related effects on warehouse consumption and environmental performance. This contribution aims at addressing this research gap. The paper proposes a simulation model based on DesignBuilder and EnergyPlus software and examines the impact of both interventions on the lighting systems and the introduction of on-site renewable generation in a distribution warehouse. Three different scenarios are proposed, and the related performance are examined in terms of consumption figures and CO_{2eq} emissions. A discussion on the roadmap towards net-zero logistics facilities is offered, and streams for future investigation are highlighted.

Keywords: Sustainable Logistics, Green Warehousing, Energy efficiency, Smart Lighting Systems, PV panels

1. Introduction

Warehouses have traditionally been recognized as key components of supply chains (Liu et al., 2010) as they have a direct impact on companies' service levels and logistics costs. Significant changes in warehouses have been observed over time, which have led to an increase in the corresponding complexity (Baglio et al., 2019). This evolution is mainly driven by the recent trends and challenges characterizing the logistics sector, such as the rise of e-commerce and omni-channel retailing – e.g., entailing the need for large regional centers and smaller urban warehouses –, digitalization and the advent of Logistics 4.0. From a sustainability perspective, all those changes have impacted the energy consumption, resource usage at the site, and the corresponding greenhouse gas (GHG) emissions (Bartolini et al., 2019).

Owing to the rising energy prices, increasing environmental concerns, and resource shortages, companies have been forced to reduce their energy consumption (Füchtenhans et al., 2023). Within this context, as the warehousing industry is growing at a rate of 6–7%, the resulting environmental impact (e.g., the corresponding emissions) is inevitably increasing and measures to mitigate such an impact should consequently be taken (Oloruntobi et al., 2023). It should be also noted the increasing pressure from a variety of stakeholders, such as investors and the entire society, are making sustainability one of the key drivers in the logistics decision-making processes (including the case of warehouses) (Perotti et al., 2022). The measures aiming to achieve improved warehouse environmental performance and higher energy efficiency have been clustered by some scholars in the concept of green warehousing, which is defined by Bartolini et al. (2019) as a managerial concept integrating environmentally friendly solutions with the objective of minimizing energy consumption, the energy cost, and the emissions of a warehouse.

From the practitioners' side, a growing interest among companies has been found in green warehousing measures. Increasing investments in this area have recently been dedicated in the warehousing industry, especially interventions on the lighting systems (e.g., energy efficient LED lamps) and the installation of on-site renewable generation (e.g., by means of rooftop photovoltaic panels). Such measures have been found to be particularly promising as they could lead to significant improvements from both the environmental and economic perspectives (Perotti et al., 2022; Maturo et al., 2022; Ries et al., 2017)

From an academic perspective, the interest towards green warehousing measures has increased considerably in recent years (Lewczuk et al., 2021). A classification of current green warehousing measures was proposed by Perotti et al. (202), where six main clusters were identified, namely green building, utilities, lighting, material handling and automation, materials, and operational practices. As of now, the most frequently discussed aspects in the extant literature concern green building and material handling, whereas lighting and utilities – such as heating, ventilation, and air conditioning (HVAC), or photovoltaic panels – have been less investigated so far (Taheri et al., 2022). Furthermore, a need has emerged to perform investigations on real cases to analyze how green measures can decrease emissions and energy consumption in warehousing (Bartolini et al., 2019).

To fill this gap, in the present paper, a simulation-based approach is proposed to assess the impact of both interventions on the lighting systems (i.e., employing energy efficient LED lamps and the utilization of a smart lighting systems) along with the introduction of on-site renewable generation (i.e., by means of rooftop photovoltaic panels) in a distribution warehouse. In this context, a real central distribution warehouse located in Northern Italy is considered and modelled. The models are developed and simulated using DesignBuilder (that use the EnergyPlus program). Accordingly, In the first step, the developed impact of replacing the lighting units with LED lamps and the influence of employing a smart lighting system (that permits reducing the lighting system's consumption through daylight harvesting) on the yearly energy consumption and CO_2 emissions of the warehouse is investigated. In the next step, while considering the reduced consumption profile (with LED lamps equipped with smart lighting system), the impact of installation of rooftop PV panels on the net (exchanged with the grid) yearly consumption of the warehouse and the resulting CO_2 emissions is assessed. In this context, a scenario with PV panels sized to address 1/3 of the building's yearly electricity demand is considered and investigated. Finally, a discussion on the roadmap towards net-zero logistics facilities is offered, and streams for future investigation are highlighted.

The remainder of the paper is structured as follows. The next section includes a background literature related to green warehousing measures, with a specific focus on interventions on the lighting systems and the use of renewable energy sources. The methodology is then described, followed by the illustration of the results for each investigated scenario. Finally, discussion and implications are provided, and conclusions are drawn, along with limitations of the study and recommendations for further studies in the sector.

2. Background literature

2.1. Lighting energy efficiency in warehouses

Lighting is often considered the main source of energy consumption in warehouses, but there is no consistent estimate in the literature (Fichtinger *et al.*, 2015) in this regard. Some scholars argue that in warehouses lighting accounts for 65% of total energy consumption, thus significantly contributing to operational energy costs and emissions of the facility (Füchtenhans et al., 2023). Other sources attest an overall share of 28% due to lighting indoors, activity cluster, with chilling of goods being equal to 35% and material handling to 19% (Dobers *et al.*, 2023)

New lighting technologies, such as LED, have recently emerged that allow achieving higher efficiency. The energy saving potential of LED lighting is enormous and this technology has already become a popular lighting equipment in the warehousing sector (Maurer, 2015). Furthermore, LED lighting systems differ from traditional lighting systems (e.g., incandescent bulbs and fluorescent bulbs) in terms of flexibility. LED bulbs can also allow a lighting control by providing the required light intensity depending on the daylight availability at the warehouse (daylight harvesting) and/or the presence of operators in the warehouse (occupancy sensor). These solutions are commonly clustered in the literature under the category of smart lighting systems (Füchtenhans et al., 2019).

2.2. Renewable energy sources in warehouses

A progressive trend in the installation of on-site renewable generation in logistics facilities (to reduce energy consumption from the grid) has been observed in recent years. In this context, the most widely used renewable energy source is solar energy through photovoltaic (PV) panels' installation (Dobers et al., 2022). It has been demonstrated that, given the continuous decrement in the price of PV panels in recent years, these units offer the lowest payback period for small/medium scale decentralized renewable generation (Maturo et al., 2022). For the case of warehouses and other similar type of building, the rooftop is often used for the installation of PV panels to maximize the incident solar irradiation and space utilization (Lewczuk et al., 2021).

The potential of PV panels is notable and several benefits have been observed over time, such as energy cost reduction (Yassine et al., 2016) through reducing the energy consumption from the grid. Benefits may vary depending on the building's characteristics, technical specifications, climate and local weather conditions (Jacobson and Jadhav, 2018).

3. Methodology

The DesignBuilder software (interface), which employs EnergyPlus energy simulation program, in coherence with previous papers assessing building energy simulation in other business sectors (Cook and Sproul, 2011) has been chosen as the modelling and simulation tool. In this extent, the warehouse of a Logistics Service Provider (LSP) located in Northern Italy is considered as the case study. Employing the geometrical characteristics of the facility and the empirical data on its main end-use types (namely, lighting, material handling equipment (MHE), auxiliary systems, and cooling) and their energy consumption, which were collected by means of interviews and on-site visits, a model of the warehouse in the existing conditions is developed. Given the purposes of the present paper that is focused on the electrical consumption, the results corresponding to the heating system's consumption (as it is fed by the natural gas) are not discussed. Using the developed model, the base-case scenario is first the simulated, in which the yearly energy consumption and the resulting CO_{2eq} emissions of the warehouse with conventional lighting system (fluorescent bulbs) and no on-site renewable generation is determined. Next, the simulations are performed considering 3 different scenarios:

- Scenario A: Replacement of existing lighting system with LED bulbs.
- Scenario B: Introduction of smart lighting systems through LED technology and lighting control.
- Scenario C: PV panels installation, sized to meet 1/3 of the building's yearly electricity demand.

The resulting net yearly energy consumption (received from the grid) and the corresponding CO_{2eq} emission, for each scenario, is then presented and discussed. For the case of Scenario C, identified number of required PV panels is also reported.

4. Simulation model

4.1. Base-case scenario

The examined warehouse is kept in ambient temperature (conditioning is only provided for offices) and has a total floorspace and building clear height of 40,000 m² and 15 m respectively. The building can be ideally divided into different functional zones based on the corresponding performed activities: storage, cross-docking, and offices (arranged on two floors) as shown in Figure 1.

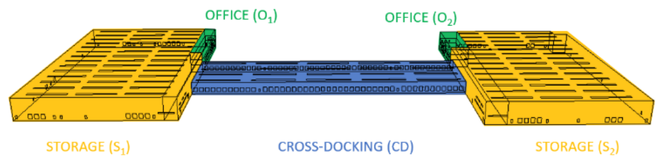

Figure 1 Base-case: layout breakdown by warehouse functional zones

On the one hand, artificial lighting is provided with large, suspended fluorescent bulbs in storage and cross-docking areas with a luminous efficiency of approximately 100 lm/W, while in the office areas is provided with compact fluorescent light (CFL) bulbs with a luminous efficiency of approximately 50 lm/W. On the other hand, natural lighting is guaranteed by skylights on the rooftop. Target illuminance and lighting power required for each activity zone are modelled according to the UNI EN 12464-1 as summarized in Table 1.

Table 1 Lighting requirements for each warehouse functional zone according to UNI EN 12464-1

Zone	Space [m²]	Illuminance [lux]	Lights [kW]
Zone S_1 (storage)	14,947	150	22.42
Zone S_2 (storage)	14,792	150	22.19
Zone C (cross-docking)	8,325	200	16.65
Zone O_1 (office) - two floors	1,105	500	11.05
Zone O_2 (office) - two floors	1,215	500	12.15

Material handling is performed manually by means of forklift trucks. Table 2 summarizes features and size of the MHE fleet and the related energy consumption in charging operations.

Table 2 Energy consumption of MHE fleet

Type	Fleet size [No.]	Average charging value [kWh/h]	Average charging time [h]	Total energy consumpti on [kWh/day]
Pallet trucks	23	1.2	1	27.6
Order pickers	10	1.68	7	117.6
Reach trucks	12	3.36	5.5	221.7
Counterbalance forklifts	18	5.6	6.5	655.2

While performing the above-mentioned scenarios, the following assumptions are made:

- Forklifts are equipped with conventional lead-acid batteries;
- Forklifts are subject to charging operations once per day (overnight);
- Charging operations entail that batteries are fully recharged, and recharging is required with 20% battery capacity;
- Charging operations are performed with standard chargers (i.e., no fast chargers);
- Lighting controls implemented in scenario B are based on daylight harvesting system with linear control. (i.e., the bulbs dim continuously and linearly from maximum light output to minimum light output as the daylight illuminance increases);
- Average yield of PV installations in Italy is considered to be 1,137 kWh/kWp per year (IEA, 2021);
- Each PV panel (sized 1.7 × 1.0 m^2) generates 0.3 kWp;
- For CO_{2eq} emission assessment, a conversion factor equal to 0.261 kg CO_{2eq}/kWh has been considered according to ISPRA (2021).

Based on these assumptions, the base-case scenario is simulated to determine the monthly electricity consumption over a year for the main end-use types of the logistics facility under investigation as shown in Figure 2.

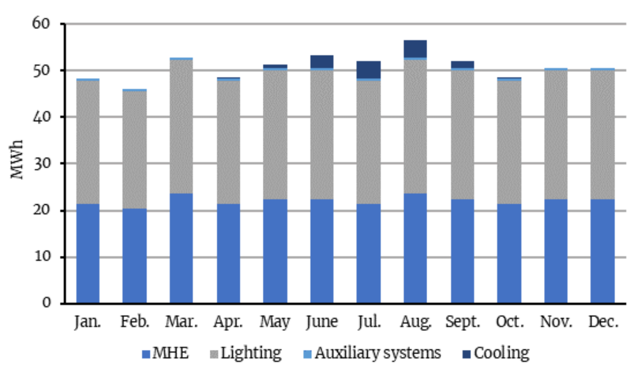

Figure 2 Monthly electricity consumption breakdown

4.2. Scenario A and B: LED technology and lighting control

Focusing on the lighting systems, the replacement of the existing lighting system with LED technology is first simulated (Scenario A) and the concurrent introduction of smart lighting systems through LED technology and lighting control is then considered (Scenario B).

4.3. Scenario C: on-site renewable generation through PV panels on the rooftop

In the next step, focused the impact of on-site renewable generation, the influence of PV panels installation on the rooftop, the size of which is chosen (iteratively through running simulations) to address 1/3 of the building's yearly electricity demand, is investigated. The total electricity consumption profile resulting from Scenario B is considered as a starting point for this scenario.

The sizing of PV power to be installed is based on guidelines provided by Jacobson, M. Z. & Jadhav, V. (2018), which denote the best configuration to adopt to increase the yield of PV panels through maximising the direct exposure to sunlight. The solar PV optimal tilt angle (number of degrees from the horizontal plane) in the simulated scenario is 27° and the PV azimuth (the direction towards which PV panels face) is considered to be south oriented.

5. Results and discussions

The simulation results of the first scenario demonstrated that the yearly electricity demand of the logistics facility has been considerably reduced, resulting in 27% decrement in comparison to the base case scenario. This decrease is mainly due to the reduction in the lighting demand and, to a lower extent, to the decrease in the cooling consumption (as improving the luminous efficiency also leads to a reduction in the heat emitted by bulbs). However, it is noteworthy that the latter effect is offset by the corresponding rise in the fuel consumption required for heating (which is not discussed in this work).

Regarding the second scenario, the results demonstrated that the total yearly electricity demand further decreases due to better use of sunlight to illuminate each zone, achieving a saving of 41% compared to the base case scenario. It should be noted that, compared to the Scenario B, the greatest savings was achieved in the summer period, as it is characterized by longer daytime duration.

Through simulating the last scenario focused on PV panels' installation on the rooftop, it was shown that the yearly consumption of the electricity, compared to the Scenario B, was expectedly reduced by over 33% (as around 1/3 of the yearly demand was planned to be addressed). Furthermore, a reduction of 61% compared to the base case scenario was demonstrated. It was also shown that to achieve the latter aim, 530 PV panels (with the size of 1.7 × 1.0 m2 generating 0.3 kWp) were required. It is also worth noting that a self-consumption ratio of only 58% of the generated renewable energy was achieved, which is largely due to inability to meet the electricity demand for material handling equipment the charging operations of which are carried out overnight.

To provide further insights on the impact of the investigated interventions, the simulated monthly electrical consumptions for the base case along with those determined for the three simulated scenarios are reported in Table 3. Furthermore, other relevant KPIs that allow internal comparisons and benchmarking with respect to other logistics facilities, such as CO_{2eq} emission intensity (measured in terms of CO_{2eq}/m2), and the Global Energy Performance (GEP) (measured in terms of kWh/m^2) are also reported in Table 3.

Table 3 Monthly consumption figures for each scenario

	Total electricity consumption [MWh]			
Month	*Base case*	*Scenario A*	*Scenario B*	*Scenario C*
Jan.	48.4	35.1	30.1	27.1
Feb.	46.1	33.4	28.2	24.5
Mar.	53.0	38.4	31.3	23.6
Apr.	48.4	35.1	27.9	16.3
May	51.4	37.2	28.6	10.2
June	53.2	38.8	29.9	9.6
Jul.	52.0	38.1	29.8	9.0
Aug.	56.6	41.5	33.0	16.9
Sept.	52.1	37.9	30.7	20.8
Oct.	48.4	35.1	29.1	23.8
Nov.	50.7	36.8	31.6	29.0
Dec.	50.7	36.8	31.8	29.5
Total [MWh]	611	444	362	240
GEP [MWh/m^2]	15,6	11,5	9,5	6,4
CO2 emission intensity [CO_{2eq}/m^2]	3,9	2,9	2,3	1,5

Moreover, the monthly CO_{2eq} emissions for each scenario were computed, as reported in Figure 3. Monthly CO_{2eq} emissions shows a similar trend for the base case, A and B scenarios. This is mainly due the type of green warehousing measures carried out in the first two scenarios aimed at reducing only a specific type of end-user electricity loads (lighting). Looking at the Scenario C, it shows a typical trend, namely bathtub curve, marked by a large CO_{2eq} emissions decrease during summer period, where PV panels' electricity generation is almost totally self-consumed.

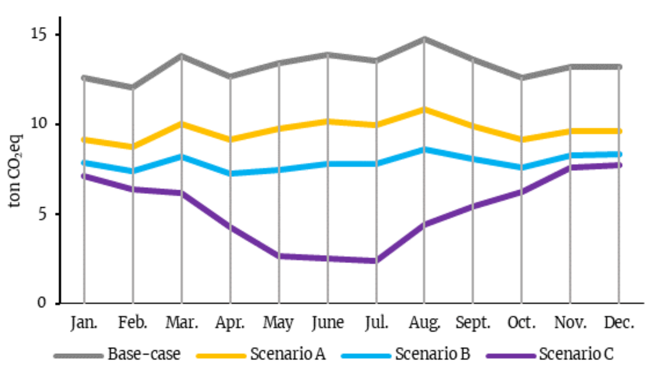

Figure 3 Monthly CO_{2eq} emissions for each scenario

6. Conclusions

Simulation performed using Designbuilder (based on EnergyPlus program) were used in this work in order to investigate the impact of smart lighting systems and on-site renewable generation in a distribution warehouse. The consumption profile of the facility was simulated with the existing conditions (base-case) and three further scenarios and the obtained results were presented in terms of consumption figures and $CO2_{eq}$ emissions. It was demonstrated that, by installing the smart lighting system equipped with the LED technology and the PV panels (with the described size), the yearly net consumption of the building is reduced by 61%. Although the results of the study address a major gap identified in the extant literature, some limitations do exist, since only electricity energy consumption was investigated, whereas the other sources of consumption suggested by previous scholars, such as fuels, refrigerants, water, and waste (Perotti et al., 2022) were not considered. However, this contribution can pave the way for future developments: (a) the model can be extended by considering other sources of consumption; (b) in terms of material handling system, the impact of lithium-ion batteries and fast partial charging operations during daytime can be taken into account, in line with (Colicchia et al., 2019); (c) the relationship between the choice of the lighting system and the effects on fuel consumption for heating purposes can be further investigated; (d) the impact of material handling operations on consumption figures and emissions can be analyzed by functional zone of the warehouse (e.g., highly-intense operations in the cross-docking area); (e) the effect of trends and seasonality on consumption and emissions can be further investigated.

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